Interim main report of the safety assessment SR-Can

Svensk Kärnbränslehantering AB

August 2004

SKB

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Preface

This document is an interim report on SKB's ongoing assessment of long-term safety for a KBS-3 repository. The assessment, SR-Can, will support SKB's application to build an Encapsulation plant for spent nuclear fuel, to be presented in 2006. The purpose of this interim report is to demonstrate the methodology for safety assessment so that this can be reviewed before it is used in a license application.

The undersigned has edited the report and has been responsible for the methodology development in collaboration with mainly Johan Andersson, JA Streamflow AB and Kristina Skagius, Kemakta Konsult AB.

The following persons have provided input to specific subject areas: Kastriot Spahiu (fuel); Lars Werme (fuel and canister); Patrik Sellin (buffer and backfill); Jan-Olof Selroos (geosphere flow and transport); Harald Hökmark, Clay Technology AB and Raymond Munier (geomechanical issues); Ignasi Puigdomenech (geochemistry); Lena Morén (climate and intrusion issues); Ulrik Kautsky (biosphere), Fred Karlsson (natural analogues) and Fredrik Vahlund and the undersigned (integrated radionuclide transport modelling).

Jürg Schneider, Nagra, Timo Vieno, VTT Energy and Margit Snellman, Posiva kindly provided comments on an early version of this document.

The report has been reviewed by the following members of SKB's international Site Investigation Expert Review Group (SIERG): Per-Eric Ahlström, SKB (chair); Jordi Bruno Enviros, Spain; John Hudson, Rock Engineering Consultants, UK; Ivars Neretnieks Royal Institute of Technology, Sweden and Mike Thorne, Mike Thorne and Associates Ltd, UK. This group provided many valuable comments and suggestions and is not responsible for any remaining shortcomings of this report.

Stockholm, August 2004

Allan Hedin

Summary

Introduction

This document is an interim report on the safety assessment SR-Can[1]. The final SR-Can report will support SKB's application to build an Encapsulation plant for spent nuclear fuel and is to be produced in 2006. The purpose of this interim report is to demonstrate the methodology for safety assessment so that this can be reviewed before it is used in a license application. The assessment relates to the KBS-3 disposal concept in which 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. Preliminary data from the Forsmark site, presently being investigated by SKB as one of the candidate for a KBS-3 repository are used to some extent as examples. However, the collected data are yet too sparse to allow an evaluation of safety for this site.

An important aim of this report is to demonstrate the proper handling of requirements on the safety assessment in applicable regulations. Therefore, regulations issued by the Swedish Nuclear Power Inspectorate (SKIFS 2002:1) and the Swedish Radiation Protection Institute (SSI FS 1998:1) are duplicated in an Appendix where references are given to sections in the main text where the handling of the different requirements is discussed. The principal acceptance criterion requires 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". "Harmful effects" refer to cancer and hereditary effects. The risk limit corresponds to a dose limit of about $1.4 \cdot 10^{-5}$ Sv/yr. This, in turn, corresponds to around one percent of the natural background radiation in Sweden

General Methodology

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,

- a number of radiation related, thermal, hydraulic, mechanical, chemical and biological processes acting within the repository system over time and

- external influences acting on the system.

A methodology in 11 steps has been developed for SR-Can, summarised in Figure 1:

1. Identification of factors to consider, FEP processing

   This step consists of identifying all the factors that need to be included in the analysis. Experience from earlier safety assessments and KBS-3 specific and international data-bases of relevant features, events and processes (FEPs) influencing long-term safety are utilised. An SR-Can FEP database is developed where the great majority of FEPs are classified as being either initial state FEPs, internal processes or external FEPs. Remaining FEPs are either related to assessment methodology in general or deemed irrelevant for the KBS-3 concept.

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[1] The SR in the acronym SR-Can stands for Safety Report and Can is short for canister. This title of this report was chosen since it supports the application to build an encapsulation plant.
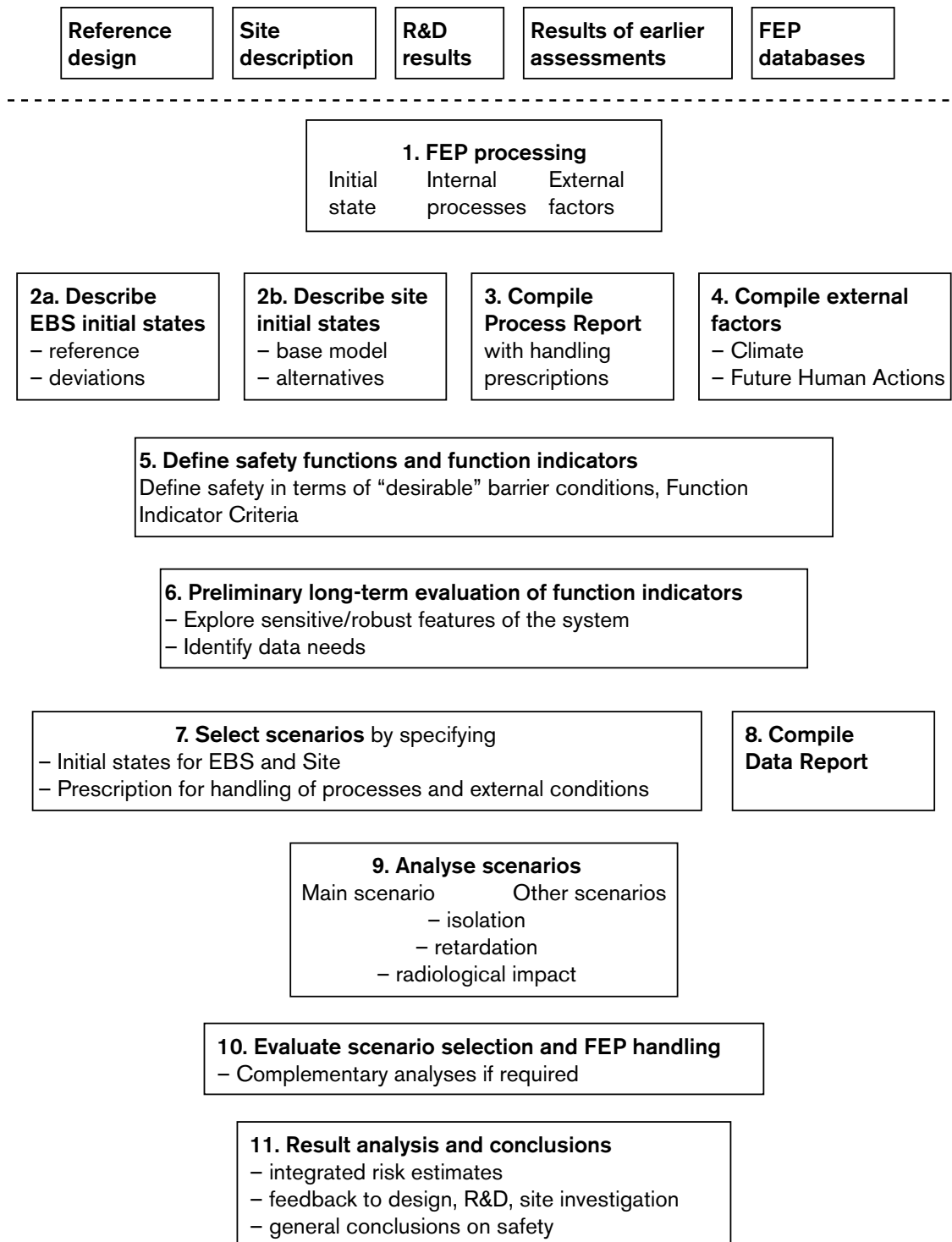
Reference design	Site description	R&D results	Results of earlier assessments	FEP databases

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1. FEP processing

Initial state	Internal processes	External factors

2a. Describe EBS initial states – reference – deviations	**2b. Describe site initial states** – base model – alternatives	**3. Compile Process Report** with handling prescriptions	**4. Compile external factors** – Climate – Future Human Actions

5. Define safety functions and function indicators
Define safety in terms of "desirable" barrier conditions, Function Indicator Criteria

6. Preliminary long-term evaluation of function indicators
– Explore sensitive/robust features of the system
– Identify data needs

7. Select scenarios by specifying – Initial states for EBS and Site – Prescription for handling of processes and external conditions	**8. Compile Data Report**

9. Analyse scenarios

Main scenario   Other scenarios
– isolation
– retardation
– radiological impact

10. Evaluate scenario selection and FEP handling
– Complementary analyses if required

11. Result analysis and conclusions
– integrated risk estimates
– feedback to design, R&D, site investigation
– general conclusions on safety

Figure 1. *An outline of the eleven main steps of the safety assessment SR-Can.*

2. Description of initial state

The initial state of the system is described, based on the design specifications of the KBS-3 repository, a descriptive model of the repository site and a site-specific layout of the repository. The initial state of the fuel and the engineered components is that immediately after deposition. The initial state of the geosphere and the biosphere is that of the natural system prior to excavation. A brief discussion of FEPs related to the initial state, e.g. mishaps and design deviations that are not detected by established control procedures, is given.

3. Description of processes

The identification of relevant processes based on earlier assessments and FEP screening as well as principles for process documentation is described. All identified processes within the system boundary relevant to the long-term evolution of the system are described in a dedicated Process report. Also short-term geosphere processes/alterations due to repository excavation are included. For each process, its general characteristics, the time frame in which it is important, the other processes to which it is coupled and how the process will be handled in the safety assessment are documented. An interim version of the process report, treating buffer processes, has been completed.

4. Description of external conditions

Factors related to external conditions are handled in the two categories "climatic and geological processes" and "future human actions". A brief description of the broad features of the long-term evolution of climate and of how this would influence the repository is given. A plan for handling uncertainties in the climatic evolution is developed, based on defined reference external conditions. The basis for the treatment of future human actions in SR-Can will be that adopted in the SR 97 assessment /SKB, 1999a/. Therefore, FEPs in the SR-Can database related to future human actions are audited against the SR 97 analysis results.

5. Definition of safety functions, function indicators and function indicator criteria

This step consists of a discussion of the safety functions of the system and of how they can be evaluated by means of a set of function indicators that are, in principle, measurable or calculable properties of the system. Criteria for the function indicators are provided. The Process report is an important reference for this step.

6. Preliminary long-term evaluation of function indicators

A preliminary evaluation of the evolution of the function indicators is provided, using a simplified process system and stylised external conditions. The purposes are to gain insights into the basic dynamics of the system, to identify critical input data through preliminary sensitivity analyses, to inform the subsequent selection of scenarios and to point to key issues for more detailed analyses.

7. Preliminary scenario selection

A preliminary set of scenarios for the assessment is selected. The bases for a comprehensive main scenario are i) the reference initial state considering also possible deviations from ideal conditions and ii) the reference external conditions with uncertainties. The function indicators and the results of the preliminary analyses of the evolution of these are used to focus the selection on key properties of importance for safety. Other scenarios are then selected to cover less probable conditions not included in the main scenario or to gain insights into the functioning of the system without necessarily being, in all respects, a reasonable representation of the system.

8. Input data selection

   Data to be used in the quantification of repository evolution and in dose calculations are selected and reported in a dedicated Data report. A flexible template for discussion of input data uncertainties has been developed. An interim version of the data report, focussing on overall methodology and migration data for the buffer, has been developed.

9. Analysis of scenarios

   The temporal evolution of the system is analysed for the selected scenarios. The isolating potential of the system is analysed in a first step, yielding a description of system evolution and a more detailed evaluation of the function indicators. If the evolution implicates breaching of isolation, the retarding potential of the repository and its environs is analysed and dose consequences are calculated for the long-term conditions in the first step. An important aim is to calculate a risk contribution for each of the selected scenarios, which are then to be added to give a total risk for the repository. This risk is to be compared to the stipulated risk criterion. Sensitivity analyses are performed on the results of the scenario analyses. Example calculations and plans for the analysis of the main scenario regarding i) general evolution and isolation potential and ii) retardation are provided in this interim report.

10. Evaluation and possible complementation of scenario selection

    Based on the insights gained in step 9, the preliminary selection of scenarios in step 7 is evaluated and, if required, complemented by the selection of additional scenarios and the undertaking of additional scenario analyses. Also, a final check that all relevant FEPs have been appropriately handled is done in this step.

11. Integration of results and conclusions

    This step includes integration of the results from the various scenario analyses, development of conclusions regarding safety in relation to acceptance criteria and feedback concerning design, continued site investigations and R&D programme. Some of the expected components in such a discussion are provided in this Interim report. The robustness of the repository system and the way in which different safety functions contribute to overall safety are natural components of this part of the safety report.

Function indicators and function indicator criteria

A number of preliminary criteria for the proper functioning of primarily the engineered barriers have been defined, based largely on results in the Interim Process report /SKB, 2004b/. The criteria are an aid in determining whether safety is maintained. If the criteria are fulfilled, the safety evaluation is facilitated, but fulfilment of function indicator criteria alone is not a guarantee that the overall risk criterion is fulfilled. On the other hand, compliance with the risk criterion could well be compatible with violation of one or several of the function indicator criteria. A violation would be an implication of caution; further analyses could be required in order to determine the consequences at a sub-system or an overall system level. Furthermore, it is recognised that there are several aspects of the repository evolution and barrier performance that cannot be readily captured by a simple comparison to a criterion. The preliminary function indicators and the corresponding criteria are summarised in Table 1.

Table 1. Summary of the function indicators and the criteria they should fulfil.

Function indicator	Criterion	Rationale
Canister		
Minimum copper thickness	$d_{\min}^{Cu} > 0$	Ensure isolation
Isostatic pressure on canister	$P_{Isostatic}^{Canister} < P_{Isostatic\ collapse}^{Can}$	Avoid isostatic collapse
Maximum canister temperature at water contact	$T^{Canister} < 100°C$	Avoid boiling on surface and thus salt deposits
Buffer		
Bulk hydraulic conductivity	$k^{Buff} < 10^{-12}$ m/s	Avoid advective transport in buffer
Swelling pressure	$P_{Swell}^{Buff} > 1$ MPa	Ensure tightness, self sealing
Maximum temperature	$T^{Buffer} < 100°C$	Ensure buffer stability
Minimum temperature	$T^{Buffer} > 0°C$	Avoid freezing
Buffer density around entire canister	$\rho_{Bulk}^{Buff} > \rho_{Sink}$ kg/m³	Avoid canister sinking (criterion to be determined)
Buffer density around entire canister	$\rho_{Bulk}^{Buff} > 1,800$ kg/m³	Exclude microbial activity
Buffer density around entire canister	$\rho_{Bulk}^{Buff} > 1,650$ kg/m³	Prevent colloid transport through buffer
Buffer density around entire canister	$\rho_{Bulk}^{Buff} < 2,100$ kg/m³	Ensure protection of canister against rock shear
Backfill in deposition tunnels		
Compressibility	$M^{Backfill} > 10$ MPa	Limit buffer expansion
Hydraulic conductivity	$k^{Backfill} < 10^{-10}$ m/s	Limit advective transport
Swelling pressure	$P_{Swell}^{Backfill} > 0.1$ MPa	Ensure homogeneity
Minimum temperature	$T^{Backfill} > 0°C$	Avoid freezing
Rock		
Redox conditions	No dissolved oxygen	The presence of measurable O_2 would imply oxidising conditions
Minimum ionic strength	$\Sigma[M^{2+}]^{GW} > 10^{-3}$ M (Total divalent cation conc.)	Avoid buffer erosion
Maximum chloride concentration or minimum pH	$pH^{GW} > 4$ or $[Cl^-]^{GW} < 3$ M	Avoid chloride corrosion of canister
Limited alkalinity	$pH^{GW} < 11$	Avoid dissolution of buffer smectite
Limited salinity	Buffer: [NaCl] < 100 g/l Backfill: [NaCl] < 35 g/l (Or other compositions of equivalent ionic strength)	Avoid detrimental effects, in particular on buffer and backfill swelling pressures
Limited concentration of detrimental agents for buffer and canister	Applies to HS^-, K^+ and Fe. The lower the better (no quantitative requirement)	Avoid canister sulphide corrosion, avoid illitisation (K^+) and chloritisation (Fe) of buffer and backfill
Limited rock shear at deposition holes	$d_{shear} < 10$ cm	Avoid canister failure due to rock shear at deposition holes

Preliminary evaluation of function indicators

The results of the preliminary evaluation of the function indicators suggest that several of the criteria will be fulfilled for the range of expected repository conditions. Data that need to be further evaluated are specified and a number of issues requiring further analysis are identified. Regarding the latter, the following are some of the conclusions:

- The likelihood of canister failure due to corrosion is very low, even when initial welding defects are taken into account. However, data for the evaluation of corrosion of welding defects need to be qualified and results based on qualified data propagated to consequence calculations.

- Canister failure due to isostatic overpressure seems to be ruled out. Considering, however, that the highest overpressures, i.e. those potentially caused by a glacial overburden, would affect all canisters, it is urgent to further substantiate this claim. In particular, it is important to establish a reliable collapse criterion through laboratory tests and supporting strength calculations.

- The likelihood of canister failure due to rock shear at deposition holes needs to be thoroughly evaluated.

- The possibility of penetration of oxygenated surface water to repository depths during glacial conditions needs to be further assessed.

- The buffer and backfill minimum temperature requirement of 0°C needs to be evaluated against maximum permafrost depths.

- Buffer and backfill erosion for dilute groundwaters (glacial conditions) needs to be further evaluated, both as regards possible water compositions and the quantitative effects of dilute waters.

- A deposition tunnel backfill material based on a mixture of clay and crushed rock is likely to fulfil the requirement on hydraulic conductivity for the expected range of repository conditions, provided that density is maintained. The swelling pressure criterion is not likely to be fulfilled for this backfill material.

- If the mixed backfill concept is to be further evaluated, it is important to study the effects of a collapsed backfill with a conducting zone at the tunnel ceiling in the consequence calculations.

Scenario selection

Applicable regulations mention 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. This has been the basis for the grouping of scenarios in SR-Can.

A scenario is defined by specifying an initial state of the engineered barrier system, an initial state (a conceptual interpretation) of the site and prescriptions for the handling of internal processes and external influences in the analysis of the scenario.

The scenario selection is based on the results of the FEP analysis, the initial state and process descriptions, the external influences and the understanding of the impact these factors have on safety as obtained from the preliminary analyses of function indicators and other sources. Table 2 summarises the preliminary scenario selection in SR-Can.

The first line of Table 2 defines the base variant of the main scenario. The repository is assumed to have been built according to specifications, i.e. the initial state of the engineered barrier system is in accordance with the design specifications with allowed tolerances. The initial state of the site is the base case interpretation of the site investigation data. Processes internal to the system are to be handled in accordance with prescriptions given in the Process report. The external conditions are defined in terms of a reference climate evolution, including a repetition of the latest glacial cycle, the Weichselian. No future human actions are considered in this scenario. Uncertainty analyses of the base variant will consider the possibility of human-induced greenhouse effects. The base variant represents the expected evolution of the repository. Other scenarios and variants are included to cover alternative interpretations of the site, alternative repository design options, future human actions etc. Most of the residual scenarios are of the "what if" type, exploring the functioning and the robustness of the system for unrealistic conditions. Several of the scenarios and variants will be defined in more detail based on results of further analyses as the project progresses.

Table 2. Results of the preliminary scenario selection. Green cells denote conditions for the base variant of the main scenario, red cells denote deviations from these conditions.

Scenario	Variant	Initial state EBS	Initial state Site	Process handling	Handling of external conditions
Main	Base	Reference ±tolerances	Base case model (with uncertainties)	According to Process report	Reference climate + uncertainty analyses No future human actions (FHA) considered
Main	ACM1* ACM2* etc	As base variant	ACM1* ACM2* etc	As base variant	Reference climate
Main	Alternative backfill material	As base, but alt. backfill mtrl	As base variant	As base variant	Reference climate
Less probable	FHA1, 2, 3…	As base variant	As base variant	As base variant	Reference climate + FHA1, 2, 3…
Less probable	Process alternatives?	As base variant	As base variant	Alt. handling	Reference climate
Less probable	Alternative external conditions?	As base variant	As base variant	As base variant	Alternative conditions
Residual	Open, pumped repository	As base, but open, pumped transportation tunnels etc	As base variant	As base, modified according to initial state	Reference climate
Residual	Open, deserted repository	As base, but open, deserted transportation tunnels etc	As base variant	As base, modified according to initial state	Reference climate
Residual	EBS initial deviations (several cases)	As base variant	As base variant	As base variant	Reference climate
Residual	Exploration of safety functions	Extreme variations	Extreme variations	Extreme variations	Extreme variations
Residual	Design basis calculations	Possibly additional cases	Possibly additional cases	Possibly additional cases	Possibly additional cases

*ACM: Alternative Conceptual Model of the site.

The main scenario

The main scenario will be analysed in two principal steps. In a first step, isolation is evaluated. If isolation is found to be breached, the further evolution of failed canisters is analysed in a second step including radionuclide transport and dose calculations for barrier conditions derived in the first step.

The analysis of the first step of the main scenario is done in a sequence of time periods: The excavation and operation phase, the first 1,000 years, a period of continued temperate climate of approximately 10,000 years, a reference glacial cycle assumed to be a repetition of the latest cycle, the Weichselian, and spanning 115,000 years and, finally, further glacial cycles until the end of the one million year assessment period. In each time period, climatic evolution, biosphere development, thermal, mechanical hydrological and chemical evolution of the host rock and evolution of the engineered barriers is analysed. At the end of each period, the function indicators are evaluated.

In this interim report, the structure for the main scenario is given and some examples of preliminary analyses results are provided. The plans for several other analyses are sketched. New analyses related to the main scenario and documented in this report, either in connection with the main scenario or in separate chapters include

- Modelling of the reference evolution of climate-related conditions, i.e. essentially a reconstruction of the Weichselian glacial cycle, with emphasis on the conditions at the Forsmark site.

- The development of the local biosphere at the Forsmark site for a temperate climate in the 1,000 and 10,000 year perspectives.

- An account of available models and modelling approaches for radionuclide turn-over in the biosphere, including new probabilistic data for consequence calculations.

- Mechanical and coupled hydro-mechanical issues, including rock shear movements at deposition holes, fracturing of the rock, time-dependent deformations (creep) and impact of mechanical processes on the host rock permeability.

- Preliminary hydrological studies of the Forsmark site in the case of an open repository and for time-dependent, saturated conditions 10,000 years into the future taking into account land-uplift.

- The analysis of resaturation of buffer and backfill and the application of these results to the hydraulic conditions at the Forsmark site.

Example analysis of failed canisters

The structure for the analysis of the second step of the main scenario has not been established in detail. In this Interim report, the second step is exemplified, for simplicity, in a case where the present climate and biosphere conditions are assumed to prevail. Failures of canisters due to corrosion are analysed and the internal evolution of failed canisters is discussed in some detail.

A probabilistic base case calculation is developed. Preliminary input data distributions are provided, and a strict determination of input data uncertainties for buffer migration parameters is obtained from an Interim data report. Probabilistic flow-related transport data for the rock from the Forsmark calculations are used.

The probabilistic base case calculation results are analysed with respect to risk dilution, which is found to be of minor importance. The base case result is decomposed with respect to dominating nuclides and release paths from the near field and subjected to global sensitivity analysis using the method of standardised rank regression. Parameter values yielding high doses are identified by conditional mean analyses.

Five variants of the base case are analysed probabilistically, exploring the potential impact of correlations not covered in the base case, of the shapes of subjectively determined input distributions, of conceptual uncertainties related to the fuel dissolution rate and to the internal evolution of failed canisters and, finally, of including co-precipitation processes when determining elemental solubilities in the canister.

Hypothetical "what if" cases are also analysed probabilistically, to illustrate the consequences if all canisters were to fail at a defined point in time, if a canister should fail due to rock shear and if geosphere retardation is neglected.

Conclusions

A methodology for the SR-Can assessment has been presented and, as far as possible at this interim stage of the project, exemplified. This is the main purpose of the interim reporting of the safety assessment SR-Can, as requested by SKI and SSI.

No conclusions regarding safety of the KBS-3 concept are drawn, since the data used in this interim assessment are preliminary and since a number of issues have not been addressed. In general, it is though noted that the findings presented confirm earlier results regarding the safety of the KBS-3 concept.

Contents of this report

Following the introductory chapter 1, this report outlines the methodology for the SR-Can assessment in chapter 2, and presents in chapters 3, 4 and 5 the initial state of the system and the plans and methods for handling external influences and internal processes, respectively. Function indicators are introduced in chapter 6 and a preliminary evaluation of these is given in chapter 7. The material presented in the first seven chapters is utilised in the scenario selection in chapter 8. Hydrogeological issues are dealt with in chapter 9; mechanical and coupled hydro-mechanical issues in chapter 10. A structure for and some example results of the analysis of the evolution of the repository for the main scenario is presented in chapter 11. Analyses of evolution of failed canisters, including radionuclide transport and dose calculations, are presented in chapter 12. Conclusions are developed in chapter 13. Appendix A is an account of how applicable regulations are addressed in the assessment. Appendix B describes how review comments on SKB's most recent safety assessment, SR 97, have been addressed and summarises methodological developments since SR 97. Appendix C presents methodology for the handling of biosphere issues.

Sammanfattning

Inledning

Detta dokument är en interimsrapport av säkerhetsanalysen SR-Can[1]. Den slutliga SR-Can-rapporten ska ligga till grund för SKB:s ansökan om att bygga en inkapslings-anläggning för använt kärnbränsle, och ska färdigställas under 2006. Syftet med denna interimsrapport är att demonstrera metodiken för säkerhetsanalysen, så att den kan granskas innan den används i en tillståndsansökan. Analysen gäller djupförvarkonceptet KBS-3, där kopparkapslar med en gjutjärnsinsats innehållande använt kärnbränsle deponeras på cirka 500 m djup i granitiskt berg och omges av bentonitlera. Preliminära data från Forsmark används i viss mån som exempel. Den platsen undersöks för närvarande av SKB som en av kandidatplatserna för ett KBS-3-förvar. Ännu är dock inte dataunderlaget tillräckligt för att tillåta en säkerhetsbedömning av Forsmark.

Ett viktigt syfte med denna rapport är att visa hur kraven på säkerhetsanalys i gällande före-skrifter hanteras. Därför återges de föreskrifter som har utfärdats av Kärnkraftsinspektionen (SKIFS 2002:1) och Strålskyddsinstitutet (SSI FS 1998:1) i en bilaga där referenser ges till de kapitel i huvudtexten där hanteringen av olika krav diskuteras. Det huvudsakliga acceptanskriteriet fastslår att förvaret måste utformas så att "den årliga risken för skade-verkningar efter förslutning blir högst 10^{-6} för en representativ individ i den grupp som utsätts för den största risken". Med "skadeverkningar" avses cancer och ärftliga skador. Riskgränsen motsvarar en dosgräns på ca $1{,}4 \cdot 10^{-5}$ Sv/år, dvs ca en procent av den naturliga bakgrundsstrålningen i Sverige.

Allmän metodik

Förvarssystemet, brett definierat som det deponerade använda kärnbränslet, de tekniska barriärerna, förvarsberget och biosfären i anslutning till djupförvaret, kommer att utvecklas över tiden. Framtida tillstånd hos systemet kommer att bero på

- initialtillståndet hos systemet,

- ett antal termiska, hydrauliska, mekaniska och kemiska processer som verkar inom förvarssystemet över tiden,

- extern påverkan på systemet.

En metodik i 11 steg har utvecklats för SR-Can. Den sammanfattas i figur 1:

1. Identifiering av faktorer att beakta, FEP-hantering

   Detta steg består av att identifiera alla faktorer som ska ingå i analysen. Erfarenhet från tidigare säkerhetsanalyser används, tillsammans med KBS-3-specifika och internationella databaser över relevanta förhållanden, händelser och processer (eng. features, events and processes, FEP) som påverkar den långsiktiga säkerheten. En FEP-databas utvecklas för SR-Can. I denna klassificeras de allra flesta FEP som relaterade till initialtillståndet, till interna processer eller till externa faktorer. Återstående FEP är antingen relaterade till analysmetodiken i allmänhet, eller bedöms vara irrelevanta för KBS-3-systemet.

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[1] Namnet SR-Can anspelar på engelskans "canister" (kapsel). "SR" står för säkerhetsrapport. Denna titel på rapporten har valts eftersom den ska ligga till grund för ansökan om att bygga en inkapslingsanläggning.

Referens-utformning | **Plats-beskrivning** | **FoU resultat** | **Resultat av tidigare analyser** | **FEP-databaser**

1. FEP-hantering
Initial-tillstånd | Interna processer | Externa faktorer

2a. Beskriv initialtillstånd för tekniska barriärer
– referens
– avvikelser

2b. Beskriv platsens initialtillstånd
– basfall
– alternativ

3. Sammanställ processrapport med hanterings-beskrivningar

4. Beskriv externa faktorer
– Klimat
– Framtida mänskliga handlingar

5. Definiera säkerhetsfunktioner och funktionsindikatorer
Uttryck säkerhet som "önskvärda" barriärförhållanden, dvs kriterier för funktionsindikatorer

6. Preliminär långsiktig utvärdering av funktionsindikatorer
– Undersök systemets känsliga/robusta egenskaper
– Identifiera databehov

7. Välj scenarier genom att specificera
– Initialtillstånd för tekniska barriärer och plats
– Beskrivningar av hur processer och externa förhållanden hanteras

8. Sammanställ datarapport

9. Analysera scenarier
Huvudscenarie | Övriga scenarier
– isolering
– retardation
– radiologisk inverkan

10. Utvärdera scenarieval och FEP-hantering
– Kompletterande analyser vid behov

11. Resultatanalys och slutsatser
– integrerade riskuppskattningar
– återkoppling till förvarsutformning, FoU, platsundersökningar
– allmänna slutsatser om säkerhet

Figur 1. *En översikt över de elva huvudstegen i säkerhetsanalysen SR-Can.*

2. Beskrivning av initialtillstånd

Systemets initialtillstånd beskrivs utgående från specifikationerna för KBS-3-förvaret, en beskrivande modell av platsen för djupförvaret och en platsspecifik layout av förvaret. Initialtillståndet för bränslet och de tekniska komponenterna avser förhållandena omedelbart efter deponering. Initialtillståndet för geosfären och biosfären avser de naturliga förhållandena innan brytningsarbetet inleds. Vidare ingår en kortfattad diskussion av FEP som är relaterade till initialtillståndet, t.ex. olyckor och avvikelser som inte upptäcks av etablerade kontrollprocedurer.

3. Beskrivning av processer

Identifiering av relevanta processer beskrivs, utgående från tidigare analyser och FEP-hantering. Alla identifierade processer inom systemet som är relevanta för den långsiktiga utvecklingen av systemet beskrivs i en särskild processrapport. Även kortsiktiga geosfärprocesser/förändringar orsakade av byggandet av förvaret ingår. För varje process dokumenteras dess generella egenskaper, under vilken tidsperiod den har betydelse, vilka andra processer den är kopplad till och hur processen ska hanteras i säkerhetsanalysen. En interimsversion av processrapporten avgränsad till buffertprocesser är färdigställd.

4. Beskrivning av externa förhållanden

Faktorer relaterade till externa förhållanden delas in i de båda kategorierna "klimat-relaterade och geologiska processer" och "framtida mänskliga handlingar". En kort beskrivning av övergripande egenskaper hos den långsiktiga utvecklingen av klimatet och av hur denna skulle påverka djupförvaret ges. En plan för hantering av osäkerheter i klimatutvecklingen utvecklas, baserad på definierade externa referensförhållanden. Utgångspunkten för hanteringen av framtida mänskliga handlingar i SR-Can är den som användes i SR 97-analysen /SKB, 1999a/. De FEP i SR-Can-databasen som avser framtida mänskliga handlingar stäms därför av mot analysresultaten i SR 97.

5. Definition av säkerhetsfunktioner, funktionsindikatorer och kriterier för dessa

Detta steg består av en diskussion av säkerhetsfunktioner hos systemet och av hur dessa kan utvärderas med hjälp av en uppsättning funktionsindikatorer som i princip utgörs av mätbara eller beräkningsbara egenskaper hos systemet. Kriterier ges för funktions-indikatorerna. Processrapporten är ett viktigt underlag för detta steg.

6. Preliminär långsiktig utvärdering av funktionsindikatorer

En preliminär utvärdering ges av utvecklingen av funktionsindikatorerna. Här används ett förenklat processystem och generaliserade externa förhållanden. Syftena är att vinna insikt i systemets grundläggande dynamik, att identifiera kritiska indata genom preliminära känslighetsanalyser, att skapa underlag för det efterföljande valet av scenarier och att peka på grundläggande frågor som kräver mera detaljerad analys.

7. Preliminärt scenarieval

En preliminär uppsättning scenarier väljs för analys. Utgångspunkten för ett omfattande huvudscenarie är i) referensinitialtillståndet, vari ingår möjliga avvikelser från ideala förhållanden, och ii) externa referensförhållanden med osäkerheter. Funktionsindikatorerna och resultaten från preliminära analyser av utvecklingen av dessa används för att fokusera valet på nyckelegenskaper för säkerheten. Därefter väljs ytterligare scenarier, för att täcka in mindre sannolika förhållanden som inte ingår i huvudscenariet, eller för att ge ökad insikt i systemets funktion. Dessa ytterligare scenarier är inte nödvändigtvis en i alla avseenden rimlig representation av systemet.

8. Val av indata

I detta delmoment väljs data som ska användas i kvantifieringen av djupförvarets utveckling och i dosberäkningar. Resultatet beskrivs i en särskild datarapport. En flexibel mall har utvecklats för diskussion av osäkerheter i indata. En interimsversion av datarapporten har tagits fram, med tonvikt på generell metodik och migrationsdata för bufferten.

9. Analys av scenarier

Systemets utveckling i tiden analyseras för valda scenarier. I ett första steg analyseras djupförvarets isoleringspotential. Detta ger en beskrivning av systemutvecklingen och en mera detaljerad utvärdering av funktionsindikatorerna. Om utvecklingen medför att isoleringen bryts, analyseras den fördröjande potentialen hos djupförvaret och dess omgivning och doskonsekvenser beräknas för de långsiktiga förhållandena från det första steget. Ett viktigt syfte är att beräkna ett riskbidrag för vart och ett av de valda scenarierna. Dessa bidrag adderas för att ge den totala risken för djupförvaret att jämföras med det föreskrivna riskkriteriet. Känslighetsanalyser utförs baserat på resultatet av scenarieanalyserna. I denna interimsrapport ingår exempelberäkningar och planer för analys av huvudscenariet med avseende på i) allmän utveckling och isoleringspotential och ii) retardation.

10. Utvärdering och eventuell komplettering av scenarieval

Utgående från insikterna från steg 9 utvärderas det preliminära scenarievalet i steg 7 och kompletteras vid behov genom val av ytterligare scenarier och flera scenarie-analyser. I detta steg görs även en slutlig kontroll av att alla relevanta FEP har hanterats korrekt.

11. Integrering av resultat och slutsatser

Detta steg innefattar integrering av resultat från de olika scenarieanalyserna, slutsatser med avseende på säkerhet i relation till acceptanskriterier och återkoppling med avseende på förvarsutformning, fortsatta platsundersökningar och FoU-program. I denna interimsrapport anges några av de komponenter som kan förväntas i en sådan diskussion. Robustheten hos förvarssystemet och hur de olika säkerhetsfunktionerna bidrar till den totala säkerheten ingår naturligt i denna del av säkerhetsrapporten.

Funktionsindikatorer och funktionsindikatorkriterier

Ett antal preliminära kriterier för avsedd funktion hos i första hand de tillverkade barriärerna har definierats, till stor del baserat på resultat i interimsversionen av processrapporten /SKB, 2004b/. Kriterierna är till hjälp för att bestämma om säkerheten upprätthålls. Om kriterierna uppfylls underlättas säkerhetsbedömningen, men uppfyllande av funktionsindikatorkriterierna utgör inte i sig en garanti för att riskkriteriet är uppfyllt. Omvänt kan riskkriteriet mycket väl vara uppfyllt trots brott mot ett eller flera av kriterierna för funktionsindikatorerna. Brott mot ett kriterium är ett varningstecken. Ytterligare analys kan vara nödvändig för att fastställa konsekvenserna på delsystemnivå eller på övergripande systemnivå. Dessutom finns flera aspekter på djupförvarets utveckling och barriärfunktioner som inte kan bedömas genom direkt jämförelse med ett kriterium. De preliminära funktionsindikatorerna och motsvarande kriterier sammanfattas i tabell 1.

Tabell 1. Sammanfattning av funktionsindikatorer och de kriterier de ska uppfylla.

Funktionsindikator	Kriterium	Motivering
Kapsel		
Minimal godstjocklek, koppar	$d_{min}^{Cu} > 0$	Säkerställa isolering
Isostatiskt tryck på kapsel	$P_{Isostatic}^{Canister} < P_{Isostatic\ collapse}^{Can}$	Undvika isostatisk kollaps
Maximal kapseltemperatur vid vattenkontakt	$T^{Canister} < 100\ °C$	Undvika kokning på ytor och därav följande saltavlagringar
Buffert		
Hydraulisk konduktivitet	$k^{Buff} < 10^{-12}$ m/s	Undvika advektiv transport i buffert
Svälltryck	$P_{Swell}^{Buff} > 1$ MPa	Säkerställa täthet och självtätande egenskaper
Maximal temperatur	$T^{Buff} < 100°C$	Säkerställa bufferstabilitet
Minimal temperatur	$T^{Buff} > 0\ °C$	Undvika frysning
Buffertdensitet kring hela kapseln	$\rho_{Bulk}^{Buff} > \rho_{Sink}$ kg/m³	Undvika kapselsjunkning (kriteriet återstår att fastställa)
Buffertdensitet kring hela kapseln	$\rho_{Bulk}^{Buff} > 1\ 800$ kg/m³	Utesluta mikrobiell aktivitet
Buffertdensitet kring hela kapseln	$\rho_{Bulk}^{Buff} > 1\ 650$ kg/m³	Undvika kolloidtransport genom buffert
Buffertdensitet kring hela kapseln	$\rho_{Bulk}^{Buff} < 2\ 100$ kg/m³	Säkerställa skydd av kapseln mot skjuvkrafter i berget
Återfyllning i deponeringstunnlar		
Kompressibilitet	$M^{Backfill} > 10$ MPa (M = kompressionsmodul)	Begränsa buffertexpansion
Hydraulisk konduktivitet	$k^{Backfill} < 10^{-10}$ m/s	Begränsa advektiv transport
Svälltryck	$P_{Swell}^{Backfill} > 0,1$ MPa	Säkerställa homogenitet
Minimal temperatur	$T^{Backfill} > 0\ °C$	Undvika frysning
Berg		
Redoxförhållanden	Inget löst syre	Närvaro av mätbara mängder O_2 skulle innebära oxiderande förhållanden
Minimal jonstyrka	$\Sigma[M^{2+}]^{GW} > 10^{-3}$ M (Total koncentration av tvåvärda katjoner)	Undvika bufferterosion
Maximal kloridhalt eller minimalt pH (kloridkorrosion)	$pH^{GW} > 4$ eller $[Cl^-]^{GW} < 3M$ (endera tillräckligt)	Undvika kloridkorrosion av kapsel
Begränsad alkalitet	$pH^{GW} < 11$	Undvika upplösning av buffertsmektit
Begränsad salthalt	Buffert: [NaCl] < 100 g/l Återfyllning: [NaCl] < 35 g/l (Eller andra sammansättningar med ekvivalent jonstyrka)	Undvik menliga effekter, särskilt på svällförmågan hos buffert och återfyllning
Begränsa koncentrationen av substanser med menlig inverkan på buffert och kapsel	Gäller HS^-, K^+ och Fe. Ju lägre desto bättre (inget kvantitativt krav)	Undvika sulfidkorrosion i kapsel, undvika illitisering (K^+) och kloritisering (Fe) av buffert och återfyllning
Begränsade skjuvkrafter i berget vid deponeringshål	$d_{shear} < 10$ cm	Undvika kapselbrott på grund av skjuvkrafter i berget vid deponeringshålen

Preliminär utvärdering av funktionsindikatorer

Resultaten av den preliminära utvärderingen av funktionsindikatorerna tyder på att flera av kriterierna uppfylls för olika förväntade förhållanden i djupförvaret. Data som fordrar ytterligare utvärdering har specificerats och ett antal frågor som kräver vidare analys identifierats, bland andra följande:

- Sannolikheten för kapselbrott på grund av korrosion är mycket låg, även med hänsyn till initiala svetsdefekter. Emellertid måste data för utvärdering av korrosion i anslutning till svetsdefekter kvalificeras och resultat baserade på kvalificerade data överföras till konsekvensberäkningar.

- Kapselbrott på grund av isostatiskt övertryck förefaller kunna uteslutas. Med tanke på att de största övertrycken, dvs. de som potentiellt orsakas av glacial belastning, skulle påverka samtliga kapslar är det dock viktigt att ge ytterligare substans åt detta påstående. Framför allt är det viktigt att etablera ett tillförlitligt kollapskriterium genom laboratorietest och stödjande hållfasthetsberäkningar.

- Sannolikheten för kapselbrott på grund av skjuvkrafter i berget vid deponeringshålen måste utvärderas noggrant.

- Möjligheten att syresatt ytvatten tränger ner till förvarsdjup under glaciala förhållanden fordrar ytterligare analys.

- Kravet på en minimal temperatur på 0 °C för buffert och återfyllning måste utvärderas mot bakgrund av maximalt permafrostdjup.

- Erosion av buffert och återfyllning orsakad av jonfattiga grundvatten (glaciala förhållanden) fordrar ytterligare utvärdering, både med avseende på möjliga vattensammansättningar och kvantitativa effekter av jonfattiga vatten.

- Ett återfyllningsmaterial för deponeringstunnlar baserat på en blandning av lera och bergkross bör uppfylla kraven på hydraulisk konduktivitet för förväntade förvarsförhållanden, förutsatt att densiteten kan upprätthållas. Svälltryckskriteriet torde inte uppfyllas för detta återfyllningsmaterial.

- Om konceptet med blandat återfyllningmaterial ska utvärderas ytterligare är det viktigt att i konsekvensberäkningarna studera effekterna av en kollapsad återfyllning med en konduktiv zon längs tunneltaket.

Scenarieval

Tillämpliga föreskrifter nämner tre typer av scenarier: Huvudscenariet som ingår i den förväntade utvecklingen av djupförvarssystemet; mindre sannolika scenarier, som innefattar alternativa händelseförlopp relativt huvudscenariet liksom även inverkan av tillkommande händelser; samt restscenarier som utvärderar specifika händelser och förhållanden för att illustrera funktionen hos enskilda barriärer. Denna indelning har legat till grund för grupperingen av scenarier i SR-Can.

Ett scenarie definieras genom att man specificerar ett initialtillstånd för det tekniska barriärsystemet, ett initialtillstånd (en konceptuell tolkning) för platsen samt föreskrifter för hantering av interna processer och extern inverkan vid analys av scenariet.

Scenarievalet bygger på resultaten från FEP-analysen, beskrivningar av initialtillstånd, processer och externa influenser samt förståelsen för vilken inverkan dessa faktorer har på säkerheten, vilket framgår av de preliminära analyserna av funktionsindikatorerna och andra källor. Tabell 2 sammanfattar det preliminära scenarievalet i SR-Can.

Den första raden i tabell 2 definierar basvarianten av huvudscenariet. Djupförvaret förutsätts vara byggt enligt specifikation, dvs. initialtillståndet för det tekniska barriärsystemet är i enlighet med konstruktionsspecifikationerna, med tillåtna toleranser. Initialtillståndet för platsen utgörs av en bastolkning av data från platsundersökningen. Interna processer hanteras i enlighet med föreskrifterna i processrapporten. Externa förhållanden definieras som ett referensfall för klimatutvecklingen, baserat på en upprepning av den senaste glaciala cykeln, Weichselistiden. Inga framtida mänskliga handlingar beaktas i detta scenarie. Osäkerhetsanalyser av basvarianten tar hänsyn till möjligheten av mänskligt orsakade växthuseffekter. Basvarianten representerar förväntad utveckling för djupförvaret. Andra scenarier och varianter täcker alternativa tolkningar av platsen, alternativ konstruktion av djupförvaret, framtida mänskliga handlingar etc. De flesta restscenarierna är s k "What if-scenarier", och behandlar systemets funktion och robusthet under orealistiska förhållanden. Flera scenarier och varianter definieras i närmare detalj, baserat på resultat från ytterligare analys efter hand som projektet framskrider.

Tabell 2. Resultat av preliminärt scenarieval. Gröna rutor anger förhållanden för basvarianten av huvudscenariet; röda anger avvikelser från dessa förhållanden.

Scenarie	Variant	Initialtillstånd, tekniska barriärer	Initialtillstånd, plats	Processhantering	Hantering av externa förhållanden
Huvud-scenarie	Bas	Referens ±toleranser	Basmodell (med osäker-heter)	Enligt process-rapport	Referensklimat + osäkerhetsanalyser Inga framtida mänskliga ingrepp (FHA) beaktade
Huvud-scenarie	ACM1* ACM2* etc.	Som basvariant	ACM1* ACM2* etc.	Som basvariant	Referensklimat
Huvud-scenarie	Alternativt återfyllnings-material	Som bas, men alt. återfyllningsmaterial	Som basvariant	Som basvariant	Referensklimat
Mindre sannolikt	FHA1, 2, 3…	Som basvariant	Som basvariant	Som basvariant	Referensklimat + FHA1, 2, 3…
Mindre sannolikt	Alternativa proc-esshanteringar?	Som basvariant	Som basvariant	Alt. hantering	Referensklimat
Mindre sannolikt	Alternativa externa förhållanden?	Som basvariant	Som basvariant	Som basvariant	Alternativa förhållanden
Rest	Öppet, dränerat förvar	Som bas, men öppna, pump-evakuerade transporttunnlar etc.	Som basvariant	Som bas, modifierat enligt initialtillstånd	Referensklimat
Rest	Öppet, övergivet förvar	Som bas, men öppna, övergivna transport-tunnlar etc.	Som basvariant	Som bas, modifierat enligt initialtillstånd	Referensklimat
Rest	Initiala avvikelser hos tekniska bar-riärer (flera fall)	Som basvariant	Som basvariant	Som basvariant	Referensklimat
Rest	Analys av säker-hetsfunktioner	Extrema variationer	Extrema variationer	Extrema variationer	Extrema variationer
Rest	Beräkningar av konstruktionssty-rande underlag	Möjligen ytterligare fall	Möjligen ytter-ligare fall	Möjligen ytterligare fall	Möjligen ytterligare fall

*ACM: Alternativ konceptuell modell av platsen.

Huvudscenariet

Huvudscenariet analyseras i två steg. I ett första steg utvärderas isoleringen. Om resultatet visar att isoleringen bryts analyseras de skadade kapslarna i ett andra steg. Detta andra steg inkluderar radionuklidtransport och dosberäkningar för de barriärförhållanden som ges av analysen av det första steget.

Analysen av det första steget i huvudscenariet görs i flera tidsperioder: Byggnads- och driftfasen, de första 1 000 åren, en period med fortsatt tempererat klimat på ca. 10 000 år, ett referensfall av en glacial cykel som antas vara en upprepning av den senaste glaciala cykeln, Weichselistiden, och som sträcker sig över 115 000 år, och slutligen ytterligare nedisningscykler till slutet av den en miljon år långa analysperioden. För varje tidsperiod analyseras klimatutveckling, biosfärutveckling, berggrundens termiska, mekaniska hydrologiska och kemiska utveckling samt utvecklingen av de tekniska barriärerna. I slutet av varje period utvärderas funktionsindikatorerna.

I denna interimsrapport redovisas huvudscenariets struktur och några exempel på preliminära analysresultat. Planerna för flera andra analyser skisseras. Bland nya analyser relaterade till huvudscenariet som dokumenteras i denna rapport, antingen i beskrivningen av huvudscenariet eller i separata kapitel ingår:

- Modellering av referensutveckling av klimatrelaterade förhållanden, dvs. i huvudsak en rekonstruktion av Weichselistiden, med tonvikt på förhållandena vid Forsmark.

- Utvecklingen av den lokala biosfären i ett tempererat klimat vid Forsmark, sett över 1 000 respektive 10 000 år.

- En redogörelse för tillgängliga modeller och modelleringsmetoder för radionuklid-omsättning i biosfären, inklusive nya probabilistiska data för konsekvensberäkningar.

- Mekaniska och kopplade hydromekaniska frågor, inklusive skjuvrörelser kring deponeringshålen, sprickbildning i berget, tidsberoende deformation (kryp) och inverkan av mekaniska processer på berggrundens permeabilitet.

- Preliminära hydrologiska studier från Forsmark för ett öppet förvar och för tidsberoende, mättade förhållanden 10 000 år framåt, med hänsyn tagen till landhöjning.

- Analys av återmättnad av buffert och återfyllning, samt tillämpning av dessa resultat på de hydrauliska förhållandena vid Forsmark.

Exempelanalys av skadade kapslar

Strukturen för analys av det andra steget i huvudscenariet har inte fastlagts i detalj. I denna interimsrapport redovisas det andra steget för ett förenklat exempel där dagens klimat- och biosfärförhållanden antas råda. Kapselskador på grund av korrosion analyseras och den interna utvecklingen av skadade kapslar diskuteras i viss detalj.

En probabilistisk beräkning av ett basfall sätts upp. Preliminära indatafördelningar ges och en strikt bestämning av osäkerheter i indata för buffertmigrationsparametrar hämtas från en interimsdatarapport. Preliminära, probabilistiskt beräknade flödesrelaterade transportdata för berggrunden vid Forsmark används.

Resultaten från den probabilistiska beräkningen av basfallet analyseras med avseende på riskspädning, vilken visar sig ha liten betydelse. Resultaten av basfallet delas upp med avseende på dominerande nuklider och utsläppsvägar från närzonen. En global känslighets-analys görs med hjälp av rangregression. Parametervärden som ger höga doser identifieras med en metod som bygger på beräkning av villkorade medelvärden.

Fem varianter av basfallet analyseras probabilistiskt för att utröna effekterna av potentiell inverkan av korrelationer som inte täcks av basfallet, alternativa fördelningsformer för subjektivt fastställda indata, konceptuella osäkerheter kring bränsleupplösningshastigheten och kring den inre utvecklingen hos skadade kapslar samt effekterna av samfällning på lösligheter i kapseln.

Hypotetiska s k "What if-scenarier" analyseras probabilistiskt för att illustrera konsekvenserna av om samtliga kapslar skulle skadas vid en viss tidpunkt, om en kapsel skulle skadas på grund av skjuvkrafter i berggrunden och om geosfärsretardationen skulle försummas.

Slutsatser

En metodik för säkerhetsanalysen SR-Can har presenterats och, så långt möjligt vid detta interimistiska skede av projektet, exemplifierats. Detta är huvudsyftet med interims-rapporteringen av säkerhetsanalysen SR-Can, så som efterfrågats av SKI och SSI.

Inga slutsatser kring säkerheten för KBS-3 systemet dras eftersom data ännu är preliminära och eftersom en rad frågor inte utretts. Generellt noteras dock att resultaten hittills bekräftar tidigare slutsatser om säkerheten hos KBS-3 systemet.

Innehållet i denna rapport

Efter ett inledande kapitel ger rapporten en översikt av metodiken för SR-Can-analysen i kapitel 2 och presenterar i kapitlen 3, 4 och 5 systemets initialtillstånd samt planer och metoder för hantering av extern påverkan respektive interna processer. Funktionsindikatorer introduceras i kapitel 6 och en preliminär utvärdering av dessa görs i kapitel 7. Materialet som presenteras i de första sju kapitlen utnyttjas i scenarievalet i kapitel 8. Hydrogeologiska frågor behandlas i kapitel 9; mekaniska och kopplade hydromekaniska frågor i kapitel 10. En struktur för och några exempel på resultat av analysen av utvecklingen av djupförvaret för huvudscenariet presenteras i kapitel 11. Analyser av utvecklingen av skadade kapslar, inklusive radionuklidtransport och dosberäkningar, ges i kapitel 12. Slutsatser presenteras i kapitel 13. Bilaga A redogör för hur tillämpliga föreskrifter hanteras i analysen. Bilaga B beskriver hur granskningskommentarerna på SKB:s senaste säkerhetsanalys, SR 97, har behandlats. Här sammanfattas även metodutvecklingen sedan SR 97. Bilaga C presenterar metodiken för hantering av biosfärfrågor.

Contents

1 Introduction

1.1 SKB's programme for spent nuclear fuel

Radioactive waste from nuclear power plants in Sweden is managed by the Swedish Nuclear Fuel and Waste Management Co, SKB. Within SKB's programme for the management of spent nuclear fuel, an interim storage facility and a transportation system are today (August 2004) in operation. Several decades of research and development has led SKB to put forward the KBS-3 method for the final stage of 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. Around 9,000 tonnes of spent nuclear fuel is forecasted to arise from the Swedish nuclear power programme, corresponding to roughly 4,500 canisters in a KBS-3 repository.

Two principal remaining tasks in the programme 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 plans.

The favoured alternative for the location of the encapsulation plant is at Oskarshamn, in conjunction with the existing interim storage facility. An application to build an encapsulation plant will be made in 2006.
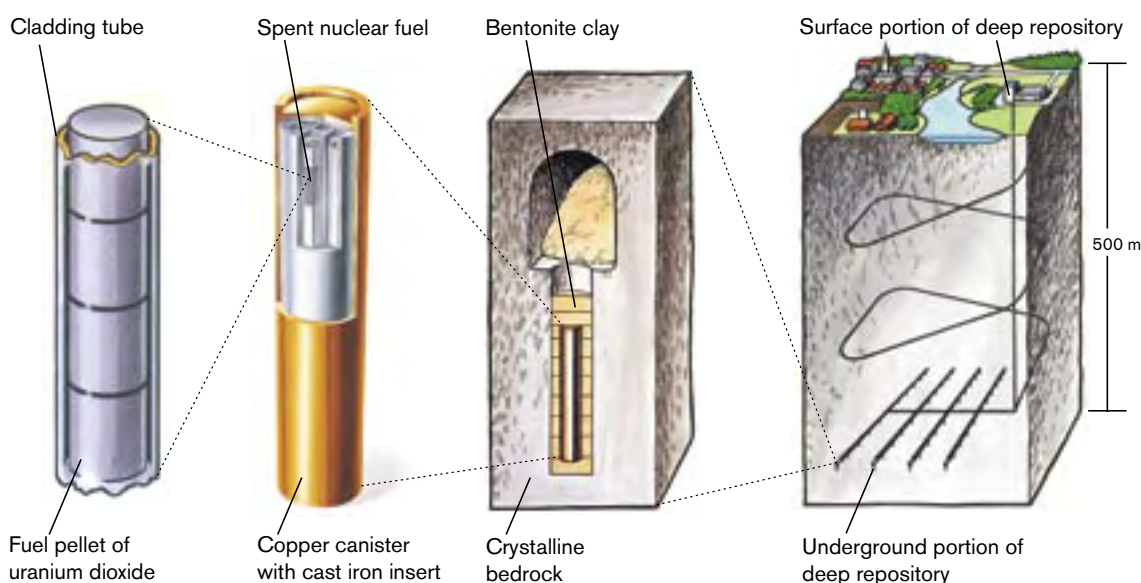
Figure 1-1. *The KBS-3 concept for disposal of spent nuclear fuel.*

1.1.1 Reporting of long-term safety during the current programme stage

The applications to build an encapsulation plant and a deep repository will both include a report on long-term safety for the deep repository. This is an obvious requirement for the application to build the repository. 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 defined by the Swedish authorities.

Two safety reports will thus be produced within the next few years; one for the application to build an encapsulation plant in 2006 and one for the application to build the repository in 2008. They will hereafter be referred to as SR-Can[2] 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.

Also, preliminary safety evaluations /SKB, 2002a/, 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 hold up in the light of borehole data and to provide feed-back to continued site investigations and site-specific repository design.

A variant with horizontal emplacement of the waste canisters, KBS-3H, is also being studied in a joint research project between SKB and Posiva, the Finnish waste management organisation. By the middle of 2007, a safety assessment of the KBS-3H variant, using the Finnish site Olkiluoto as the reference location, will be presented by Posiva.

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 purposes of the safety assessment SR-Can are the following:

1. Primarily, to assess the safety of potential KBS-3 repositories at Forsmark and Simpevarp to dispose of canisters as specified in the application to build the encapsulation plant.

2. Secondarily, to provide feedback to design development, to SKB's R&D programme, to further site investigations and to future safety assessment projects.

As SKB's waste management programme continues, the encapsulation technique will be further developed and selection of materials for buffer and backfill and procedures for manufacturing and deposition of engineered barriers will be further specified. Also, the sites will be progressively better known and excavation techniques specified in more detail. Safety assessments at various stages of the programme will draw on the information available at that particular stage. Information on all the components is needed at every stage, since safety is a result of the integration of all these elements. The focus of a particular assessment will however be determined not only by the information available but also by the purpose of the assessment, i.e. the decision or decisions that it is intended to support.

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[2] The SR in the acronym SR-Can stands for Safety Report and Can is short for canister. This title of this report was chosen since it supports the application to build an encapsulation plant.

The objective of SR-Can is to investigate whether canisters of the envisaged type are suitable for disposal, given the host rock conditions at the sites in so far as they can be specified after the preliminary site investigation phase. The intention is not to fully establish the suitability of the studied sites – this will be done in SR-Site. The intention is also not to finally establish the technical system for disposal – but rather to investigate the safety of the system as it is specified at that stage, and to give feedback for the further development. SR-Can is thus not part of a license application for a repository – it is part of a license application for the encapsulation plant.

The detailed extent of information and analyses that have to be presented in SR-Can remains in part to be determined. The situation is influenced by the fact that the SR-Can analysis will be superseded by the SR-Site analysis two years later, possibly before the review of the application to build an Encapsulation Plant is finalised. The role of these two safety assessments in the licensing of the two facilities, and the implication these roles have on their contents, will have to be further established in consultation with the authorities that oversee SKB's activities, i.e. the Swedish Nuclear Power Inspectorate, SKI, and the Swedish Radiation Protection Authority, SSI.

1.3   Purpose of this Interim report

The main purpose of this Interim report is to demonstrate the methodology to be used in the assessment, so that this can be reviewed before it is used for the applications. The report has been requested by SKI and SSI. In this context, it is e.g. desirable to demonstrate that the substance of the review comments /SKI and SSI, 2001/ concerning methodological issues in SKB's previous safety assessment, SR 97 /SKB, 1999a/, have been adequately addressed.

The methodology and the treatment of specific issues presented in the report are developed and detailed to the extent possible at this stage of the project.

This interim report demonstrates results from the application of modelling tools but no conclusions on safety are drawn at this stage. The final SR-Can report will go much further in defining the motivation for and selection of simulation models and input data to these models.

The structure of this Interim report largely follows that envisaged for the final SR-Can report. This is particularly the case for the eight first chapters, leading up to and including the preliminary selection of scenarios. The structure is compatible with requirements in applicable regulations. For example, SKIFS 2002:1, see section 1.4, states in an Appendix a number of items that must be reported regarding analysis methods and analyses of post-closure conditions. Furthermore, the contents of the safety report should be consistent with international consensus in this field, e.g. as expressed in /NEA, 1997a/.

1.3.1   The authorities' expectations on the SR-Can Interim report

Within the framework of the formal consultation process regarding safety assessments during SKB's site investigation phase, SKI and SSI have jointly requested that a number of issues be covered in the SR-Can Interim report. In summary, the authorities mentioned the following issues (SKB's summary based on material presented at a consultation meeting in December 2003):

• The main purpose of the Interim report is to provide an account of the safety assessment methodology (facilitating feedback prior to the SR-Can main report).

- Important steps in the safety assessment should be described and, as far as possible, exemplified.

- A structured account of how the methodology has been developed since SR 97 should be provided.

- A discussion on how review comments by the authorities and by the NEA on SR 97 have been handled should be provided.

- The application of the authorities' regulations SSI FS 198:1 and SKIFS 2002:1 should be described and, if possible, exemplified.

- Scenario selection including discussion on scenario probabilities and risk contributions should be included.

- Examples of FEP descriptions, initial state descriptions and process diagrams should be provided.

- Examples of choice of models, documentation of models, choice of input data and of calculation cases (including "what if" cases) and sensitivity analyses should be provided.

- Consequence calculations for a scenario (or variant or part of a scenario) should be undertaken – for simplicity these may be without climate and biosphere changes (like the canister defect scenario in SR 97).

- Examples of reporting of results and evaluation relative to the risk criterion should be presented (with no requirement of completeness).

- The strategy for handling of uncertainties should be described (with explicit examples for judgement of the level of ambition).

A number of issues that <u>do not</u> have to be covered were also explicitly stated:

- Completeness, not even for the aspects for which consequence calculations are presented.

- The integrity of the barrier system on long time scales (handled in an ongoing series of workshops).

- Details of site descriptive models (handled in conjunction with the authorities' review of the site investigations).

- Details regarding intrusion, human influences and climate development, even though these issues should be discussed when selecting scenarios.

Furthermore, the authorities have, in their terms of reference for the international review team of the SR-Can Interim report, specified a number of methodology issues to be reviewed:

- Description of the initial state of the repository and its components.

- Description of features, events and processes (FEPs) that are relevant to repository evolution.

- Strategy for safety demonstration (e.g. allocation of safety to different barrier functions and the role of dilution).

- Basis and methods for scenario selection and evaluation.

- Assessment of the model framework for consequence analysis and compliance evaluation.

- Methods for biosphere modelling including the transition zone from basement rock to Quaternary deposits and ecosystems.

- Methods for risk analysis, including the use of probabilistic methods, uncertainty and sensitivity analyses, estimation of probabilities, averaging of risk.

- Quality assurance measures including handling of expert judgements.

The above items are revisited in the concluding chapter 13, where references to the sections of the report where the issues are handled are given.

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 SKI and SSI. The regulations are based on items of framework legislation, the most important being the Nuclear Activities Act and the Radiation Protection Act. Guidance on radiation protection matters is provided by a number of international bodies, and national legislation is often, as in the case of Sweden, 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).

These two documents are included in their entirety in Appendix A to this report. The way in which SKB intends to fulfil the requirements is indicated by references to relevant sections of this report, as inserts in the regulatory text in the Appendix.

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

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 which states 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". "Harmful effects" refer to cancer and hereditary effects. The risk limit corresponds, according to SSI, to a dose limit of about $1.4 \cdot 10^{-5}$ Sv/yr. This, in turn, corresponds to around one percent of the natural background radiation in Sweden.

- 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 than for later times.

SSI has also issued a report with background discussion and comment relating 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 Appendix A.

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

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,
  - analysis methods 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 requires 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 information regarding the e.g. classification of scenarios and uncertainties is given. Excerpts from the Recommendations, relevant to an assessment of long-term safety are also given in Appendix A, along with indications of how SKB intends to fulfil the requirements.

1.5   Related projects

The safety assessment project is closely linked to ongoing site investigation and engineering activities at SKB, see Figure 1-2.

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 produces a site descriptive model of the geosphere and the biosphere, see, e.g. /SKB, 2004e/. 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
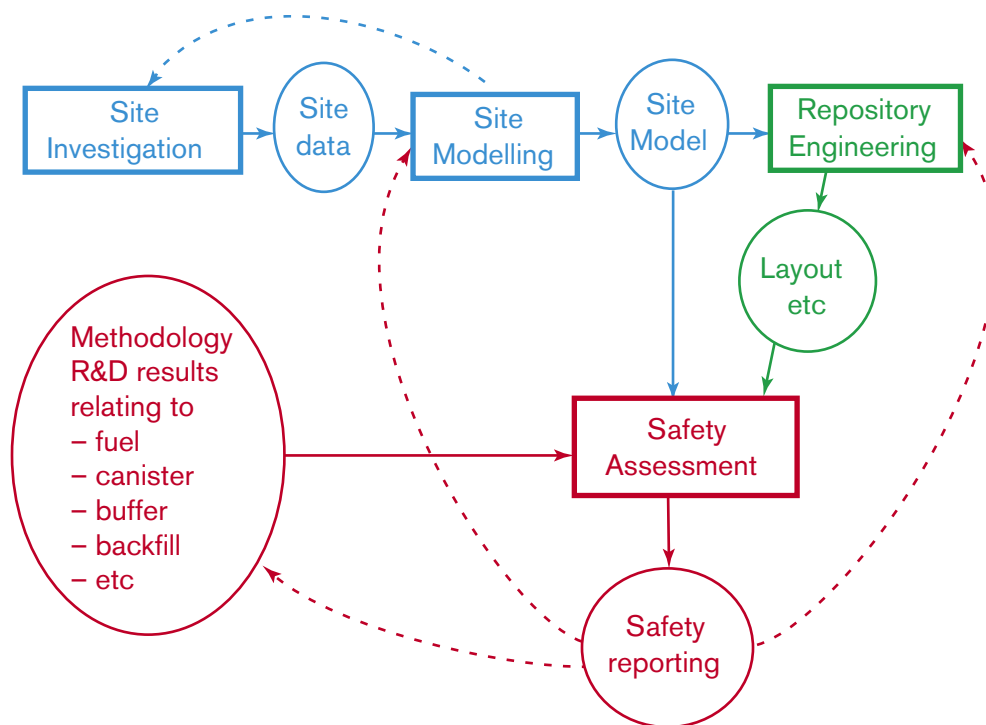
Figure 1-2. *Relations to other project. Activities are shown as rectangles and products as ellipses. As indicated by the dashed lines, the safety report provides feedback to repository engineering concerning e.g. layout issues and choice of backfill materials and to site investigations, via the site model, concerning further site investigation needs. The latter type of feedback is also given by the site modelling group independent of the safety assessment. Feedback is also given from the safety assessment to SKB's R&D programme.*

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 the descriptions of the present geosphere and biosphere conditions for the safety assessment.

The model describes the situation prior to rock excavation for the deep repository. Analyses of how the excavation activities will affect the undisturbed, natural state of the rock are thus needed and 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 descriptions of the geosphere and the biosphere, the site descriptive model gives an understanding of past and ongoing processes at the site. This information will be useful for the description and modelling of the future development of the site and repository, the results of which should be compatible with the understanding of the site history.

The safety assessment will use the hydrogeological and transport 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, informed by the insights from the site analysis group.

2 Overview of methodology

2.1 Introduction

This chapter outlines the methodology to be used for SR-Can. The methodology builds on that presented in the SR-Can Planning report /SKB, 2003a/ which in turn was a development of the methodology used in SKB's most recent comprehensive safety assessment, the SR 97 study /SKB, 1999a/. The methodology development has also been influenced and inspired by several recent safety assessment studies in e.g. Switzerland /Nagra, 2002/, Finland /Vieno and Nordman, 1999/, Belgium /ONDRAF/NIRAS, 2001/, Japan /JNC, 2000/ and the U.S. /BSC, 2002/ and by international cooperation in the area organised by the OECD Nuclear Energy Agency /NEA, 1997a, 1999, 2001, 2004a,b/.

Details of the methodology will be further developed during the project, as a result of the outcome of further analyses and in response to review comments on this report. The updated methodology will be presented in the SR-Can final report. Several methodological issues presented in this chapter are developed and exemplified in subsequent chapters.

A 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 established by comparing estimated releases of repository derived radionuclides and associated radiation doses with regulatory criteria.

Appropriate scientific and technical support for all statements made and data selected is essential to give confidence in the calculated results. Demonstrating understanding of the disposal system and its evolution is thus a crucial component in any safety assessment.

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

- its initial state,

- a number of radiation related, thermal, hydraulic, mechanical, chemical and biological 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 affecting the engineered barriers and the composition of 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 determine repository evolution, can never be fully described or understood. There are thus uncertainties of various types 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. This 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. It also implies comparing the results of the assessment with regulatory criteria in such a way that appropriate allowance is made for the uncertainties associated with the assessment.

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 ensure that any releases from the canister are retarded and dispersed sufficiently to allow decay to levels that do not cause unacceptable consequences. The two issues of isolation and retardation are thus in focus throughout the assessment.

The next section gives a brief overview of the assessment methodology. The subsequent sections in this chapter elaborate on various general aspects of the methodology. Several important parts of the methodology, like the selection of scenarios, are difficult to fully explain without demonstrating how the methodology is applied. Much of the methodology is therefore further developed and applied in the subsequent chapters.

2.2   Methodology in eleven steps

The safety assessment SR-Can will consist of a number of main steps, which will be carried out partly concurrently, partly consecutively. From a project management point of view, many of the steps can be seen as sub-projects in a larger integrated safety assessment project. Figure 2-1 is a graphical illustration of the steps and the main products resulting from them.

The main steps of the assessment are the following:

1. Identification of factors to consider, FEP processing

    This step consists of identifying all the factors that need to be included in the analysis. Experiences from earlier safety assessments and KBS-3 specific and international databases of relevant features, events and processes (FEPs) influencing long-term safety are utilised. An SR-Can FEP database is developed where the great majority of FEPs are classified as being either initial state FEPs, internal processes or external FEPs. Remaining FEPs are either related to assessment methodology in general or deemed irrelevant for the KBS-3 concept. This step is further described in section 2.4. The FEP database is documented in /SKB, 2004a/.

2. Description of initial state

    The initial state of the system is described, based on the design specifications of the KBS-3 repository, a descriptive model of the repository site and a site-specific layout of the repository. The initial state of the fuel and the engineered components is that immediately after deposition. The initial state of the geosphere and the biosphere is that of the natural system prior to excavation[3]. A brief discussion of FEPs related to the initial state, e.g. mishaps and design deviations that are not detected by established control procedures, is given. This step is further described in chapter 3. The reference design is given in /SKB, 2004d/ and the site description in /SKB, 2004e/.

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[3] Note that this is different from the definition given in the SR-Can Planning report /SKB, 2003a/ where the initial state of the entire system was defined as that at the time of deposition. The definition of the point in time for the initial state is further discussed in section 3.1.

| Reference design | Site description | R&D results | Results of earlier assessments | FEP databases |

1. FEP processing

| Initial state | Internal processes | External factors |

2a. Describe EBS initial states
– reference
– deviations

2b. Describe site initial states
– base model
– alternatives

3. Compile Process Report
with handling prescriptions

4. Compile external factors
– Climate
– Future Human Actions

5. Define safety functions and function indicators
Define safety in terms of "desirable" barrier conditions, Function Indicator Criteria

6. Preliminary long-term evaluation of function indicators
– Explore sensitive/robust features of the system
– Identify data needs

7. Select scenarios by specifying
– Initial states for EBS and Site
– Prescription for handling of processes and external conditions

8. Compile Data Report

9. Analyse scenarios

Main scenario   Other scenarios
– isolation
– retardation
– radiological impact

10. Evaluate scenario selection and FEP handling
– Complementary analyses if required

11. Result analysis and conclusions
– integrated risk estimates
– feedback to design, R&D, site investigation
– general conclusions on safety

Figure 2-1. *An outline of the eleven main steps of the safety assessment SR-Can.*

3. Description of processes

The identification of relevant processes based on earlier assessments and FEP screening, as well as principles for process documentation, is further described in chapter 5. All identified processes within the system boundary relevant to the long-term evolution of the system are described in a dedicated Process report. Also short-term geosphere processes/alterations due to repository excavation are included. For each process,

general characteristics, the time frame in which it is important, the other processes to which it is coupled and how the process will be handled in the safety assessment are documented. An interim version of the process report, treating buffer processes, is provided in /SKB, 2004b/.

4. Description of external conditions

Factors related to external conditions are handled in the two categories "climatic and geological processes" and "future human actions", see further chapter 4. A brief description of the broad features of the long-term evolution of climate and of how this would influence the repository is given. A plan for handling uncertainties in the climatic evolution is developed, based on defined reference external conditions. The basis for the treatment of future human actions in SR-Can will be that adopted in the SR 97 assessment /SKB, 1999a/. Therefore, FEPs in the SR-Can database related to future human actions are audited against the SR 97 analysis results.

5. Definition of safety functions, function indicators and function indicator criteria

This step consists of a discussion of the safety functions of the system and of how they can be evaluated by means of a set of function indicators that are, in principle, measurable or calculable properties of the system. Criteria for the function indicators are provided. The Process report is an important reference for this step. This step is documented in chapter 6. An introductory discussion on safety is provided in section 2.6.

6. Preliminary long-term evaluation of function indicators

A preliminary evaluation of the evolution of the function indicators is provided, using a simplified process system and stylised external conditions. The purposes are to gain insights into the basic dynamics of the system, to identify critical input data through preliminary sensitivity analyses, to inform the subsequent selection of scenarios and to point to key issues for more detailed analyses. This step is documented in chapter 7.

7. Preliminary scenario selection

A preliminary set of scenarios for the assessment is selected. The bases for a comprehensive main scenario are i) the reference initial state considering also possible deviations from ideal conditions and ii) the reference external conditions with uncertainties. The function indicators and the results of the preliminary analyses of the evolution of these are used to focus the selection on key properties of importance for safety. Other scenarios are then selected to cover less probable conditions not included in the main scenario or to gain insights into the functioning of the system without necessarily being, in all respects, a reasonable representation of the system.

8. Input data selection

Data to be used in the quantification of repository evolution and in dose calculations are selected and reported in a dedicated Data report. A flexible template for discussion of input data uncertainties has been developed. The compilation of input data is further discussed in section 2.7 and an interim version of the data report, focussing on overall methodology and migration data for the buffer, is provided in /SKB, 2004c/.

9. Analysis of scenarios

The temporal evolution of the system is analysed for the selected scenarios. The isolating potential of the system is analysed in a first step, yielding a description of system

evolution and a more detailed evaluation of the function indicators. If the evolution implicates breaching of isolation, the retarding potential of the repository and its environs is analysed and dose consequences are calculated for the long-term conditions identified in the first step. An important aim is to calculate a risk contribution for each of the selected scenarios, which are then to be added to give a total risk for the repository. This risk is to be compared to the stipulated risk criterion. Sensitivity analyses are performed on the results of the scenario analyses. Example calculations and plans for the analysis of the main scenario are provided in chapter 11 regarding general evolution and isolation potential and in chapter 12 regarding retardation.

10. Evaluation and possible complementation of scenario selection

Based on the insights gained in step 9, the preliminary selection of scenarios in step 7 is evaluated and, if required, complemented by the definition of additional scenarios and the undertaking of additional scenario analyses. Also, a final check that all relevant FEPs have been appropriately handled is done in this step.

11. Integration of results and conclusions

This step includes integration of the results from the various scenario analyses, developments of conclusions regarding safety in relation to acceptance criteria and feedback concerning design, continued site investigations and R&D programme. Some of the expected components in such a discussion are given in chapter 13. The robustness of the repository system and the way in which different safety functions contribute to overall safety are natural components of this part of the safety report.

2.3 System boundary

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 the SR-Can FEP database (see below), the system boundary was defined in more detail. The following key aspects are taken 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. Depending on the analysis context this definition may be somewhat modified.

- Roughly the corresponding portion of the geosphere down to a depth of about 1,000 m is regarded as part of the system. Depending on the analysis context, this definition may also be somewhat modified.

- Future human behaviour on a local scale is internal to the system, but not issues related to the characteristics and behaviour of future society at large.

- In general, a strict boundary definition is neither possible nor necessary, and the same boundaries will not necessarily be relevant to all parts of the safety assessment. The above definitions were the basis for the FEP sorting – and thus have affected on the system description.

2.4 FEP database

An important and formal tool for ensuring that all relevant factors have been considered in the safety assessment is provided by available databases of features, events and processes (FEPs) relevant to long-term safety of nuclear waste repositories.

A new version of SKB's database of FEPs relevant to the long-term safety of a KBS-3 repository has been developed for SR-Can. Documentation of this work is in progress but an interim version is available /SKB, 2004a/. The SR 97 version of the database was largely focussed on the long-term processes relevant to repository safety. That database has been systematically compared with other national databases included in the NEA international FEP database to ensure that all relevant factors are taken into account. The structure of the SR-Can database is closely related to the information structure described above. In the database all items have been classified as one of the following:

- Processes within the system boundaries relevant to long-term safety.

- Factors affecting the initial state of the repository, either directly related to a specific aspect or to the initial state in general.

- External factors relevant to long-term safety, e.g. climatic evolution and human intrusion.

Most FEPs in the NEA database could be mapped to one of these categories. All other FEPS were characterised as general methodology issues or deemed as irrelevant for the KBS-3 system.

In general, the initial state FEPs that are not automatically covered by the description of the repository design or by the site description, concern deviations from the intended initial state as a consequence of undetected mishaps, sabotage etc. These are propagated to the selection of scenarios described in chapter 8.

A few internal processes for the engineered barriers or the geosphere were added as a result of the auditing against the NEA database. Biosphere processes were not included in the SR 97 Process report and there is therefore not the same basis for updating these descriptions as for the engineered barriers and the geosphere. All biosphere FEPs, most of which are processes, have therefore been collected in a single category to be further handled in the safety assessment.

External FEPs were subdivided into the categories

- Climate processes and effects.

- Large-scale geological processes and effects.

- Future human actions.

- Other.

It was checked that all relevant external FEPs were included in the plans for managing these issues in SR-Can. Climate and large-scale geological FEPs were compared against the plans for modelling these phenomena and the characterisation of future human actions was compared with that in SR 97, which forms the basis for the approach in SR-Can.

It is important to note that it is not possible to formally verify that all relevant FEPs have been addressed in this Interim version of the SR-Can report. Such a final verification will be performed at the end of the SR-Can project and documented in the database.

The handling of FEPs in SR-Can is summarised in Figure 2-2.
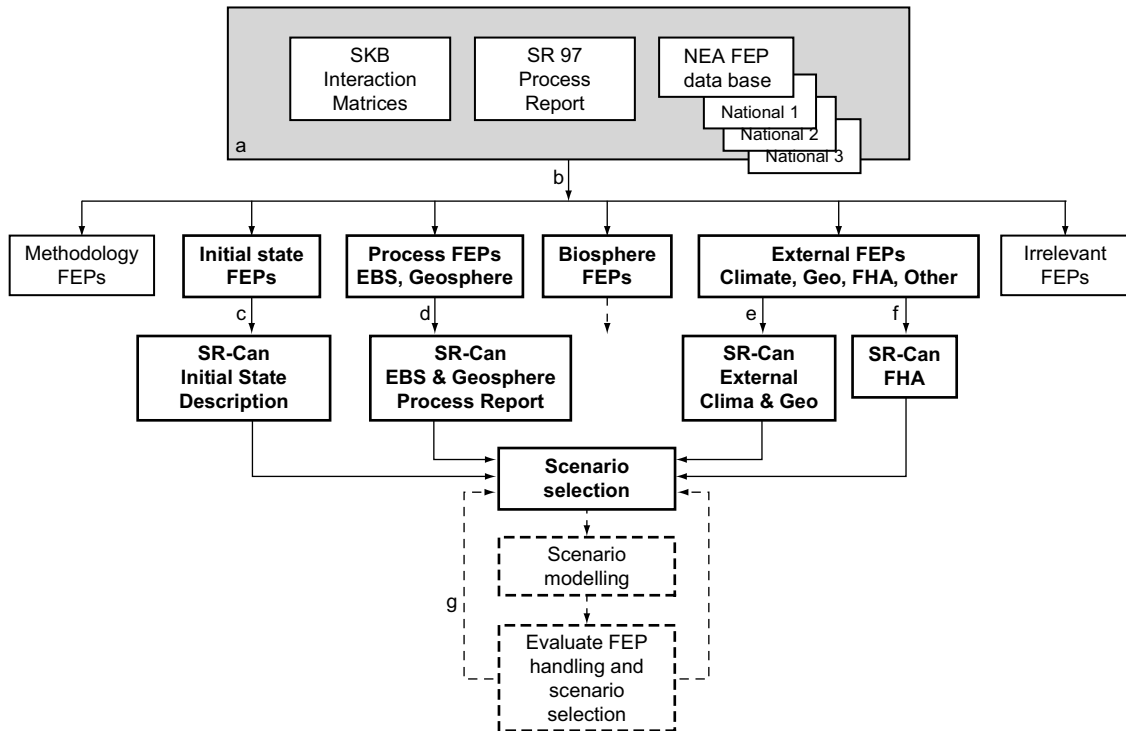
a. The starting points for the SR-Can FEP handling are FEPs in i) the SKB interaction matrices, ii) the SR 97 processes as documented in the SR 97 Process Report and iii) the NEA international FEP database with a number of national data bases linked to it.

b. FEPs were sorted into three main categories: i) initial state, ii) process and iii) external FEPs. Biosphere FEPs were compiled and remain to be further handled. FEPs were also categorised as irrelevant or as being related to methodology at a general level.

c. Initial state FEPs were either i) included in the initial state description in SR-Can, i.e. the reference description of the KBS 3 repository, the site description or the site-specific layout of the repository or ii) propagated to the scenario selection if they describe circumstances outside the reference conditions.

d. Process FEPs were used to update the SR 97 set of internal processes for the EBS and the geosphere. The resulting SR-Can set of processes are documented in the SR-Can Process Report.

e. External FEPs related to climate and large-scale geosphere processes were audited against the plans for handling these phenomena in SR-Can, which builds on the treatment in SR 97.

f. External FEPs related to future human actions (FHA) were audited against the FHA FEP treatment in SR 97. The coverage was found satisfactory. The only "other" external FEP, meteorite impact, was dismissed as being extremely unlikely.

g. Following scenario selection and modelling, an evaluation of the comprehensiveness of the selected scenarios and of the FEP handling will be carried out.

Figure 2-2. *The handling of FEPs in SR-Can.*

2.5 Timescales

2.5.1 Regulatory requirements and guidance

The SKI regulations SKI FS 2002:1 state that the safety assessment should cover the period during which the barrier functions are needed, though to at least 10,000 years after closure. 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 period.

2.5.2 Timescale covered by the safety assessment

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 2-3. The latter comparison is equivalent to comparing the radiotoxicity of the amount of natural U-235 and U-238 consumed in the reactor, to the radiotoxicity of the amounts of the new products created in the reactor (fission products and actinides) remaining after 100,000 years.

Another criterion that may be used to justify a timescale for a safety assessment is that the period analysed should go beyond the point in time at which peak doses from the repository occur. In SKB's most recent 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 inappropriate.

In SR-Can the timescale for the assessment will be one million years. This timescale is longer than that needed to reduce the radiotoxicity of the inventory to a level comparable to that of the corresponding amount of natural uranium ore and is also in accordance with the suggestions in SKI's recommendations cited above. However, a brief general discussion of the evolution beyond one million years will also be given in SR-Can.
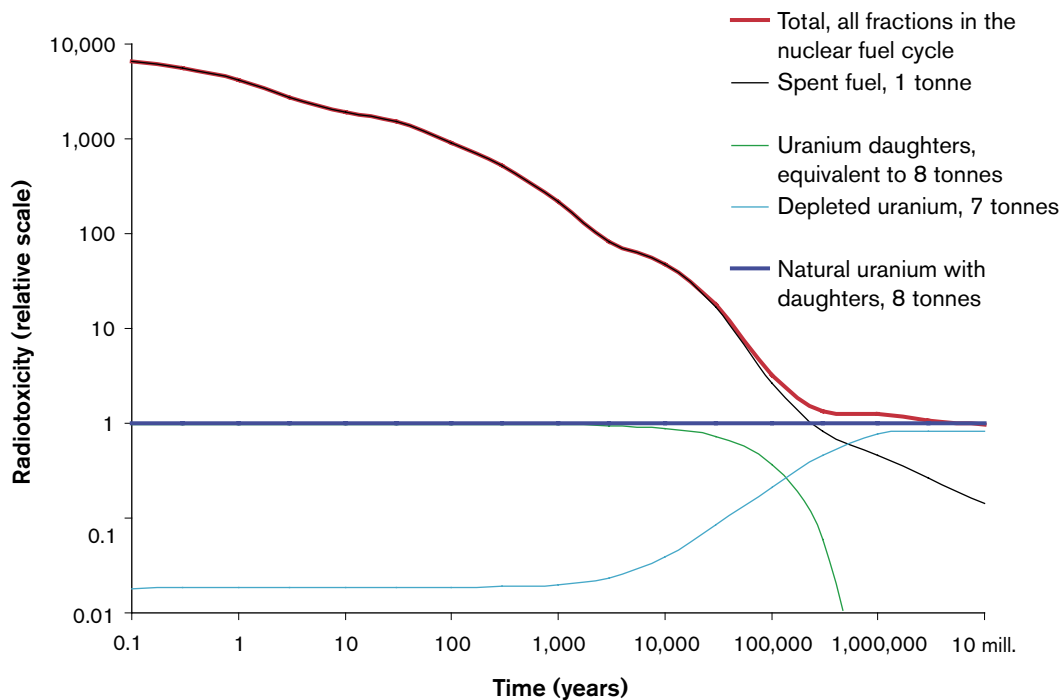
Figure 2-3. *Radiotoxicity on ingestion of uranium ore (blue line), and of the sum of all fractions that arise when the same quantity of uranium mineral is used in the nuclear fuel cycle (red line). The time refers to the time after reactor operation. The different fractions comprise the spent fuel (38 MWd thermal energy/kg U of type SVEA 64 BWR), the depleted uranium and the uranium daughters that are separated in the uranium mill. From /Hedin, 1997/.*

2.5.3 Timescales relevant for repository evolution

There are a number of timescales relevant for the repository evolution:

- A fundamental timescale is that relevant for the development of the radiotoxicity according to Figure 2-3. At the time of deposition the radiotoxicity has decreased by roughly a factor of ten compared to the situation one month after operation, and then continues to decrease by about a factor of ten for every ten-fold increase in time. As mentioned above, the radiotoxicity of the spent nuclear fuel is comparable to that of the natural uranium ore once used to produce the fuel after about 100,000 years.

- Long-term geological processes, occurring over millions of years, include movements of tectonic plates and associated ridge push caused by these movements.

- The climate has, for the past million years, evolved in roughly 100,000 year cycles, each including, in Sweden, several episodes of permafrost and glacial conditions. The mechanical, hydraulic and groundwater chemical conditions in the host rock will vary in accordance with the climatic evolution, in particular as a result of glacial loading. It is debated whether these cycles will in the future be perturbed by human-induced climate changes.

- There are a number of timescales on which biological evolution occurs; man is e.g. expected to evolve considerably during a period of one million years.

- The natural development of ecosystems in general leads to considerable changes in a 1,000 year perspective.

- Most parts of society have changed drastically over the past 100 years and significant changes may occur abruptly or over only a few years time. Historical records of humanity cover a few thousand years.

- The thermal evolution of a KBS-3 repository due to the residual power of the fuel results in peak temperatures in the near field after about ten years, and elevated temperatures in the host rock for a few thousand years.

- The resaturation of the buffer, the backfill and the host rock typically requires tens to hundreds of years for Swedish conditions.

- The chemical conditions in the host rock after excavation and operation of a deep repository are expected to, in most parts, have returned to natural conditions in a 100 or 1,000 year perspective. The chemical conditions in the buffer will change to some degree during the 1,000-year period of elevated temperatures. The buffer is then expected to be chemically stable in the environment offered by a deep repository in Swedish granitic rock. Canister corrosion under typical repository conditions requires millions of years to cause canister failures.

Timescales is a recurring issue in this report, e.g. in the context of process descriptions, section 5.3, and when analysing repository evolution, chapter 11. The issue of timescales in safety assessments has recently been addressed in an NEA Workshop /NEA, 2004a/ in which SKB participated.

2.6 Safety

2.6.1 Safety principles for the KBS-3 repository

Since the development of the Swedish deep repository project commenced at the end of the 1970s, SKB has established a number of principles for the design of a deep repository. The principles can be said to constitute the safety philosophy behind the KBS-3 concept. They are in summary the following:

- By placing the repository at depth in a long-term stable geological environment, the waste is isolated from both societal changes and direct effects of long-term climate alterations.

- By locating the repository at a site where the host rock can be assumed to be of no economic interest to future generations, the risk of human intrusion is reduced.

- The spent fuel is surrounded by several safety barriers.

- The primary safety function of the barriers is to isolate the waste.

- Should isolation be breached, the secondary safety function is to retard and disperse a potential release from the repository.

- Engineered barriers shall be made of naturally occurring materials that are long-term stable in the repository environment. The long-term properties of the materials shall be verifiable.

- The repository shall be constructed so that temperatures that could have detrimental effects on the long-term properties of the barriers are avoided.

- The barriers should be passive, i.e. they should function without human intervention and without supply of matter or energy.

Together with many other considerations, like the geological setting in Sweden and the requirement that the repository must be feasible to construct from a technical point of view, these principles have led to the development of the KBS-3 system for spent nuclear fuel.

2.6.2   Safety functions and measures of safety

The key safety related features of the repository can be summarised in the safety functions isolation and retardation.

The fuel is placed in corrosion-resistant copper canisters with a cast iron insert providing mechanical strength. The copper canisters are surrounded by bentonite clay in deposition holes at a depth of approximately 500 m in the host rock. The bentonite clay protects the canisters from minor rock movements and limits the inflow of the low levels of corrosive agents in the groundwater. The host rock provides a long-term chemically and mechanically stable environment for the canisters and the bentonite clay. The canisters therefore constitute an isolating barrier with a very long life-time in the environment provided by the buffer and the host rock.

The fuel, the canister, the buffer and the host rock contribute to retarding any potential release of radionuclides should a canister be damaged. The fuel matrix is in itself stable in the environment at repository depth. Many of the most hazardous radionuclides have a very low solubility in groundwater and are thereby inaccessible. Both the cast iron insert and the copper canister limit the inflow of water even if damaged. The buffer limits the inflow of water to a damaged canister and the release of radionuclides. The groundwater moves slowly in the fracture system of the rock and many radionuclides have a strong propensity for diffusion into, and sorption in, the host rock matrix.

The fundamental criterion regarding safety is expressed in SSI's regulation SSI FS 1998:1 where it is stated that the aim is to ensure 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 risk criterion corresponds to doses that are roughly one per cent of naturally occurring background radiation.

Results of risk calculations in the safety assessment are compared with this criterion in order to assess compliance. However, the risk results depend in a complex fashion on a large number of factors. In a safety assessment, it is necessary to not only assess compliance with an overall criterion, but also to demonstrate how safety is related to key properties of the barriers and how these properties vary over time. An obvious property would be the integrity of the copper canisters. This in turn depends on a number of factors like the buffer properties and the chemical environment of the repository.

In chapter 6, a number of function indicators for the barriers are developed. Criteria are provided for properties like canister temperature and buffer and backfill density, hydraulic conductivity and swelling pressure. Demonstrating compliance with these criteria provides arguments that the barriers are functioning as intended as the repository system evolves. Conversely, should a function indicator criterion be breached, this signals that safety in one way or the other is potentially jeopardised and that the consequences need to be further considered. However, it does not automatically imply that overall system performance is unacceptable.

Chapter 6 also provides a discussion of alternative "top level" indicators to the risk criterion. The alternative criteria are more directly related to releases from the geosphere which do not require detailed assumptions about biosphere conditions or human habits.

2.7 Compilation of input data and data uncertainty

All input data used in quantitative aspects of the safety assessment have 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 handled. A methodological approach for the determination of input data with uncertainties and the subsequent handling of the uncertainties is therefore required.

The set of input data parameters for the safety assessment is very large. Some input data uncertainties will have a substantial influence on safety related output uncertainty whereas others will essentially not influence output uncertainty at all. An 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 and, where feasible, reduction of input data uncertainties. It is also important to have a high degree of confidence in the data that are used to conclude that certain nuclides will never contribute to dose.

However, the sensitivity analyses themselves 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 prioritise and 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 database, and other appropriate sources.

2.7.1 Objectives of the SR-Can Data report

In SR 97, a standardised procedure was employed for defining all input data required for radionuclide transport calculations. The outcome was presented in the SR 97 Data report /Andersson, 1999/. The uncertainty treatment in SR 97 is discussed in the SKI/SSI review /SKI and SSI, 2001/. The authorities have since conducted some investigations on the approach to elicitation and use of 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, 2003/.

A new procedure, based on the one used in SR 97 and taking into account review comments has been developed in the interim version of the SR-Can Data report /SKB, 2004c/. The objective of this report is to compile input data, with uncertainties, for the SR-Can assessment calculations and for a wide range of conditions. In contrast to SR 97, data are provided not only for the radionuclide migration calculations, but also for some important aspects of quantification of the repository evolution.

The interim version of the data report supplies data for the dose consequence calculations presented in this SR-Can interim report and a preliminary inventory of other data to be qualified, but most of its content is preliminary. The standardised procedure for data assessment is only demonstrated in full on the buffer migration data, whereas more preliminary procedures are applied on other data presented at this stage. In the final SR-Can version of the data report, the standardised procedures will be applied to all data.

2.7.2 Inventory of data

The mapping of safety relevant processes to models, see section 5.4, yields a set of models which are used to quantify the system evolution, including models for radionuclide transport and risk calculations. 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. While data for all the several hundred input parameters must be quality assured, only a limited sub-set are uncertain to an extent critical to the safety evaluation, thus requiring a detailed quantification of uncertainty. These data will be identified by sensitivity analyses of calculation results using preliminary input data ranges, often from earlier assessments. A number of calculation end-points regarding both isolation and retardation will be considered and sensitivities of these to input parameter uncertainty will be determined. Preliminary evaluations of calculation end-points and sensitivity analyses are provided in chapters 7 and 11, regarding general evolution, and in chapter 12, regarding radionuclide dose and risk. These, and more developed results from later stages of the SR-Can project, will be used to continuously update the list of data needing a rigorous qualification for the SR-Can assessment. A preliminary list of such data is provided in the Interim Data report /SKB, 2004c/.

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 typically highly skewed, as is often the case in this type of calculation. The skewness is not 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 different input data distributions. 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.

2.7.3 Procedure for assigning values

The new procedure, based on the one used in SR 97 and taking into account review comments, takes the form of a protocol to be used for all relevant data for the safety assessment. The protocol is 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.

The data and uncertainty estimation is made for various subject areas. The evaluation of uncertainties and the final selection of input data for various conditions are presented in a standard form. Each subsection summarises input from experts and shows the judgements made by the SR-Can team. The standard form and the substance of the instructions to the experts are provided below.

In subject areas where data may have a large impact on assessment results, specific subject area data assessment reports are produced. These special reports follow a fixed outline with instructions to the author on how to address uncertainty, and clearly differentiate between input provided by identified experts and input provided by the SKB SR-Can team. For this interim version of SR-Can, one such special report has been produced. This is the buffer migration data report by /Ochs and Talerico, 2004/.

Expert input and judgement by SR Can team

The individuals providing the expert input are identified in the respective supporting document and will also be included in the SR-Can Expert Database, see section 2.10.

The data report separates between expert inputs and judgements made by the SR-Can team. This is achieved both through clear referencing and by specific subsections entitled "Expert

Input" and "Judgement by SR-Can Team". Although the experts may suggest values, the SR-Can team makes all the final judgements on which values and ranges to use in the assessment calculations. However, the concerned experts have the opportunity to review these judgements and their review comments will be documented.

Modelling in SR-Can

Each subject section of the data report starts with a brief explanation of how the data to be supplied are used in SR-Can. This information is provided for precisely defining the input data and explaining the context in which the data will be used. Motivation for the use of these models in the assessment is provide in the SR-Can report, in the process report – or elsewhere.

Conditions for which data are supplied

The next section, according to the protocol for data uncertainty discussion, lists the various "conditions" for which parameter values and uncertainty estimates are needed. "Conditions" refer to boundary conditions, barrier states and other circumstances, which potentially may affect the values of the parameters to be estimated. Alternative "conditions" may arise because of various initial states, evolution within a scenario or conditions under different scenarios.

Sensitivity to assessment results

As appropriate, the next section, according to the protocol, will explain what sensitivity analyses have been performed in order to prioritise uncertainty assessments for those parameters and conditions judged to be potentially important to performance (both for overall endpoints such as risk and on conditions affecting the state of the system).

If sensitivity analyses have been performed, the following will be discussed:

- For what ranges of the parameter is the impact on safety significant and are there ranges where the impact is negligible?

- Is the impact monotonic, i.e. is there a unidirectional relationship between the parameter value and performance, or is there an "optimal" value, or is the impact complexly dependent upon the values of other input parameters?

- What precision is needed to adequately quantify safety assessment results?

It should also be stated whether the answers apply to all applicable conditions – or only to some.

Conceptual uncertainties

The next section, according to the protocol, explores conceptual uncertainty by addressing the following questions:

- Are there conceptual uncertainties related to the model in which the parameter is used?

- Are there conceptual uncertainties related to models used for deriving the parameter value?

- In light of the previous point, can the conceptual (model) uncertainty be expressed/ illustrated through parameter uncertainty in the given model?

Data uncertainty, spatial and temporal variation

The next section, according to the protocol, concerns spatial and temporal variations and data uncertainties. The following questions will be addressed:

- What is known about the spatial variation of the parameter? Is there any information about the uncertainty in the spatial variability? How is this considered in the parameter value and uncertainty estimates?

- What is known about the temporal variability of the parameter? How is this considered in the parameter value and uncertainty estimates?

- If the parameter value and its uncertainty are drawn from a database, is this site-specific or "generic"? In the latter case, how have the lack of site-specific data influence the uncertainty?

- Are parameter values and uncertainty estimates based on analyses of field/laboratory data? Are there any measurement errors etc and how are they considered in the uncertainty estimates?

- If data for estimating the parameter have been produced using a model, what uncertainties does this introduce?

Correlations

The extensive work with the FEP databases and the Process report should imply that most functional dependencies between parameters are identified - and the important ones implemented in the safety assessment models. Also the assessment of impacts from various conditions should cover most potential correlations. Still, other statistical correlations may exist. The following questions should be addressed, according to the protocol:

- If the data varies in space or time – is anything known about its autocorrelation structure?

- Is there any other reason (apart from already cited functional relations etc) to suspect correlation between parameters considered as input to SR-Can?

Quantification of uncertainty

Finally, according to the protocol, the various sources of information are combined into quantified data values and uncertainty estimates. Based on their previous assessment, i.e. also considering conceptual uncertainty etc justified uncertainty estimates of the applicable data will be provided. Depending on possibilities and assessed importance, the uncertainty estimates may be given either as a distribution function, subjective percentiles or as a range.

The preferable option is to describe the uncertainty as a distribution function, but the distribution has to be justified. For example, for a spatially varying function, well described by a given stochastic process, e.g. through a variogram or as realised in a DFN, a potential distribution function may be to state that all realisations of this spatially varying function are equally probable.

Another option is to only provide subjective percentiles a_i in the distribution function: $P(x<a_i)=p_i$, i.e. a_i is the parameter value where subjective probability that the parameter will take a value less than a_i is p_i. If sensitivity analyses show that only part of the range has an impact on the function, less effort may be given to quantification of the distribution parameter values outside this range.

If distribution functions or subjective percentiles cannot be supplied, the uncertainty may instead be described as a range. However, the meaning of the range must then be provided, e.g. does it represent all possible values, all "realistically possible" values or just the more likely values?

The uncertainty estimates should also provide information on correlations. For spatially/ temporal varying functions this includes information on auto-correlation.

Final judgement

Finally the SR-Can team judges whether the expert input can be supported. In particular the expert input on uncertainties and correlations may need to be interpreted into more closed form mathematical expressions (such as distribution functions), such that it can be used for the assessment calculations. For instance, if a most likely value and an upper and a lower bound have been given, a triangular distribution may be selected by the assessment team.

2.8   Methodology for the biosphere

The biosphere is in some respects handled in a different manner than other parts of the system, as defined in section 2.3. This is essentially due to the complexity and relatively rapid changes in the biosphere compared to the repository and the host rock. Therefore, some general issues regarding biosphere methodology are discussed in this section. More detailed accounts of some of these issues are given in Appendix C.

The biosphere is an essential part of the system that has to be understood and analysed in a safety assessment of a nuclear waste repository, since the consequences of a potential release occur in the biosphere. For the time scales of relevance to the safety assessment, the biosphere will undergo considerable development, in particular due to expected future climate changes involving periods of permafrost and glacial conditions or extended warm periods. A realistic, site-specific handling of the biosphere is likely to yield very low doses during most of the assessment period for several reasons. Due to expected shore-line displacements over a glacial period, coastal sites are likely to be submerged for extended periods of time, leading to both stagnant groundwater and potentially a considerable dilution of any releases from the geosphere (though also with the possibility of accumulation in bottom sediments). Glacial conditions, meaning that the site is covered by ice, will for obvious reasons lead to very low, if any doses. The highest doses are expected for the parts of temperate periods during which the site is not submerged, an assumption that however needs to be further supported by explicit calculations. See also the approach to dilution in the overall safety evaluation in section 6.2.

As will become apparent in later sections of this report, releases from the repository are expected to be negligible for thousands of years into the future when today's biosphere has undergone considerable development. Nevertheless, it is essential to obtain a thorough understanding of the current biosphere since this is the best available basis for a description of future biospheres during temperate conditions. Also, an important factor affecting the biosphere structure in an interglacial period is the position of the shore line which is fairly predictable, partly since it is strongly related to the local topography. Furthermore, much of the knowledge required to describe the functioning of the biosphere is generic in nature meaning that results regarding the current biosphere are applicable also for altered future biosphere conditions. Studying and analysing the biosphere is therefore an essential part of the ongoing site investigations and the results of these studies are of direct relevance for the safety assessment.

2.8.1   Handling of the temporal development of the biosphere

For the present temperate period, the overall development of the biosphere at the site will be outlined in a 1,000 year perspective and beyond, essentially based on the ongoing shore-line displacement and the understanding of the impact this has on the biosphere. This is further developed in sections 11.2.1 and 11.3.1. The information will be summarised as a succession of biosphere maps of the site, each representing a certain part of the temperate period, Figure 2-4. The maps will be the basis for the further modelling of the biosphere.

The development during permafrost and glacial conditions are addressed in section 11.4.5.
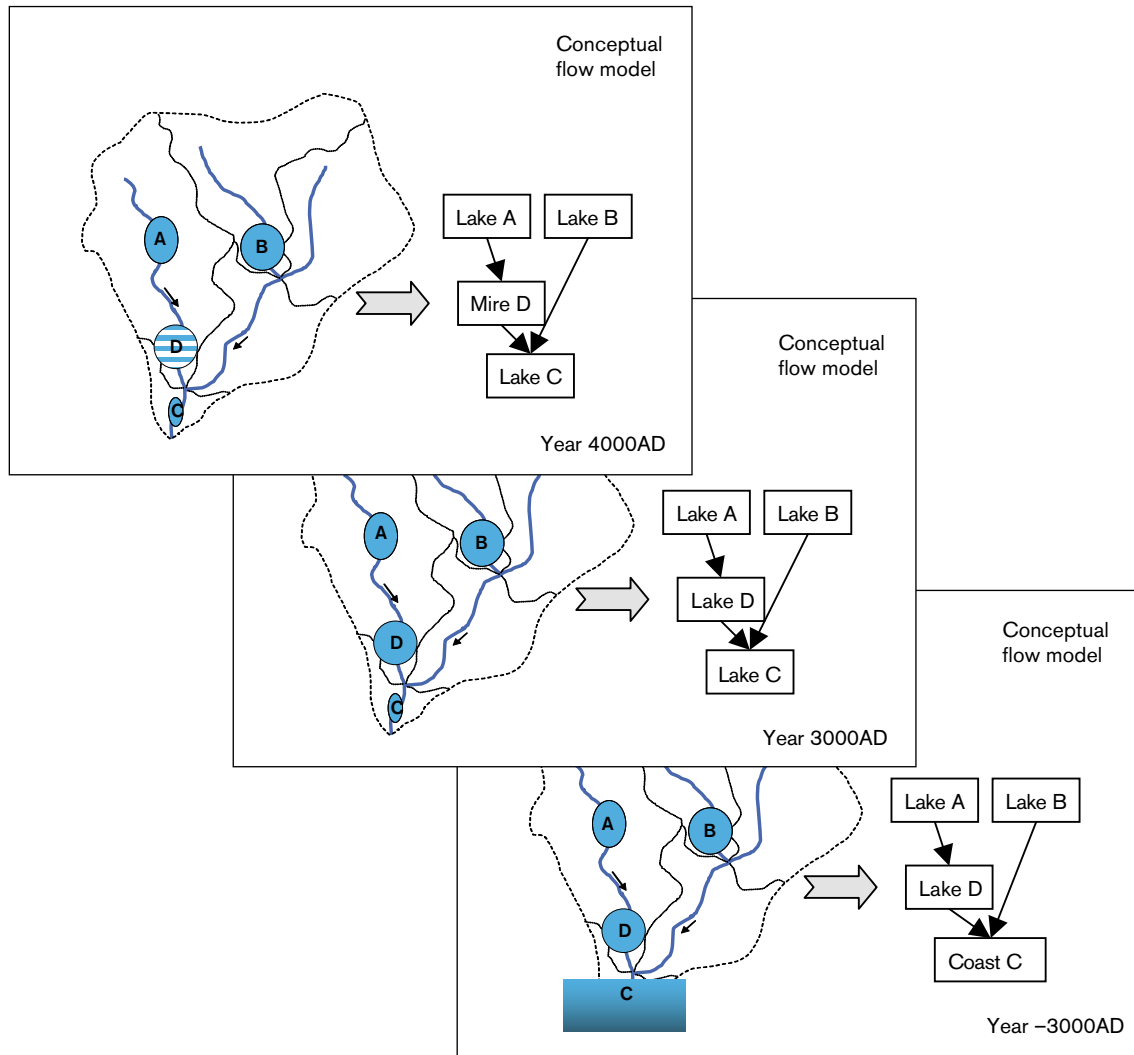
Figure 2-4. *Example of a succession of biosphere maps for temperate conditions. The maps represent different periods with different biosphere objects and data. A new map is compiled for a new state when a relevant change from the previous state has occurred.*

2.8.2 Biosphere modelling for the present temperate period

Based on the scientific understanding of the biosphere at the site and its development during an interglacial, biosphere models can be constructed in which the turnover of radionuclides can be analysed. The methodology and the available tools for this are described in detail in Appendix C. Below, a brief overview of the modelling strategy is given.

The temporal development of the biosphere during an interglacial period is handled by building biosphere models for the succession of situations described by the maps mentioned above. For each situation, the landscape (the local biosphere) is described as a number of connected biosphere objects constituting an integrated landscape model, Figure 2-4. The descriptions of the biosphere objects are based on the ecosystem models and on local field data.

The two main categories of ecosystems, aquatic and terrestrial, are further subdivided into a number of ecosystem types. Aquatic ecosystems include marine systems, lakes and running water and examples of terrestrial systems are agricultural land, mire and forest. For each of these, there are, in general, several possible ecosystem models that can be applied, as further described in Appendix C.
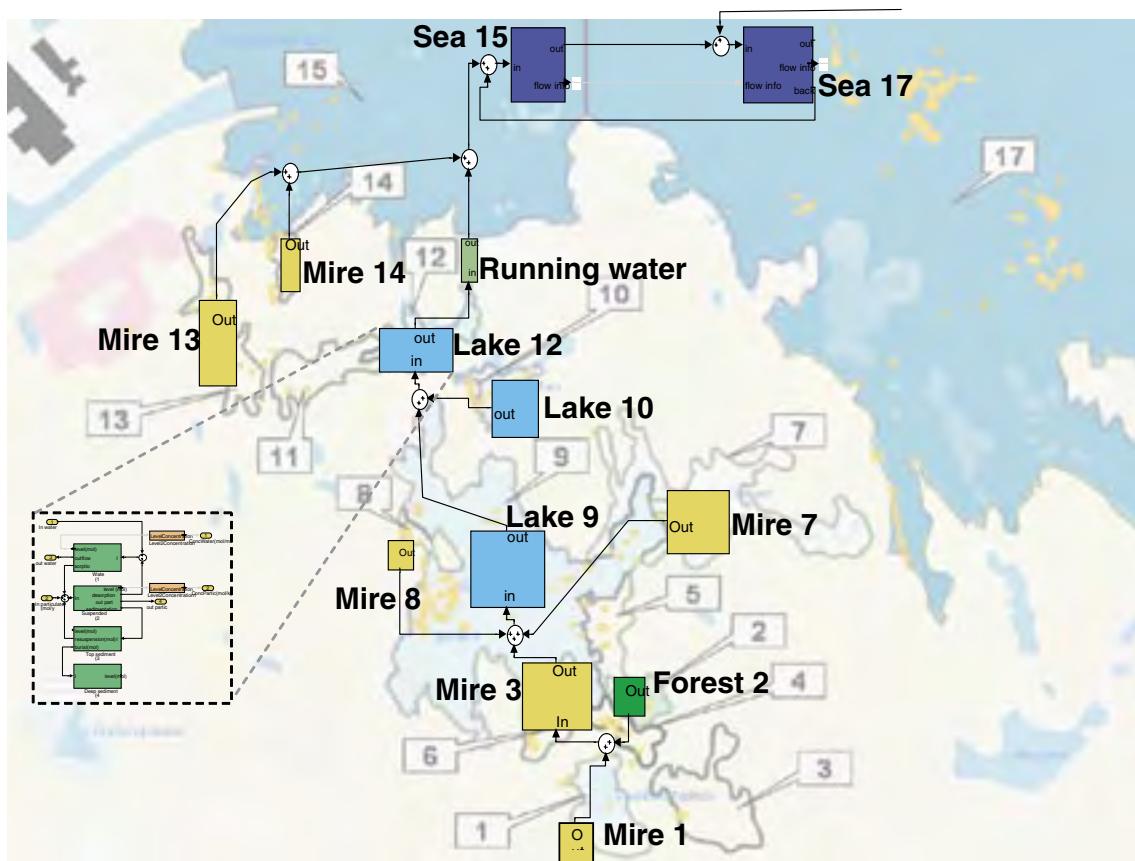
Figure 2-5. *For each map, an integrated landscape model consisting of a number of connected biosphere objects is constructed and analysed. Each biosphere object is a representation of under-lying biosphere model, cf Lake 12 and the hatched panel at the left. Further details are given in Appendix C.*

By introducing radionuclides at different locations in the integrated model, it is possible to follow their fate as they move through the connected ecosystem objects, and to assess where and to what extent they may accumulate in the system. Combined with information on calculated locations of radionuclide releases from the geosphere to the surface hydrological system this gives a view of how radionuclides become distributed through the integrated landscape model over time. A first example of such a study is provided in Appendix C.

In order to assess doses to humans, given the calculated distribution of radionuclides in the landscape, a number of assumptions have to be made concerning living habits and exploitation of the landscape. Many of these must be generic, but the characteristics of the site and its potential future states do provide a number of constraints on such assumptions. It is e.g. possible to estimate the number of individuals that can live off the natural resources at a site. Such constraints will be assessed and utilised in the dose modelling for the final SR-Can report. An early example for the Forsmark site is provided in Appendix C.

Wells constitute an important pathway for human exposure to potential releases from the repository. The approach to modelling of wells in SR-Can, based partly on site-specific information and considering constraints on the size of a population that can utilise a local well is developed in Appendix C.

2.8.3   Application to probabilistic consequence calculations

For the complex and extensive, probabilistic consequence calculations that will be executed for the entire repository system over the one million year assessment period, exemplified in chapter 12, the biosphere modelling needs to be further simplified. The treatment of the biosphere in the example calculations in this interim report aims at capturing situations that are representative of high dose consequence conditions that could reasonably occur during a temperate period, assuming that the biosphere and its use by humans resembles that at present.

Two situations are considered in this interim report. One is a mire being used for agriculture, representing a terrestrial ecosystem in which radionuclides are assumed to be accumulated over a long period of time but where exposure may be limited to a shorter period. The properties of the mire are taken to be, as far as possible, representative of the Forsmark site. The other is a self-sustaining farm obtaining drinking and irrigation water from a local well. For these two systems, ecosystem-specific dose conversion factors integrated over 10,000 years, EDFs, are calculated probabilistically, see Appendix C. The EDF distributions will be used to transform calculated radionuclide releases from the geosphere to effective doses to the most highly exposed hypothetical future individuals.

In the final SR-Can report, this strategy for including the biosphere in the consequence calculations will be reconsidered and updated, as appropriate. The revised strategy will build on the results of further studies of the integrated landscape models. It is however premature at this stage to determine whether these results will be used to derive new dose conversion factors or if a more complex approach will be identified as being required. A fully time-dependent treatment of the biosphere is however not envisaged, since this would lead to a situation where the overall calculation result is entirely dominated by the biosphere uncertainties and relatively rapid temporal variations, quenching essential uncertainties and temporal characteristics related to the properties of the safety bearing engineered barriers and the host rock.

2.8.4 Doses to biota

Also the potential effects on the environment from exposure to radionuclides need to be assessed. In the SAFE project, the model developed by Kumblad /Kumblad, 2001/ was used to calculate C-14 doses in Gray to different functional groups of organisms in the coastal ecosystem. The intention is to use an extension of this approach for estimating concentrations in biota also from other nuclides in the coastal ecosystem and, if possible, also for the lake ecosystems. For other ecosystems, the FASSET methodology /FASSET, 2004/ and its development in ERICA (EU - 6th Framework Programme), can be used. In general, it is expected that the concentrations will be very low in biota and in their immediate environment, giving radiation levels much less than background.

2.9 Use of natural analogues

This interim report does not discuss natural analogues at any length, but they will be discussed in the final SR-Can report. This section presents the current plans in this context.

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 and matrix diffusion.

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 SR-Can, see chapter 5. It will be considered whether to present analogues in the high-level document as well as 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 of the main report. The following is a provisional 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).

Greatest weight will automatically be put on the material analogues (for spent fuel, copper, bentonite), since they provide useful arguments for safety assessment and are therefore well represented in the Process report.

Illustrating basic conclusions

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

Discussing "negative analogues"

This chapter/section should also be a forum for commenting "negative analogues", i.e. analogues that give results which seem to contradict input assumptions to, or conclusions from 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 in the report and be put 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, 1999a/. Another example is the Boda Caves phenomenon discussed in SKB's RD&D-programme 2001 /SKB, 2001/.

2.10 Expert judgements

Information based on expert judgements of various nature will permeate the safety assessment. Expert judgements could include anything from a scientist's interpretation of a result of a straightforward experiment to an expert's judgement on the impact of human-induced greenhouse effects on the future climatic evolution or to an assessment of the likelihood of a certain type of future human actions that could have an impact on repository evolution. A judgement could consist of anything from a well-justified quantitative or qualitative statement in a report, to an exhaustive and formal questioning of a carefully selected panel of experts using an approved elicitation protocol.

Furthermore, there are issues on which different experts have differing views. In cases where a consensus view or statement cannot be achieved, it is necessary to take the differing views into account in the assessment.

Most of the information based on expert judgements in SR-Can will be provided either in the form of reports written by one or several experts or as decisions made by generalists in e.g. the screening of FEPs, the selection of scenarios or the formulation of calculation cases. The formal questioning of a panel of experts could possibly be employed in a few cases, if the nature of the issue so requires.

2.10.1 Documentation of expert judgements

For the traceability of the assessment, it is important to clearly state where expert judgements are made and by whom. For this purpose, a database with descriptions of all important experts providing in one way or the other expert judgements for SR-Can will be developed. A template will be used, requiring information on e.g.

- level of education,

- experiences in the field,

- scientific publications of relevance to the particular area of expertise,

- role in SR-Can.

References to the appropriate experts represented in the database will then be made where the judgements are used in the assessment. In order to not burden the text with numerous references of this nature, these will be provided at the end of the relevant sections/chapters of the main report, or in the preface or introduction of an underlying report authored by a single expert.

2.10.2 Selecting experts

There will in general be no formal rules for the selection of experts. The generalists in the core team of the assessment will provide a large part of expert judgements and these individuals have, as will be documented in the database, been working with the safety of the KBS-3 system for a number of years and will thus be among the most experienced individuals available on the various aspects of the analysis of the system.

Regarding experts for the documentation of process understanding, for the selection of models or of input data etc for the quantitative aspects of the assessment, the ambition is to contract the best available experts in the field. The merits of these experts will be documented in the database, but there will be no formalised selection procedure. The documentation in the database of the merits of the selected experts should provide a sufficient justification for their involvement.

Should formal elicitations of a panel of experts be required to resolve an issue, the selection of experts for such a panel would be justified and documented in a more detailed manner.

2.11 Overall information/uncertainty management and QA

A safety assessment handles a vast amount of information of qualitative and quantitative nature, including the uncertainties associated with that information. This section gives an overview of issues related 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 section 2.2, but with emphasis on information/uncertainty management and quality assurance. The outlined plans 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.

2.11.1 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 outline 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 actions 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, taking into account all the types of uncertain factors mentioned 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 defining a structure for a 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 of whether all aspects important for the safety evaluation have been identified and whether 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 relates to 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 coupled processes, but also how well they are represented in a mathematical model of the repository evolution. Furthermore, several models describing a specific process, and simplified to different degrees, may be used for different purposes in a safety assessment.

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. The input data required by a certain model is in part a consequence of the conceptualisation of the modelled process, meaning that conceptual uncertainty and data uncertainty are to some extent intertwined. Also, there are several conceivable strategies for deriving input data. One possibility is to strive for pessimistic data in order to obtain an upper bound on consequences 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 2.7 and in the Interim Data report /SKB, 2004c/.

In all management of uncertainty, it is urgent to consider the significance of the uncertain issue relative to the purposes of the safety assessment.

The plan presented in section 2.11.3 below demonstrates how all the discussed types of uncertainty will be managed in the safety assessment.

2.11.2 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 development is 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 stronger and associated with partly irreducible, large uncertainties. Although some aspects of the development of the biosphere at a particular location can be reasonably forecasted in maybe a 1,000 year perspective, a large part of the description, particularly of 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 progresses.

Also in relation to the effects of external conditions the uncertainty management will largely have to be through stylised examples aiming at covering the range of possible future evolutions, e.g. regarding the climate and landform change. A detailed treatment of all the processes involved in 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 that could have a deleterious effect on 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,

- intrusion of waters of extreme composition, such as oxygenated glacial melt water of low ionic strength,

- extreme surface boundary conditions for groundwater flow possibly leading to high groundwater fluxes at repository level or groundwater movements that could cause intrusion of deeply lying saline groundwaters and

- conditions leading to extreme permafrost depths.

The inner parts of the system, which provide the safety functions isolation and retardation, will therefore be treated most fully in the management of uncertainty, whereas the biosphere and the external conditions are handled in a more stylised manner.

2.11.3 QA measures and 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 regulations and

- to give feedback to design, research and development 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 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.

Application of Quality Management systems

Quality, on a general level, is assured by applying SKB's quality management routines to the SR-Can project. The overall management system for work carried out within SKB integrates systems for managing quality, environmental aspects, security, nuclear safety, occupational health and administration. These systems are certified according to the requirements of EN ISO 9001:2000 and ISO 14001:1996.

The management system includes documented procedures dealing with e.g. project control, documentation, purchasing, contract review, management review, internal auditing and issues of non-conformance. Procedures needed for day-to-day work are accessible for all personnel through SKB's Intranet.

SR-Can is a sub-project to a larger project that aims at producing all documentation needed for the application to build an Encapsulation Plant. Applicable parts of the management system and the procedures included in it will be applied in these projects. In particular, the routines for project management and for quality assurance of data and documentation will be important for assuring quality in the SR-Can project.

Reviews

Another general principle promoting quality assurance is the use of reviews of different aspects of the safety assessment. Reviews can be applied to the bases for the safety assessment, e.g. in the form of documents supplying important data or parts of the knowledge base. Also key expert decisions/judgements and results of the safety assessments can be reviewed. This concerns e.g. important central decisions regarding general methodological issues, the handling of various FEPs and the selection of scenarios.

For each review activity, it is important to consider the extent to which the reviewers need to be external and independent for the review to be meaningful and contributing to confidence building.

This interim report has been reviewed by SKB's external Site Investigation Expert Review Group (SIERG) whose members have a profound expert knowledge of matters related to long-term safety. Several of the background documents have also been reviewed by selected experts in this group. For the final SR-Can reporting, a review plan, covering the main report and important background documents, will established.

Specific to the safety assessment, a number of steps and measures are taken to obtain quality assurance regarding the handling of uncertainties. The following presentation is structured according to the three main categories of uncertainty defined above.

System uncertainty

System uncertainty is generally handled through the proper management of FEPs in the FEP database according to the routines described in the Interim FEP report /SKB, 2004a/ and summarised in section 2.4.

The database structure and FEP management routines have been set up to assure that the following is obtained:

- A comprehensive set of initial conditions. This is obtained by including all initial state FEPs in the database. These are however often generally formulated and have to be expressed in a way that is specific to the KBS-3 system. This is obtained through the systematic documentation of a reference initial state in accordance with the description in the initial state report /SKB, 2004d/ and by using that reference initial state as a starting point for alternative initial states.

- A comprehensive set of internal, coupled processes. This is obtained by including in the assessment all relevant process FEPs in the database. It is important to note that the database already from start includes the result of several earlier exercises aiming at process identification for the KBS-3 concept. This is further described in section 5.1.1. Influences between processes are handled by, in the process documentation, systematically going through a set of defined physical variables that could mediate influences and by the systematic treatment of boundary conditions for each process. These procedures are further described in section 5.3. Hence, in addition to including FEPs describing influences and couplings, the procedures for process documentation are set up in a way that enforces a systematic search for such influences.

- A comprehensive set of external influences. This is obtained by including in the assessment all relevant external FEPs found in the database and by compiling, within SKB's R&D programme, potentially relevant external influences. As the description of external conditions is a complex matter, partly handled by stylised examples as explained above, it is difficult demonstrate unambiguously that a complete treatment has been achieved.

The final check that all FEPs have been appropriately handled in the assessment, that is carried out after the selection and analyses of scenarios, plays an important role in assuring completeness concerning all the above factors.

Another aspect of system uncertainty concerns the selection of a comprehensive set of scenarios, by which all relevant FEPs are considered in an appropriate way in the analysis. The selection of scenarios is a task of subjective nature, meaning that it is difficult to propose a method that would guarantee the correct handling of all details of scenario selection. However, several measures will be taken to build confidence in the selected set of scenarios:

- A structured and logical approach to the scenario selection, see further chapter 8.

- The use of function indicators in order to focus the selection on safety relevant issues, see chapter 6.

- The use of bounding calculation cases to explore the robustness of the system to the effects of alternative ways of selecting scenarios, including unrealistic scenarios that can put an upper bound on possible consequences.

- A check that all FEPs have been properly handled in the assessment, carried out after the analysis of repository evolution for all scenarios, and the possibility of complementing the scenario selection as a result of that check.

- The use of independent reviews.

In particular the final check that all FEPs have been appropriately handled is a crucial step in assuring an adequate handling of also this aspect of system uncertainty. This step will be documented in the FEP database.

Conceptual uncertainty

The handling of conceptual uncertainty for internal processes is essentially described in the Process report. For each process, the knowledge base, including remaining uncertainties, is described and, based on that information, a handling of the process in the safety assessment is established. (Uncertainty regarding influences between processes can be seen as either system uncertainty or conceptual uncertainty, it is described as system uncertainty above.)

QA aspects: Through the use of a defined format for all process description, see section 5.3, it is assured that the processes and their associated conceptual uncertainties are described in a consistent manner. External reviews of central parts of the process documentation will also be considered.

Conceptual uncertainty for external influences is handled in a more stylised manner, essentially through the definition of a comprehensive set of scenarios and by using state-of-the-art models for the quantification of external influences, e.g. ice models for the modelling of glacial cycles. Another method is the use of bounding cases that ensure that the consequences are overestimated.

Data uncertainty

Data uncertainties are handled according to the routines described in section 2.7 and further in the Interim Data report /SKB, 2004c/.

QA aspects: Quality assurance is obtained through the use of a template for data uncertainty documentation, through clearly defined roles for participating experts and generalists and by the use of external reviews prior to finally establishing input data for the assessment.

QA in modelling

An essential part of the assessment concerns the quantification of repository evolution and in particular of dose and risk consequences, through mathematical modelling. Apart from requiring appropriately defined models that represent relevant conceptualisations of the processes to be modelled and quality assured input data, this step requires

- good model documentation, including results of code verification and results of benchmarking against other models

- procedures to detect and protect against human error in the execution of the models.

Models central for the assessment will be documented as necessary. This report contains references to several examples of such documentation. The mapping of processes to models, see chapter 5, provides an overview of the used. A guiding principle is that models and data should be documented in sufficient detail to allow calculations to be reproduced.

Human errors can be prevented e.g. by formal procedures for checking that input data are correct and by the use of alternative, often simplified, models for crucial aspects of quantification. An example of the latter is given in calculations of radionuclide transport and dose in chapter 12. A plan for these aspects of quality assurance will be established.

Documentation of expert judgements

The proper documentation of all types of expert judgements is an important aspect of both quality assurance, transparency and traceability of the safety assessment, see further section 2.10. This documentation will be provided for decisions regarding FEPs in the FEP database, for each process description in the Process report, for each group of input data in the Data report and for key decisions regarding scenario selection etc in appropriate documents, often the Main report of the assessment. As described in section 2.10, an expert database will be built, in which all participating experts will be included.

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.

2.12 Approach to Risk Calculations

2.12.1 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 effective 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 an effective dose limit of about $1.4 \cdot 10^{-5}$ Sv/yr.

According to SSI's background comments to the regulation, the dose used in a risk calculation is an integration or summation over all exposure pathways, to a hypothetical future individual, 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 criterion "concerns a repository undisturbed by man" according to the background comments issued by SSI.

2.12.2 Application in SR-Can

This section describes some basic aspects of how SSI's risk criterion will be implemented in SR-Can. Most of the material below has been presented and discussed at a recent NEA Workshop on the role of risk in safety assessments /NEA, 2004c/ and at an international conference on probabilistic safety assessment and management /Hedin, 2004b/.

Scenario disaggregation

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 cannot 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 will then be 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 during course of 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.

Overestimation of risk

The formulation of scenarios, variants and calculation cases, and the subsequent weighing together of these to give 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, in combination with the modelling capacity for consequence calculations, 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. Regarding e.g. future climate, both repetitions of past 100,000 year glacial cycle and an alternative where this development is considerably perturbed by a greenhouse effect can be envisaged. Although the two are mutually exclusive, both must be regarded as likely. In the risk summation, the logical position will be adopted that the summed consequence of a set of mutually exclusive scenarios can, at any point in time, never exceed the maximum of the individual scenario consequences. For scenarios and variants where defendable probabilities

are difficult to derive, a scenario or variant giving high consequences can pessimistically be assigned unit probability and other scenarios and variants yielding lower dose impacts can 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 basis exists for a quantitative treatment and further that the pessimistically neglected features of the system should be included in a discussion of sensitivities.

Size of the exposed group

The size of the group to which the above risk limit is to be applied must be defined in order to evaluate compliance with the risk criterion. No detailed definition is given in SSI FS 1998:1. However, in justifying the annual risk limit of 10^{-6}, SSI in its background document, discusses the possibility of ten repositories in the same region giving overlapping outflows. Furthermore, in the authorities' review of SR 97, where the risk criterion was used for the first time, it is stated that the risk limit 10^{-6}/yr applies to "large populations" /SKI and SSI, 2001/. These two statements give an indication of the size of the group to consider. If terms like "overlapping outflows", "large populations" and "regional groups" are to be relevant, at least people living in an area of many square kilometres seems to be implied.

Another option, according to SSI's background document, is to "perform calculations with respect to an individual who is estimated to have a high dose commitment" within a larger, regional group. In that case a higher risk limit of 10^{-5}/yr (equivalent to 140 μSv/yr) applies.

There is thus a choice between calculating an average dose to individuals in a regional group on the one hand and to highly exposed individuals within that larger group on the other, and the risk criteria to be applied in the two cases differs by a factor of 10.

The detailed application of these two options in SR-Can is further developed in connection with the consequence calculations in chapter 12.

Time dependent risk or peak over entire assessment period?

In SKB's most recent 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 quantity 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". The "peak of the mean" interpretation is meaningful given the statement in SSI's background document that all exposure pathways to hypothetical individuals living in the future should be considered whereas the "mean of the peaks" concept is more difficult to interpret. In SR-Can, it is thus SKB's intention to present risk as a function of time by weighing together the time-dependent mean doses from each scenario to obtain a time dependent risk. An example of the two types of results is given in Figure 2-6.
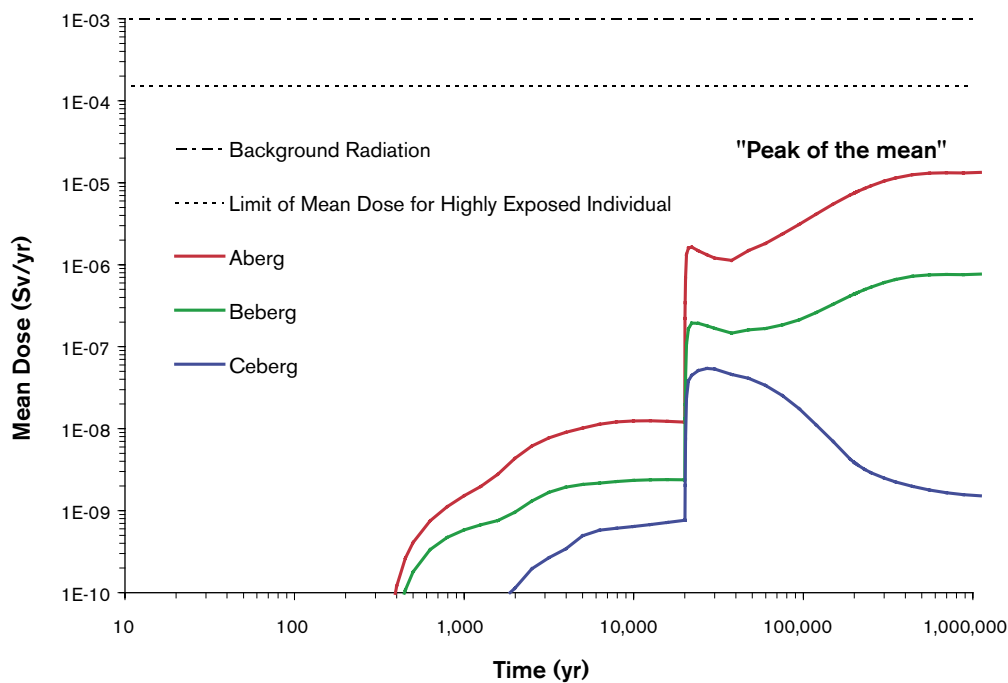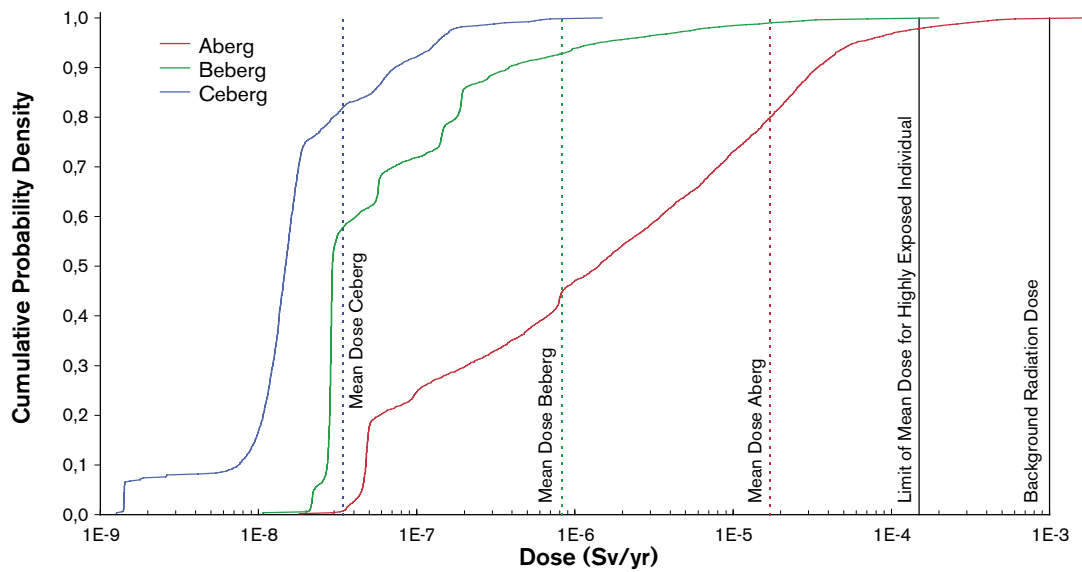
Figure 2-6. *Probabilistically determined peak dose distribution for the three sites analysed in SR 97 (upper) and probabilistically determined mean doses as a function of time for the sites (lower). Both figures are derived from the results of the same probabilistic calculation.*

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 to a highly exposed individual at a certain point in time is used as the safety indicator. Less knowledge will spread the dose over more individuals and over longer times. The total exposure to all individuals over all times could be the same or larger, whereas more distinct knowledge will "concentrate" the risk to fewer individuals and shorter periods of time. This can e.g. be the case when there is uncertainty concerning the point in time of an event that

would lead to canister rupture. 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 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 as defined in SSI's regulation and is thus an inevitable consequence of a risk criterion which is to be applied as a function of time and where the quantity to be determined is the mean value considering all relevant uncertainties. The above effect should thus be tolerable given the Swedish regulations.

A related phenomenon concerns biosphere development during the expected long periods of permafrost or glacial conditions. Assume that appreciable doses to man could occur only during temperate periods, and that these periods, as suggested by historical evidence relevant to Sweden, in the long run will prevail in total during about ten percent of the time, but that the temporal location of these temperate intervals cannot be predicted beyond, say 10,000 years into the future. In principle this situation could be handled by simulating a number of future situations where the onsets of the temperate periods are allowed to vary randomly beyond 10,000 years. Averaging over all these results would, at each point in time beyond 10,000 years, yield a dose consequence a factor of ten smaller than that obtained during a temperate climate period. This simplistic example demonstrates another type of risk dilution, again caused by an uncertainty in the point in time of the occurrence of a phenomenon, which could in principle be compatible with the Swedish risk criterion. The effect will however be avoided in the safety assessment e.g. by assuming the same temporal sequence of climate types in each simulation or by assuming today's biosphere.

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 distributions that might influence the calculation end-point in this way are not unduly broadened.

- The above risk dilution effect can be quantified by complementing a "peak of the mean" calculation with a "mean of the peaks" calculation, as described in 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.

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. Unresolved questions are:

- Time frames for risk calculations.

- The treatment of time dependencies and probabilities in biosphere models.

- Delimitation of potentially exposed groups and definition of potentially exposed individuals.

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

3 Initial state description and handling

3.1 Introduction

As mentioned in section 2.2, a thorough description of the initial state of the repository system is one of the main bases for the safety assessment.

There is no obvious definition of the time of the initial state. For the engineered barrier system, the time of deposition is a natural starting point when a specific part of the system is concerned, e.g. an individual deposition hole with its canister and buffer. However, if the entire ensemble of deposition holes is considered, there is no unique time of deposition. Neither is the time of repository closure a suitable choice for the engineered barrier system, since different parts of the repository will, at that time, have reached different stages of e.g. thermal and hydraulic evolution depending on the time of deposition and on spatial variability of rock conditions within the repository. The most reasonable approach is therefore seen as defining the time of the initial state as that of deposition for each deposition hole with its canister, buffer and backfill, and then describing the common evolution that all deposition holes will go through, taking the spatial variability into account.

For the geosphere and the biosphere, the state at the time of beginning of excavation of the repository is a natural starting point since this relatively undisturbed state is available through the site descriptive models that are derived from site investigation data. An alternative would be to consider, for each deposition hole, the state of the surrounding host rock at the time of deposition. Irrespective of which alternative is chosen, the short-term evolution of the host rock from the undisturbed state to that after excavation will have to be considered in a safety assessment that is based on observations made prior to excavation. For the biosphere, the problem is less pronounced since it will be less affected by the excavation of the repository.

Based on these considerations, the initial state in SR-Can is defined as the state at the time of deposition for the engineered barrier system and the natural, undisturbed state at the time of beginning of excavation of the repository for the geosphere and the biosphere. The evolution of the natural system will thus, at least in some aspects, be followed from the time of beginning of excavation in the safety assessment. Short-term geosphere processes/ alterations due to repository excavation will therefore be documented in the SR-Can Process report, see chapter 5.

The initial state of the engineered parts of the repository system is largely obtained from the design specifications of the repository, including allowed tolerances or deviations. Also the manufacturing, excavation and control methods need to be described in order to adequately discuss and handle initial states outside the allowed limits in the safety assessment. The initial state of the engineered parts for SR-Can is compiled in a dedicated report /SKB, 2004d/.

The initial state of the geosphere and the biosphere must, as mentioned, be determined by site investigations. Field data from the site investigations are analysed, within the site investigation project, to produce a site descriptive model of the geosphere and the biosphere /SKB, 2004e/.

This chapter contains a brief description of the initial state with uncertainties, summarising information in the EBS initial state report /SKB, 2004d/, the site descriptive model /SKB, 2004e/, a preliminary site-specific repository layout and the results of the FEP analyses reported in /SKB, 2004a/. The level of detail in this chapter is meant to be sufficient for understanding the remaining parts of the safety report without reading the above reference documents.

3.1.1 Overview of system

The repository system is based on the KBS-3 method, where 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 3-1.

The facility design with rock caverns, tunnels, deposition positions etc in the deep repository for spent fuel is based on the design originally presented in the KBS-3 report /SKBF/KBS, 1983/ which has been developed in more detail. The deposition tunnels are linked by tunnels for transport, communication and ventilation. One ramp and five shafts connect the surface facility to the underground repository. The ramp is used for heavy and bulky transports and the shafts are for utility systems and for staff transports. The different parts of the deep repository are sketched in Figure 3-2.

Cladding tube
Spent nuclear fuel
Bentonite clay
Surface portion of deep repository
500 m
Fuel pellet of uranium dioxide
Copper canister with cast iron insert
Crystalline bedrock
Underground portion of deep repository
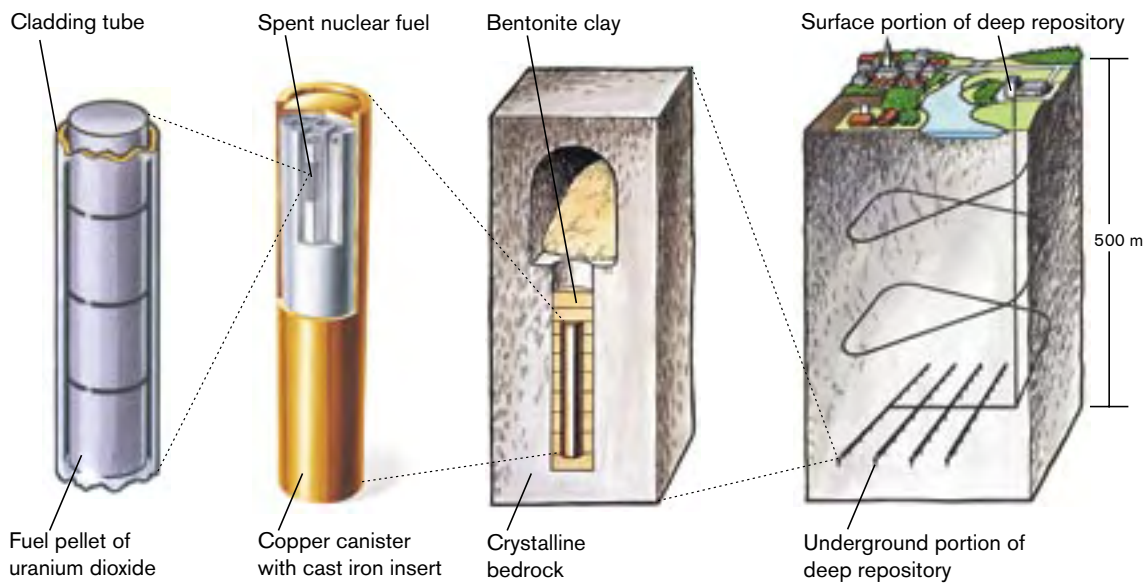
Figure 3-1. *The KBS-3 concept for storage of spent nuclear fuel.*
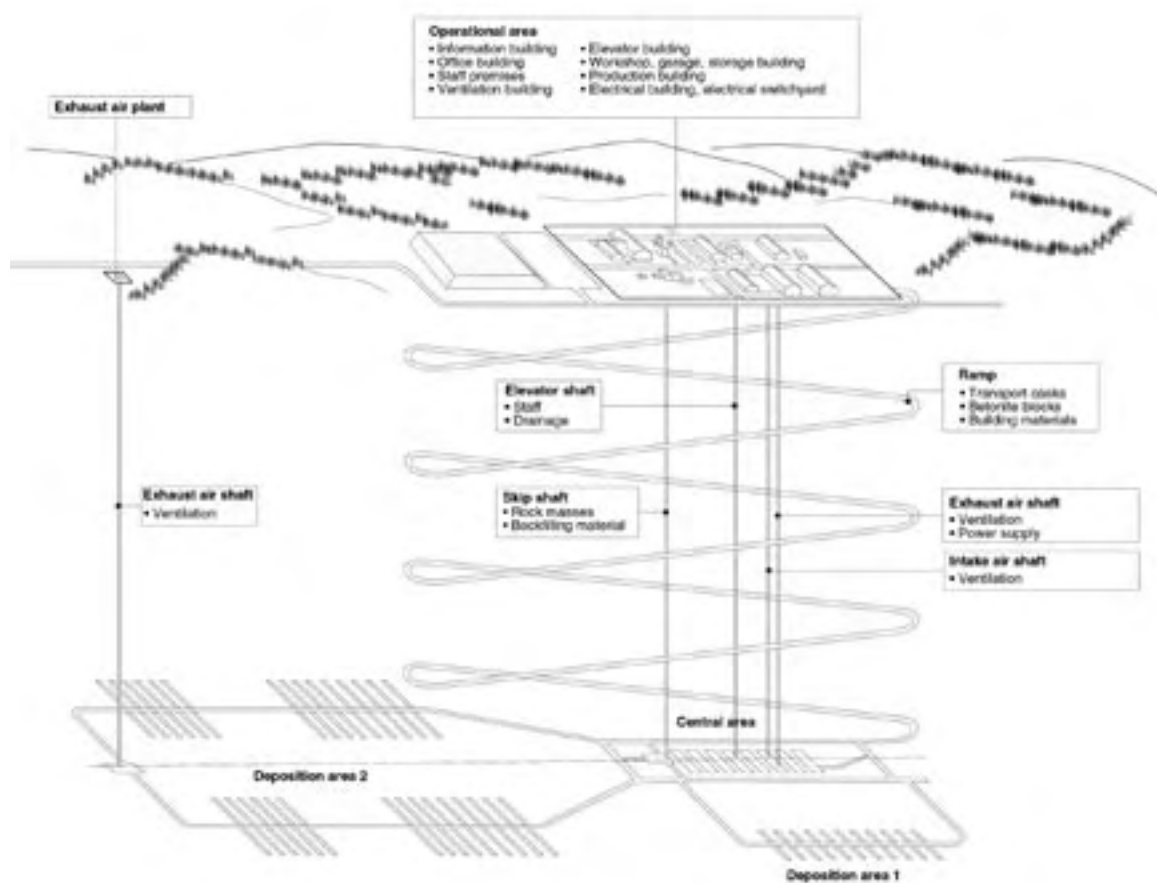
Figure 3-2. *Generic arrangement for the reference case.*

Around 9,000 tonnes of spent nuclear fuel is forecasted to arise from the Swedish nuclear power programme /SKB, 2003b/, corresponding to roughly 4,500 canisters in the repository. These figures are based on an assumed reactor lifetime of 40 years.

For the purposes of the safety assessment, the system has been sub-divided into a number of components or sub-systems. These are

- The fuel, (also including the cavity in the canister since strong interactions between the two occur if the canister is ruptured).

- The cast iron insert and the copper canister.

- The buffer.

- The bottom plate in the deposition holes.

- The deposition tunnel with its backfill material.

- Other repository cavities with their backfill materials.

- Repository plugs.

- Investigation boreholes with their sealing material.

- Rock.

- Biosphere.

This particular sub-division is dictated by the desire to define components that are as homogeneous as possible without introducing an unmanageable multitude of components. Homogeneity facilitates both characterisation of a component and the structuring and handling of processes in its long-term evolution. Also, the importance of a particular feature for safety has influenced the resolution into components. In principle, components close to the source term and those that play an important role for safety are treated in more detail than more peripheral components. The components are described in more detail in section 3.2.

3.1.2 Initial state FEPs

As mentioned in section 2.4, the initial state FEPs constitute a main category in the SR-Can FEP database. A fraction of these, stating simply that one aspect or the other should be included in the assessment, are automatically included in the description of the initial state.

Several initial state FEPs relate to design deviations due to undetected mishaps during manufacturing, transportation, deposition and repository operations etc. These issues are handled in SR-Can by referring to the procedures for manufacturing, operation and control etc for each component in the EBS initial state report and considering possible deviations in the scenario selection in chapter 8.

Severe mishaps like fire, explosions, sabotage and severe flooding will be excluded from scenario selection. 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.

Another FEP category concerns the effects of an unsealed abandoned or monitored repository. This issue is also propagated to the scenario selection in chapter 8.

Several FEPs refer to the effects of phased operation. This affects mainly the geosphere and the subsequent development of the entire repository. The hydrological state of the bedrock is perturbed as soon as repository excavation starts (a smaller perturbation even occurs earlier during site investigations). Different parts of the repository, completed at different points in time, will be exposed to different hydrological conditions, affecting e.g. the saturation of the buffer and backfill. Possible upconing effects could also vary between different parts of repository due to phased operation. Other factors to consider are the effects of blasting and underground traffic on completed parts of the repository. All these issues are part of the expected evolution of the repository, but are not automatically captured in the system of processes describing the repository evolution over time or by the initial state descriptions. They need to be adequately included in the discussion of the repository evolution and are therefore propagated to the scenario selection in chapter 8.

3.2 Reference initial state for fuel and engineered barriers

The reference initial state of the engineered barriers is defined as the design specifications with tolerances including allowance for deviations according to the manufacturing and control procedures.

The tolerances should in principle be possible to derive or verify from the manufacturing and control procedures employed in the engineering activities. At the current stage of the deep repository programme, such procedures have reached varying degrees of maturity.

This means that the tolerances are more or less well specified for different aspects of the EBS initial state. For example, in respect of the crucial issue of the quality of the canister seals, the intention for SR-Can is to base the tolerances on test statistics from a prototype sealing system including non-destructive testing. In other cases, the given tolerances are, at this stage, aims for the design of the production system in question. For example, this is the case for the buffer density. Here, a qualitative description of a tentative manufacturing and control system exists along with preliminary test results, but the data do not allow a derivation of a quantified tolerance.

The approach of managing the uncertainties represented by the tolerances, including the possibility of initial state values outside the tolerances, and the use of safety assessment results in the further design work, is developed in conjunction with the selection of scenarios in chapter 8.

It should also be noted that many parts of the system are as yet not finally designed – there can be many changes in the future. The design and technical solutions presented here are representative of the current stage of development.

3.2.1 Format for EBS initial state descriptions

Each component in the EBS initial state is described by a specified set of physical variables, selected to allow an adequate description of the long-term evolution of the component in question in the safety assessment. Examples of important variables for describing the buffer are buffer geometry, temperature, swelling pressure, water content, smectite content and impurity content. The structure of components characterised by variables is fully utilised in the EBS initial state report, whereas a more free format is used here, focusing on the most important aspects of the initial state.
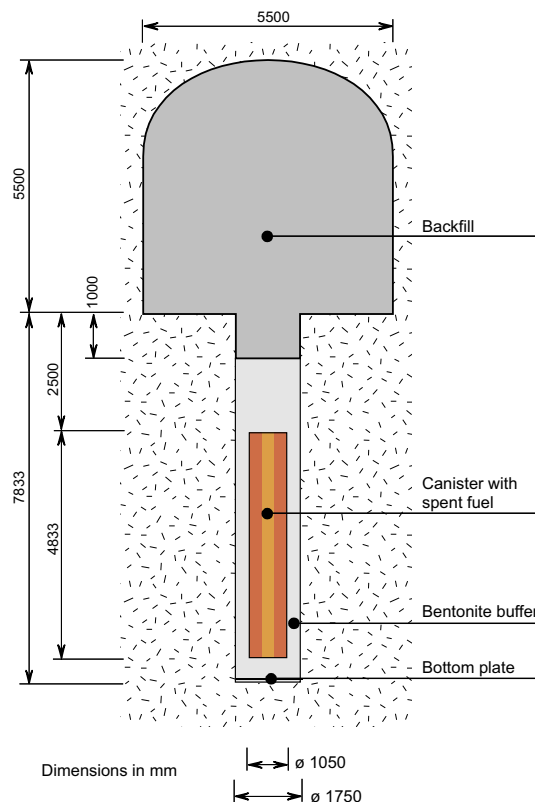
Figure 3-3. *Deposition hole with bentonite buffer and canister.*

3.2.2 Fuel/cavity in canister

The total quantity of fuel obtained from the Swedish nuclear reactors will depend on operating time, energy output and fuel burn-up. At the beginning of 2003, approximately 5,700 tonnes of spent fuel have been generated /SKB, 2003b/. With an operating time of 40 years for all reactors, except for Barsebäck 1 which was taken out of operation during 1999, the total quantity of spent fuel can be estimated at 9,500 tonnes /SKB, 2003b/.

Several types of fuel are to be deposited in the repository. For the option with 40 years of reactor operation, the quantity of BWR fuel is estimated at 7,200 tonnes and the quantity of PWR fuel at 2,300 tonnes /SKB, 2003b/. In addition, 23 tonnes of MOX fuel and 20 tonnes of fuel from the reactor in Ågesta will be deposited. The fuel burn-up may vary from 15 up to 60 MWd/kgU thermal output /SKB, 2001/.

Nuclear fuel consists of cylindrical pellets of uranium dioxide. The pellets are stacked in approximately 4-metre-long cladding tubes of Zircaloy, a durable zirconium alloy. The tubes are bundled together into fuel assemblies. Geometric aspects of the fuel cladding tubes of importance in the safety assessment are, as a rule, handled sufficiently pessimistically in analyses of radionuclide transport that differences between different fuel types are irrelevant. The material composition of the assemblies is well known and the uncertainties are small, largely since the quality requirements in the fabrication of fuel assemblies are very strict.

Radionuclides are formed during reactor operation by nuclear fission of uranium-235 and plutonium-239 in particular, and by neutron capture by nuclei in the metal parts of the fuel. Most of the radionuclides are embedded in the fuel matrix of uranium dioxide. A few fission products are relatively mobile in the fuel and may migrate to the surface of the fuel pellets during operation. The inventory of radionuclides in the fuel at the time of deposition can be calculated with relatively high accuracy. The uncertainty is typically a few tens of percent and is mostly related to the fuel's burn-up and initial enrichment. Uncertainties related to the inventories of higher actinides and some activation products may be higher. The relative differences in radionuclide inventory with respect to burn-up are small. BWR fuel and PWR fuel differ only marginally regarding radionuclide content. Deviations in inventory and deviating or damaged fuel are not considered in the SR-Can interim reporting but will be handled in the final reporting of SR-Can.

The canister insert is sealed at atmospheric pressure (dry air or noble gas) and the maximum permissible quantity of water in a canister is 600 grams. This value is equivalent to the void in one fuel rod and thus presumes that no more than one Zircaloy cladding tube is defective. For the safety assessment, it can however not be ruled out that more than one tube is defective.

3.2.3 Cast iron insert and copper canister

The canister consists of an inner container, the insert of cast iron and an outer shell of copper, see Figure 3-4. 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 cylindrical canister has a length of approximately 4.8 metres and a diameter of 1.05 metres. The copper shell is made of pure oxygen-free copper. The insert is cast from spheroidal graphite cast iron and has channels where the fuel assemblies are placed. The uncertainties in material composition are small for the canister materials.
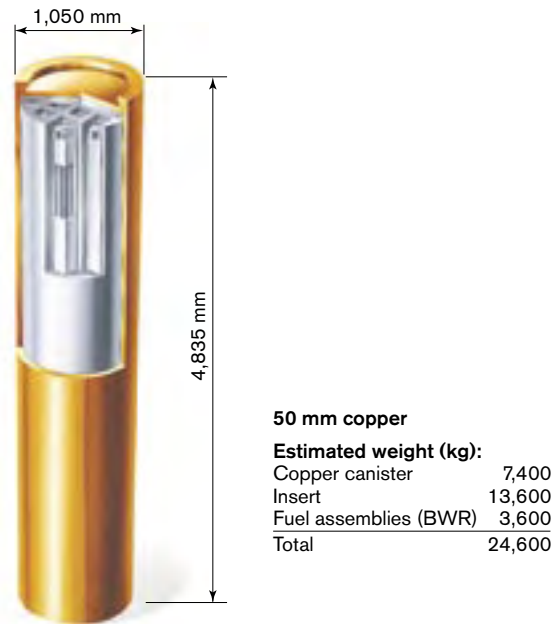
Figure 3-4. *The canister with its cast iron insert and copper shell.*

The insert is presently available in two versions: one for 12 BWR assemblies and one for 4 PWR assemblies. A canister holds about two tonnes of spent fuel. Canisters with BWR and PWR assemblies weigh 25 and 27 tonnes, respectively. The decay heat in the spent fuel disposed in one canister is limited to 1,700 W, to fulfil temperature requirements at the canister surface in the deposition hole. A total of about 4,500 canisters will be produced according to current estimates.

Four possible methods for fabrication of the copper tube have been tested by SKB: roll forming of copper plate to tube halves which are welded together, seamless tubes by extrusion, pierce and draw processing, and forging. All these methods produce a copper cylinder that must be machined internally and externally as well as on the end surfaces to get the desired dimensions. The reference canister is foreseen to be fabricated with a seamless tube. Lids and bottoms of copper are machined to the desired dimensions from hot forged blanks. The mass production of the canister parts, i.e. the insert, copper tube, lid, and bottom, may very well be done by different companies applying different methods that all fulfil the set requirements.

Welding of the lid and bottom of the copper canister can be done either by friction-stir welding (FSW) or by electron-beam welding (EBW). The aim is to select one welding method during 2005. Methods for non-destructive testing (NDT) of the canisters and welds are being developed. Examples of applied methods for this are radiographic and ultrasonic testing.

The fuel will be placed in the canister in the encapsulation plant. The insert will be closed with a lid which is fastened with a bolt. The copper shell's lid is then attached by welding, and the integrity of the weld is verified by NDT. Uncertainties in the initial geometry of the canister primarily concern canister integrity. The canisters are to be fabricated, sealed and inspected to guarantee that no more than 0.1 percent of the finished canisters will contain discontinuities that are greater than what is permitted by the acceptance criteria. The probability of a defect is greatest in the lid weld, since the possibilities of inspection and testing are better for the bottom weld.

3.2.4 Buffer

In the deposition holes, the copper canister is surrounded by a buffer of clay. The buffer is deposited as bentonite blocks below and above the canister and rings surrounding the canister mantle area. Each bentonite unit is about 500 mm high and has a diameter of 1,690 mm. The thickness of the rings is 315 mm. One block is placed below the canister, nine rings surround the canister and four blocks are placed above the canister. The blocks placed immediately below and above the canister must be processed so as to fit the canister geometry properly.

Two different types of bentonite are considered as reference buffer material for the purpose of SR-Can. One is a natural Na-bentonite of Wyoming type (MX-80) supplied by the American Colloid Company and the other is a natural Ca-bentonite (Deponit CA-N) from Milos supplied by Silver and Baryte. The bentonite consists mainly of the smectite mineral montmorillonite with the characteristic property that it swells in contact with water. Data for the two buffer materials are summarised in Table 3-1.

There are primarily two methods available for fabrication of bentonite blocks and rings; unaxial pressing and isostatic pressing. Objects thicker than 0.5–1 m cannot be easily produced by unaxial pressing and the development of isostatic pressing is therefore important, since no equipment to fabricate full size buffer components with isostatic pressing is available in Sweden today. Fabrication of the blocks and rings by isostatic pressing requires that the objects are machined to the tolerances specified. The bentonite, bought in bulk form and transported by ship, is subject to quality control both before loading in the ship and at reception. Quality control is undertaken also during the manufacture of the blocks and rings; one important check is the water content before pressing so that this can be adjusted.

Table 3-1. Bentonite composition of MX-80 and Deponit CA-N. The uncertainties are mainly related to the precision of the analysis method used.

Component	MX-80 (wt-%)	Deponit CA-N (wt-%)	Uncertainty (± wt-%)
Calcite + Siderite	0	10	1
Quartz	3	1	0.5
Cristobalite	2	1	0.5
Pyrite	0.07	0.5	0.05
Mica	4	0	1
Gypsum	0.7	1.8 (anhydrite)	0.2
Albite	3	0	1
Dolomite	0	3	1
Montmorillonite	87	81	3
Na-	72%	24%	5
Ca-	18%	46%	5
Mg-	8%	29%	5
K-	2%	2%	1
Anorthoclase	0	2	1
CEC (meq/100g)	75	70	2
Organic carbon	0.2	0.2	-

The important aspect in the manufacture of bentonite blocks and rings and the subsequent deposition process is to achieve a specific final density in the water-saturated buffer. The density requirement for the saturated buffer is 1,950–2,050 kg/m³. The bulk density is dependent on the annular slots between the canister and buffer and between buffer and rock, left in order to facilitate deposition. The annular slot between the canister tube and the buffer is 5 mm wide and that along the circumferential boundary between the buffer and the rock is 30 mm. The slots are left filled with air.

The buffer emplacement in a tunnel may take place several months after the drilling of the deposition holes. The deposition holes are assumed to be filled with water in the meantime, which is why draining is the first step in the preparation of the holes. Deposition starts with the hole at the far end of the tunnel. The buffer is put into position by a specially designed buffer filling vehicle. The bentonite lining is thereafter checked. The emplacement of the copper canister is done with a specially designed deposition machine which also places a top bentonite block immediately after the canister is emplaced. The emplacement of the canister will probably be documented with a photograph of the canister in its final position before the remaining bentonite blocks are emplaced. The final handling procedures and the final design of the buffer filling vehicle and the deposition machine are not decided yet, but do not affect the description of the work procedures. Small geometric tolerances in the deposition holes mean a very small risk for faulty emplacement of the buffer and canister.

The bentonite must be protected from water or high humidity until the tunnel is backfilled. The reason is that the buffer may start swelling before the deposition of the canister and before the tunnel backfilling can apply its counterforce on the buffer. One possible method is to insert a drain tube in the deposition hole and to protect the whole buffer with a plastic bag that is kept sealed until the backfilling of the tunnel starts. The plastic bag and drain tube would be removed after use.

3.2.5   Bottom plate in deposition holes

The bottom of the deposition hole is levelled off with a cast concrete base plate. The base plate serves as a rigid support and the pile of bentonite blocks thereby has a vertical centre line defined, so that the canister can enter gently and the slot between blocks and rock surface is even enough to allow the block lifting tools and the other parts to pass freely.

The thickness of the cast base plate will be adapted to the roughness of the rock and is about 5 cm at the thinnest part and 10 cm as a maximum. The base plate is cast of concrete with low pH cement. The development of suitable cement is in progress, but a final recipe is presently not available. A copper plate, a few millimetres thick, is placed on the concrete surface to protect the bentonite from being wetted with ground water penetrating the concrete plate. A periphery slot is left between the concrete base plate and the rock wall where ground water can be collected and pumped up from the hole as long as the deposition tunnel is open.

3.2.6   Backfill of deposition tunnels

The extent of this sub-system component is defined in geometrical terms as the deposition tunnel and the upper one meter of the deposition holes. All materials within the tunnel are included i.e. the backfill material itself, grout in grout holes and the relatively limited amounts of structural and stray materials left in the tunnels. Exploratory boreholes and the plug at the end of the deposition tunnel are distinct sub-systems. Grout in rock fractures is associated with the geosphere.

The final decision on excavation technique for the deposition tunnels has not been taken and two possible techniques, drill and blast or mechanical excavation (tunnel boring machine, TBM), are analysed in SR-Can. The excavation technique will have implications on the dimensions, the shape of the deposition tunnels and the extent of the excavation damaged zone in the host rock. The cross section in a drill and blast deposition tunnel is a square with an arched roof, whereas the cross section in a mechanically excavated tunnel is circular.

Two different backfill concepts are analysed. One is an in situ compacted mixture of crushed rock and bentonite of the same type as in the buffer and the other comprises pre-compacted blocks of Friedland clay which consists of 45% mixed layer minerals, 24% quartz, 13% mica, 5% feldspar, 2% cabonates, 1–4% pyrite and 1% glauconite.

The upper metre of the deposition holes will be filled with the mixture in the first concept and with bentonite blocks with buffer quality in the second concept. The mixing concept will have a final clay fraction density of around 1,600 kg/m^3 when water saturated.

The manufacturing of the backfill material will take place in a production facility close to the deep repository. Quality control of the composition of the material will take place at three stages: the clay and the ballast will be sampled and analysed before mixing, the composition will be controlled after mixing, and samples will also be taken after emplacement in the tunnel to ensure that the homogeneity of the mixture is good.

The aim is to limit the amount of construction and stray materials left in the deposition tunnels. Rock supports, mainly rock bolts and reinforcement nets will be left in the tunnels, as they are essential to workers' safety, whereas the other installations and structures, e.g. roadbeds, will be removed before closure of the deposition tunnels. In addition, the tunnels will be cleaned with highly pressurised water.

3.2.7   Backfill of other repository cavities

The extent of this sub-system is defined in geometrical terms as all rock excavation volumes except those in the deposition tunnels and deposition holes. The definition thus includes the volumes of, e.g. access ramp and shafts, transport and main tunnels, ventilation shafts, and the central area, which together make up the necessary space for access to and operation of the underground facility and its deposition areas.

For the purpose of SR-Can, it is assumed that the same backfill concept will be used in these cavities as in the deposition tunnels. It is further assumed that the same working methods for application and quality control of the backfill are used.

As part of the decommissioning of the facility and as for the deposition tunnels, installations and building components will be stripped out prior to the backfilling of the underground facility. Materials like roadbeds will be removed, whereas rock supports like shotcrete and rock bolts, as well as grout in grout holes, will be left.

3.2.8   Plugs

Each backfilled deposition tunnel needs to be sealed awaiting the backfilling of the main tunnel. The plug provides a mechanical support to the backfill material and it is sized to be strong enough to withstand the combined pressure from groundwater and the swelling of the bentonite. The plug is also required to prevent water flow.

The plug considered is a reinforced concrete plug grouted with low pH cement anchored in a slot in the rock. The design considered is similar to the reinforced plugs installed in the Prototype Repository in Äspö HRL.

The plugs will be left in the repository at its closure, but they have no long-term safety functions.

3.2.9 Borehole seals

A number of more or less vertical investigation or surface-based characterisation boreholes are to be drilled during site investigations in order to obtain, e.g. data on the properties of the rock. These boreholes will be sealed, no later than at the closure of the deep repository. Some holes will be bored from the repository tunnels during the construction phase, meaning that horizontal and upwards-directed holes also have to be sealed.

The borehole seals must prevent short-circuiting of flow of contaminated groundwater from the repository. They should, therefore, not be more permeable than the undisturbed, surrounding rock. Time-dependent degradation must be accepted, but the goal is to use plug materials that maintain their constitution and tightness for a long time.

Seals for boreholes are under development as part of SKB's RD&D programme. The concept adopted for surface-based boreholes in SR-Can comprises the following materials at different depths: compacted moraine (0–3 m), close-fitting rock cylinders from the site (3–50 m), compacted moraine (50–60 m), smectite pellets (60–100 m), and highly compacted smectite clay contained in perforated copper tubes (below 100 m). Tunnel-based boreholes are assumed to be filled with highly compacted smectite clay in perforated copper tubes. These boreholes are plugged with concrete at the tunnel.

3.3   Initial state of geosphere and biosphere

All the data in this section are presented for illustration only. The numbers used for assessment calculations are taken either directly from /SKB, 2004e/, or taken from this reference and then further elaborated in the SR-Can data report. In particular, this section, as it stands, does not fully describe uncertainties in the numbers given.

Furthermore, confirmation of the validity of a site descriptive model is not a direct responsibility of the safety assessment, but is handled within the site descriptive modelling. The assessed confidence in the site model, which depends on the outcome of site descriptive modelling, is an essential input to the safety assessment.

3.3.1   Site descriptive models

The initial state of the geosphere and biosphere is defined as the state of these systems at the time of start of excavation for the repository. For the interim reporting of SR-Can, the initial state of the geosphere and biosphere is provided by version 1.1 of the Forsmark Site Descriptive Model /SKB, 2004e/, since this was the most developed site description available from the site investigations when the Interim report was compiled. This model version is based on version 0 of the site description /SKB, 2002b/ and quality-assured, geoscientific and ecological field data from Forsmark that were available in the SKB databases SICADA and GIS at April 30, 2003. These data originate from surface investigations on the candidate

area and its regional environment as well as from drilling and investigations in boreholes. The surface-based data sets were rather extensive whereas the data sets from boreholes were limited to information from one c 1,000 m deep cored borehole and eight 150 to 200 m deep percussion-drilled boreholes in the Forsmark candidate area. Due to the sparse amount of data from depth, there are large uncertainties in version 1.1 of the site descriptive model.

A somewhat different situation is expected for version 1.2 of the site descriptive model, which will be built on much more data, especially from depth. This will facilitate a more elaborate evaluation of geosphere and biosphere properties and processes and their uncertainties. Model version 1.2 for Forsmark and Simpevarp will provide comprehensive site descriptions in support of the complete safety assessment SR-Can.

Figure 3-5 shows the candidate area for the site investigations at Forsmark and the regional and local model volumes selected for version 1.1 of the site description. All information compiled in the following subsections is extracted from the version 1.1 report /SKB, 2004e/ if not otherwise stated. All data are presented for illustrative purposes only. Data, including uncertainties, for safety assessment calculations in SR-Can, are taken directly from the site descriptive model report /SKB, 2004e/ with its supporting documentation or from the interim SR-Can Data report /SKB, 2004c/ where the site data are further elaborated for the purpose of safety assessment calculations.

3.3.2   Overview of the Forsmark site

The Forsmark site is located in northern Uppland within the municipality of Östhammar, about 170 km north of Stockholm. The candidate area, approximately 6 km long and 2 km wide, is located along the shoreline of Öregrundsgrepen. The regional and local model volumes, for which the site description is provided, have surface areas of 165 km^2 and 31.5 km^2, respectively.

The water composition and water movement in Öregrundsgrepen are affected by the freshwater discharge from rivers which flow into the Gävle bay north of Öregrundsgrepen and by the wind. The freshwater discharge from Gävle bay moves south along the coast and passes Öregrundsgrepen, causing a lower salinity in this area compared with the part of the Baltic sea located east of the island Gräsö.

Östhammar municipality is situated on the border between two different landscape types – "Woodlands south of Limes Norrlandicus" and "Coast and archipelagos of the Baltic sea". The vegetation in the coastal area, where the candidate area is located, is mainly forest, with pine as the dominant forest type. Wetlands are also frequent. The coastal and archipelago area is valuable from a nature conservancy viewpoint and the south-easterly extension of the candidate area is bounded by a protected area, the Kallriga nature reserve.

The region is part of the sub-Cambrian peneplain belonging to the Fennoscandian shield and is relatively flat with a gentle slope to the NE. The candidate area lies at low altitude and post-glacial shoreline displacement is significant in the area. The whole regional model area was covered by sea water until 2,500 years ago and the Baltic still covered the Forsmark candidate area 1,500 years BP. This means that the area has been exposed to different non-saline and brackish lake/sea stages in the past, which together with the shoreline displacement process have affected the present hydrogeological and hydrogeochemical conditions at the site.
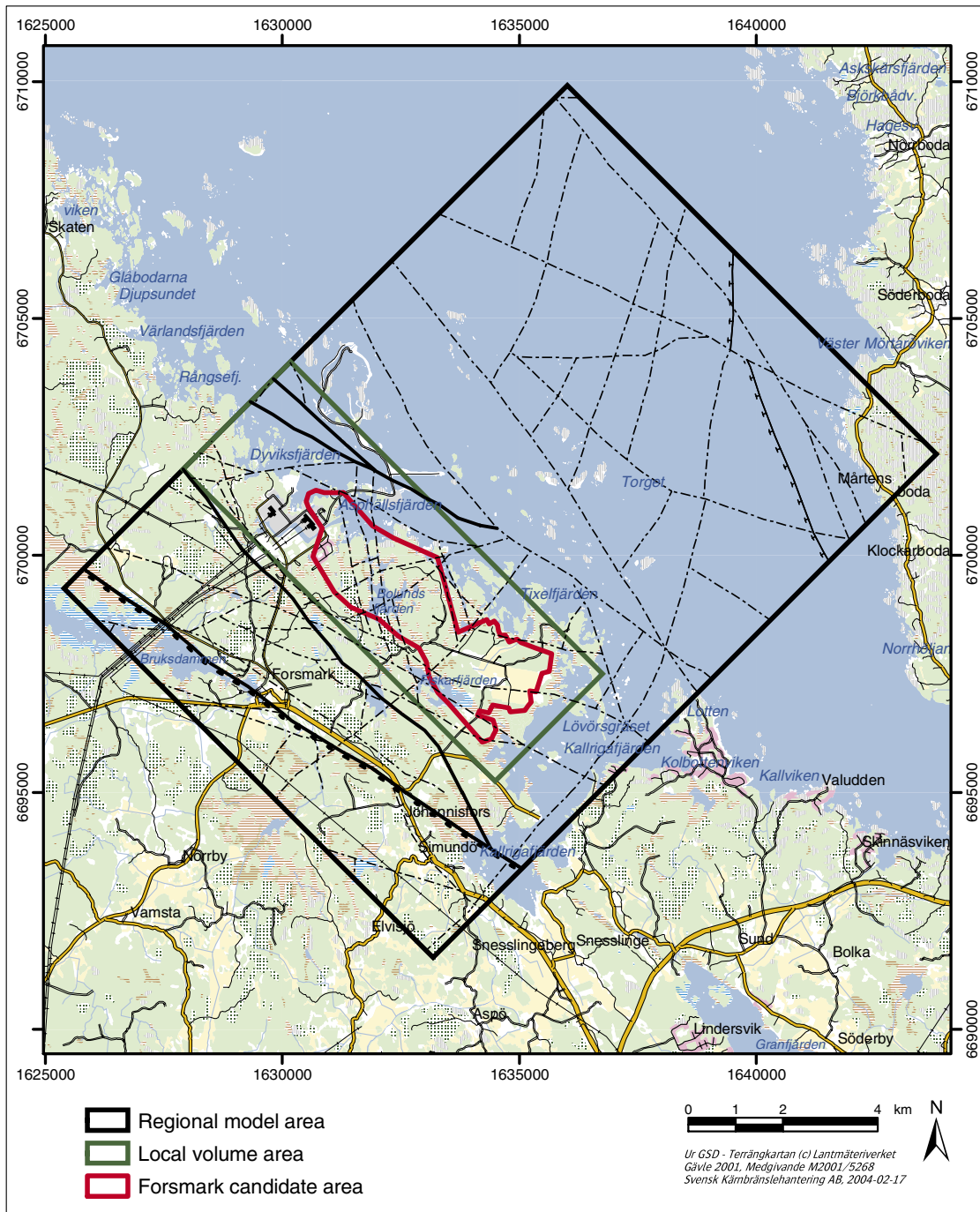
Figure 3-5. *The depth range is defined as 1,100 m below sea-level to 100 m above sea-level. The figure also shows the lineaments (dashed lines) and fracture zones (solid lines) identified in model version 0 (from /SKB, 2004e/).*

3.3.3 Rock types

The predominating rock type in the region is grey to red, equigranular, metagranitoids that are rich in quartz (mean values > 30%). The major part of the bedrock was formed about 1,900 million years ago and it has been affected by both ductile and brittle deformation. The ductile deformation has resulted in large-scale ductile high-strain zones and the brittle deformation has given rise to large-scale faults and fracture zones. "Tectonic lenses", in which the bedrock is much less affected by ductile deformation, are enclosed between the ductile high-strain zones. The candidate area is located in one of these tectonic lenses.

Based on rock composition, grain size, degree of inhomogeneity and degree of ductile deformation, the bedrock at the Forsmark site has been divided into thirty-four rock domains (see Figure 3-6 and Figure 3-7). The general character of the rock domains varies in a highly consistent pattern, from southwest to northeast, across the regional model volume. The tectonic lens that includes the candidate area consists of folded rock domains with mineral lineations and fold axes that plunge to the southeast.
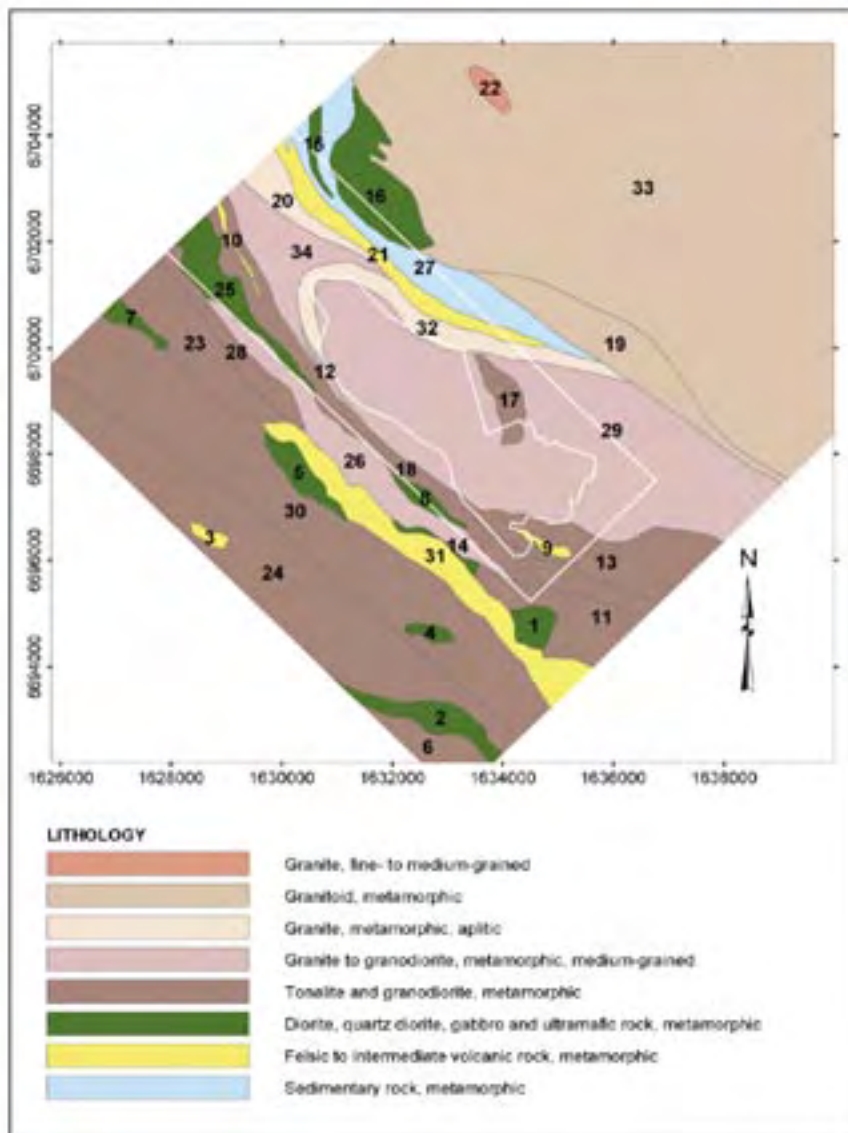
Figure 3-6. Surface view of the rock domains (numbered from 1 to 34) in the regional model volume The colours show the rock units that were defined on the basis of dominant rock type.
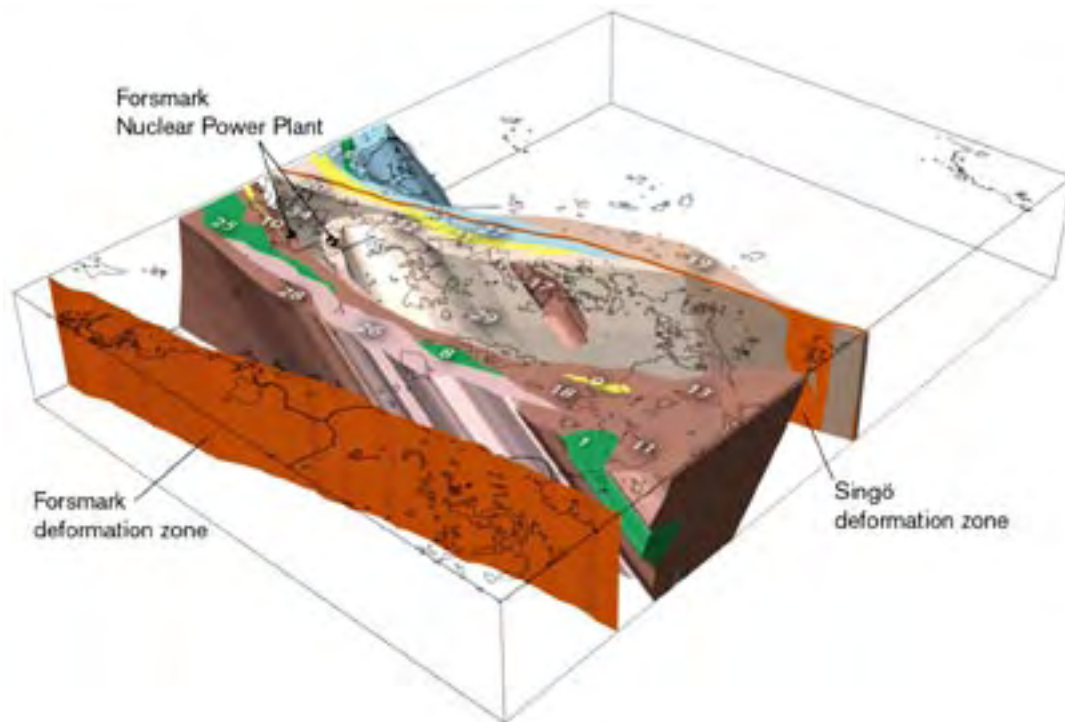
Figure 3-7. *Rock domain model viewed to the north. Domains 29 and 34 are unshaded in order to show the major folding within the tectonic lens at the Forsmark site. The domains southwest of the rock domain 26 are unshaded in order to show the modelled southeasterly elongation of several domains. The dominant rock type in each domain is illustrated with the help of different colours (see the rock domain map at the surface in Figure 3-6).*

The candidate area is dominated by one rock domain (domain 29). This rock domain and rock domain 34, which lies NW of the candidate area, are homogeneous and predominantly composed of metamorphosed, medium-grained granite. Rock domain 32, located at the north-westerly to northern border of the candidate area, is inhomogeneous, banded and contains some rocks that show an inferred high degree of ductile deformation. This rock domain is dominated by a fine-grained metagranite that contains few dark minerals, i.e. an aplitic metagranite. Metamorphosed tonalite to granodiorite dominates rock domain 17 in the south-eastern part of the candidate area. Metamorphosed tonalite and granodiorite as well as metavolcanic rocks with a dacitic to andesitic composition dominate the marginal rock domains. Iron oxide mineralisations are also present in the metavolcanic rocks that are located both to the southwest and to the northwest of the candidate area. Intermediate, mafic and ultramafic rocks, in which quartz is generally lacking, are also a conspicuous bedrock component in the marginal domains (e.g. rock domain 1).

3.3.4   Deformation zones

Potential deformation zones (zones exposed to ductile and brittle or brittle deformation) larger than 1 km are described in a deterministic structural model in version 1.1 of the Forsmark site description. The confidence of occurrence of these zones is judged to vary from high to very low. Detailed information concerning the properties of the deformation zones is given in the site report.

Three important types of deformation zones are present within the group of thirteen deformation zones that are judged to have a high confidence of occurrence. These types are:

- Regionally important deformation zones (ductile and brittle) with north-westerly strike and vertical dip.

- Fracture zones (brittle deformation) with north-easterly strike and vertical or steep, south-easterly dips.

- Fracture zones (brittle deformation) that are sub-horizontal or dip gently to the southeast.

The Forsmark and Singö deformation zones, which belong to the zones with north-westerly strike and vertical dip, are the two master regional deformation zones at the Forsmark site (see Figure 3-8). The Eckarfjärden deformation zone forms an important splay north of the Forsmark zone. The zones ZFMNW0002 and ZFMNW0805 form splays to the north of the Singö deformation zone. All these splays show strike directions that are more northerly in orientation but their dips are also vertical. Both ductile and brittle deformation are present along these zones.
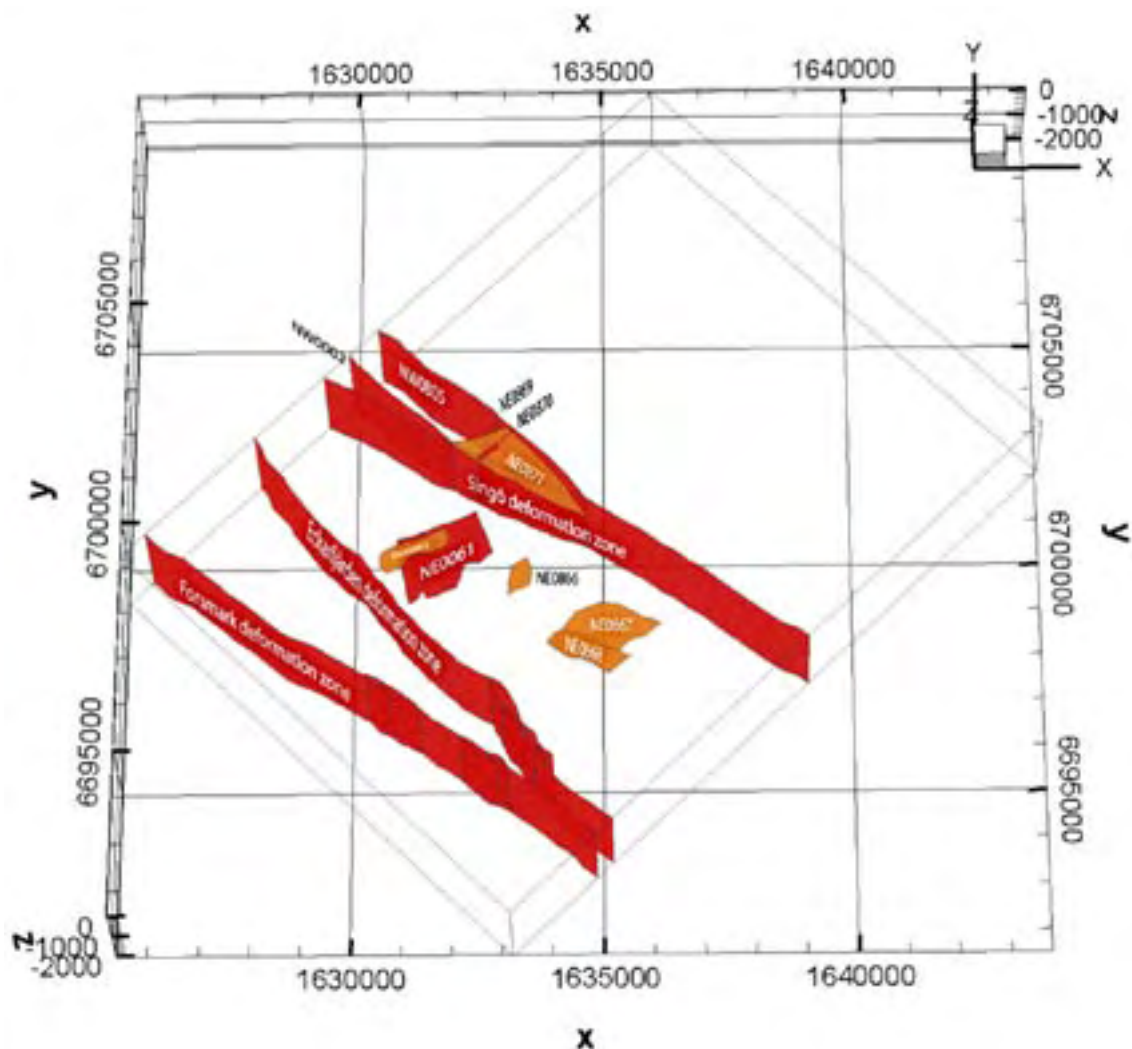
Figure 3-8. *Base structural model in the regional model volume for the thirteen deformation zones along which there are confirmatory geological and geophysical data and which are judged to have a high confidence of occurrence. Vertical or steeply dipping zones are shown in red and sub-horizontal and gently dipping zones in orange.*

One of the high-confidence fracture zones that strikes in a north-easterly direction (ZFMNE0061) dips steeply towards the southeast and cuts across the candidate area. This zone is characterized by a high frequency of sealed fractures with laumontite, chlorite and calcite as fracture fillings. The two other zones within this subgroup (ZFMNE0869 or Zone 3 at SFR and ZFMNE0870 or Zone 9 at SFR) dip vertically and enclose the SFR site. All these zones are locally major in character and only show brittle deformation. They are confined between the regionally more important zones with north-westerly strike.

The five remaining zones that are judged with high confidence to be present at the Forsmark site are either sub-horizontal (ZFMEW0865) or strike in a north-easterly direction and dip gently towards the southeast (ZFMNE0871 that is equivalent to Zone H2 at SFR, ZFMNE0866, ZFMNE0867 and ZFMNE0868). All these zones show only brittle deformation.

In the base structural model, the sub-horizontal and gently dipping fracture zones are taken to terminate at the nearest vertical or steeply-dipping deformation zone, and the regional structural significance of these zones is limited. The zones are local major or local minor in character and are restricted to the crustal segment above the critical 400−600 m level in the rock model volume, where it is proposed that the repository would be located.

All the inferred deformation zones in the base structural model, irrespective of the judgement concerning their confidence of occurrence, are shown in Figure 3-9. Four of the zones with medium confidence are regional in character and are situated under the sea area. The remaining zones are local major in character.

Because of the major uncertainty concerning the along-strike continuity and down-dip extension of the sub-horizontal and gently dipping fracture zones, an alternative structural model has also been developed for these zones. It only differs from the base model in respect of the along-strike and down-dip extension of the five fracture zones that are sub-horizontal or dip gently to the southeast. The alternative model allows these five fracture zones to continue in both strike and dip directions to the margins of the regional model volume.
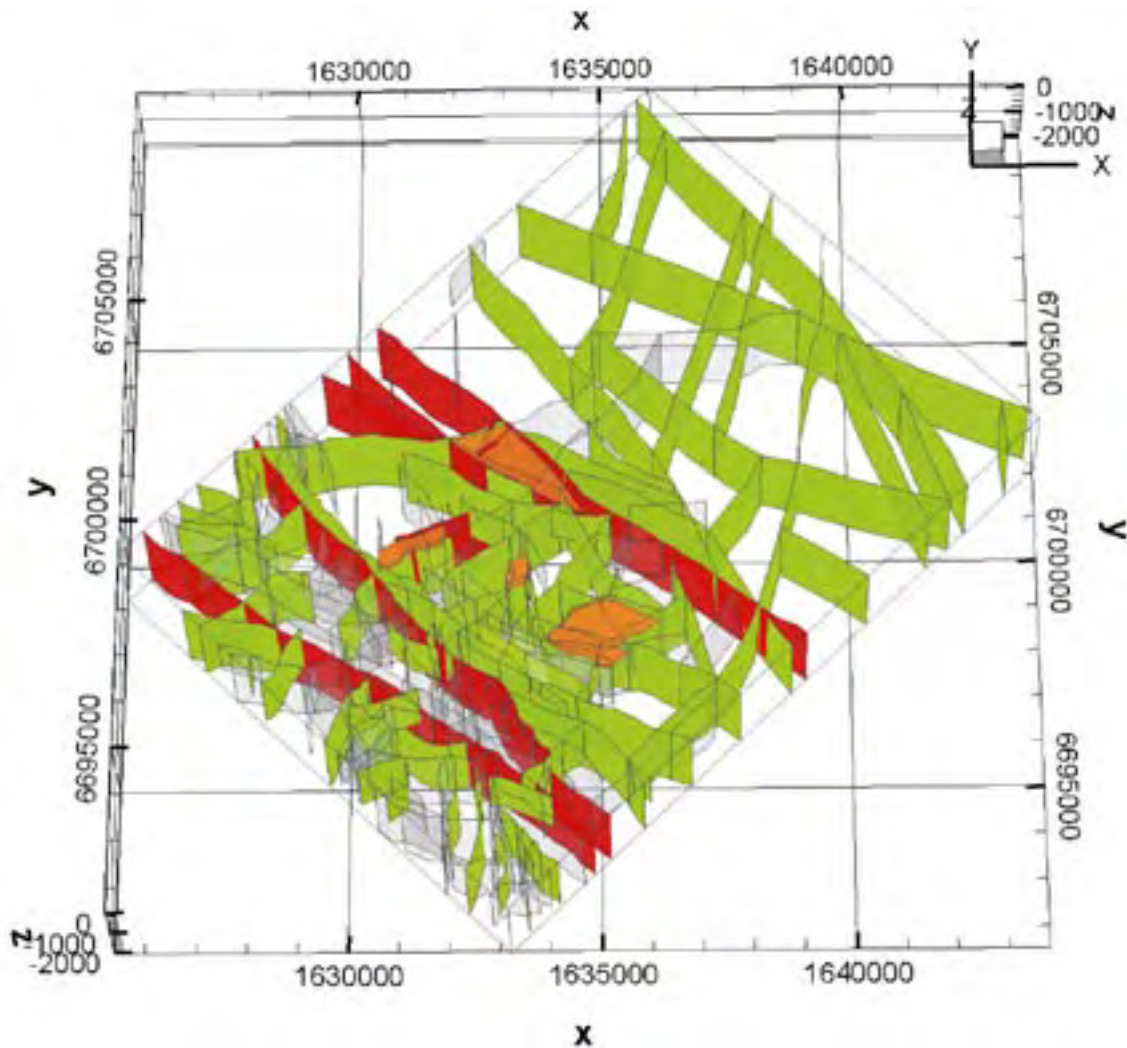
Figure 3-9. Base structural model for all deformation zones in the regional model volume. The red and orange colours mark zones with a high confidence of occurrence; vertical or steeply dipping zones are shown in red and sub-horizontal and gently dipping zones in orange. The green colours show the zones with medium confidence of occurrence and the grey colours indicate zones with low or very low confidence of occurrence.

3.3.5 Fractures in the rock in between fracture zones

The information on fractures in the bedrock is still very sparse and is restricted to information from the section 100 to 1,000 m depth in one cored-drilled borehole (KFM01A) located in rock domain 29. A total of 1,516 fractures were detected over a borehole length of 900 m, and 201 of these were classified as open fractures, i.e. having an open aperture > 0. Of these open and potentially water-conducting fractures, 147 were found in the depth interval 100 to 400 m and the remaining 54 at depths below 400 m (see also 3.3.9 Hydrogeological properties). The upper 400 m of the rock seems to have a higher frequency of fractures. About 60% of all fractures and more than 70% of the open fractures were found in the borehole section −100 to −400 m.

Statistical analyses of lineaments, fracture data from outcrops and from the 1,000 m deep borehole (KFM01A), in support of a discrete fracture network (DFN) description of the geometry of fractures, indicate the presence of four sets of vertical fractures trending

NW, NE, NS and EW, respectively, and a fifth set of sub-horizontal fractures. Values of the intensity of fractures in terms of fracture surface per unit volume of rock, P_{32} (m^2/m^3), have been calculated. The intensity of sub-horizontal fractures are higher in the uppermost 400 metres of the rock ($P_{32} = 1.63$ m^{-1} for all fractures and 0.34 m^{-1} for open fractures) than below 400 m depth ($P_{32} = 0.56$ m^{-1} for all fractures and 0.15 m^{-1} for open fractures). Especially at depth, these fracture intensities are quite low compared to other locations in the Fennoscandian shield.

The most abundant fracture fillings in the cored borehole KFM01A are chlorite, laumontite and hematite. Open fractures are dominated by chlorite and calcite fillings with chlorite being the dominant mineral in over 55% of the open fractures. The sealed fractures have an equal proportion of chlorite- and laumontite-fillings, around 28% of each. Minerals such as epidote, pyrite, prehnite, iron hydroxides and biotite are lumped together under the denomination "others" and comprise the fill of less than 5% of the sealed fractures. These minerals are absent in the open fractures.

The most superficial rock (c upper 100 m) in the Forsmark candidate area seems to be extensively fractured. Dry, sediment-filled fractures of large aperture were observed during percussion and core-drilling in the candidate area. Similar observations have previously been made in the Forsmark power plant area.

3.3.6   Stress conditions

No new data on rock stresses in the local model domain were available for the development of model version 1.1. Based on geological observations in the candidate area and re-interpretation of old stress data from boreholes DBT-1 and DBT-3 in the nuclear power plant area, estimates of stress magnitudes for the local model volume have been made. The rock stresses are high and depth dependent with a rather steep gradient indicating stress levels on the order of 30 to 35 MPa at 300 m depth and around 55 MPa at 500 m depth. The general trend for the major horizontal stress is in a NW-SE direction, rather close to alignment with the coast line and following the general trend in Fennoscandia.

3.3.7   Mechanical properties

The rock mechanics evaluation carried out in support of model version 1.1 has provided mechanical properties for rock domain 29. The compressive strength of the rock mass is in average on the order of 100 to 130 MPa in the more fractured rock in the depth interval 100 to 400 m and higher (170 MPa) in the less fractured rock at larger depths. The homogeneous rock in domain 29 is of good quality, which is reflected by a deformation modulus that on average is high at all depth (45–70 GPa).

The deformation modulus in the Singö zone (ZFMNW0001) has been estimated to be about 3–10 MPa. This range of values is proposed as an estimate of the properties of all the deformation zones in version 1.1 of the site description.

3.3.8   Thermal properties

Temperature loggings in the deep cored borehole located in rock domain 29 in the candidate area indicate an increase in temperature from about 7°C at a depth of 100 m to about 13°C at 600 m and to about 18°C at 1,000 m. The temperature gradient increases with depth, from about 11°C / km at 400 m to about 14°C / km at 900 m.

The mean value of the thermal conductivity in rock domain 29 is reported to be 3.3 to 3.4 W/(m·K). Mean values for other rock domains in the area (rock domains 13, 17, 18, 21, 30, 31, 32 and 34) are in the range 2.7 to 3.0 W/(m·K).

3.3.9 Hydrogeological properties

All the high-confidence fracture zones in the Forsmark regional model volume have been investigated hydraulically, except the Forsmark zone. These zones have been assigned transmissivity values in accordance with the reported results. The sub-horizontal and three of the gently dipping fracture zones are interpreted to be most conductive with an assigned transmissivity of $5 \cdot 10^{-5}$ m²/s. The regional and larger Singö, Eckarfjärden and Forsmark zones have been assigned a transmissivity of $2.4 \cdot 10^{-5}$ m²/s. The lowest transmissivity ($1.5 \cdot 10^{-10}$ m²/s) was assigned to one of the gently dipping fracture zones (ZFMNE0868) and to the steeply dipping zone ZFMNE0061 that cuts across the candidate area. The hydraulic properties of all medium and low confidence fracture zones are currently unknown. In order not to exaggerate their hydraulic impact, intermediate hydraulic properties were assigned.

The hydraulic properties of the rock in between the fracture zones (HRD) are derived from statistical analyses of fracture transmissivity data in the single deep cored borehole (KFM01A) in rock domain 29. These data suggest that the bedrock in the Forsmark area may be of very low conductivity at depth. Out of the total of 201 "open" fractures in the borehole, 34 fractures only were found to yield water above the detection limit for the equipment. All these fractures were located in the depth interval 100 to 400 m. The stochastic description of the transmissivity of fractures derived based on the observations gave the range $9.4 \cdot 10^{-10}$ to $5.8 \cdot 10^{-8}$ m²/s for fractures of lengths ranging between 100 and 1,000 m.

3.3.10 Groundwater flow

The geometry of water-bearing structures and the hydrogeological properties assigned to zones and fractures imply that the hydrogeological model is very discrete. That is, the fractures in the rock in between fracture zones will not contribute significantly to the connectivity of the advective flow system. The groundwater storage not readily accessible to advective flow constitutes, more or less, an immobile volume of groundwater accessible mainly through diffusion processes. The larger the immobile volume, the longer the "initial" groundwater conditions in the bedrock between the flowing fractures will be preserved.

Paleohydrogeological simulations considering shoreline displacement and the historical evolution of the seawater salinity show that the present-day hydrogeological conditions are not at steady state. The shoreline displacement process and the changing sea water conditions have resulted in spatial variability in the salinity of the advective groundwater flow system in the area.

3.3.11 Groundwater composition

The present conceptualisation of the hydrogeochemistry at Forsmark is that the water composition is the result of: a) present-day meteoric recharge/discharge hydraulic gradients of local extent with potentially a more saline regional discharge contribution from depth, b) the forced introduction of glacial melt water to unknown depths during glacial retreat, c) density turnover influences from saline waters introduced during past marine transgressions (e.g. the Litorina Sea) since the last glaciation, and d) recent introduction of brackish water when the Baltic Sea covered the Forsmark site area. Because of the generally flat topography close to the coast, the present-day local hydraulic gradients are relatively

weak thus preserving the more saline, denser Litorina Sea, Litorina Sea/glacial water and probably brackish Baltic Sea mixtures as pockets and lenses in the bedrock in association with both sub-vertical and sub-horizontal hydraulic structures.

Because of lack of data from depth, the groundwater composition reported for the Forsmark area in model version 1.1 is restricted to depths of less than 200 m. Two major water types are identified: fresh waters with a bicarbonate imprint and short residence times and brackish-marine waters with Cl contents of up to 6,000 mg/L (10 g/L TDS) and longer residence times.

The chemistry of the first water type represents shallow groundwaters. It is mainly controlled by the chemistry of the recharge waters and, most importantly, by water-rock interaction processes in the overburden (regolith). Closer to the coast and with depth, the influence of marine water is detected. The major water-rock interaction processes are organic matter decomposition, dissolution of the more soluble phases such as calcite and sulphides and alteration of the upper granitic bedrock. Primary and secondary silicates and alumino-silicates are related by incongruent reactions which seem to control silica and aluminium contents and participate in the loss or gain of elements such as K, Mg and, to some extent, Na (through dissolution-precipitation or ion exchange processes).

Waters of the brackish-marine type represent deeper bedrock groundwaters and have a longer residence time and a higher mixing component with older waters with different origins. These waters are found at depths larger than c 50 to 100 m. Heterogeneous reaction processes, although much less important than in the first water type, can be described mostly in relation to the same set of minerals. A major difference is that calcite is precipitating instead of dissolving. Also, in some of these waters microbial reactions and dissolution-precipitation of Fe-mineral phases become important in controlling sulphate and iron contents, as well as the redox state of the system. As an example of the composition of these waters, a water sample from 110–121 m depth in the cored borehole KFM01A revealed Eh of −180 mV, pH of 7.5 and TDS of 7.8 g/L.

3.3.12 Transport properties

No site-specific data on transport properties of the rock domain were available from cores or from boreholes from the site in support of model version 1.1. Based on an analysis of data for Finnsjön rock materials with mineralogical and geological characteristics similar to that of rock domain 29 in Forsmark, it is concluded that there is no support for assuming formation factors, and hence, effective diffusivities, for Forsmark other than those used in the previous safety assessment SR 97 /SKB, 1999a/.

3.3.13 Regolith (Overburden)

Unconsolidated Quaternary deposits cover c 82% of the land area in the regional model area and artificial fill, principally around the Forsmark nuclear power station and an area close to Johannisfors, c 3%. Exposed bedrock or bedrock with only a thin (< 0.5 m) regolith cover occupies c 15% of the land area.

Glacial till is the dominant Quaternary deposit. Glaciofluvial sediments are deposited in the small esker of Börstilåsen. The till and glacial clay are rich in $CaCO_3$, which originates from Palaeozoic limestone, present at the sea bottom north of the area. Post-glacial sediment and peat form the youngest group of Quaternary deposits. In general, they overlie till and, locally, glacial clay or crystalline bedrock.

Clay gyttja or gyttja clay, a dark freshwater mud with abundant organic matter deposited in a marsh or lake, are the dominant organic deposits in the surface of the wetlands, whereas peat accumulations > 50 cm thick are rare. Existing peat accumulations are concentrated in the more elevated areas, e.g. south east of Lake Eckarfjärden. The organic sediment is often thinner than 1 m, underlain by sand or gravel and till or glacial clay.

A typical feature of the area is a large number of small (< 50 m) wetlands often submerged by shallow water during the spring and early summer. A typical stratigraphy in these wetlands comprises a thin layer of organic cover, sand or gravel and glacial clay on top of bedrock or glacial till.

The recorded thickness of the regolith varies between 0 and 17 m in the area with local large differences in short distances. The altitude of the upper surface of the regolith varies between c 4 and 2 masl. This corresponds to an undulating upper surface of the bedrock and a till cover that fills out the depressions.

The distribution of marine and lacustrine sediments in the Forsmark region is fairly consistent. The total thickness of the sediments in lakes (not including glacial till) is in general less than 2 m. Offshore deposits are dominated by till which rests on the bedrock. Locally, till is covered by clay. Glacial clay is overlain by a thin layer of sand and gravel, i.e. similar to the onshore distribution. The thickness of the offshore deposits varies considerably from < 2.5 m to > 10 m.

3.3.14 Shallow groundwater and surface waters

The Forsmark area is characterised by low relief with small-scale topography and relatively shallow regolith. From regional data, the specific discharge can be estimated to approximately 200 mm/year (approximately 6.5 L/s/km^2). The infiltration capacity exceeds the rainfall and snow melt intensity with few exceptions and unsaturated overland flow is uncommon and only occurs over short distances. Annual precipitation is relatively low, 600–650 mm, and the specific runoff is approximately 200 mm. Groundwater levels are shallow. In recharge areas usually < 3 m below ground and in discharge areas < 1 m.

The flat terrain and shallow groundwater levels mean that the extension of the recharge and discharge areas may vary considerably during the year. Furthermore, the shallow groundwater levels mean that there will be a strong interaction between evapotranspiration, soil moisture and groundwater which will influence the groundwater level and its recession during summer.

The regolith, totally dominated by till, from a hydrogeological point of view, can be divided into three layers with significant difference in hydraulic properties. The upper one meter, strongly influenced by soil forming processes, has a relatively high hydraulic conductivity and effective porosity (10^{-5}–10^{-4} m/s and 10–20%, respectively). Below approximately one meter depth, the hydraulic conductivity as well as the effective porosity are substantially lower, with hydraulic conductivities between 10^{-8} and 10^{-6} m/s and typical effective porosities of 2–5%. Relatively high values of the hydraulic conductivity have been recorded for 1 m long sections in the contact zone between the till and the bedrock, with a geometric mean of $1.18 \cdot 10^{-5}$ m/s. The cause of this is not clear. Several indications are, however, available of heavily fractured rock at shallow depths in the area.

The lakes are assumed to be important discharge areas. The actual discharge strongly depends on the permeability of the bottom sediments of the lakes. Also, the creeks are considered to be important discharge areas, although unsaturated during parts of the year. The

wetlands can either be in direct contact with the groundwater zone and constitute typical discharge areas or be separate systems with little or no contact with the groundwater zone.

Twenty five "lake-centred" catchment areas have been delineated, varying in size from 0.03 km^2 to 8.67 km^2 (Figure 3-10). Forest is dominant and covers between 50 and 96% of the areas of the catchments (see Figure 3-11). Wetlands, both forest-covered and open, are frequent and cover more than 20% of the area in five of the catchments. Only in one catchment area does agricultural land constitute an important part of the total area (Bredviken with 27% agricultural land, catchment area 20 in Figure 3-10).

Of all the more or less permanent pools of water which could be characterized as lakes, only Lake Fiskarfjärden (catchment area 16 in Figure 3-10), Lake Bolundsfjärden (catchment area 10 in Figure 3-10) and Lake Eckarfjärden (catchment area 12 in Figure 3-10), are larger than 0.2 km^2. The by far most abundant lake type in the regional model area is the oligotrophic hardwater lake, to which all the larger lakes belong. The hardwater lakes are chemically characterised by their high conductivity and by their richness in calcium and magnesium which are dissolved in the water. The investigated oligotrophic hardwater lakes in the Forsmark area have an average depth of 1 m and the renewal times of the water are short. In some of the lakes, which as yet have not been fully separated from the shoreline, the hydrological conditions also include intrusions of water from the Baltic Sea during low pressure weather conditions which create a high sea level.
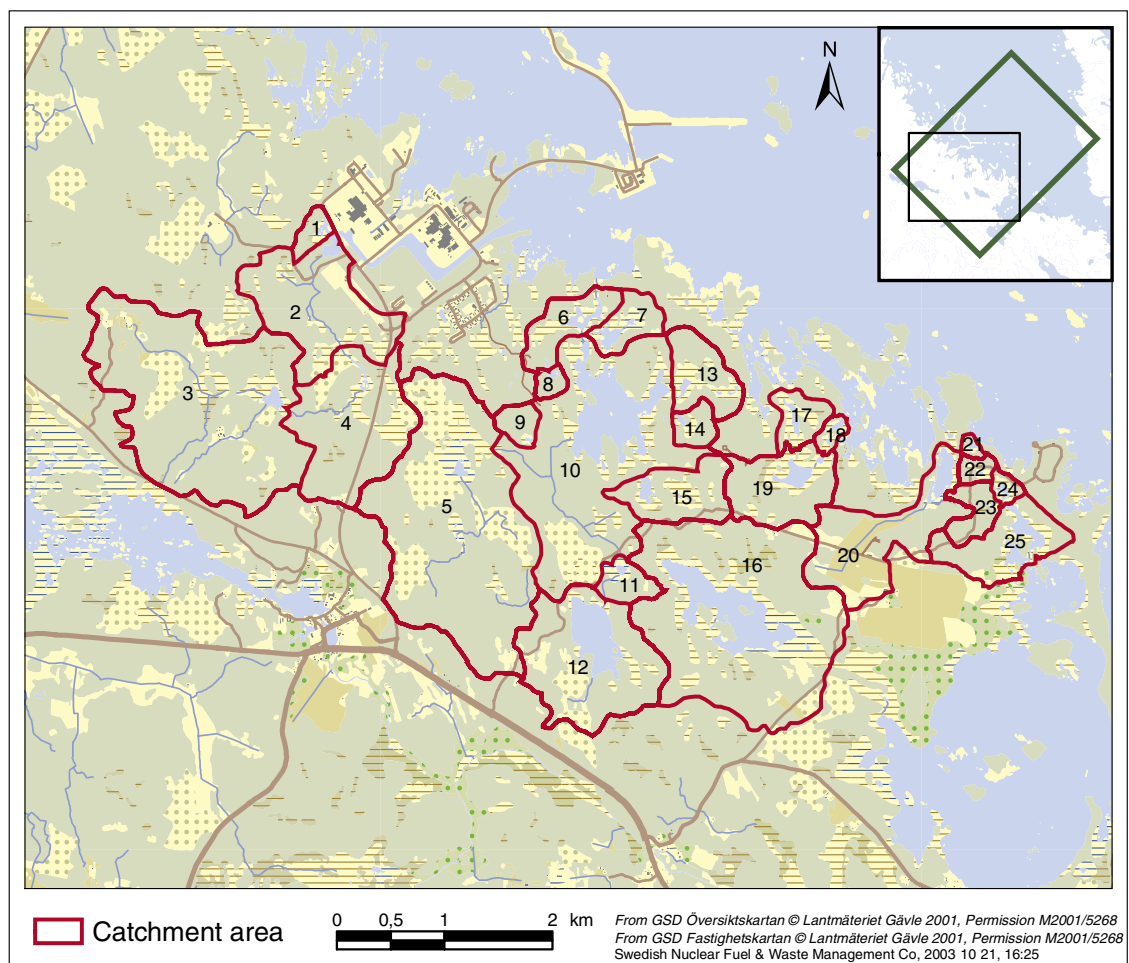
Figure 3-10. Delineated catchment areas in the locality of Forsmark.

The candidate area is located along the shoreline of Öregrundsgrepen. The maximum depth of Öregrundsgrepen is about 60 m and the water retention time varies between 12.1 days (surface) and 25.8 days (bottom), as an annual average. The water level shows considerable temporal variations, especially during the autumn and winter when monthly mean water level can differ as much as ± 1 m between extreme years. The variations in water temperature are small from year to year during winter and spring, whereas variations are large in summer and autumn.

The salinity in Öregrundsgrepen in 1977–78 was between 4.5–5.8‰ in surface water and 5.6–6.4‰ at a depth of 40 m. During the winter period, when Öregrundsgrepen can be ice-covered, the salinity can decline to less than 1‰ in the upper decimetre of the water column. Modelling results indicate a homogeneous distribution of surface salinity, except at the mouth of Kallrigafjärden where two streams discharge and cause depletion in surface salinity.

Due to the rapid water turnover of Öregrundsgrepen, the oxygen saturation is high, on average 95%. The concentration of nutrients in the water varies throughout the year, with the highest concentration at the time for break-up of the ice. Generally, the open water area is poor in nutrients during summer. The content of total nitrogen in Öregrundsgrepen varies between c 200 and 300 µg/L and total phosphorus between c 10 and 15 µg/L.

3.3.15 Biota

Producers

The most common forest type in the Forsmark area is the 70-year old pine forest, typical of broken terrain in eastern Svealand. In addition to pine, spruce, birch, oak and other broad-leaved trees are present (Figure 3-11). The most common undergrowth in the Forsmark region is the nutrient-rich herb type, which is often found in calcareous areas. In general, the coniferous forests in the area have a major element of deciduous trees and shrubs as undergrowth. In wetter parts, the deciduous trees are dominant together with increasing amounts of herbs and grasses. Biomass and primary production of terrestrial organisms in the Forsmark regional model area are calculated to be 3.5 kg C/m^2 and 0.9 kg C/(m^2·year), respectively.

The oligothrophic hardwater lakes in the Forsmark area have low phytoplankton total biomass. The macroflora of the littoral zone (i.e. mostly the floating outer edge of the mire) is characterised by two species: *Sphagnum* in the bottom layer and *Phragmites* in the field layer. The stoneworts, *Charales*, strongly dominate parts of the light-exposed soft-bottom sediments. The outermost parts of floating mats constituting the littoral zone of the lakes are mires. The mires often have a mixed character with components of pine bog, poor fen, rich fen, extremely rich fen and, at the edge of the lake, *Phragmites*-populated floating *Sphagnum*-mats.

During the spring, the phytoplankton community in Öregrundsgrepen is dominated by diatoms and dinoflagellates, whereas the biomass in summer and autumn mainly is composed of bluegreen algae and small flagellates. On shallow soft bottoms, the vegetation is dominated by vascular plants. Other marine aquatic producers verified as present include bladder wrack, filamentous green algae and perennial red algae.
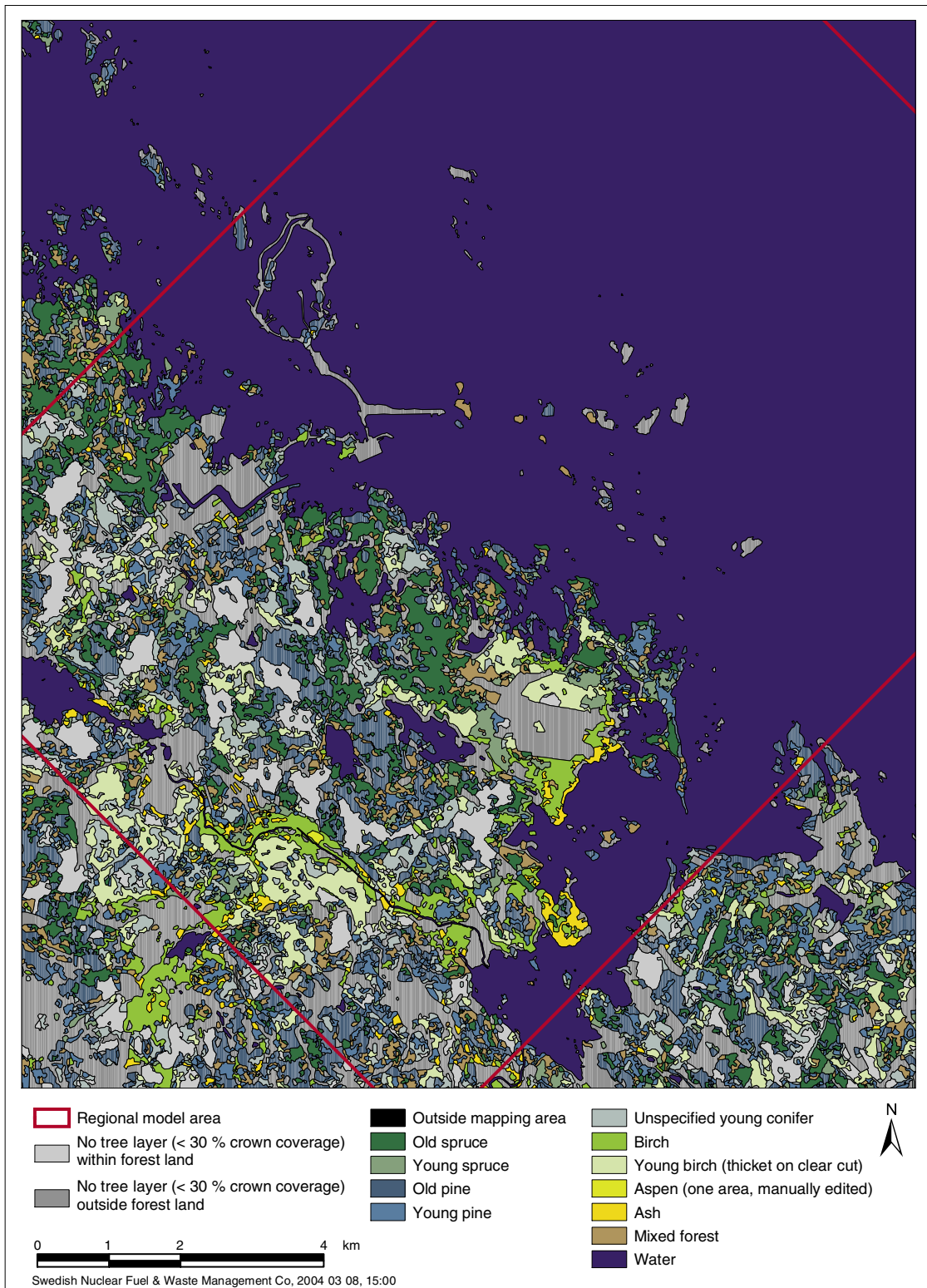
Figure 3-11. *Vegetation map for the Forsmark area. The limits of the Forsmark regional model area are shown by a red line.*

Consumers

Inventories of terrestrial consumers, i.e. mammals and birds, in the Forsmark area showed that roe deer is the most common mammal species (59 deer/10 km^2). Moose was also common, but less than expected from earlier studies (0.7 moose/km^2). European and mountain hare were fairly low in abundance compared with other regions. Other observed mammals were badger, fox, marten, mink, otter and wild boar.

The number of bird species was quite high compared with surrounding regions in Uppland. Site-specific data on biomass for terrestrial consumers were not available for version 1.1 of the site descriptive model.

Standardised survey gill-net fishing in six of the lakes in the Forsmark area has shown an average catch (catch per unit effort, CPUE) of 3.6 kg in terms of biomass and 36 individuals in terms of abundance.

Marine aquatic consumers observed at 2–4 m depth are filter feeders, herbivores and detrivores. At larger depths, the detrivores dominate, with a high biomass down to 15 m. More details regarding species composition and biomass are given in the site descriptive report.

3.3.16 Humans and land use

Since many of the data were available on the parish level, this level of resolution was used to describe the situation in the Forsmark model area. The Forsmark parish is very similar in size to the model area and covers some 90% of its land area.

The Forsmark area is very scarcely populated (1.8 persons/km^2). The main employment sector is within electricity supply and there is a clear net daily in-migration to the main employer (the Forsmark nuclear power plant). The land use is dominated by forestry and wood extraction is the only significant outflow of biomass from the area. The dominating leisure activity, by far, is hunting. Besides this, the area is only extensively used for leisure. This is probably a result of both the scarce population and the areas relative inaccessibility and distance from major urban areas. The agriculture in the area is limited in extent and the major crop is barley.

Quantifications of the variables describing human characteristics and land use are given in the site descriptive model report.

3.3.17 Uncertainties in geosphere and biosphere descriptions

As anticipated at this stage of site investigations, when the data density still is poor and few results from modelling studies are available, there is much uncertainty in the geosphere and biosphere descriptions.

One of the main uncertainties in the geosphere description concerns the occurrence and geometry of vertical and steeply dipping fracture zones in the area. The uncertainty in occurrence is indicated by the assignment of confidence levels to the zones included in the present model. Another main uncertainty concerns the existence and geometry of sub-horizontal fracture zones in the area. The present view of the characteristics of fracturing of the rock in between the fracture zones is based on a number of assumptions that remain to be verified and tested when more site data from depth in the bedrock becomes available.

The uncertainties in occurrence and geometry of fracture zones and fractures are propagated into the hydrogeological description of the site. In addition, the hydrogeological properties

are uncertain due to lack of supporting data and few results of modelling and sensitivity analyses. The conceptual understanding of the hydrogeology and hydrogeochemistry at the site are associated with uncertainties concerning the past evolution. Advances in this respect require more hydrogeochemical data from depth, which should become available for development of model version 1.2.

The uncertainty in rock stress magnitudes and distribution with depth should be reduced significantly by the measurements planned in support of the site descriptive model version 1.2.

The major uncertainty in the description of the biosphere system is related to spatial and temporal variability. Much of the current uncertainty in the surface system properties and processes is expected to be significantly reduced by the data that will be available in support of the site descriptive model version 1.2.

3.3.18 Ore potential

A survey has been made of existing information concerning the potential for exploration for and exploitation of ore and industrial minerals in and near the Forsmark candidate area /Lindroos et al, 2004/. The results of this survey are that granitic rock in the candidate area can be described as sterile from an ore viewpoint. There is an elongate northwest-southeast zone south and southwest of the candidate area which has a potential for skarn iron ore, and possibly for copper and zinc, although to a lesser degree. The small iron ore deposits in the Forsmark area were judged to have no economic value, probably not even in the future. There are no deposits of industrial minerals or commercial stone in the area. Existing pegmatites are uninteresting from an ore viewpoint.

3.3.19 Handling of alternative site descriptive models in later versions

A key issue for safety assessment will be the evaluation and propagation of uncertainties in the site descriptive model. A main method for evaluating such uncertainties is the formulation of alternative conceptual models that are compatible with the primary observations and propagating these to safety assessment.

The site modelling will aim at describing a "best estimate" base case model. Alternative models will be developed by altering parts of the base case model to cover uncertainties that are not included in the base model.

Few alternative conceptual (sub-)models of the site are presented in the Forsmark 1.1 version. There is an alternative to the base case geological model including more sub-horizontal zones, but this has not been propagated to the hydrology model. Alternative versions of the DFN model are also briefly discussed, but must be seen as very preliminary. There is also an initial attempt to address alternatives in the hydrogeochemical model.

However, a quite different situation regarding alternative conceptual models in version 1.2 is forecast. A host of alternatives covering variations in several disciplines is planned. The number of possible combinations that could in principle be propagated to safety assessment might become very large.

A plan for constraining this propagation, selecting a restricted number of alternatives, and suggesting levels to which each should be propagated will be developed in co-operation with the site modelling team as soon as version 1.2 is mature enough for this.

3.4 Site-specific layout

Based on the design specifications of a KBS-3 repository and the site descriptive model described above, a site-specific layout at the Forsmark site has been developed. A generic layout of the deep repository is an important point of departure for the site-specific layout. The recommendation for the generic layout is to use a ramp combined with a skip shaft and preferably having only one operational area /Bäckblom et al, 2003/. The layout also includes shafts for passenger lifts and ventilation air. The main advantage with this arrangement is that the ramp is used only for a small number of transport movements, namely transport casks, buffer material and some bulky or heavy building material, whereas the skip shaft is used for frequent transports of excavated rock and backfilling material. The risk of fires or accidents at the ramp is thereby greatly reduced. Another advantage is that excavation work to a great extent can be separated from deposition work. If excavation of the skip shaft and ramp is started at the same time, it is also possible to reduce the time needed for construction. Figure 3-2 shows the generic arrangement.

Based on site descriptive model version 1.1 for Forsmark and the reference layout, a site-specific layout for the underground facility was developed. When information was missing in site model version 1.1, older material (version 0) was used.

In principle, the analyses underpinning the layout followed the scheme described in a "preliminary underground design requirements report" version D1/1, draft 1. All steps in the scheme were however not performed in this first exercise; instead a number of assumptions were made in order to simplify the work and shorten the time schedule:

- As in the reference case the deposition tunnels were taken to be separated by 40 m and the spacing between the deposition holes 6 m.

- The length of the deposition tunnels vary between 100 and 300 m, compared with 265 m in the generic arrangement.

- The deep repository was located in the northern part of domain 29.

- Fracture zones were assumed to be vertical when information on dip was missing.

- The operational area was placed at the area used for temporary housing for service personnel.

- The underground facility was placed 500 m below ground.

Rock mechanical analyses based on data from site model version 0 implied problems due to spalling in deposition holes if the underground facility was located at a depth of 500 m. Therefore, the underground facility was developed for a depth of 400 m below ground. This issue will be revisited as new data emerge from further site investigation.

A tunnel orientation in parallel with the direction of highest principal stress minimises the probability of spalling. Therefore, it was proposed that the deposition tunnels would have that orientation thus minimising problems during construction and deposition as well as the required amounts of stray materials for rock support, like steel and concrete.

Deformation zones and associated respect distances had a great influence on the layout. When developing the layout shown in Figure 3-12 only fracture zones with high or medium confidence were taken into account and the total portion of abandoned deposition holes was assumed to be 10 per cent.

The results of a preliminary assessment of the needs for rock support and grouting did not differ significantly from earlier generic assumptions.

Figure 3-12. *Layout Forsmark. 400 m level.*

A number of conclusions for the future can be drawn from the preliminary analyses made:

- Rock mechanical analyses showed that rock stresses had a great impact on both the orientation of tunnels and the number of deposition holes that had to be abandoned due to spalling. Therefore, the criterion for determining the risk from spalling is important.

- The strike and dip of fracture zones and the respect distance to them had a great influence on the layout.

- The DFN model is crucial for the layout work. If the DFN model is of sufficiently high resolution to indicate anisotropy in fracture intensity or hydraulic connectivity, it can be used for analyses of wedge stability and preliminary estimates of hydraulic conditions affecting seepage as was done in the first layout step.

3.5 Monitoring

Repository construction and operation will cause significant disturbances of the site. The safety relevant aspects of these will be handled in the assessment. Monitoring these disturbances will be important for advancing the understanding of the site and the envisaged repository. Monitoring may also be considered after repository closure. The monitoring strategy of SKB is evolving. /Bäckblom and Almén, 2004/ summarise the current SKB strategy on these matters.

Monitoring for the baseline description

Many of the investigated site parameters like precipitation and groundwater levels, will show a pattern of more or less pronounced temporal variation. One reason for such variation is the seasonal fluctuations in temperature and precipitation. There may, however, also be other and more unpredictable reasons, such as long-term variations or trends in meteorological parameters, which can cause variation in one or several of the parameters. Furthermore,

investigations and underground activities themselves may give rise to changes or variation in some parameters.

The site descriptive model produced after completion of the site investigations is also the baseline description of the site. As set out in the overall SKB strategy for monitoring /Bäckblom and Almén 2004/, the general idea with establishing the Baseline conditions during the site investigations from surface is to get a reference against which the changes caused by repository development can be recognised and distinguished from natural and other man-made temporal and spatial variations in the repository environment.

Understanding temporal variation is important when establishing the Baseline conditions. However, this does not imply that all aspects of natural time variation need to be charac-terised. As discussed by /Andersson et al, 2004a/ site-specific monitoring can hardly reveal more than "within-year" variation, whereas longer-term variation needs to be assessed through more generic ("regional") knowledge and modelling.

Monitoring results should be seen as inputs to an integrated site description, and not as individual indicators of site properties. Decision support for major decision points in the programme is obtained from the safety assessment based on the current version of the site description.

Even if extensive sampling programmes for the collection of time series data is restricted to one or two years, the programmes would not be terminated after this period. Instead, a reduced number of carefully selected sampling points would be included in long-term monitoring programmes. Data collected in these monitoring programmes would, together with the initially collected baseline data, form the reference against which any changes caused by repository construction could be recognised and distinguished from natural and other man-made temporal and spatial variations in the repository environment.

Monitoring impact of repository construction

The detailed characterization of site-specific conditions and processes planned to be carried out during the Site Investigation Phase will for most parameters ensure the establishment of undisturbed baseline conditions with sufficient accuracy. Before repository construction commences a monitoring programme covering key parameters potentially affected by investigation and construction activities will be set up. Monitoring aspects of the engineered barriers may also be considered /see Bäckblom and Almén, 2004/.

Monitoring after waste emplacement

Repository closure is a stepwise process from consecutively closing a deposition tunnel to closing one or several deposition areas before the whole repository is closed. As stated by /Bäckblom and Almén, 2004/ rationales for monitoring of the post-closure phase, such as verification of safeguard requirements, may develop. The extent of the post-closure monitoring programme will essentially be determined by decisions made at closure and it is appropriate that any decisions on post-closure monitoring are taken by the generation that is the decision-maker at the time of closure. As the responsibility for the repository is trans-ferred to the State after closure, it is also necessary to clarify the responsibility for execution of the post-closure monitoring. In SR-Can no consideration is given to monitoring after waste emplacement. Nor is any credit taken for the potential indications of performance arising from such monitoring.

4 Handling of external conditions

4.1 Introduction

The external conditions at the repository site are highly likely to change considerably over the time scale of the safety assessment. In the SR-Can FEP database, see section 2.4 and /SKB, 2004a/, external FEPs are one of the three main categories. The external FEPs identified in the database have been further sorted into groups related to:

1. Climate processes and effects.

2. Geological processes and effects.

3. Future human actions.

4. Other.

Climate changes with associated altered shore-levels, permafrost development and expanding ice sheets are expected. The timing and extent of these changes are uncertain due to the complexity and non-deterministic aspects of the climate system. Additional uncertainty regarding climate evolution is introduced by the uncertain impact and duration of human influence on the climate due to emissions of greenhouse gases. Climate changes will, whatever their cause, alter subsurface conditions and a safety assessment must thus address the potential impact of climate changes on repository performance and safety.

Geological processes and effects include erosion and uplift (other than those induced by glacial loading and unloading) and plate tectonics. These processes are active in a very long time perspective. Within the assessment period of one million years, the alterations of external conditions caused by these processes are deemed to be of minor importance for repository performance.

Another main category of external FEPs that may impact the repository is future human actions. These can be divided into actions at or close to the repository site like utilisation of resources from the bedrock and regional or global actions, e.g. those resulting in severe pollution.

In the fourth group, only "Meteorite impact" was identified. Meteorite impacts will be excluded from further analyses, since the probability that a meteorite, large enough to damage the repository, will actually hit is deemed to be extremely low. Furthermore, the direct effects of the event are deemed to be much more severe than its possible radiological consequences.

In the following, a brief plan is presented for the handling of i) factors related to climatic and geological processes, including human induced climate change and ii) future human actions (other than human-induced climate change).

A first audit of external FEPs in the SR-Can database /SKB, 2004a/ showed that most of these FEPs were handled in SKBs most recent safety assessment SR 97 /SKB, 1999a/. The knowledge base and tools for the analyses required have since been further developed. There will be no formal account of the handling of all FEPs related to these issues early in the project. Rather, at a later stage, it will be formally checked that all relevant factors have been included in the analysis.

4.2   Factors related to climatic and geological processes

Climate changes or climate-related changes, such as the ongoing shore-level displacement are the most important naturally occurring external factors affecting the repository in a time perspective from tens to hundred of thousands of years. Most of the processes occurring in the biosphere and geosphere regarded as internal to the repository system are affected by climate and climate-related changes. In very long time perspectives, millions to several millions of years, geological processes like plate tectonic movements and uplift or down-warping (additional to those crustal displacements due to glacial loading and unloading) will affect both the repository and the earth climate system.

Climate changes are caused by factors external to the climate system and by internal dynamics of the climate system. Example of external factors affecting climate in the time perspective of interest for performance assessment are volcanism, solar variability and changes in insolation due to variations of the earth orbital parameters. Internal dynamics affecting the climate include evolution of the atmosphere, ocean circulation and feedback processes such as those relating to atmosphere-ocean interactions, sea-ice extent and albedo. In addition, to naturally occurring processes, human emissions of greenhouse gases have been identified as a potentially significant cause of climate alterations.

Past climate

For the past 2.5 million years Scandinavia has experienced several cycles of growth and decay of ice sheets. Periods during which ice sheets gradually grow to a maximum extent are known as glacials. Periods with warm climate when the ice sheets wane to an extent similar to that at the present day are called interglacials. A glacial cycle consists of a glacial and an interglacial. Glacial cycles also include colder and warmer stages denominated stadials and interstadials, respectively.

Over the last 800,000 years about 100,000 year long glacial-interglacial cycles have dominated climate variation. These cycles consist of a long period of cooling followed by a fast transition to a warm climate. During the cold period, ice sheets and glaciers have successively – by repeated advances and decays – grown world wide to a maximum extent and during the following transition to a warm climate they have melted away very fast to residual extents similar to that of the present. The climate during the past 700,000 years can be depicted in the relationship between the two stable oxygen isotopes O-18 and O-16 $(\delta^{18}O)$[4] as shown in Figure 4-1.

Human induced climate change

During the last few decades, human impact on climate has been much debated. In particular, recent studies utilising both Earth Models of Intermediate Complexity and more conventional General Circulation Models have projected a very long period of warm climate similar to the climate seen in the warm phases of past interglacials /Bioclim, 2001, 2003/. In these model simulations, the emission of green-house gases is assessed to result in a long-term perturbation of the pattern of glacial cycles observed in the past. The perturbation will remain until the emitted greenhouse gases have been removed from the surficial

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[4] In a cold climate, the fraction of the heavier oxygen isotope, O-18, in the oceans increases. The lighter isotope, O-16, evaporates more easily and is bound in snow and ice in the ice sheets. The ratio between the oxygen isotopes is expressed in parts per mille, normally in accordance with a standard (SMOW) as $\delta^{18}O = (R_{sample}/R_{ref} - 1)*1,000$ where R_{sample}= O-18/O-16 in the sediment and R_{ref} is a reference value for the same ratio.
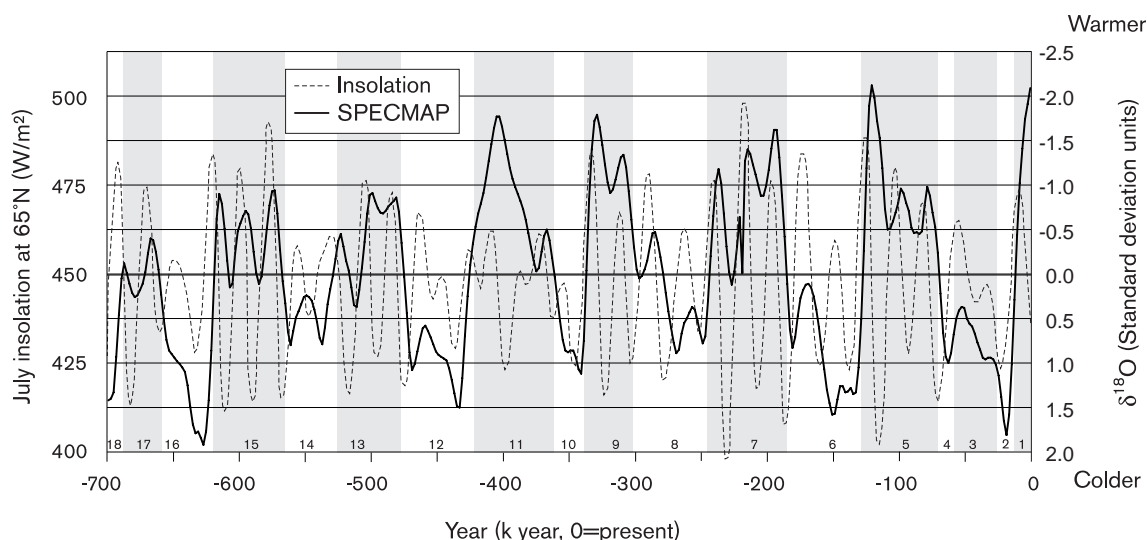
Figure 4-1. $\delta^{18}O$ *variation from 5 drill cores of deep sea sediments expressed as number of standard deviations from the long-term mean /from Imbrie et al, 1984/.* $\delta^{18}O$ *variations reflect the temperature of the sea and, more importantly, the volume of water that has been bound in land-based ice sheets and glaciers all over the world. The grey and white fields and the figures at the bottom edge indicate warm and cold periods called marine isotopic stages (MIS).*

ocean-atmosphere system and sequestered in the lithosphere. Within the BIOCLIM prject, this timescale has been estimated at 200,000 years or more. However, the knowledge of the carbon cycle is incomplete and both the total emissions and the recirculation to the lithosphere are uncertain.

There is also uncertainty regarding the response of the complex climate system to global warming. It has for instance been suggested that induced changes in ocean circulation may give rise to a colder climate in the northern hemisphere /Broecker, 2003/.

4.2.1   General climatic evolution

In the following, some basic characteristics of the climatic evolution are briefly discussed and a strategy for characterising potential patterns of climatic evolution in SR-Can is developed.

It is currently not possible to predict the evolution of future climate in any detail and any presented climate evolution is associated with large uncertainties. However, the extremes within which the climate of Sweden may vary can be predicted with reasonable confidence. Within these limits characteristic climate conditions can be identified. The conceivable climate conditions 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. These 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. If it can be shown that a repository for spent nuclear fuel fulfils the safety requirements independent of the prevailing climate domain, and the possible transitions between them, then the uncertainty regarding their extent in time and space is of less importance.

The extent of the climate domains will vary in time and space. In a specific area, the succession of climate domains will generally follow a cyclic pattern, see Figure 4-2. The duration of each domain depends both on global climate changes and on the location of the site. The glacial domain will, for instance, prevail longer in a northern, inland location than in a southern, coastal location. Although overall evolution will, in general, follow the pattern shown in Figure 4-2, all domains will not necessarily occur at a specific site.

The advance and decay of ice sheets will have a substantial impact on surface and subsurface conditions. If the climate gets colder, the glaciers in the Scandianvian mountains will start expanding, eventually forming ice caps that will expand into ice sheets. The ice sheets are expected to advance towards the Norwegian coast and in a south-easterly direction. An ice sheet is a dynamic feature which deforms under its own weight and interacts with the bed and the climate. If the accumulation of snow and ice on the high central part of the ice sheet is greater than the ablation at the front, the ice sheet will expand and vice versa.
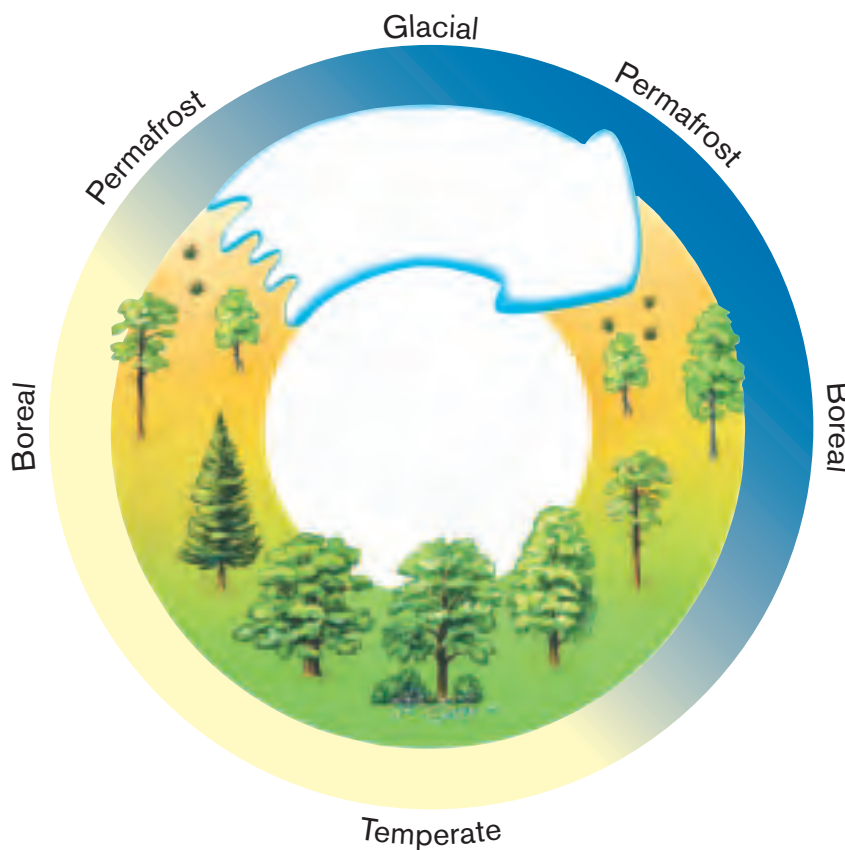
Figure 4-2. *The climate domains succeed each other in a cyclic pattern.*

In front of the ice sheet permafrost may develop. As the ice sheet grows, the weight of the ice will cause an isostatic depression of the earth crust. Simultaneously, as ice sheets and glaciers expand all over the earth, an eustatic lowering of the sea surface will occur as water is transported from the oceans to the land-based ice sheets and glaciers. The eustatic and isostatic processes will alter the shore-level. In most parts of Sweden, the isostatic component of shore-level displacement is greater than the eustatic component, i.e. the relative sea-level tends to increase during glacial episodes.

Isostatic and eustatic processes will in the beginning of a glacial result in regression, lowering of the relative shore-level. If the ice sheets continue to expand the regression will be altered to transgression, elevation of the relative shore-level, where and when the isostatic depression exceeds the eustatic lowering of the sea surface. When the ice sheets melt, water is returned to the sea and the sea level rises, at the same time the earth crust is relieved from the ice load, and a rapid isostatic rebound occurs in previously ice-covered areas. Sites at current low altitudes that have been ice covered will be submerged and experience a lowering of the relative shore level.

The ice load and isostatic process will also alter the rock stresses. Currently, the main principal stress is horizontal down to a depth of about 400 to 500 meters. When an ice sheet of great thickness overlies the bedrock, a surplus of vertical stress is expected along with an increase of horizontal stresses. The increments of the horizontal stresses vary in a complex way in relation to the ice load. When the ice load is removed, the stresses decrease and non-isotropic stress states due to different relaxation times of vertical and horizontal stresses, in combination with high residual pore pressures, may lead to instability. Further, the basal conditions of the ice sheet are important both for the hydrological boundary conditions and effective stresses. A cartoon showing the course of events as an ice sheet grows and decays along a schematic transect from the Norwegian coast towards the south-east is shown in Figure 4-3.
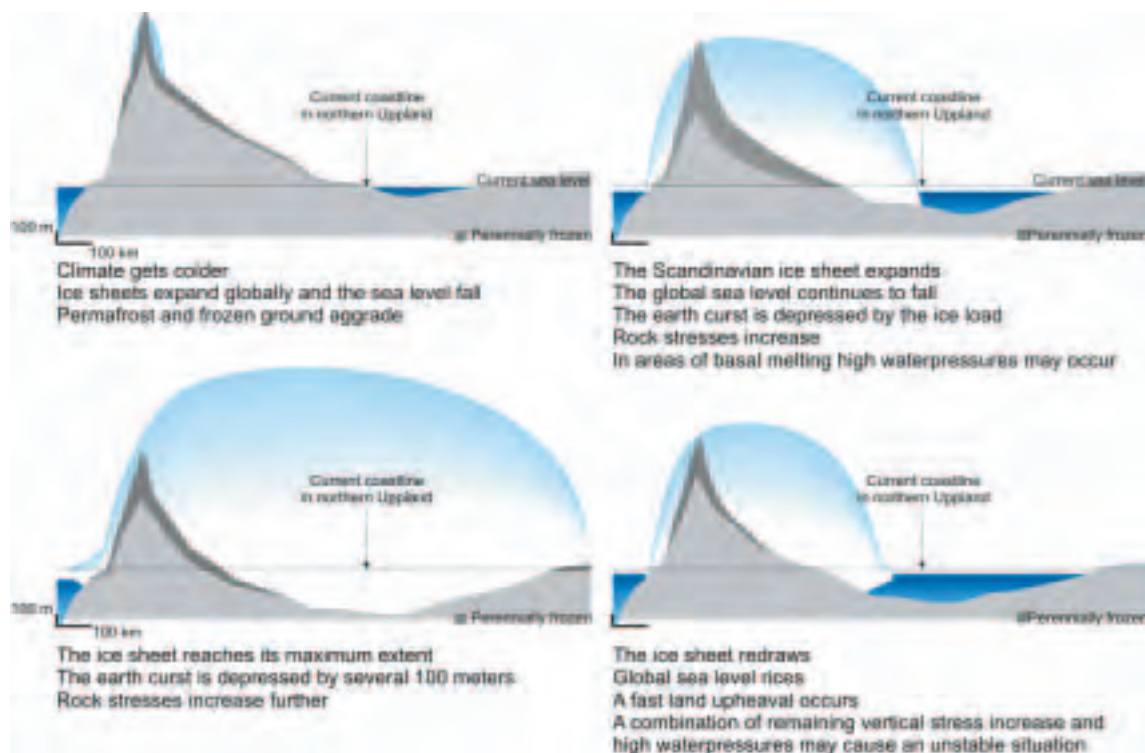
Figure 4-3. The course of events as an ice sheets expands and decays along a schematic transect from the Norwegian coast towards the south-east.

4.2.2   Impact on repository safety

Climate changes, permafrost and the growth and decay of ice sheets will alter not only surface but also subsurface conditions. Freezing, shore-level displacement and the presence of ice sheets will change permeability, water turnover, groundwater pressures, groundwater flow and composition. The ice load will alter rock stresses and during different phases of a glaciation the principal stresses will change in both direction and magnitude. This will alter bedrock permeability and as the ice melts away a combination of large horizontal stresses and high water pore pressures may cause post glacial faulting. In general, the integrated effects of the continuous climatic evolution need to be considered, but there are also a number of more specific phenomena of importance for repository performance that require special attention. Based on the results of earlier assessments, these include:

- The maximum hydrostatic pressure occurring at repository depth for glacial conditions.

- The maximum permafrost depth throughout the glacial cycle.

- The possible penetration of oxygen to deep groundwaters during glacial conditions.

- The possible occurrence of dilute groundwaters during glacial conditions potentially causing erosion of buffer and backfill.

- The maximum groundwater salinity occurring at repository depth during the glacial cycle.

- Post-glacial faulting.

- Factors affecting retardation in the geosphere, like high groundwater fluxes and mechanical influences on permeability.

4.2.3   Strategy for managing the uncertain long-term climatic evolution

Predictions of the future long-term climate are currently not possible to make due to both the complexity of the natural climate system and uncertainties regarding the extent and long-term impact of human-induced greenhouse effects. It is however highly likely that the three climate domains will appear repeatedly during the one million year assessment period, i.e. any reasonable evolution will have to cover them. It is furthermore possible to put bounds on the conditions that could reasonably occur during each type of domain.

For compliance purposes, it is particularly important to include sequences covering external conditions yielding, with a high likelihood, the peak risk during the assessment period. Based on results of earlier analyses, the highest risks are likely to occur during temperate periods. Typical situations are i) a terrestrial system that has accumulated radionuclide releases over a long time, possibly at early stages as sea sediment and that is later used for agriculture and ii) a well intruding into the host rock and used for domestic purposes.

It is also important to include the climate domains and sequences deemed to have the greatest impact on repository safety. Phenomena that may impact barrier safety functions are mentioned above, the most severe effects are related to the development of permafrost and the advance and decay of ice sheets.

Preliminary analyses demonstrate that canister failures are not expected until far into the future, thus relaxing, from this particular point of view, the demands on a detailed description of the early external conditions.

Based on these premises, the following approach is taken to handle climatic evolution in SR-Can:

1. A reference climate evolution including the identified climate domains and the possible transitions between them is defined and modelled.

2. Based on the modelling results of the reference evolution, bounding conditions with respect to repository safety are sought.

3. A variation of the reference evolution with a human induced greenhouse effect is also considered.

Reference climate evolution

The site-specific climate evolution will be described both in a quasi-stationary manner and continuously. The quasi-stationary evolution consists of a time series of climate domains and the continuous evolution is expressed as the continuous variation over time of a set of key parameters affecting repository safety:

- Temperature at the surface above the repository.

- Shore level and salinity of sea/lake water.

- Ice thickness.

- Groundwater recharge and/or pressure.

Bounding conditions

Based on the modelled reference evolution and of the understanding of the safety functions of the repository, a number of key phenomena potentially threatening the safety of the repository and occurring as a consequence of the climatic evolution will be identified. The list based on earlier assessment results presented in section 4.2.2 is expected to contain all the major issues needing attention.

The sensitivity of these phenomena to uncertainties in the climatic evolution will then be explored within the framework of the identified climate domains and the possible transitions between them. The extremes comprise the climatically determined setting and the associated values of the key parameters listed above, the duration of a specific domain and the rate of change. The generic studies of climate domains and the possible transitions between them will be based on process understanding. Within each climate domain extremes of climatic and other environmental conditions will be discussed and estimated, considering past glacial-interglacial cycles for the whole of the Quaternary period. These extremes can be related to the regional and global climate conditions required to attain them. Based on this and further modelling (section 11.4), it will be possible to put bounds on the values of parameters of importance for repository performance and safety and also to make judgements on the probability of the occurrence of the extremes.

Greenhouse variant

As a variant of the reference evolution comprising all the identified climate domains, a future without ice sheets and permafrost in Scandinavia during the next 200,000 years, based on the simulations from the Bioclim-project /Bioclim, 2003/, will be studied.

The level of ambition regarding the analyses of the variation is considerably lower than that of the reference evolution. Primarily, a relatively simple discussion of differences compared to the reference evolution will be carried out.

4.3 Future human actions

A great number of external FEPs related to future human actions (FHA) were identified in the SR-Can FEP database, as a result of an audit /SKB, 2004a/ against the NEA international database. These include actions like rock drilling, mining, severe pollution, underground excavations in relation to urbanisation and intentional or inadvertent repository intrusion. The identified FEPs were further briefly audited against the results of the analyses of scenarios based on future human actions carried out in the SR 97 assessment /SKB, 1999a/. The majority of the identified FEPs were included in the SR 97 analyses. The latter study was carried out without reference to the NEA database.

The further handling of FHA FEPs is presented in conjunction with scenario selection in chapter 8, section 8.5. At a later stage of the SR-Can project, it will be checked that all relevant FHA-related external FEPs in the SR-Can database have been appropriately handled.

5 Handling of internal processes

5.1 Introduction

A thorough understanding and handling of the processes occurring over time in the repository system is a fundamental basis for the safety assessment. The basic sources of information for this are the results of decades of R&D efforts by SKB and other organisations. In a broader sense, these are based on the knowledge accumulated over centuries of scientific and technological development. The R&D efforts have led to the identification and understanding of a number of processes occurring in the engineered barriers and the natural systems relevant to long-term safety. For the purpose of the safety assessment, the relevant process knowledge for the engineered barriers and the host rock is compiled in a Process report which also, for each process, contains a prescription for its handling in the safety assessment. Also short-term geosphere processes/alterations due to repository excavation are included. For the SR-Can interim reporting, an interim version of the process report, focussing on buffer processes, is provided /SKB, 2004b/.

This chapter describes how processes are documented in the SR-Can Process report, including the principles for their handling in the safety assessment taking into account relevant uncertainties. Formats for graphically illustrating the system of coupled processes are discussed in section 5.2. The format for process documentation in the SR-Can Process report is described in section 5.3. Section 5.4 gives, as an example, an overview of the handling of buffer processes in SR-Can, based on the material in the Interim Process report /SKB, 2004b/.

5.1.1 Identification of processes

The identification of relevant processes has been a continuing effort over many years, based on R&D results, findings in earlier safety assessments etc. In SKB's most recent safety assessment, SR 97, an identification of the set of processes to be managed in the safety assessment was made /Pers et al, 1999/ and this set was the starting point for process identification in SR-Can.

As mentioned in section 2.4, in an audit against the contents of the international FEP database a large number of FEPs were mapped to the set of relevant processes in the SKB database leading also to the identification of a few additional processes relevant to the engineered barriers or the geosphere.

Furthermore, the division of system components was revised and refined, see section 3.1.1. The deposition tunnel backfill has been included as a distinct system component, rather than being described together with the buffer as in SR 97. Also, the components "bottom plate in deposition hole", "plugs", "borehole seals" and "backfill of other repository cavities" have been added, requiring dedicated process descriptions also for these. The new components are however in general not crucially linked to safety, meaning that the handling of processes for these will be less developed.

A check that all process FEPs in the NEA database have been properly managed in SR-Can will be performed at the end of the SR-Can project and documented in the database.

5.1.2 Biosphere processes

As mentioned earlier, biosphere processes were not included in the SR 97 Process report and there is thus not the same basis for updating these descriptions as for the engineered barriers and the geosphere. All biosphere FEPs have therefore been collected in a single category to be further handled in the safety assessment.

In the SAFE project, a biosphere interaction matrix was developed. This matrix will be reviewed and the biosphere processes documented in a Biosphere Process report. A first issue of the process report and the interaction matrix will be finished for SR-Can. The report will be updated for SR-Site.

It is expected that for a major part of the processes in the biosphere, it will not be necessary to develop numerical models. The documentation and scientific reasoning in the process report and the numerous reports from the sites are expected in many cases to be a sufficient basis for simplifying or omitting the processes in question in the calculations. Part of the understanding is expected to develop during the final part of the site investigation when sufficient data have been produced. Thus, the numerical models used are likely to change from SR-Can to SR-Site.

5.2   Format for process representations

For the purpose of the safety assessment, the repository system is divided into several system components and each component is characterised by a number of specified time-dependent physical variables, section 3.2.1. Within a specific system component, a number of processes act over time to alter the state of the system, i.e. changing the variables. Examples from the buffer are heat transport, water uptake, swelling, chemical decomposition and ion exchange.

The coupling between the processes will be expressed by the network of connected processes and variables and the system of coupled processes need to be managed in the safety assessment. Couplings between system components are handled via the time-dependent boundary conditions at the component interfaces.

Variables, processes and their dependencies may be graphically represented in different ways. In SR 97, the representation was in the form of Process Diagrams, one for each system component. Figure 5-1 shows the SR 97 process diagram for the buffer. The diagram also shows which variables influence each process as well as the influences a particular process has on the set of variables. Also, interactions over the boundaries of the system component are described. Another example of graphical representation is the so called Interaction Matrices /e.g. Skagius et al, 1995/. Both these condense a vast amount of information graphically. Both interaction matrices and process diagrams have been used to force the analyst to work in a structured way in identifying relevant processes and barrier properties and their dependencies. They however also share a difficulty: It is difficult to grasp even the main features of system evolution by studying these graphical representations. The graphical information in the diagrams or matrices has thus not been utilised in the safety assessment, e.g. for illustrating the evolution of the system. Rather than clarifying the important features of the system dynamics, the interaction matrices and the process diagrams convey a (true) impression of complexity, but with no guidance as to the relative importance of different traits of system evolution. This is partly related to the lack of distinction between the different time frames of the repository evolution. Most processes
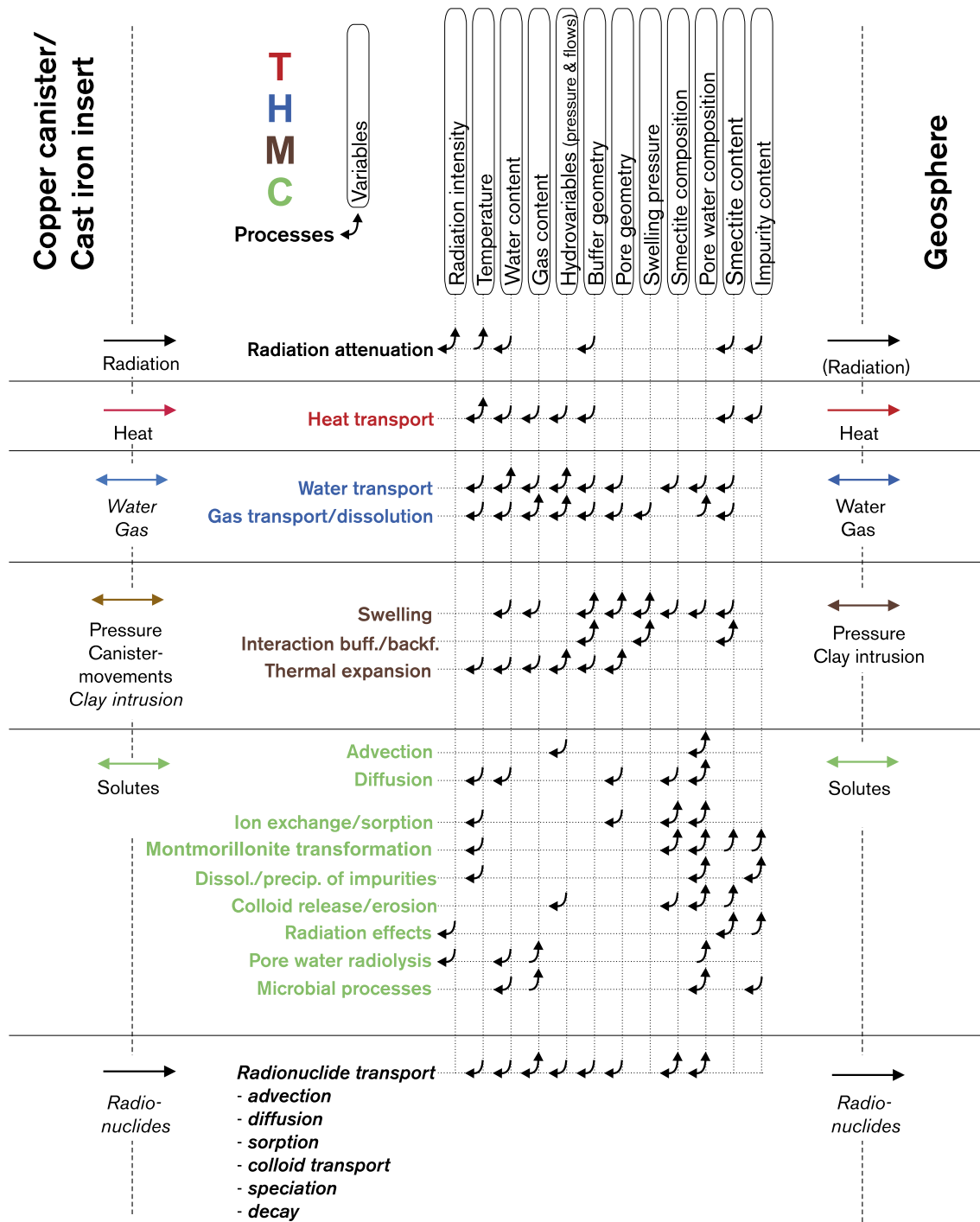
Figure 5-1. *The SR 97 version of the process diagram for the buffer. Thermal hydraulic, mechanical and chemical processes are listed in the left column, the variables are given in the top row. Influences between variables and processes are described by arrows in the diagram. Processes and interactions in italics only occur if isolation of the copper canister is broken.*

and influences on barrier properties are only relevant in some of the several time frames that need to be considered in the safety assessment. The SR-Can database, in which all process information is stored, can generate both types of representation, but neither of these is expected to have a central role in the further analyses in SR-Can.

Rather, the benefits of the structured treatment of processes and variables in the process diagrams will be utilised in the process documentation in the SR-Can Process report. For each process, a table will be produced describing, for each variable in the system component, if it influences or is influenced by the process in question. For a given process, the table will thus correspond to the arrows for that process in Figure 5-1. The table format allows also comments to be included and thus gives a more elaborate description than the arrows in the diagram. In conjunction with the table, the influences will be documented.

The graphical representation of processes in SR-Can will be in the form of tables, where the handling of the processes in different time frames is explained. This is further developed in section 5.4.

5.3   Format for process documentation

The SR-Can Process report is a documentation of all processes in the fuel, the canister, the buffer, the backfill and the host rock identified as relevant for long-term safety of a KBS-3 repository as discussed in section 5.1.1.

The purpose of the Process report is to document the scientific knowledge of the processes to a level required for an adequate treatment in the safety assessment SR-Can. The documentation is thus from a scientific point of view not fully exhaustive since such a treatment is neither necessary for the purposes of the safety assessment nor possible within the scope of an assessment.

The purpose is further to determine a handling of each process in the safety assessment and to demonstrate how uncertainties are taken care of given the suggested handling.

All identified processes are documented using the following template, where many of the headings are the same as those used in the SR 97 Process 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.

Under this heading, a table is produced documenting how the process is influenced by the specified set of physical variables in the relevant system component and how the process influences the variables.

Boundary conditions

The boundary conditions for each process will be discussed. These refer to the boundaries of the relevant system part. For example, for buffer processes the boundaries are the buffer interfaces with the canister, the walls of the deposition hole and the backfill. The processes for which boundary conditions need to be described are, in general, related to transport of

material or energy across the boundaries. For example for chemical processes occurring within a system component, like illitisation in the buffer, the discussion of boundary conditions will relate 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 will be summarised. This documentation will be the major source of information for many of the processes.

Natural analogues/observations in nature

If relevant, natural analogues and/or observations in nature regarding the process will be documented under this heading.

Time perspective

The time scale or time scales on which the process occurs is documented, if such timescales can be defined.

Handling in SR-Can

Under this heading, the handling in the safety assessment SR-Can is described. Typically, the process is either

- neglected on the basis of the information under the previous headings,

- neglected provided that a certain condition is fulfilled, e.g. that the buffer density is within a certain range,

- included by means of modelling.

The following aspects need to be covered, although no prescribed format for the documentation is given:

Time periods: On what time periods is the process relevant for the system evolution? In e.g. the case of the buffer, relevant time periods might be

- the resaturation phase extending from the time of deposition until the point in time when the buffer is fully water saturated,

- the so called thermal phase extending from the time of deposition and throughout the approximately 1,000 year time period of elevated temperature in the buffer or

- the long-term time scale extending throughout the one million year assessment time and including the varying conditions in the bedrock caused by long-term climate and other environmental variations.

By documenting the relevance of the process for applicable time periods, the process system can be simplified by omitting the process in time periods during which it is not relevant.

Boundary conditions: How are the boundary conditions handled? Are e.g. spatially and temporally varying chemical and hydraulic conditions considered?

Influences and couplings to other processes: The handling of the documented influences will be discussed as will couplings to other processes within the system component.

The special cases of failed canister and of earthquakes altering deposition hole or tunnel geometry: These special cases imply altered conditions that could influence many processes in particular for the fuel, the canister, the buffer and the backfill and they may thus need to be discussed separately. Canister failures and earthquakes of a magnitude that could affect the deposition hole or tunnel geometry are not expected during the several thousands of years after deposition when temperate conditions are likely to prevail, meaning that the special cases are not relevant for many "early" processes. Should the assumptions regarding the lack of occurrence of significant, early canister failures or earthquakes not be corroborated by more detailed and integrated analyses in the safety assessment, this simplification of the handling of the special cases will be reconsidered.

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, see section 5.4 for an example. The mapping will be characterised on different time scales.

Handling of uncertainties in SR-Can

Given the adopted handling in the safety assessment SR-Can as described above, the handling of different types of uncertainties associated with the process will be summarised.

Uncertainties in mechanistic understanding: The uncertainty in the general understanding of the process will be discussed based on the available documentation and with the aim of answering the question: Are the basic scientific mechanisms governing the process understood to a level necessary for the suggested handling? Alternative models may sometimes be used to illustrate this type of uncertainty.

Model simplification uncertainties: In most cases, the quantitative representation of a process will contain simplifications. These may result in a significant source of uncertainty in the description of the system evolution. Alternative models or alternative approaches to simplification for a particular conceptual model 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 for the suggested handling 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.

References

A list of references used in the process documentation.

5.3.1   Documentation of participating experts and decisions made

Generally, all arguments including bases for decisions, and underpinning references will be provided in the process description under the appropriate headings. In addition, a short record will be provided on which expert(s) assembled the basic information on the process, which expert(s) were involved in the decision regarding treatment in the safety assessment and the dates for the final revision of the text and for the final decision on handling. While many decisions are expected to be made on a consensus basis, there could also be cases where disagreement between experts will lead to, e.g., alternative calculation cases.

5.4   Process mapping/process table

To graphically illustrate and summarise the handling of processes in the safety assessment, a table showing the handling of each process in different time frames will be produced, based on the handling documented in the process report. One table per system component will be provided. In the table, the process is either "mapped" to a model by which it will be quantified or associated with a brief verbal description of how it will be handled. Table 5-1 shows a preliminary version of the SR-Can process table for the buffer.

Table 5-1. Process table for the buffer describing how buffer processes will be handled in different time frames and in the special cases of earth quakes and failed canisters. Green fields denote processes that are neglected or irrelevant for the time period of concern. Red fields denote processes that are quantified by modelling in the safety assessment. Orange fields denote processes that are neglected subject to a specified condition.

Buffer	Resaturation/ "thermal" period	Long-term after saturation and "thermal" period	Earthquakes	Notes
Intact canister				
Radiation attenuation/heat generation	Neglected	Neglected	Neglected	
Heat transport	System model	(System model)	Irrelevant	Consider poorly centred canister?
Freezing	Neglected	Neglected if buffer temperature > 0°C. Otherwise bounding consequence calculation.	Irrelevant	Repository temperature in long term obtained from permafrost depth modelling.
Water uptake and transport for unsaturated conditions	THM model	Irrelevant by definition	Irrelevant	
Water transport for saturated conditions	Irrelevant by definition	Neglected if hydraulic conductivity < 10^{-12} m/s	Consider pressure transients	Evaluate effects on conductivity of chemical evolution and mass redistribution and of possible changes of hydraulic gradients for permafrost and glaciation
Gas transport/ dissolution	Through dissolution	(Through dissolution)	(Through dissolution)	
Piping/erosion	Model study	Irrelevant	Irrelevant	
Swelling/Mass redistribution	THM modelling including interaction buffer/backfill and thermal expansion System model (final swelling)	Integrated evaluation of erosion, convergence, corrosion products, creep, swelling pressure changes due to ion exchange and salinity, canister sinking	Part of integrated assessment of buffer/ canister/rock	Need to also consider deviations in amount of buffer initially deposited.
Liquefaction	Irrelevant	Irrelevant	To be determined	
Advection	Simplified assumptions of mass transport of dissolved species during saturation.	Neglected if hydraulic conductivity < 10^{-12} m/s	Consider pressure transients	See "Water transport for saturated conditions"

Buffer	Resaturation/ "thermal" period	Long-term after saturation and "thermal" period	Earthquakes	Notes
Diffusion	Chemistry model (thermal, saturated phase; unsaturated phase disregarded)	Chemistry model System model	Consider altered geometry (diffusion pathways)	Consider varying ground water compositions Thermal transient in chemical model?
Sorption (including ion-exchange)	Chemistry model (thermal, saturated phase; unsaturated phase disregarded)	Chemistry model System model		
Alterations of impurities	Chemistry model (thermal, saturated phase; unsaturated phase disregarded)	Chemistry model System model		
Pore water speciation	Chemistry model (thermal, saturated phase; unsaturated phase disregarded)	Chemistry model System model		
Osmosis	System model (initial swelling)	Evaluation through comparison with empirical data System model		Handling of long-term intrusion of saline water
Montmorillonite transformation	Model calculations (thermal, saturated phase; unsaturated phase disregarded)	Model calculations		
Colloid release/ erosion	Neglected	Neglected if $[M^{2+}] > 1$ mM Otherwise modelled		
Radiation-induced transformations	Neglected	Neglected		
Radiolysis of pore water	Neglected	Neglected		
Microbial processes	Neglected if $\rho > 1{,}800$ kg/m^3, otherwise quantitative estimate of sulphate reduction	Neglected if density $> 1{,}800$ kg/m^3, otherwise quantitative estimate of sulphate reduction		

Failed canister

	Resaturation/ "thermal" period	Long-term after saturation and "thermal" period	Earthquakes	Notes
Gas transport/ dissolution	Irrelevant	Quantitative estimate based on empirical data		
Colloid transport	Irrelevant	Neglected if density $< 1{,}650$ kg/m^3, otherwise bounding calculation		
Speciation of radionuclides	Irrelevant	Assumptions based on empirical data		
Transport of radionuclides in water phase	Irrelevant	COMP23 Analytic		
Transport of radionuclides in gas phase	Irrelevant	Quantitative estimate based on empirical data		

The information in the table can be summarised as follows:

For the initial saturation phase, the peak canister and buffer temperatures and the THM evolution as the buffer saturates need to be quantified. Modelling of the thermal evolution of the entire near field will be performed with the near field system evolution model to evaluate peak canister and buffer temperatures. Coupled THM modelling of the buffer will be performed to elucidate the hydraulic evolution for different hydraulic conditions in the bedrock. The swelling at the end of the saturation phase is addressed by both the system model and the THM model, where the former can be used for rapid evaluations of the final result of the swelling for a number of input data combinations, including osmosis effects due to intruding saline water and the latter could simulate the pathway to the final result.

The chemical evolution during the thermal phase of elevated and varying temperature in the buffer will be addressed by the chemistry model.

Most other processes are neglected during the early saturation and thermal phases.

The long-term chemical evolution following the thermal phase will be addressed by both the chemistry model and the system model and for the varying boundary conditions expected as a result of climate change etc. The former model provides a spatially resolved result and involves more chemical reactions whereas the latter can be used for rapid evaluations for a number of input data combinations. Montmorillonite transformation is handled by separate modelling. Erosion due to dilute intruding groundwater during glacial conditions must be addressed if the hydrogeochemical analyses imply that ionic strengths below the given criterion cannot be excluded. Colloidal release needs to be modelled accordingly.

The effects of the chemical evolution on key properties like swelling pressure and hydraulic conductivity will be evaluated using empirical relationships. A number of issues related to mass redistribution in the buffer need to be evaluated for the long-term evolution.

In the case of a canister failure, the release of gas from the corroding cast iron canister insert will be handled by quantitative estimates based on experimental studies of gas transport through bentonite. Diffusion of radionuclides through the buffer is calculated with radio-nuclide speciations, necessary for the selection of diffusion and sorption data, estimated on the basis of experimental data. Transport of fuel colloids through the bentonite is neglected if the buffer density exceeds a specified value, otherwise the effect of this process on dose consequences is estimated by a bounding calculation case.

6   Safety functions and function indicators

6.1   Introduction

As mentioned earlier, the primary safety function of the KBS-3 concept 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 of primary importance throughout the assessment. It should be noted that the isolation function is more prominent in the KBS-3 concept than in many other repository concepts for spent nuclear fuel or high level waste e.g. /Nagra, 2002; ONDRAF/NIRAS, 2001/. This is also reflected in the methodology and structure of the safety assessment, which focuses to a comparatively large extent on the isolating capacity of the repository.

6.1.1   Function indicators

The overall criterion for evaluating repository safety is the risk criterion issued by SSI, which states 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". This is a "top level" criterion which requires input from numerous analyses on lower levels, and where the final risk calculation is the integrated result of various model evaluations using a large set of input data.

In order to break down the problem and evaluate and understand the safety functions in a more detailed and quantitative manner, a detailed operational definition of the safety functions is required. In principle, the functions need to be expressed as measurable or calculable quantities or barrier conditions.

The problem is different from safety evaluations of many other technical/industrial systems in an important sense: The performance of the repository system or parts thereof do not, in general, change in discrete steps, as opposed to e.g. the case of a pump or a power system that could be characterised as either functioning or not. The repository system will evolve continuously and in many respects there will be no sharp distinction between acceptable performance and a failed system on a sub-system level or regarding detailed barrier features. Nevertheless, as will be demonstrated in this chapter, there are some crucial barrier properties on which quantitative limits can be put.

Regarding isolation, an obvious condition is the requirement that the copper canister should nowhere have a penetrating defect, i.e. there should, over the entire surface of the canister, be a non-zero copper thickness. In addition to this direct measure of isolation performance, a number of quantitative supplementary criteria can also be defined. These relate, for example, to the peak temperature on the canister surface and to requirements on buffer density and buffer swelling pressure giving favourable buffer properties for maintaining isolation. Most of them determine whether certain potentially detrimental processes can be excluded from the assessment. An example is that the buffer should be homogeneous with a density higher than 1,800 kg/m^3 in order to be able to exclude microbial activity in the buffer.

Factors like the buffer density are referred to as *function indicators.*[5] The quantitative criteria that imply whether the desired function is provided or not are called *function indicator criteria*. A set of function indicators with quantitative criteria is developed in section 6.3. Again, it is emphasised that the breaching of a function indicator criterion does not mean that the repository is unsafe, but rather that more elaborate analyses and data are needed in order to evaluate safety.

There are many factors which are important for repository performance but on which no limit for acceptable performance can be given. The groundwater concentrations of canister corroding agents or agents detrimental to the buffer are examples of this kind of factor related to isolation. Usually, they enter in more complex analyses where a number of parameters together determine, e.g. the corrosion rate of the canister. Most of the factors determining retardation are of this nature. This matter is further elaborated in section 6.4. In that section, also alternatives to the "top level" dose criterion are discussed. The alternative criteria are in general directly related to releases from the geosphere and thereby independent of assumptions regarding the biosphere and human habits.

6.2   Approach to dilution

Dilution is not seen as a safety function for the KBS-3 system. The main reasons for this are that dilution essentially can not be controlled by the design of the repository and only to some extent by site selection. Nevertheless, dilution will play an essential role in a realistic estimate of the consequences of a potential release from the repository. A coastal site can be expected to be submerged for extended periods of time and dilution of potential releases in sea water could drastically lower the calculated consequences. Also for present conditions, hydraulic gradients at the coastal sites under consideration may imply that potential releases would occur to the Baltic Sea for extended periods of time.

The future climate evolution, which will be a determining factor for dilution, is however highly uncertain. Although marine discharges can be predicted to exist intermittently, these will also with high likelihood be interrupted by periods during which releases occur to terrestrial ecosystems, or when earlier releases accumulated in sea sediments will be present in terrestrial systems due to land uplift. These latter conditions will likely be associated with the peak risks as the contaminated terrestrial systems could be used for, e.g. agriculture. The compliance discussion for a repository will have to be based on these unfavourable but, in a long-term perspective, not unlikely conditions where dilution in large water bodies will not occur.

Inevitably, dilution will have to be included in quantitative assessments of wells but also in this case many of the data will have to be generic and will not be amenable to control by repository design or site considerations.

A related phenomenon concerns the fact that the repository is distributed in space and that the host rock and the near-surface hydrological systems will redistribute potential releases from the repository before they cause human exposure. These phenomena will have to be included in the quantification of consequences of potential releases. The redistribution effects can not however be straightforwardly described as positive or negative.

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[5] In choosing the term "function indicator", it was observed that the two terms "performance indicator" and "safety indicator" in this context normally refer to releases of radionuclide or resulting dose consequences /EU, 2002/. Those terms were thus avoided.

6.3   Function indicators for isolation

The criteria presented below are often selected from a cautious perspective and further studies and engineering development may show that some of the criteria presented here may be relaxed. Furthermore, additional criteria may be added.

6.3.1   Canister

The canister integrity can be threatened either mechanically or chemically. An obvious requirement regarding canister integrity is that the copper shell of the canisters should not be penetrated. This can be expressed such that the minimum copper thickness taken over the entire canister surface shall be larger than zero:

$$d_{\min}^{Cu} > 0$$

As long as this criterion is strictly fulfilled for all canisters, isolation is complete and no releases occur.

Mechanical loads on the canister can be complex and for some load situations it is not straightforward to define a single criterion to which a load can be compared in order to determine if integrity is maintained. However, for the isostatic pressure on the cast iron insert, it is possible to formulate such a criterion.

Tensile tests of the insert material have indicated a large spread of the failure strain for tensile specimens /Andersson et al, 2004b/. Fractographic and radiographic investigations of the tensile specimens indicate that the low failure strain and its scatter are caused by a combination of casting defects and microstructural inhomogenities. These findings suggest that the same kind of defects would also induce failure of a large component of the same material. The probability of having a critical defect increases with the material volume and as a consequence the failure load decreases. A mock-up representative canister was therefore designed and loaded to high hydrostatic pressure to determine its failure load and the failure mechanism. To have a rigorous assessment of the size effect, the insert in the pressure test mock-up came from the same full-scale insert used in the detailed material characterization tests.

The pressure test mock-up was designed to be as representative as possible for the copper/cast iron canister with the restriction that its weight did not exceed 5 tons due to size limitations of the available isostatic press. Figure 6-1 shows the 700 mm long part of the tested insert together with the copper tube and the two 48 mm thick steel plates positioned between the insert and the two copper lids (not shown in the picture). Except for its length, all dimensions of the mock-up corresponded to those of a full-scale canister.

Four load-cycles were performed with maximum pressures of 40, 70, 100 and 130 MPa respectively. After the 40 MPa load-cycle a deformation from 0.5 to 2 mm was measured. These values correspond to the closure of the 2 mm gap between the insert and the tube. The residual deformation after the 70 MPa was almost identical to that measured for the 40 MPa load-cycle. After the 100 MPa load-cycle, the measured residual deflection was almost 5 mm, which suggested that the insert had undergone some plastic deformation. In the final 130 MPa load-cycle, the maximum residual radial deflection was measured to 20 mm. The mock-up was however still leak-tight.

The fact that the mock-up did not fail even at the relatively high loads indicates that casting defects are less critical for the integrity of the canister than expected.

Figure 6-1. *Part of cast iron insert and copper canister for pressure test.*

The test result indicates that the insert for BWR fuel withstands an isostatic pressure of around 120 MPa. (For comparison, the hydrostatic pressure at 500 m depth is 5 MPa, and the atmospheric pressure around 0.1 MPa.) The test was made on an insert that did not meet the manufacturing requirements, and could be regarded as a first, cautious estimate of the isostatic collapse pressure of the cast iron insert. The isostatic collapse pressure will vary between canisters and is to be further evaluated by both full-scale tests and ongoing probabilistic strength calculations.

Pending a better founded numerical value of the isostatic collapse pressure, the function indicator criterion is formulated such that the isostatic pressure in the buffer/canister interface should be smaller than the isostatic collapse pressure of the canister insert.

$$P_{Isostatic}^{Canister\,/\,Buffer\,interface} < P_{Isostatic\,collapse}^{Can}$$

Further, the temperature of the canister surface should be restricted so that at the time when water comes in contact with the canister, boiling will not occur. Boiling may result in salt deposits on the canister surface and such deposits could cause corrosion in a way that is difficult to analyse quantitatively. Therefore

$$T^{Canister} < 100°C$$

where $T^{Canister}$ is to be interpreted as the temperature at water contact. This is essentially achieved by limiting the initial activity of the fuel in each canister and by adapting the layout of the repository. No credit is taken for the effect of increased hydrostatic pressure on the temperature, since it can not be guaranteed that this has developed when the peak temperature occurs. Nor is any credit taken for an increased boiling point due to solutes in the contacting water since no minimum solute concentration can be guaranteed.

6.3.2 Buffer

An important function of the buffer is to limit transport of dissolved copper corroding agents to the canister and potential radionuclide releases from the canister. The material of the buffer surrounding the canister has been chosen so as to prevent advective transport in the deposition hole. A guideline is that the hydraulic conductivity of the buffer should fulfil /SKB, 2004b/.

$$k^{Buff} < 10^{-12} \text{ m/s}$$

The requirement refers to all parts of the buffer, i.e. the variability within the buffer must be such that the requirement is everywhere fulfilled.

For any reasonable hydraulic gradient in the repository, this condition will mean that transport in the buffer will be dominated by diffusion. The hydraulic conductivity is strongly related to the density of the buffer, to the adsorbed ionic species and to the ionic strength of the surrounding groundwater.

The buffer homogeneity is provided partially by the fact that the buffer is made of a clay material that swells when water saturated. A swelling pressure criterion is therefore formulated /SKB, 2004b/:

$$P_{Swell}^{Buff} > 1 \text{ MPa}$$

The requirement refers to all parts of the buffer, i.e. the variability within the buffer must be such that the requirement is everywhere fulfilled.

The buffer temperature should not exceed 100°C in order to limit chemical alterations /SKB, 2004b/. The peak buffer temperature will however always be lower than the peak canister temperature, so that this criterion is automatically fulfilled if the criterion on canister temperature is fulfilled, with the possible exception of canister temperatures exceeding 100°C prior to water contact.

$$T^{Buffer} < 100°C$$

If the buffer freezes, its properties will change drastically. Therefore, the buffer temperature should not fall below the freezing temperature of a water-saturated buffer. The minimum buffer temperature will occur at the buffer rock interface, therefore the limit is applied to this boundary. Note that the entire repository needs to be considered, i.e. all deposition hole positions. As the heat released from the canisters may, depending on the elapsed time after closure, play a role, it is necessary to consider deposition holes at the edge of the deposition area where the temperature will be the lowest. The criterion is the following /SKB, 2004b/:

$$T^{Buffer} > 0°C$$

A number of important buffer properties are related to the buffer density. It affects the thermal conductivity (of importance for the canister temperature), the swelling pressure and the hydraulic conductivity. These influences of density are thus handled by the requirements set out above.

The buffer should furthermore be dense enough to prevent bacteria from surviving in it, leading to the criterion /SKB, 2004b/.

$$\rho_{Bulk}^{Buff} > 1800 \text{ kg/m}^3 \text{ (Exclude microbial activity)}.$$

The requirement refers to all parts of the buffer, i.e. the variability within the buffer must be such that the requirement is everywhere fulfilled.

Also, the density should be sufficient to prevent the canister from sinking in the deposition hole. Currently, this phenomenon has however only been studied for buffer densities of 2,000 kg/m³. The following general formulation is therefore used pending a quantitative criterion:

$$\rho_{Bulk}^{Buff} > \rho_{Sink} \quad \text{(Ensure carrying capacity)}$$

Another function of the buffer is to protect the canister from rock movements, in particular as a consequence of rock shear movements. Also here the buffer density plays a critical role, and the following criterion has been determined:

$$\rho_{Bulk}^{Buff} < 2100 \text{ kg/m}^3 \text{ (Ensure protection of canister against rock shear)}$$

This is further discussed in section 10.1.1. A related phenomenon concerns the possible liquefaction of the buffer in the event of an earthquake. Although the occurrence of this phenomenon is related to the buffer density, a quantitative criterion cannot be formulated based on current understanding, see further section 10.1.2.

Furthermore, the buffer should allow gas produced within a potentially damaged canister to escape. Again, the gas transport properties are related to the buffer density but quantitative limits for favourable buffer function in this respect cannot be formulated. The buffer issues related to liquefaction and gas transport must be dealt with in detailed analyses of the phenomena in the safety assessment.

The concentration of canister corroding agents in the buffer should be low. Apart from unavoidable initial concentrations of oxygen, the pyrite concentration could pose a long-term problem, as pyrite, if not oxidised by initially present or intruding oxygen, will be transformed to sulphide, a canister corroding agent. There is however no absolute criterion placed on this concentration; the corrosion effects of measured concentrations will have to be evaluated quantitatively. As pyrite could also act as a scavenger for any initially present or intruding oxygen in the repository, the evaluation of the effects of the presence of this material in the buffer is complex.

6.3.3 Backfill in deposition tunnels

The buffer swelling will cause an upward expansion with a resulting compression of the backfill. This needs to be counteracted by the backfill in order to keep the buffer density within the desired limits. A requirement of the backfill, consisting of a 30/70 mixture of bentonite and crushed rock, is therefore that its compressibility, M, should fulfil

$$M^{Backfill} > 10 \text{ MPa}$$

The basis for this criterion will be documented in final SR-Can Process report.

For a backfill consisting only of clay, the swelling pressure is the relevant property. A criterion has not yet been formulated.

As for the buffer, there is also a requirement that the backfill in the deposition tunnels should not freeze, thus:

$$T^{Backfill} > 0°C$$

The concentration of canister corroding agents in the backfill should be low. As for the buffer, a certain amount of initially entrapped oxygen is unavoidable in the backfill, and the pyrite concentration could pose a long-term problem. There is however no specific constraint placed on this concentration; the corrosive effects of the measured concentrations will have to be evaluated quantitatively.

6.3.4 Geosphere

Most aspects of the host rock functions cannot be captured by simple criteria, but require more complex analyses where the combined effect of a number of factors determine the outcome. This is discussed in a report on geoscientific suitability indicators and criteria for siting and site evaluation /Andersson et al, 2000/.

In the following, some critical constraints on groundwater composition useful in the safety assessment are provided.

Groundwater properties

Several characteristics of the groundwater composition are essential for providing a chemically stable environment for the repository. A fundamental requirement is that of reducing conditions. A necessary condition is the absence of dissolved oxygen, because any evidence of its presence would indicate oxidising conditions. Other indicators of redox conditions, like negative redox potential, are not always well defined and thus less useful as a basis. Nevertheless, redox potential is a measure of the availability of all kinetically active oxidising species.

This requirement ensures that canister corrosion due to oxygen dissolved in the groundwater is avoided. Furthermore, should a canister be penetrated, reducing conditions are essential to ensure a low dissolution rate of the fuel matrix, to ensure favourable solubilities of several radioelements and, for some elements, also redox states favourable for sorption in buffer, backfill and host rock.

In addition to dissolved O_2, other oxidated groundwater components could be considered, for example nitrate and sulphate. However, while dissolved oxygen may react directly e.g. with the copper canister or the spent fuel, nitrate and sulphate can only be reactive by the intervention of microbes, which require both nutrients and reduced species such as dissolved hydrogen, methane or organic matter in order to be able to reduce nitrate or sulphate.

The salinity of the groundwater should neither be too high, nor too low. The total concentration of divalent cations should exceed 1 mM in order to avoid chemical erosion of buffer and backfill, hence /SKB, 2004b/:

$$\Sigma[M^{2+}]^{GW} > 10^{-3} \text{ M}$$

Groundwaters of high ionic strengths would have a negative impact on the buffer and backfill properties, in particular on the backfill swelling pressure and hydraulic conductivity. In general, ionic strengths corresponding to NaCl concentrations of approximately 35 g/l are an upper limit for maintaining backfill properties whereas the corresponding limit for the buffer is around 100 g/l. The limit of tolerable ionic strength is however highly dependent on the material properties of these components and since, in particular for the backfill, alternative materials are to be evaluated in the assessment, no specific criterion is given here. Rather, the effects of groundwaters of different ionic strengths on the different materials of interest are analysed in section 7.7.

Regarding canister corrosion, there should be low groundwater concentrations of other canister corroding agents, in particular sulphide, HS^-. For sulphide to pose a problem, considerably higher concentrations than have ever been observed in Swedish groundwaters would be required. The quantitative extent of such corrosion also depends on the groundwater flow around the deposition hole and on the transport properties of fractures intersecting the hole.

A further requirement is that the combination of low pH values and high chloride concentrations should be avoided in order to exclude chloride corrosion of the canister. In quantitative terms, the requirement is assigned a preliminary criterion

$pH^{GW} > 4$ or $[Cl^-]^{GW} < 3M$

The basis for this criterion will be documented in the final SR-Can Process report.

Furthermore, low groundwater concentrations of agents detrimental to long-term stability of the buffer and backfill, in particular potassium and iron, are desirable /SKB, 2004b/.

Regarding pH, a criterion can be formulated from the point of view of buffer and backfill stability /SKB, 2004b/:

$pH^{GW} < 11$

This is fulfilled for any natural groundwater in Sweden. However, construction and stray materials in the repository, in particular concrete, could contaminate the groundwater such that high pH values are reached.

In addition, the concentration of natural colloids should be low to avoid transport of radionuclides mediated by colloids. The stability of colloids is largely decreased if the concentration of divalent cations exceeds 1 mM, a condition that, as discussed above, is also required for the stability of the buffer and backfill.

Mechanical erosion (piping) of the buffer and in backfill during and shortly after deposition is a possible concern. It may be possible to formulate a criterion on the flow rate required to prevent piping of the buffer and backfill.

Mechanically stable environment

The mechanical stability of the host rock cannot, in most respects, be simply evaluated. Two main reasons for mechanical failure of the canisters can be identified. These are isostatic collapse and failure due to earthquakes causing secondary movements in fractures intersecting deposition holes. A strongly contributing factor to the former could be high groundwater pressures such as might occur during a glaciation. Addressing the latter failure mode requires a complex evaluation of shear movements for a range of mechanical load situations. For assessing the consequences of such movements, a limit on a maximally allowed shear displacement of a fracture intersecting a deposition hole can be formulated for canister integrity to be maintained, see further section 10.1.1:

$d_{shear} < 10$ cm.

6.4   Function indicators for retardation

Several of the above criteria are related only to the isolation properties of the system. This is e.g. the case for the minimum copper coverage, the isostatic collapse load, the peak canister temperature, etc.

However, should a canister be breached, a number of additional phenomena and processes become relevant. The further evolution of a failed canister will depend on the geometry of the defect in the copper shell which will determine the influx of water to the canister interior, the corrosion of the cast iron insert as it is contacted by intruding water and the fate of the hydrogen gas generated due to the corrosion. Furthermore, alterations in the mechanical properties of the corroding cast iron insert and the copper canister will potentially lead to enlargement of the initial damage, collapse of the insert and establishment of a continuous water pathway between the fuel and the canister exterior. All these processes are discussed in chapter 12.

Should release of radionuclides occur, release limitation and retardation is provided by

• the slow dissolution of the ceramic waste form,

• the low solubilities of several of the most hazardous radionuclides,

• transport resistances in the fuel cladding and the damaged canister,

• slow transport in the buffer (avoiding advection and providing sorption),

• transport resistances between the buffer and fractures intersecting the deposition hole,

• slow transport in the backfill (limiting advection and providing sorption) and

• slow transport in particular in the near-field host rock (limited groundwater flow, diffusion into the rock matrix where also sorption is provided).

Some of these release limiting and retarding phenomena are such that they can be evaluated through comparisons to criteria. This is, e.g. the case for the avoidance of advective transport in the buffer (the same criteria as for the corresponding functions above). The backfill should not be a preferred pathway for radionuclide transport. For this to be fulfilled the backfill should have a certain swelling pressure to assure tightness and homogeneity and a limited hydraulic conductivity. The quantitative criteria are the following:

$$P_{Swell}^{Backfill} > 0.1 \text{ MPa}$$

and

$$k^{Backfill} < 10^{-10} \text{ m/s}$$

The basis for these criteria will be further analysed and documented in final SR-Can Process report.

The buffer should furthermore be dense enough to prevent transport of colloids through it. This requirement is put on the buffer so that fuel colloids should not be able to escape a defective canister. Thereby, the releases of several key radionuclides will be limited by their solubilities. This requirement has led to the following criterion /SKB, 2004b/.

$$\rho_{Bulk}^{Buff} > 1650 \text{ kg/m}^3 \text{ (Prevent colloid transport)}$$

Another quantitative and general criterion also mentioned above is that of reducing conditions which is of particular importance for maintaining a stable fuel matrix and low solubilities.

Most others properties relating to the retarding capacity of the system will change gradually and be present to some degree, requiring a more detailed and integrated evaluation where the total outcome can be compared to a dose or risk criterion.

Table 6-1 provides a list of key properties related to the release limiting and retarding factors mentioned above.

In section 7.9, input data to the radionuclide transport models are listed and a brief discussion on sensitivities of dose results to these data, based on earlier assessments, is provided.

The fuel properties and geometrical arrangement in the canister should further be such that criticality is avoided if water should enter a defective canister, but there is no meaningful simple criterion to use for such an evaluation. The issue has to be addressed in an integrated analysis.

The buffer should allow passage of gas formed by corrosion of the cast iron insert of a defective canister at a certain maximum gas pressure, but it is presently not possible to formulate a quantitative criterion, see further section 12.2.3.

6.4.1 Alternative safety indicators for retardation

The dose/risk safety indicator provides a measure of radiological impact on future man due to the existence of the repository. Several aspects of biosphere development are highly uncertain, even over a relatively short time perspective. The evaluation of safety will depend on a number of assumptions made in order to handle these uncertainties. It is therefore of interest to complement the dose/risk indicator with alternative indicators which do not require detailed assumptions about the biosphere or concerning 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 fluxes of radionuclides to the biosphere.

Table 6-1. Key properties related to release limitation or retardation.

Release limiting or retarding factor	Parameter
Slow dissolution of the ceramic waste form	Fuel dissolution rate
Low radionuclide solubilities	Solubilities of radio elements
Transport resistances in the fuel cladding and the damaged canister	Damage geometries
Slow transport in the buffer (avoiding advection and providing sorption)	Buffer hydraulic conductivities, diffusivities and sorption coefficients
Transport resistance between the buffer and fractures intersecting the deposition hole	Groundwater flow, (fracture geometry)
Slow transport in the backfill (limiting advection and providing sorption)	Backfill hydraulic conductivities, diffusivities and sorption coefficients
Slow transport in host rock (limited groundwater flow, matrix diffusion and sorption)	Transport resistance (F factor), diffusivities, sorption coefficients

A problem with alternative indicators is that there is, in general, no obvious criterion to which the calculated quantities can be compared. In some cases, calculation results can be compared to natural concentrations or fluxes at the site or elsewhere. Such criteria do however not provide points of reference for man-made radionuclides. That problem can be partly overcome by comparing naturally occurring sum concentrations/fluxes of α- and β-emitters to the corresponding repository induced quantities, or by comparing overall toxicities by scaling by dose per unit intake values.

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 release constraints

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

These 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 α-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 that 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 1,000 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 release constraints have been developed.

Other studies

An SKI/SSI study /Miller et al, 2002/ compiled from the published literature a substantial database of elemental abundances in natural materials and, using these data, calculated 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.

Implications for SR-Can

As an alternative indicator, the Finnish activity constraints will be used in SR-Can. Possibly, measured concentrations of naturally occurring radionuclides in ecosystems at the candidate or other sites will also be used.

6.5 Summary, key issues to evaluate over time

The material presented above aims at defining in qualitative and quantitative terms a number of criteria that indicate safe performance of the repository. These function indicator criteria are mainly related to isolation and to the engineered parts of the repository. The idea is to compare calculated results of barrier evolution at later stages of the analysis to the criteria, and so obtain a quantitative evaluation of safety performance, both overall and by component.

It is emphasised that the criteria are an aid in determining whether safety is maintained. If the criteria are fulfilled, the safety evaluation is facilitated, but fulfilment of criteria alone (other than that of minimum copper coverage) is not a guarantee that the overall risk criterion is fulfilled. On the other hand, compliance with the risk criterion could well be compatible with a violation of one or several of the criteria. A violation would be an implication of caution; further analyses could be required in order to determine the consequences on a sub-system level or a system level. A violated condition could be a reason for including the situation leading to the violation as a stand-alone scenario or as a variant of another scenario.

Table 6-2 summarises the function indicators and the criteria they should fulfil. The table thus points to a number of key properties that need to be evaluated as the repository system evolves in time. As is also evident from the presentation in this chapter, there are aspects of the repository evolution and barrier performance that can not be readily captured by a simple comparison to a criterion.

Table 6-2. Summary of the function indicators and the criteria they should fulfil.

Function indicator	Criterion	Rationale
Canister		
Minimum copper thickness	$d_{min}^{Cu} > 0$	Ensure isolation
Isostatic pressure on canister	$P_{Isostatic}^{Canister} < P_{Isostatic\ collapse}^{Can}$	Avoid isostatic collapse
Maximum canister temperature at water contact	$T^{Canister} < 100°C$	Avoid boiling on surface and thus salt deposits
Buffer		
Bulk hydraulic conductivity	$k^{Buff} < 10^{-12}$ m/s	Avoid advective transport in buffer
Swelling pressure	$P_{Swell}^{Buff} > 1$ MPa	Ensure tightness, self sealing
Maximum temperature	$T^{Buffer} < 100°C$	Ensure buffer stability
Minimum temperature	$T^{Buffer} > 0°C$	Avoid freezing
Buffer density around entire canister	$\rho_{Bulk}^{Buff} > \rho_{Sink}$ kg/m³	Avoid canister sinking (criterion to be determined)
Buffer density around entire canister	$\rho_{Bulk}^{Buff} > 1,800$ kg/m³	Exclude microbial activity
Buffer density around entire canister	$\rho_{Bulk}^{Buff} > 1,650$ kg/m³	Prevent colloid transport through buffer
Buffer density around entire canister	$\rho_{Bulk}^{Buff} < 2,100$ kg/m³	Ensure protection of canister against rock shear
Backfill in deposition tunnels		
Compressibility	$M^{Backfill} > 10$ MPa	Limit buffer expansion
Hydraulic conductivity	$k^{Backfill} < 10^{-10}$ m/s	Limit advective transport
Swelling pressure	$P_{Swell}^{Backfill} > 0.1$ MPa	Ensure homogeneity
Minimum temperature	$T^{Backfill} > 0°C$	Avoid freezing
Rock		
Redox conditions	No dissolved oxygen	The presence of measurable O_2 would imply oxidising conditions
Minimum ionic strength	$\Sigma[M^{2+}]^{GW} > 10^{-3}$ M (Total divalent cation conc.)	Avoid buffer erosion
Maximum chloride concentration or minimum pH	$pH^{GW} > 4$ or $[Cl^-]^{GW} < 3$ M	Avoid chloride corrosion of canister
Limited alkalinity	$pH^{GW} < 11$	Avoid dissolution of buffer smectite
Limited salinity	Buffer: [NaCl] < 100 g/l	Avoid detrimental effects, in particular on buffer and backfill swelling pressures
	Backfill: [NaCl] < 35 g/l (Or other compositions of equivalent ionic strength)	
Limited concentration of detrimental agents for buffer and canister	Applies to HS^-, K^+ and Fe. The lower the better (no quantitative requirement)	Avoid canister sulphide corrosion, avoid illitisation (K^+) and chloritisation (Fe) of buffer and backfill
Limited rock shear at deposition holes	$d_{shear} < 10$ cm	Avoid canister failure due to rock shear at deposition holes

7 Preliminary long-term evaluation of function indicators

7.1 Introduction

7.1.1 General

In this chapter, preliminary analyses are made in order to demonstrate some basic traits of system evolution, focussing on an evaluation over time of the function indicators discussed in chapter 6.

The purposes of the analyses are to gain a basic understanding of crucial safety related issues early in the assessment, to identify critical input data for the assessment, to inform the preliminary scenario selection and to focus the detailed analyses to be performed in subsequent stages of the project.

Detailed aims are to

- Provide a basic understanding of how corrosion affects canister integrity over the assessment period, taking account of defects in the copper canister seals.

- Provide preliminary results on the isostatic loads to which the canister will be subject.

- Determine the peak canister and buffer temperatures.

- Demonstrate how the initial swelling of the buffer affects buffer density.

- Provide a basic understanding of the long-term buffer chemical evolution and the consequences the chemical alterations will have for important buffer properties like hydraulic conductivity and swelling pressure.

The two first points deal with two important potential threats to canister integrity. A third potential threat, rock shear movements at deposition holes, is considerably more complex to analyse and is discussed in chapter 10.

The role of the results of the preliminary analyses in the SR-Can final 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 may be left out in the final report.

7.1.2 Basic assumptions and premises for the analyses

The analyses focus on near-field evolution and primarily on aspects of importance for isolation. The initial state for the analyses is, in general, the reference initial state for the fuel and the engineered repository components as given in chapter 3. Thermal data and a representative groundwater composition from the Forsmark site will be used, whereas other site-specific conditions will not be considered. From the repository layout adapted to the Forsmark site, the repository depth and the canister and tunnel spacings will be used in the thermal calculations.

To understand chemical aspects of the near field evolution, e.g. canister corrosion, and buffer and backfill chemical alterations, a number of representative groundwater compositions for current and expected future conditions will be used. Table 7-1 shows the compositions that will be used.

Additional to groundwater compositions representative of current conditions at Forsmark and three other Swedish sites at repository depth, also saline waters encountered at 1,500 m depth at the Laxemar site and at the Olkiluoto site in Finland are included. These are generic examples of groundwater compositions that the repository could be subject to due to upconing (extraction of deeper groundwaters caused by the drainage during repository construction and operation).

As discussed in the SR-Can planning report /SKB, 2003a/, the varying groundwater composition during a glacial cycle may, in many respects, be bounded by two extreme groundwater types: the "saline ice-front" and the "non-saline melting zone". The saline water at the ice front may occur as a consequence of hydraulic up-lift effects. At the other extreme, dilute meltwaters may penetrate the geosphere under certain circumstances as a consequence of high hydraulic pressures beneath the ice-sheet. Water compositions representative of these two situations will therefore also be used in the chemical analyses.

Groundwater compositions representing a cement leachate and sea water are also included in the table.

There will be no attempt to analyse the climatic evolution in the preliminary analyses. Rather, key results from previous studies will be used when relevant. In addition to the groundwater compositions mentioned above, also the mechanical, isostatic effects of applying a load corresponding to a glacial thickness of about 3,500 metres and the thermal effects of a permafrost depth of about 400 metres will be considered. Both these figures were regarded as extreme values in the safety assessment SR 97 /SKB, 1999a/.

Table 7-1. Groundwater compositions. All concentrations except pH are total concentration in kmoles/m³.

	Forsmark	Äspö	Finnsjön	Gideå	Grimsel: interacted glacial meltwater	"Most saline" groundwater at Laxemar	"Most saline" groundwater at Olkiluoto	Cement	Ocean water	Maximum salinity from glacial upcoming
pH	7.2	7.7	7.9	9.3	9.6	7.9	7.0	12.5	8.15	7.9
Na	0.089	0.091	0.012	0.0046	0.00069	0.349	0.415	0.002	0.469	0.25
Ca	0.023	0.047	0.0035	0.00052	0.00014	0.464	0.449	0.018	0.0103	0.27
Mg	0.0093	0.0017	0.0007	0.000045	0.0000006	0.0001	0.0053	<0.0001	0.053	0.0001
K	0.0009	0.0002	0.00005	0.00005	0.000005	0.0007	0.0007	0.0057	0.01	0.0005
Fe(II)	33×10^{-6}	4×10^{-6}	32×10^{-6}	0.9×10^{-6}	0.003×10^{-6}	8×10^{-6}	60×10^{-6}	$\leq10\times10^{-6}$	0.04×10^{-6}	2×10^{-6}
HCO_3^-	0.0022	0.00016	0.0046	0.00023	0.00045	0.00010	0.00014	≈0	0.0021	0.00015
Cl⁻	0.153	0.181	0.0157	0.0050	0.00016	1.283	1.275	≈0	0.546	0.82
SO_4^{2-}	0.0052	0.0058	0.00051	0.000001	0.00006	0.009	0.00009	≈0	0.0282	0.01
HS⁻	≈0	5×10^{-6}	–	$<3\times10^{-7}$	–	$<3\times10^{-7}$	$<1.6\times10^{-7}$	≈0	-	$<3\times10^{-7}$
O_2 fugacity (bar)	$<<10^{-20}$	$<<10^{-20}$	$<<10^{-20}$	$<<10^{-20}$	$<10^{-0.17}$ (a)	$<<10^{-20}$	$<<10^{-20}$	$≈10^{-20}$	$10^{-0.7}$	$<<10^{-20}$
Ionic strength (kmol/m³)	0.19	0.24	0.025	0.006	0.0013	1.75	1.76	0.057	0.65	1.09
TDS (g/L)	9.32	11.1	1.33	0.33	0.08	73.7	73.4	1.63	35.1	47.2
Reference	Sicada database	/Laaksoharju et al, 1998/	/Laaksoharju et al, 1998/	/Laaksoharju et al, 1998/	/Hoehn et al, 1998/	/Laaksoharju et al, 1995/	/Pitkänen et al, 2003/	/Engkvist et al, 1996; Berner 1987/	/Stumm and Morgan, 1996/	
Notes	Borehole KFM02A; depth=512 m	repository depth	repository depth	repository depth	O_2 fugacity only to illustrate effect	depth ≈1,500 m. TDS ≈7%	See also /Pitkänen et al, 1999/ depth=863 m; sample 42			Laxemar water at 1,350 m

Notes:

(a) Oxygen fugacity for glacial conditions: The maximum content is 1.4×10^{-3} M for glacial meltwater at 0°C. The corresponding maximum fugacity at 0°C is 0.67 bar /Ahonen and Vieno, 1994/. In Grimsel the O_2 content is less than 3×10^{-8} M.

7.1.3   Analysis tools and methods

A main tool for the analysis will be a newly developed integrated near-field evolution model /Hedin, 2004a/. This model consists of a number of integrated sub-models that each mimics a model that was used in the SR 97 assessment. The sub-models of interest here are:

- The thermal sub-model that calculates the temperature as a function of time in the fuel rods, the cast iron insert, the copper canister, the buffer (in all cases at mid-height where the peak temperature occurs) and at an arbitrary point in the host rock.

- The copper corrosion sub-model that handles the dominating corrosion modes due to impurities present in the buffer initially and in the groundwater.

- The buffer rheology sub-model that calculates the redistribution of buffer mass due to the initial buffer swelling, including osmotic effects caused by intruding saline groundwater.

- The buffer chemistry sub-model that handles ion exchange processes and dissolution of minerals in the buffer.

Also, there is a source term sub-model that handles the radioactive inventory as a function of time, including chain decay, and a canister internal evolution sub-model that deals with the processes inside the canister as a consequence of water intrusion should the copper shell be damaged. The two latter are, however, not used for the preliminary analyses. (The heat production for the thermal model is obtained from a curve fit to SR 97 results rather than from source term model.) The set of models together comprising the near field evolution model are shown schematically in Figure 7-1.

The sub-models have been benchmarked /Hedin, 2004a/ to the "process models" that they mimic with discrepancies that are small and in most cases negligible for the purposes of the calculations to be presented below. It is important to note that the sub-models are in general not conceptually simplified compared to the corresponding process models. In most cases, the same equations are solved. The method for solution is though often simplified and tailored to the problem at hand, rather than utilising a more time-consuming general purpose code. This is the case for the buffer chemistry and thermal sub-models. Also, in some cases the models have been developed to focus on quantities and aspects of the evolution of direct interest for safety, whereas the process models may provide more detailed information on aspects of secondary importance to safety. This applies to the buffer rheology sub-model where the final state of the buffer after water saturation and swelling is calculated whereas the corresponding process model handles the saturation process in detail. In other cases, the "process models" are in themselves mathematically quite simple and have thus been directly adopted in the sub-model representation. This is the case for the copper corrosion sub-model, the source term model and the routine for calculating osmotic effects on swelling pressure in the buffer rheology sub-model.

In addition to near-field evolution studies, additional analyses of the results obtained with the model will be carried out by comparisons with recently obtained experimental data concerning buffer hydraulic conductivity and swelling pressure for a range of densities and compositions of intruding groundwater. Also, some important results from the SR 97 analysis will be used.

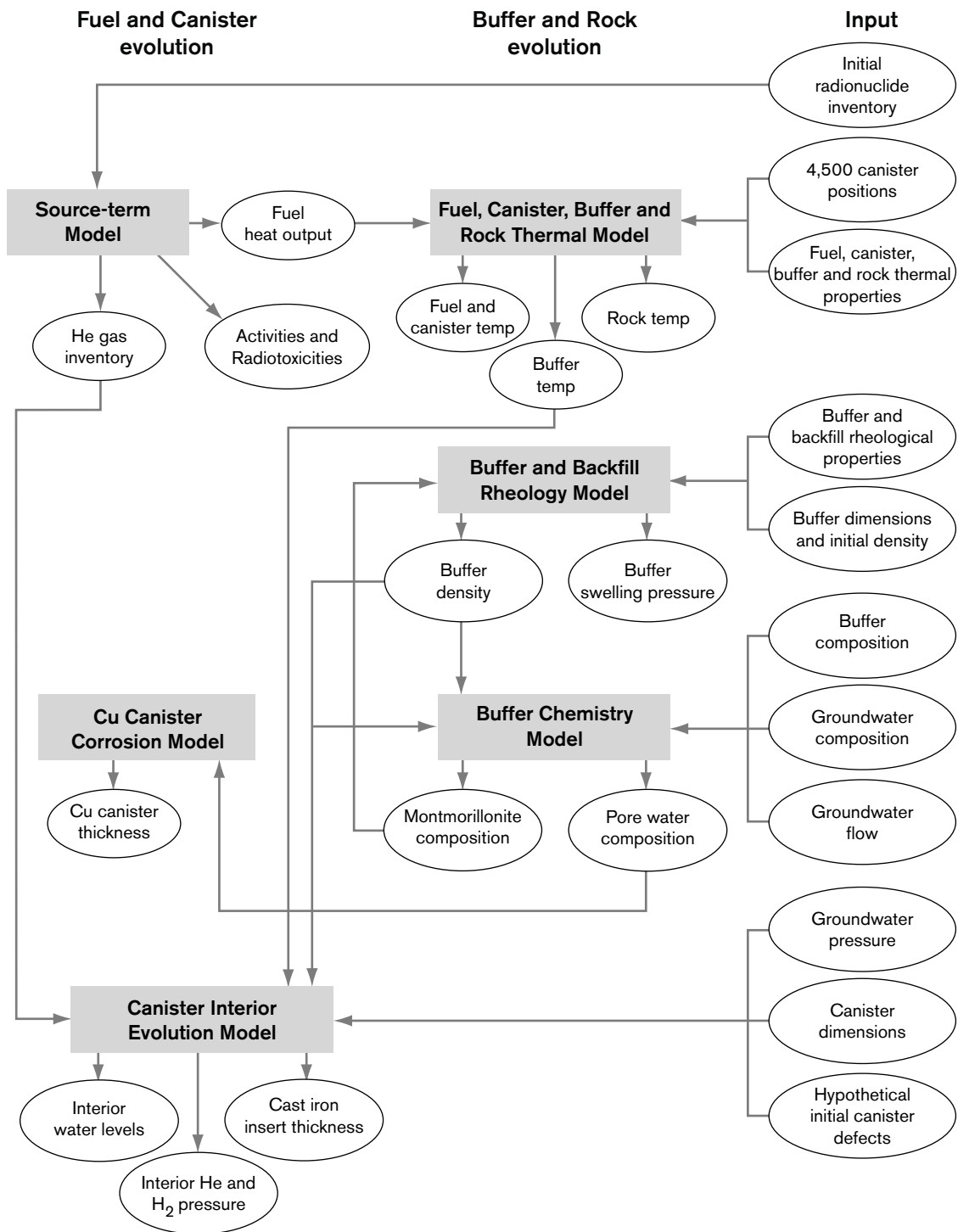**Figure 7-1.** *The near-field evolution model with sub-models represented as rectangles; input data and time-dependent calculation results as ellipses. Several dependencies between sub-models are not handled automatically in the present version.*

7.2 Canister minimum copper thickness

The copper shell of the canisters will be slowly corroded in the deep repository. A number of potential corrosion modes have been identified and discussed, and several of these have been rejected as insignificant or negligible, see, e.g. the SR 97 Process report /SKB, 1999b/ and /King et al, 2001/. Rejected corrosion modes include pitting corrosion under reducing conditions, stress corrosion cracking and corrosion caused by radiolysis. A renewed evaluation will be made in the final version of the SR-Can Process report (the Interim Process report does not treat canister-related processes). A few corrosion processes do, however, require a more detailed quantification in the safety assessment. These comprise corrosion due to oxygen initially entrapped in deposition holes and the deposition tunnels and corrosion due to sulphide initially in the buffer material and in the groundwater. An additional issue is the possibility of penetration of oxygenated water during glacial conditions. Furthermore, should the state of the buffer be altered in such a way that microbes could be active in the buffer, microbially mediated corrosion must also be considered.

In the following, deterministic modelling of corrosion of the 50 mm thick canister due to corroding agents in the buffer and groundwater is described in section 7.2.1. This exercise was undertaken as an introduction, for the sake of completeness. It has been demonstrated several times in previous safety assessments that a 50 mm thick copper canister will maintain its integrity despite corrosion for extremely long times.

In section 7.2.2, corrosion of weld defects is modelled probabilistically for the ensemble of 4,500 canisters in the repository, yielding an estimate of the number of penetrated canisters as a function of time. The aim of this exercise was to obtain a first numerical estimate of this quantity which is then to be propagated to the radionuclide transport calculations.

Finally, the effects of corrosion due to oxygenated groundwater have been modelled without attempting to evaluate the likelihood or duration of such conditions in the deep repository. The aim of these calculations was to understand the magnitude of the potential problem from a consequence perspective.

The canister corrosion sub-model of the near-field evolution model /Hedin, 2004a/ is used in these calculations. This sub-model is based on the type of analytical expressions used in earlier assessments /Neretnieks, 1986a,b/, utilising the concept of equivalent flow rate. The corrosion is determined solely by transport resistances and mass balance considerations. All reactions are assumed to be instantaneous and irreversible.

7.2.1 Corrosion of the canister

Figure 7-3 shows the results of a calculation of copper canister corrosion due to sulphide initially in the buffer and in the groundwater for the geometry shown in Figure 7-2. Key input data for the calculation are given in Table 7-2. In section 7.2.4 below, crucial data related to canister corrosion are identified. These have been submitted to the data qualification procedures described in the Interim Data report /SKB, 2004c/ so that qualified data for the final SR-Can report can be generated.

Table 7-2. Canister corrosion sub-model data

Diffusivity of sulphide in buffer	0.001 m²/yr
Diffusivity of cations in buffer	0.02 m²/yr
Darcy velocity	0.002 m/yr
Concentration of sulphide in buffer pore water	0.00005 kmoles/m³
Equivalent concentration of sulphide in solid phase	0.16 kmoles/m³
Pitting factor for oxygen corrosion	5
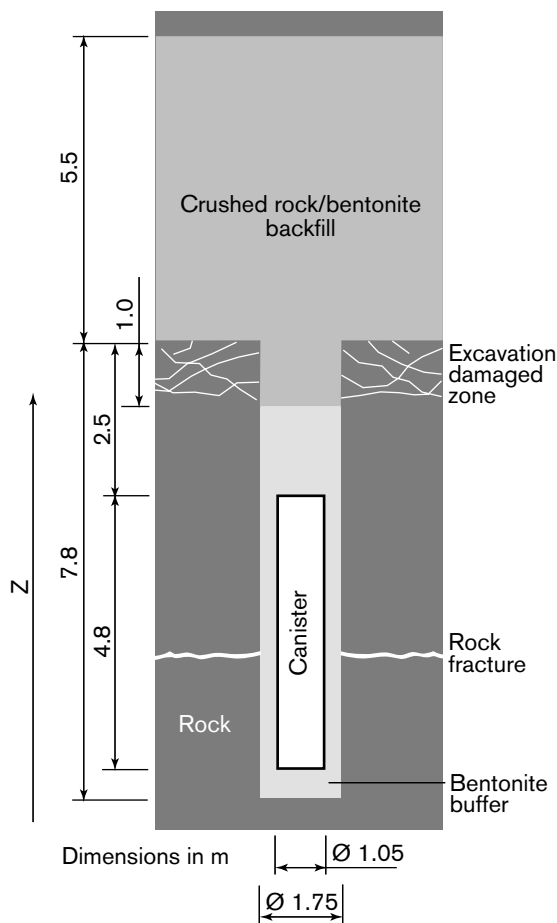
Figure 7-2. Corroding agents initially in the buffer will diffuse to and attack both the lateral surface and the lid. Corroding agents in groundwater entering from an intersecting horizontal fracture will corrode a section of the canister lateral surface. The potential pathway through the excavation damaged zone, EDZ, around the deposition tunnel remains to be evaluated. (There is also a minor EDZ around the deposition, not shown in the figure.)
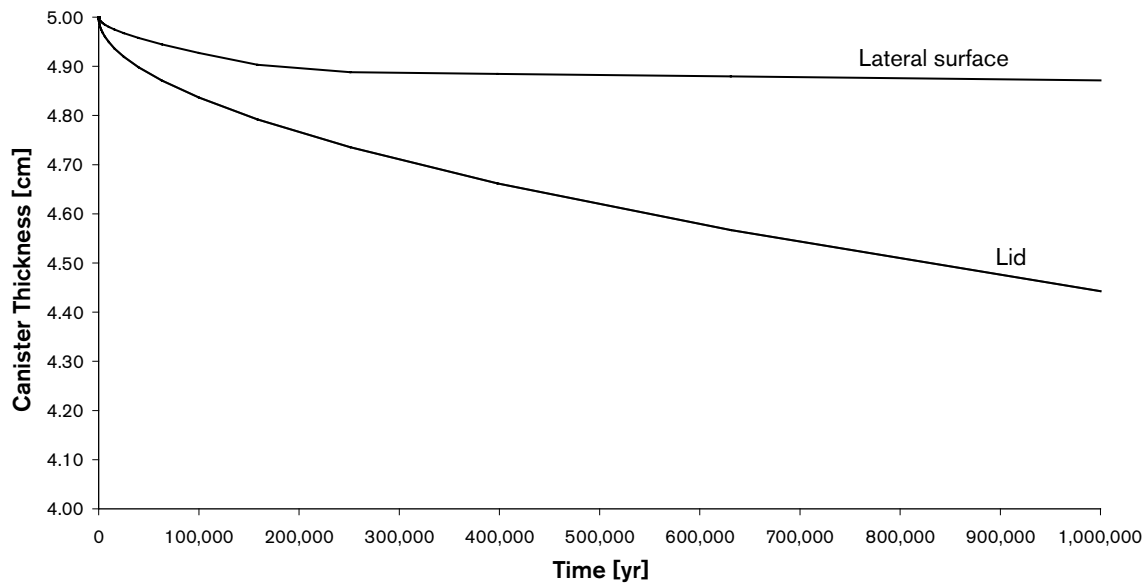
Figure 7-3. *Corrosion due to sulphide initially in buffer (as pyrite) and in groundwater.*

The premises for the calculation were the following:

- Several corrosion modes are not included based on arguments presented in e.g. /King et al, 2001/ and to be further elaborated in the final version of the SR-Can process report. These include pitting corrosion under reducing conditions, stress corrosion cracking and corrosion caused by radiolysis.

- Initially entrapped oxygen in the deposition tunnels is assumed to be consumed by microbes. This assumption needs to be further corroborated. The minor effects of initially entrapped oxygen in the buffer could readily be included by means of a mass balance calculation, considering also its reaction with pyrite.

- Sulphide in the buffer diffuses to the lid and to the lateral surface, slowly depleting the buffer of pyrite, the source of sulphide in the buffer. As long as this process is on-going, no sulphide from the groundwater will enter the buffer since the sulphide concentration in the groundwater will not exceed that in the buffer pore water.

- Sulphide in the groundwater diffuses from a fracture intersecting the deposition hole to the canister's lateral surface. Mass transfer of sulphide between groundwater and buffer is calculated by analytic approximations.

- There are no active sulphate-reducing bacteria in the buffer since its density is assumed to be sufficiently high.

7.2.2   Corrosion of initial defects in canister seals

The above calculation is based on an initial copper thickness of 50 mm, for which the results show that around 6 mm of copper will be corroded during the one million year assessment period. Hence no penetration will occur due to corrosion in this case. Furthermore, the dominating corroding agent is the sulphide originating from the pyrite initially present in the buffer (and not consumed by initially present oxygen), whereas sulphide from the groundwater will not contribute until the buffer has been depleted of

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pyrite. A more critical issue for the safety assessment is however to apply the calculation to estimate the distribution of minimum copper thickness for the ensemble of canisters deposited in the repository.

The minimum copper thickness will most likely occur at welds, and in particular the seal of the canister top lid, as this seal cannot be as readily inspected as other welds. Electron beam welding and friction stir welding are the two processes now being considered for sealing copper canisters. /Müller and Öberg, 2004/ outline a strategy for verification and demonstration of the encapsulation process defined as the sealing of the canister by welding followed by quality control of the weld by non-destructive testing.

Pending test results from the sealing and testing processes, it has been assumed here that the design criteria for the processes can be just met, i.e. that one canister in a thousand will leave the encapsulation plant with a minimum copper thickness of less than 15 mm at the top seal. The distribution of initial canister thickness below 15 mm has been assumed to be triangular with a minimum at zero thickness and a mode and a maximum at 15 mm. Both the probability of occurrence and that of passing the detection system should decrease with defect size and for simplicity a direct proportionality between probability density and copper coverage is assumed, see Figure 7-4. The sensitivity to the shape of the probability density function could readily be explored by assuming alternative distributions.
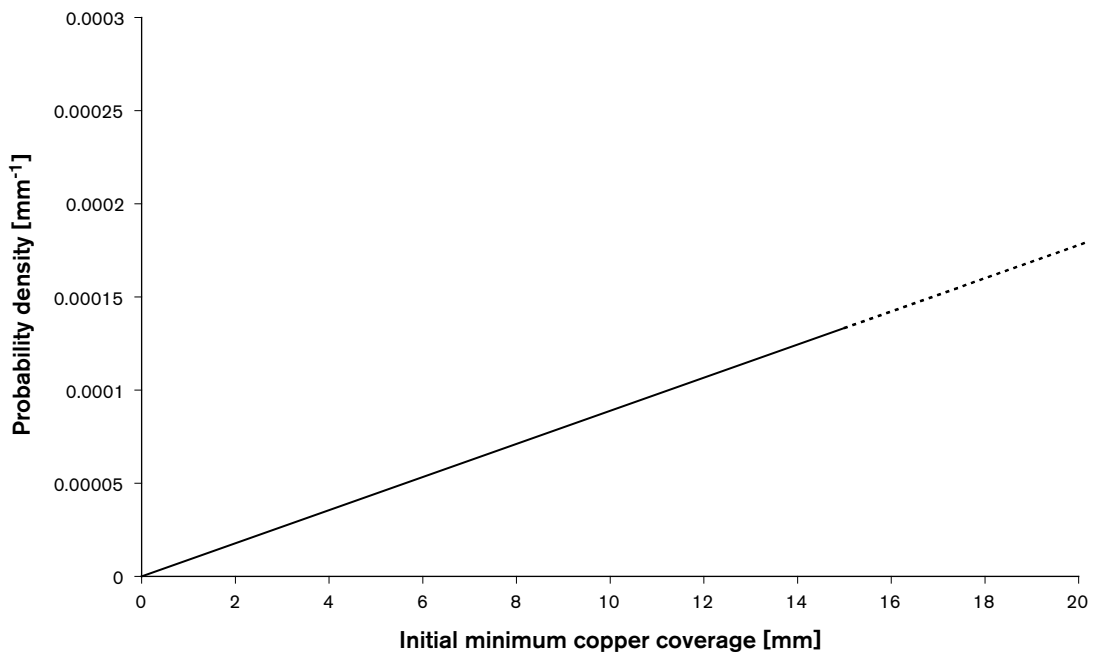
Figure 7-4. *Triangular distribution (only initial part shown) of initial minimum copper thickness at the top seal for a single canister, based on the premise that the design criterion for the encapsulation process is just met, i.e. that the probability of a canister having less than 15 mm copper thickness is 10^{-3}. This is reflected by the fact that the area under the distribution for $0 < d_{min} < 15$ mm is 10^{-3}. The shape of the distribution beyond 15 mm is not of primary importance as it is difficult to foresee circumstances under which such a thickness could be corroded away during the assessment period.*

With this distribution of initial minimum copper thickness, the number of penetrated canisters due to the corrosion mechanisms mentioned above was calculated as a function of time for the ensemble of 4,500 canisters, see Figure 7-5.

It was assumed that conditions for lid corrosion apply also to the seals although these are located some 50 mm below the canister top. This is pessimistic since the lid corrodes at a higher rate than the lateral surface according to the analysis above. It was further assumed that the initial defect pores are located internally in the copper bulk and that they are connected to the canister interior. Hence all corrosion prior to penetration will occur on a smooth canister surface and none in the pores. This is pessimistic, since any corrosion that would occur inside a pore would consume copper not only in the direction of the canister radius, but also in corroding the pore walls perpendicular to that direction which would slow the progression in the radial direction considerably.

After about 4 million years, the portion of the buffer above the canister will be depleted of sulphide in this calculation, but as the backfill material is also likely to contain sulphide, the calculation was continued to 10 million years to illustrate the behaviour of the model on this time scale.

The number of penetrated canisters due to corrosion caused by pyrite initially in the buffer can, assuming a triangular distribution for copper thickness as in Figure 7-4 and using the analytical expressions in /Hedin, 2004a/, be shown to be directly proportional to the time after deposition and to the product of

- the pore water concentration limit of sulphide,

- the effective diffusivity of sulphide in the buffer and

- the concentration of pyrite in the buffer.
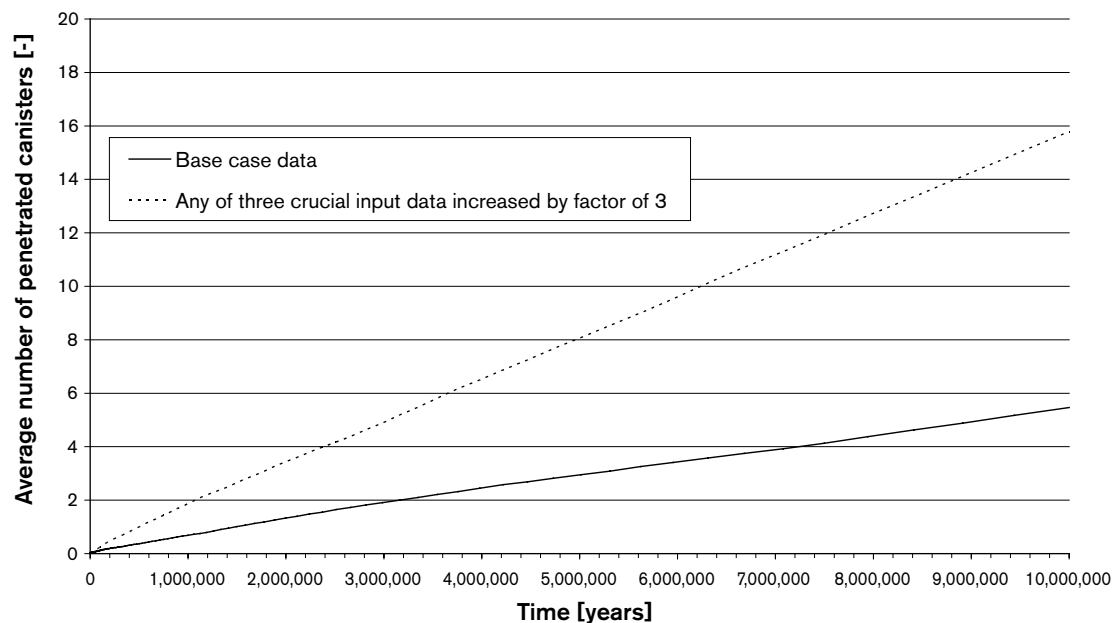
Figure 7-5. *Average number of penetrated canisters out of a population of 4,500 as a function of time for different assumptions as to the distribution of initial minimum copper thickness and parameters controlling diffusion. Probabilistic calculation.*

Figure 7-5 illustrates both how the number of defective canisters increases linearly with time and how an assumed increase in any of the critical input parameters mentioned above affects the result. This simple sensitivity analysis thus demonstrates that it is urgent to determine the three uncertain quantities in a quality assured manner.

A preliminary probabilistic evaluation of new data for the two buffer materials of concern indicates that the calculated case is a good representation of the Milos material, whereas the performance of the MX-80 material is underestimated, since MX-80 has a lower pyrite content.

7.2.3 Consequences of corrosion due to potentially intruding oxygen

Figure 7-6 shows the result of a penetration of oxygenated water in a fracture intersecting the deposition hole. The oxygen concentration has been set to 0.0007 moles/litre, i.e. that of water in equilibrium with atmospheric oxygen at standard conditions. Furthermore, since the glacial conditions that could give rise to oxygen penetration could temporarily also induce considerably elevated Darcy velocities at repository depth, the Darcy velocity was increased by a factor of ten to 0.02 m/yr in this scoping calculation. The diffusivity of oxygen in bentonite was set to 0.02 m^2/yr. Pitting, i.e. localised corrosion cannot be excluded and a pitting factor (the quotient of local to general corrosion depth) of 5 was pessimistically assumed. It is interesting to note that for these assumptions, the part of the canister wall closest to the fracture carrying the oxygenated water will resist penetration for around 400,000 years, according to Figure 7-6.
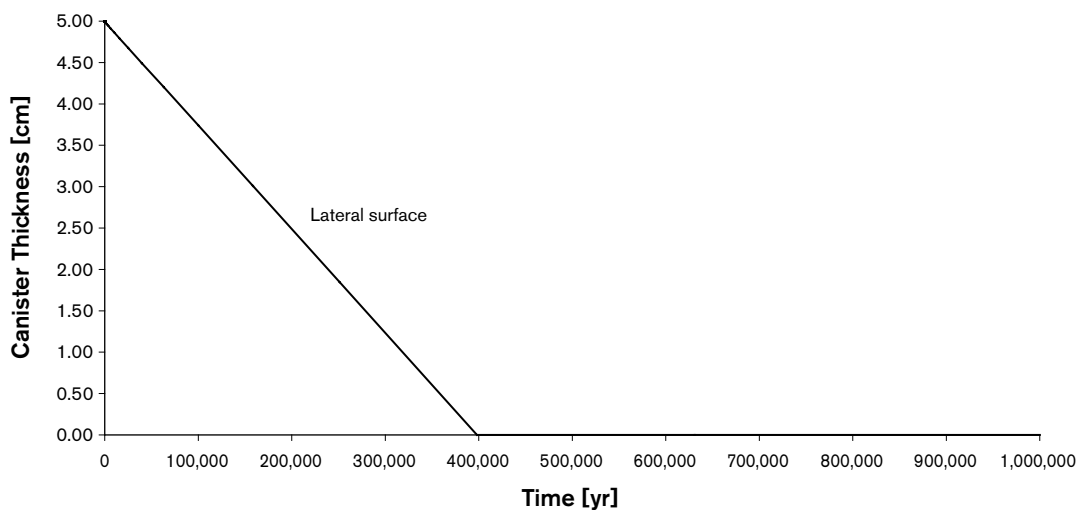
Figure 7-6. *Corrosion due to oxygenated water in a fracture intersecting the deposition hole.*

7.2.4 Conclusions

Sensitive input data

The above calculations demonstrate that the function indicator depends critically on the following uncertain input data:

- The distribution of initial minimum copper thickness at in the top seal.
- The initial content of pyrite (i.e. the source of sulphide) in the buffer material.
- The concentration limit of sulphide in the pore water.
- The diffusivity of sulphide in the buffer.

These data related to canister corrosion will be discussed in more detail in the final version of the SR-Can Data report.

Remaining issues

Important issues remaining to be further studied are:

- The consumption of initially entrapped oxygen in deposition tunnels, so that a bound can be put on the fraction of this oxygen that could reach the canisters.
- The possibility of penetration of oxygenated water to repository depth for glacial conditions. (The duration of the possible oxygenated conditions and the Darcy velocity for the flowing water also need to be evaluated.)
- The possibility and degree of microbial corrosion.

Preliminary feedback to design

Depending on the outcome of the final analysis of this function indicator, it could be relevant to consider a requirement on the initial pyrite contents of the buffer material. The need to characterise the canister seals has long been identified as an important issue in SKB's RD&D programme.

7.3   Peak canister surface temperature

The thermal sub-model calculates the peak temperatures as a function of time in the fuel, the cast iron insert, the copper canister, the buffer and the host rock. It is based on analytical solutions describing the canisters as a set of point sources in the host rock and on steady-state heat conduction expressions for heat conduction in the buffer. Furthermore, heat transfer due to combined radiation and conduction in gaps between canister and buffer and in the canister interior is calculated analytically.

Similar treatments are presented for the host rock and buffer in /Hökmark and Fälth, 2003/. These authors also treat heat transfer in the canister/buffer gap in separate calculations where the radiation contribution is handled in an approximate but sufficiently accurate fashion. Benchmarking against the results of /Hökmark and Fälth, 2003/ and of numerical finite element calculations for buffer and rock yields discrepancies of peak canister peak temperatures of less than one degree /Hedin, 2004a/. A comparison with a numerical calculation of fuel and cast iron insert peak temperatures also yields negligible discrepancies /Hedin, 2004a/.

Figure 7-7 shows the thermal evolution at a number of points located on a radius extending horizontally from the canister mid-point along the deposition tunnel. The function indicator, the peak canister surface temperature is 87.6°C in this central case, with data as listed in Table 7-3.
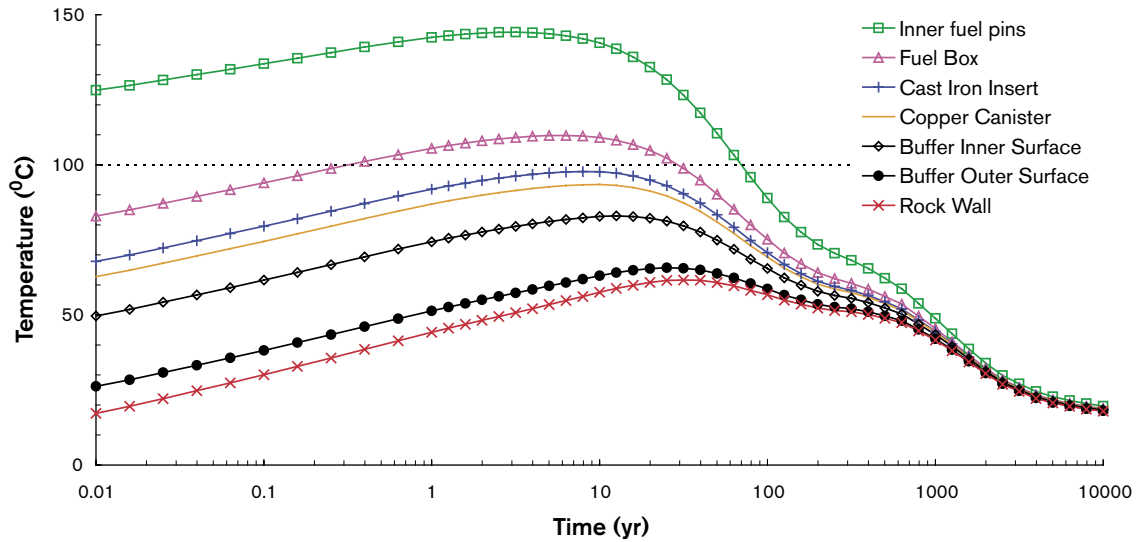
Figure 7-7. *The thermal evolution for a number of points at canister mid-height for data given in Table 7-3.*

Table 7-3. Thermal sub-model data for the central case presented in Figure 7-7. Site-specific data are taken from the Forsmark site; repository layout data from the draft D1 version of the site-specific layout at Forsmark. Geometry data for canister and buffer in Figure 7-2. The canister is assumed to be filled with air.

Repository depth	400 m
Canister spacing	6 m
Tunnel spacing	40 m
Canisters per tunnel	160
Initial gap copper/buffer, assumed open	0.005 m
Initial gap buffer/rock,	0.03 m
Initial canister power, P_0	1,700 W
Rock thermal conductivity	3.4 W/(m·K)
Rock heat capacity	2.08 MJ/(m³K)
Temperature at repository depth	12°C
Buffer thermal conductivity	1 W/(m·K)
Emissivity of buffer inner surface	0.88
Emissivity of copper outer surface	0.1
Thermal conductivity in copper/buffer gap	0.03 W/(m·K)
Emissivity of copper inner surface	0.03
Emissivity of cast iron outer surface	0.24
Emissivity of cast iron inner surface	0.3
Emissivity of Zircalloy surfaces	0.4

It was cautiously assumed that no groundwater is taken up by the buffer since this would lead to an increased thermal conductivity and eventually to a closure of the gaps at the buffer interfaces. The treatment also neglects the presence of the tunnel backfill above the deposition hole, but this has been demonstrated to influence the critical temperature only marginally /Hökmark and Fälth, 2003/.

7.3.1 Sensitivity analyses

The peak canister surface temperature depends on several uncertain input data. The following figures show the dependence on these.

Figure 7-8 shows the dependence of canister and buffer peak temperatures on the canister outer surface emissivity. A value of 0.1 was used for the central case as this is an average of recently conducted laboratory measurements /Roos and Gelin, 2003/. /Hökmark and Fälth, 2003/ back calculated the emissivity from measured temperatures from SKB's prototype repository and obtained an emissivity of 0.3. In the thermal calculation performed as part of the SR 97 assessment /Ageskog and Jansson, 1999/ an emissivity of 0.63 was used, which appears unrealistically favourable.

The effect of varying the gap width is shown in Figure 7-9. The strong dependence on width is related to the low emissivity of the copper canister, meaning that heat transfer by radiation (which is independent of gap width) only gives minor contributions. Following deposition, heating of the buffer could lead to drying of its inner parts, possibly accompanied by shrinkage of the buffer and an increase in gap width. This issue needs to be further assessed.

Figure 7-8. *Sensitivity of canister and buffer peak temperatures to the emissivity of the outer copper surface. Other data as central case in Table 7-3.*

Figure 7-9. *Sensitivity of canister and buffer peak temperatures to the width of the gap between canister and buffer. Other data as central case in Table 7-3.*

Figure 7-10 shows the effects of varying rock thermal conductivity. The central case uses a rock thermal conductivity obtained as an average of a number of mineral samples from rock domain 29 at Forsmark /SKB, 2004e/. The distribution is roughly normal with a standard deviation of about 0.4 W/(m·K). The dominating mineral type, which has a higher than average conductivity, is, however, under represented in the selection of samples, meaning that a more careful evaluation will likely show that the central value is pessimistic. A related issue concerns the homogeneity of the host rock with respect to thermal properties, in particular thermal conductivity. The scale on which the thermal properties vary needs to be determined as do the magnitude of the variations. This issue will thus be further evaluated and is also discussed more extensively in the site descriptive model for Forsmark /SKB, 2004e/.

Figure 7-10. *Sensitivity of canister and buffer peak temperatures to the rock thermal conductivity. Other data as central case in Table 7-3.*

Figure 7-11 shows how the peak temperatures depend on initial canister power, if either all or only the central canister is assumed to have a deviating power. The initial power can to a large extent be controlled by administrative measures and Figure 7-11 provides input to the development of such measures so that they can be made rigorous enough to prevent violations of the peak temperature criteria.

Figure 7-12 shows how the peak temperatures depend on the buffer thermal conductivity. The buffer thermal conductivity depends on its degree of water saturation and was pessimistically set to 1 W/(m·K) in the central case. This corresponds to a degree of water saturation of around 65 percent and is lower than the experimentally determined heat conductivity of 1.1 W/(m·K) for the buffer at deposition (80 percent saturation). A fully saturated buffer has a heat conductivity of around 1.3 W/(m·K) Full saturation may, for many deposition holes, however occur considerably later than the peak temperature. In reality, the buffer conductivity will vary within the buffer. This can be included in the modelling, but was not done since data are scarce and uncertain. All buffer data were obtained from /Hökmark and Fälth, 2004/.

Figure 7-13, finally, shows how the peak temperatures vary with the centre-to-centre spacing of the canisters. This distance is controlled by the implementer and is thus not uncertain in the same sense as several of the data discussed above. It is nevertheless important to carefully select an appropriate spacing since this determines the overall requirements on space for the deep repository.
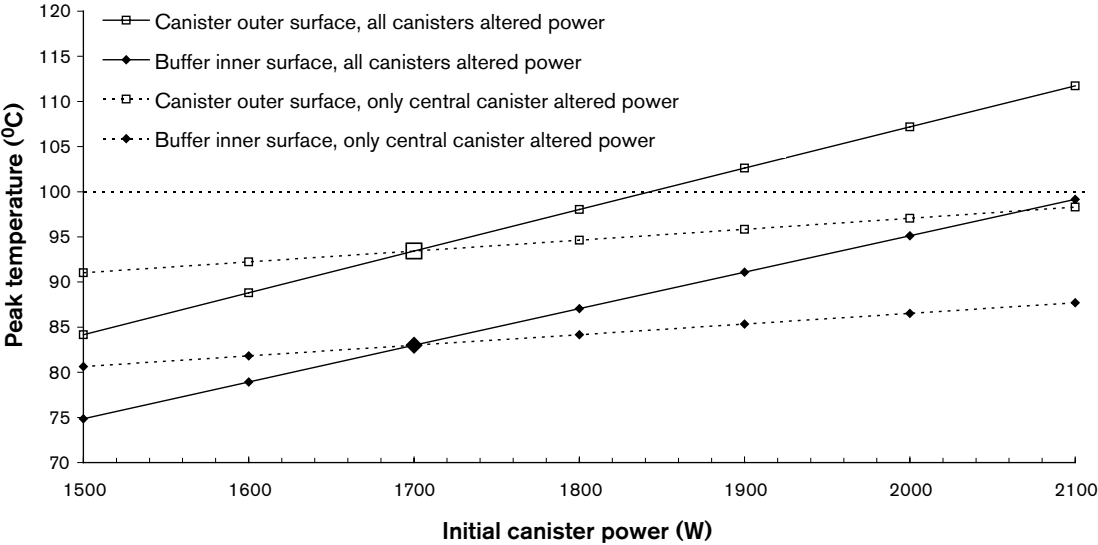
Figure 7-11. *Sensitivity of canister and buffer peak temperatures to alterations in initial power of either all or only the central canister. Other data as central case in Table 7-3.*
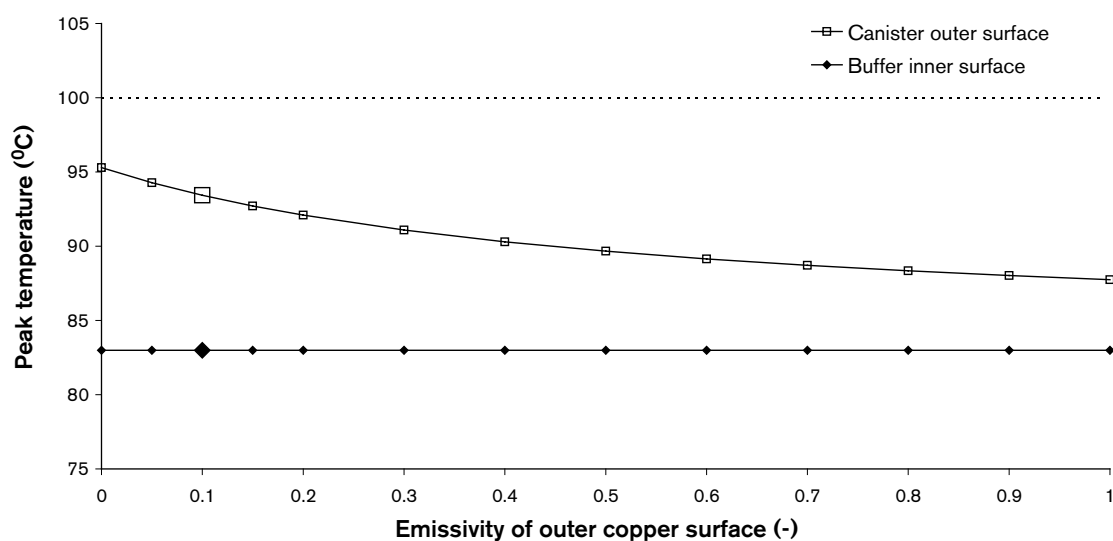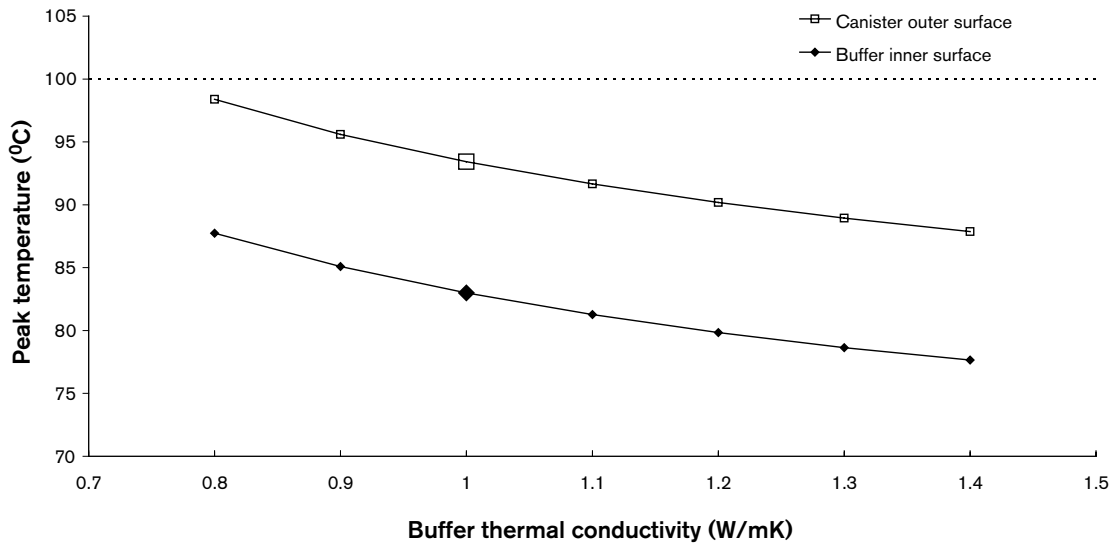
Figure 7-12. *Sensitivity of canister and buffer peak temperatures to the thermal conductivity of the buffer. Other data as central case in Table 7-3.*
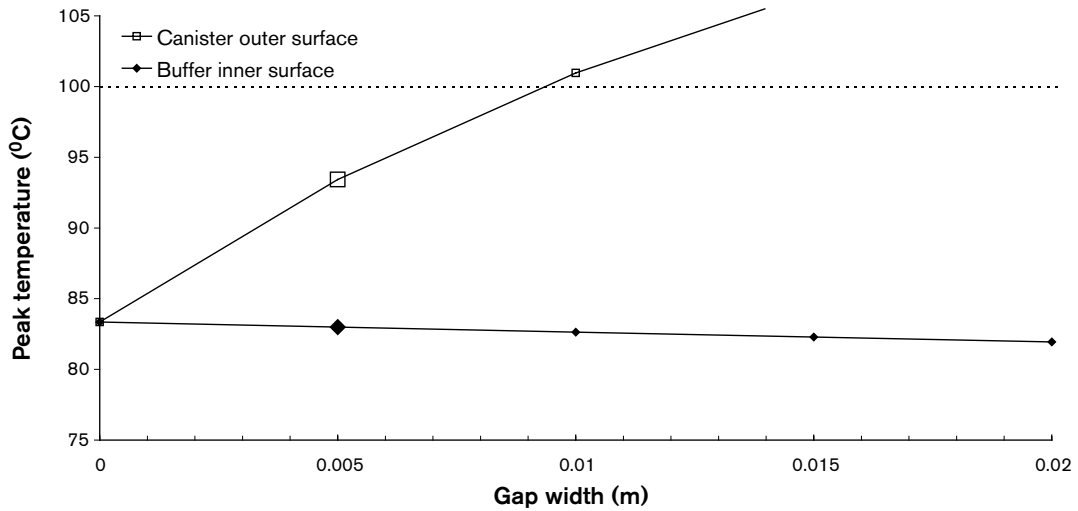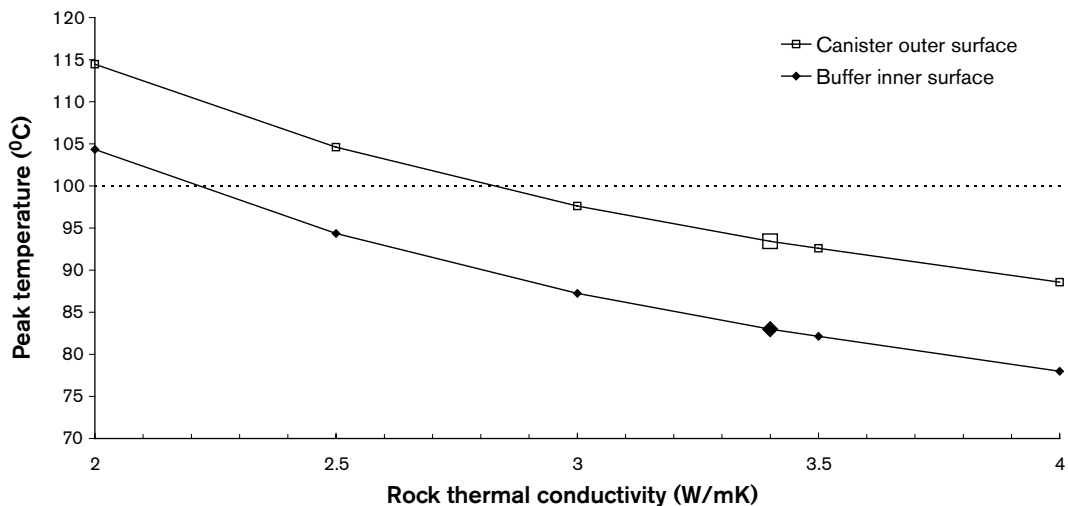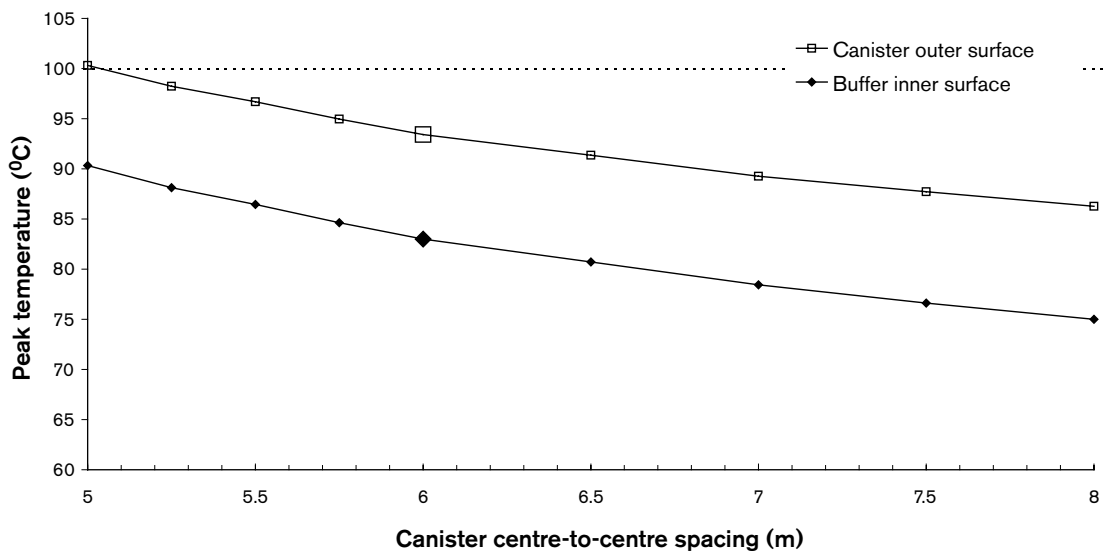

Figure 7-13. *Sensitivity of canister and buffer peak temperatures to the distance between deposition holes. Other data as central case in Table 7-3.*

7.3.2 Conclusions

The central case demonstrates that there is a margin relative to the criteria for the peak canister and buffer temperatures and the sensitivity analyses provide input for further discussions on how input data uncertainties and design decisions affect the results.

Generally, it is concluded that the peak buffer temperature is lower than the stipulated 100°C with ample margin. Considering that, in the central case, the buffer and rock heat conductivities and the emissivity of the canister outer surface are pessimistically chosen, it is also likely that the great majority of canister surfaces will not experience temperatures exceeding 100°C. Furthermore, the canister criterion applies when water contacts the canister surface, see section 6.3.1. This is not likely to occur until the buffer has been saturated and swelled so that the gap between the buffer and the canister is closed. Before saturation the buffer has a high propensity for absorbing water which should ensure dry conditions in the gap. In a situation where the gap is closed, the peak canister surface temperature equals the peak buffer inner surface temperature. Thus, the above results indicate that also the canister criterion is fulfilled with ample margin.

The treatment of the gap between buffer and rock and the handling of inhomogeneous thermal rock properties need to be further developed.

The data used for the above calculations should be considered as candidates for inclusion in the Data report.

7.4   Buffer density

It is obvious from chapter 6 that the buffer density plays a key role for many of the intended functions of the repository. It is therefore essential to identify and analyse all potential causes for buffer density alterations, in particular those leading to loss of buffer mass. On the basis of the processes of relevance for the long-term evolution of the buffer, see section 5.4 for a summary and more details in the Interim Process report /SKB, 2004b/, the following needs to be considered:

• Buffer dilution due to the initial swelling;

• Erosion caused by dilute groundwater under glacial conditions;

• Effects of swelling pressure changes caused by ion exchange and osmosis (salinity effects);

• Effects of very long-term convergence of the deposition hole;

• Creep of the buffer material leading to canister sinking;

• Piping effects before the rock is resaturated.

Buffer dilution due to swelling is addressed below and effects of ion exchange and osmosis in section 7.7.

According to the criteria given in chapter 6, erosion of the buffer (and backfill) and hence a loss of density can be excluded if the sum total concentration of divalent cations exceeds 1 mM. However, as seen in Table 7-1 in section 7.1.2, this is not fulfilled for a typical glacial melt water that has had limited interactions with the bed rock (as, e.g. the waters

encountered at the Grimsel or Gideå sites). The issue of buffer erosion thus needs to be further evaluated for glacial conditions.

Effects of long-term convergence are negligible according to preliminary results presented in section 10.3.1.

Creep in the buffer material is directly related to canister sinking, and a criterion for avoidance of canister sinking remains to be established. Should such a criterion not be fulfilled, a number of buffer functions are simultaneously jeopardised. This situation will be studied as a residual scenario, see further section 8.6. Another type of creep could potentially lead to long-term reduction of friction between the buffer and the wall of the deposition hole. This is addressed as a limiting calculation case in section 7.4.1 immediately below.

7.4.1   Swelling calculations

The buffer rheology sub-model

At deposition, the buffer is not in hydraulic equilibrium with the surrounding, saturated rock. Saturation of the buffer will typically occur within a few tens of years but may take considerably longer, depending on the water supply from the fractured rock surrounding the deposition hole and from the deposition tunnel backfill on top of the buffer, see further section 11.2.5. At the end of the saturation process, a swelling pressure will develop in the buffer and it will expand upwards and compress the backfill to some extent. Due to friction against the walls of the deposition hole, the expansion of the buffer will finally result in a gradually decreasing density in its upper part. The details of the swelling process are not important to long-term safety, if the final density distribution of the buffer after swelling can be determined and if it can be demonstrated that the buffer will not be harmed in any other way by the saturation process. In the buffer rheology sub-model described in /Hedin, 2004a/, the final density distribution is approximately obtained by a numerical equilibrium calculation where the upward expansion of the buffer is balanced by friction against the walls of the deposition hole and the force exerted on the buffer by the compressed backfill. The model builds on earlier work by /Börgesson, 1982/ and has been benchmarked against the detailed process model used in the SR 97 assessment /SKB, 1999a/. The process model yielded a buffer expansion of 8 cm as compared to 9.5 cm for the buffer rheology sub-model /Hedin, 2004a/. This is seen as a reasonable result, since it errs on the pessimistic side and since the process model was not optimised to handle the mechanical interactions involved. Furthermore, the sub-model can handle relationships between density and swelling pressure that take into account osmotic effects of intruding saline water /Karnland et al, 2002/.

Calculations

The rheology sub-model has been used to calculate a central case for the buffer expansion, Table 7-4, and a number of variation cases to explore sensitivities to various input data. A relationship between swelling pressure and density for an MX-80 clay purified from accessory minerals was used in the calculations. This is slightly pessimistic with respect to buffer expansion, since it does not take into account the accessory minerals present in the reference material that would reduce the swelling pressures somewhat. The results are representative also for the Milos clay material since its swelling properties are similar to those of MX-80.

Figure 7-14 shows the result of the central calculation case. Note that the tolerances of the buffer density, 2,000±50 kg/m^3, yields swelling pressures between 5.8 and 13 MPa.

Table 7-4. Buffer/Backfill rheology sub-model data for the central case.

Initial clay density, ρ	2,000±50 kg/m³
Buffer temperature, T	50°C
Groundwater salinity (NaCl)	0 M
Friction angle buffer/deposition hole, Φ	10°
Friction angle backfill/deposition hole	30°
Compression modulus of backfill, M	40 MPa
Earth pressure coefficient	0.5
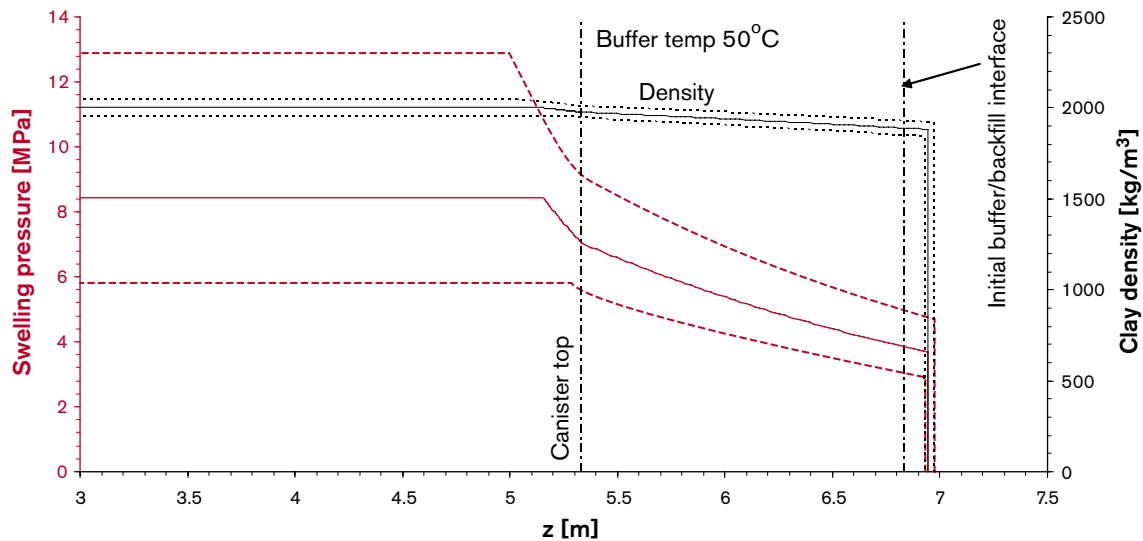
Figure 7-14. *Swelling pressure (red curves) and clay density along vertical axis of deposition hole after initial swelling. Solid line: Initial density 2,000 kg/m³; Dashed lines: initial densities 1,950 and 2,050 kg/m³.*

For all the variation cases in Table 7-5, the buffer density and swelling pressure are within the limits for the function indicators given in chapter 6, i.e. the buffer density is well above 1,800 kg/m³ and the swelling pressure well exceeds 1 MPa. This is the case even for the limiting case of no friction against the wall of the deposition hole in combination with the lower limit of the assumed buffer density. The case of lower buffer temperature was included since swelling would occur after the period of elevated buffer temperatures if the supply of groundwater is low, see further section 11.2.5.

The above analyses assume that the backfill is water saturated before the buffer swelling commences. This is the most likely sequence of events since, in general, the supply of water in the deposition tunnel will be higher than that in the deposition holes. The opposite case must be considered as rare but not impossible and needs to be further addressed, in particular for block backfill.

Table 7-5. Results of single parameter variations from the central case described by Table 7-4.

Variation	Buffer/backfill interface displacement (m)	Buffer density 35 cm above canister top (kg/m³)	Swelling pressure 35 cm above canister top (MPa)
Base case	0.11	1,958	6.1
Φ = 5°	0.12	1,940	5.5
Φ = 20°	0.095	2,000	8.2
M = 30 MPa	0.13	1,950	5.7
M = 50 MPa	0.098	1,960	6.5
T = 20°C	0.11	1,960	5.7
Salinity = 0.3 M (1.8%) NaCl	0.094	1,960	5.2
Salinity = 1 M (6%) NaCl	0.069	1,970	3.8
ρ = 1,950 kg/m³	0.093	1,920	4.8
ρ = 2,050 kg/m³	0.14	1,990	7.9
Log-linear swelling function from SR 97 process model	0.096	1,960	5.4
No friction between buffer/backfill and wall of deposition hole, ρ = 2,000 kg/m³	0.28	1,948	5.7
No friction between buffer/backfill and wall of deposition hole, ρ = 1,950 kg/m³	0.22	1,911	4.4

7.4.2 Conclusions

The preliminary evaluation of the buffer density indicates that:

- The initial swelling will not lead to unacceptable consequences; a few cases remain to be handled and the data used in the evaluation needs to be qualified;

- Erosion under glacial conditions needs further consideration;

- Effects of convergence of the deposition hole can likely be neglected, but this needs to be confirmed by conclusions from on-going studies.

Effects of chemical alterations of the buffer (ion exchange and osmosis effects) are discussed in section 7.7.

7.5 Buffer pH and adsorbed ionic species

The buffer chemistry sub-model /Hedin, 2004a/ simulates the evolution, in a million year perspective, of the buffer chemistry due to the continuous, slow diffusion-controlled exchange of dissolved species between the buffer pore water and the groundwater. Dissolution of, and reactions involving, accessory minerals originally present in the buffer, and exchange of ionic species adsorbed to the montmorillonite clay fraction of the buffer with those dissolved in the buffer pore water are treated. The buffer is modelled as a mixed tank and the understanding of the chemical evolution is entirely based on the corresponding process model /Bruno et al, 1999/ used in the SR 97 assessment. The evolution is modelled in a number of consecutive time steps of typically several thousand years, their length being determined by the slow groundwater flow around the deposition hole and the diffusion properties of the buffer. In each time step, the pore water is completely replaced by groundwater and the resulting chemical equilibrium is calculated. A calculation algorithm specifically designed for this equilibrium calculation was developed for this sub-model. Benchmarking /Hedin, 2004a/ shows very good agreement with the corresponding results in /Bruno et al, 1999/. It should be noted that the process model has recently been developed to also include detailed transport within the buffer, a more developed treatment of accessory minerals and temperature dependence /Arcos et al, 2000/. The latter is important for the modelling of the initial 1,000 years when the buffer temperature is elevated.

Critical aspects of the chemical evolution of the buffer depend on the following data related to the buffer material:

- The initial concentrations of pyrite and carbonates.

- The initial CEC value (i.e. the content of ion-exchange sites).

- The initial content of "edge sites" controlling surface acidity.

- The initial population of cations at ion exchange sites (NaX, CaX_2 and MgX_2).

- The initial state of protonation at edge sites.

- The equilibrium constants for the ion-exchange reactions and for the surface acidity reactions.

Furthermore, the time constant for the exchange of pore water, which depends on the boundary conditions describing the exchange of species over the boundary will influence the time scale of the evolution.

Below, the model is applied to MX-80 bentonite and a range of groundwater compositions. All buffer data were taken from /Bruno et al, 1999/. The aim is to demonstrate how two important buffer characteristics are influenced by the chemical evolution: the adsorbed ionic species and buffer pH. Figure 7-15 shows the chemical evolution of the buffer for the example of Äspö groundwater and assuming an equivalent flow rate at the deposition hole of $2 \cdot 10^{-4}$ m^3/yr.

The same calculation was done for most of the groundwaters represented in Table 7-1 and the final distribution of adsorbed ionic species was determined, Figure 7-16. Starting from a situation where Na^+ dominates as adsorbed species, all groundwater compositions lead to a dominance of Ca^{2+} due to the combined effects of the groundwater composition and the buffer's higher affinity for Ca^{2+} ions. The groundwater at the Forsmark site (not covered by the results presented in the figure), is, according to Table 7-1, similar to that of Äspö.

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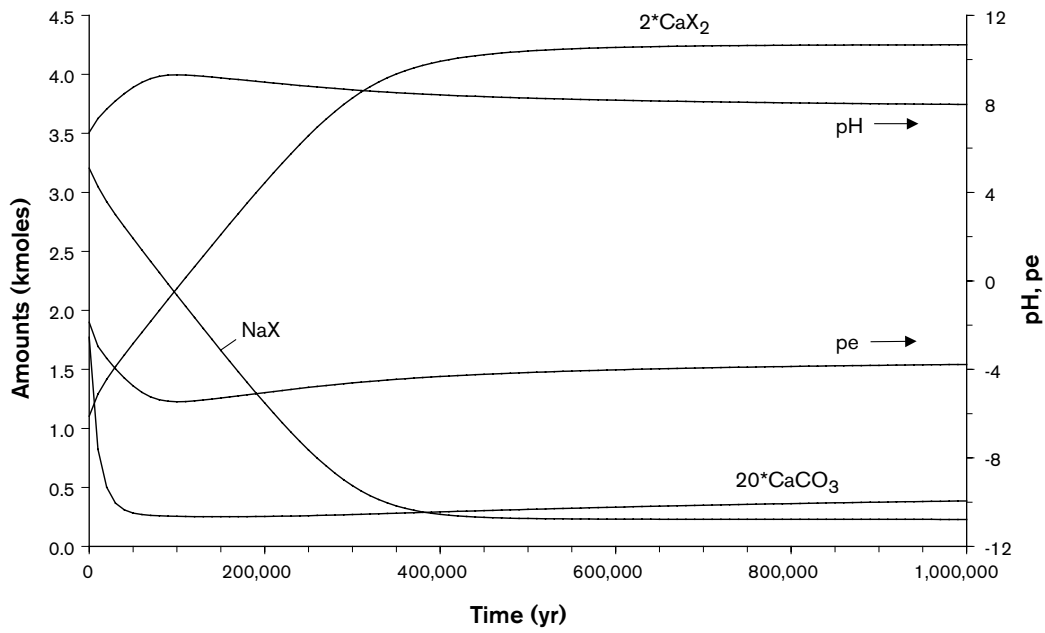
Figure 7-15. *Buffer chemical evolution showing the master variables pH and pe as well as the exchange of Na⁺ ions for Ca²⁺ ions at the surface positions, X, of the clay mineral, driven initially partly by the dissolution of calcite, CaCO₃.*
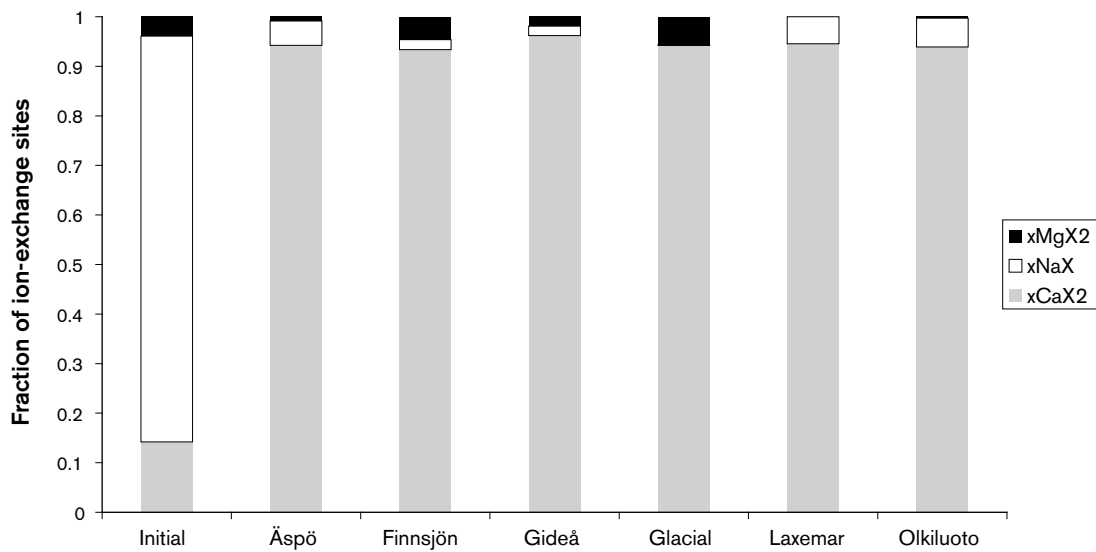
Figure 7-16. *The initial and final distributions of adsorbed ionic species in the clay material when equilibrated with the groundwater compositions given in Table 7-1.*

The span of pH values covered in the chemical evolution for the different cases is shown in Figure 7-17. The ranges are in general within those desired for favourably low radionuclide solubilities, stable conditions for the copper canister etc. The crosses denote the pH of the groundwater, which will, in the final state, also be that of the buffer pore water.

The results indicate that an evaluation of long-term buffer properties like swelling pressure and hydraulic conductivity must consider, in the case of MX-80, both Na^+ and Ca^{2+} as adsorbed species. The time for reaching the final state in which Ca^{2+} dominates will depend on the groundwater composition and the flow conditions at the deposition hole. The latter will vary considerably over the ensemble of 4,500 deposition holes in the repository. In reality, the situation is further complicated by the fact that the groundwater composition and flow rate will vary over time. For a Milos bentonite, the initial state is dominated by Ca^{2+} rather than Na^+, see Table 3-1 .

The results above will be used together with new data on swelling pressure and hydraulic conductivity of the buffer and backfill materials to evaluate the criteria for these function indicators in section 7.7.

Considerably more detailed chemical calculations for some of the groundwater compositions will also be performed in SR-Can, see further sections 11.2.7 and 11.3.6.
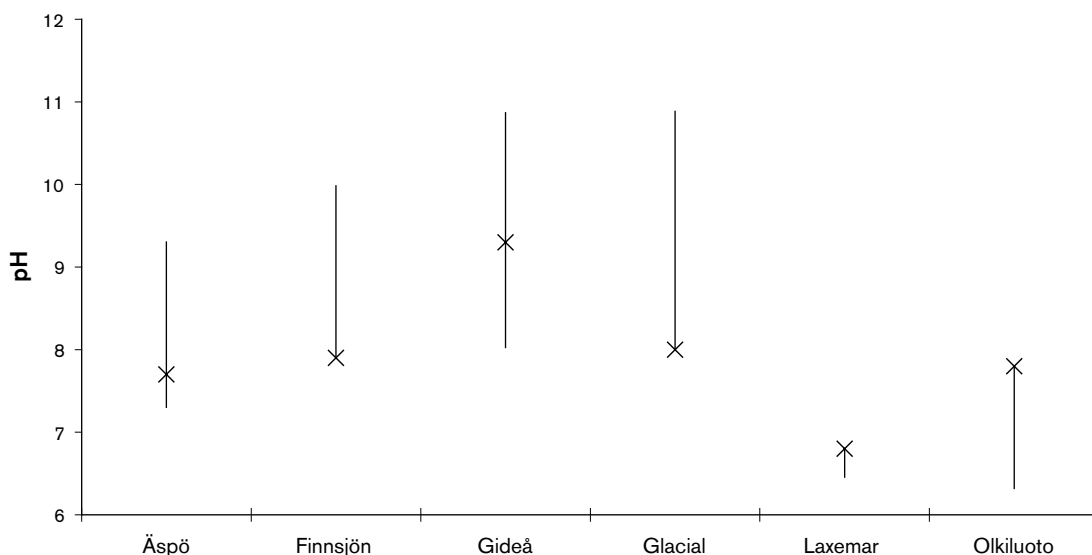
Figure 7-17. *pH ranges covered in the buffer chemistry modelling for interactions with different groundwaters. The crosses denote the pH of the groundwater and the vertical lines are the spans in buffer pH occurring during the chemical evolution.*

7.6 Buffer minimum temperature

As mentioned in section 6.3, the requirement on minimum temperature for both buffer and backfill is that they should exceed 0°C. The evaluation of this criterion will essentially be a comparison of estimated maximum permafrost depths to the repository depth. The influence of the residual power of the fuel on the thermal conditions in the repository will probably be negligible by the time that a first severe permafrost episode is expected, but this needs to be confirmed.

7.7 Buffer and backfill swelling pressure and hydraulic conductivity

The swelling pressure and the hydraulic conductivity of the buffer and backfill will depend on density, adsorbed ionic species and the ionic strength of the surrounding solution. These dependencies have recently been determined in a series of experiments for the two buffer candidate materials MX-80 and Milos.

7.7.1 Buffer

Figure 7-18 shows the swelling pressure for the MX-80 and Milos materials exposed to NaCl and $CaCl_2$ solutions, respectively.

The figure indicates that if the buffer density exceeds 1,900 kg/m^3, the requirement that the buffer swelling pressure should be above 1 MPa is fulfilled even in the case of a 3 M solution, i.e. for all groundwater compositions in Table 7-1. For a density of 1,800 kg/m^3 or less, fulfilment of this requirement can not be claimed.

Figure 7-19 shows the hydraulic conductivity for the MX-80 and Milos materials exposed to NaCl and $CaCl_2$ solutions, respectively.

The figure indicates that if the buffer density exceeds 1,800 kg/m^3, the requirement that the buffer hydraulic conductivity should be below 10^{-12} m/s is fulfilled even in the case of a 3 M solution, i.e. for all groundwater compositions in Table 7-1.
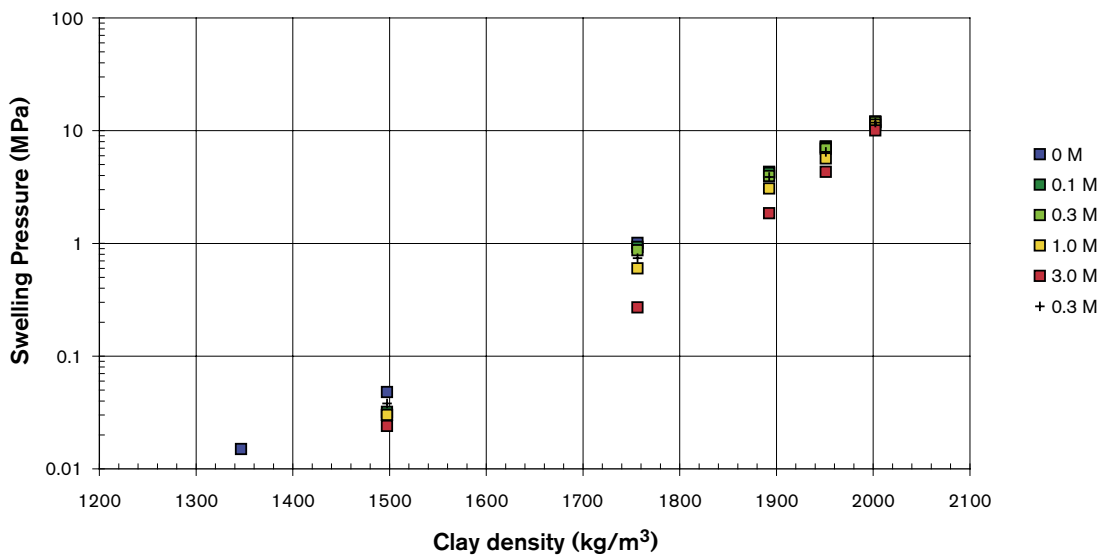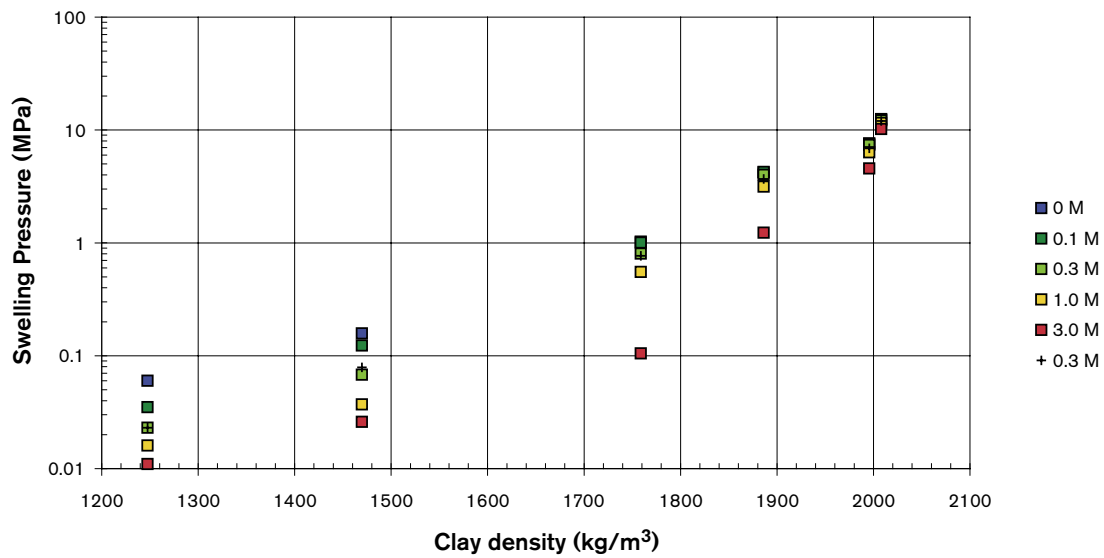
Figure 7-18. *Swelling pressures of MX-80 exposed to NaCl solutions (upper) and Milos clay exposed to CaCl₂ solutions (lower).*
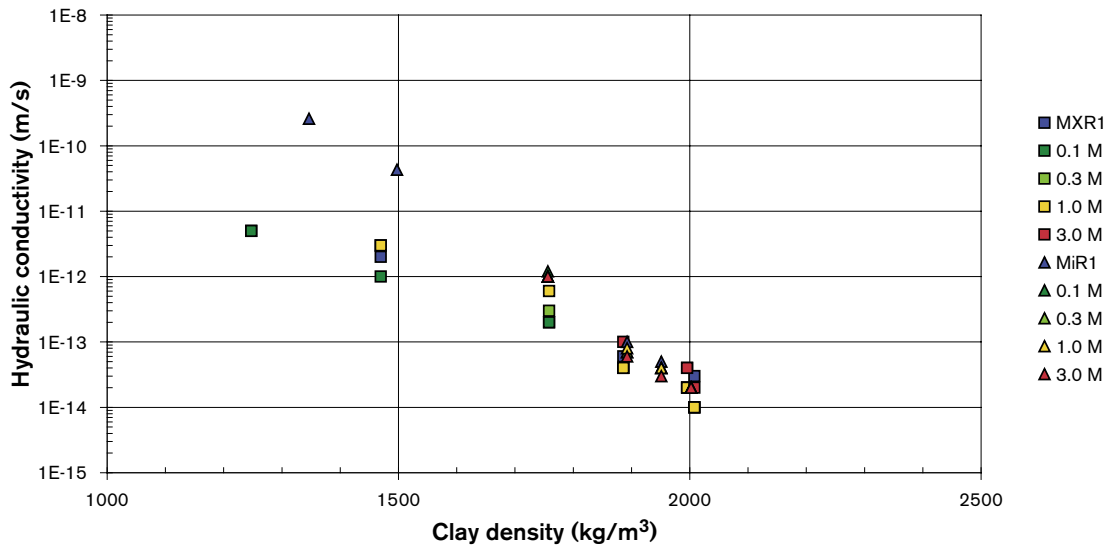
Figure 7-19. *Hydraulic conductivities of MX-80 exposed to NaCl solutions and Milos clay exposed to CaCl$_2$ solutions.*

7.7.2 Deposition tunnel backfill

The clay fraction of the deposition tunnel backfill concept consisting of a mixture of MX-80 bentonite and crushed rock is expected to have a clay density of around 1,600 kg/m^3, assuming a dry density of the mixed material of 1,700 kg/m^3. This means that the swelling pressure criterion for the backfill (> 0.1 MPa) is likely to be fulfilled for an MX-80 bentonite at low ionic strengths but not for a Milos bentonite.

The requirement on hydraulic conductivity however seems to be fulfilled for both materials for both low and high ionic strength groundwaters. This is however of secondary relevance if the swelling pressure criterion is not fulfilled, since the latter is required to ensure that no preferential flow pathways exist in the backfill.

If the mixture backfill concept is to be further evaluated, it is important to study the effects of a collapsed backfill with a conducting zone at the tunnel ceiling in the consequence calculations.

The Friedland clay as a backfill material will be evaluated in as the SR-Can project progresses. Data are available for this evaluation.

7.8 Maximum isostatic pressure on a canister

The canister will be subjected to isostatic loads from a number of sources in the repository.

- The groundwater pressure at repository depth. For the present layout at the Forsmark site, the depth is 400 m and the groundwater pressure accordingly around 4 MPa.

- The swelling pressure from the bentonite. According to the above results, for the upper limit of the allowed buffer density, this will be around 12 MPa.

- Additional glacial loads. In the SR 97 analysis /SKB, 1999a/, a maximum glacial ice thickness was, somewhat pessimistically, estimated at 3,500 m. If the glacial load is added to the water pressure, this would mean an increased water pressure of around 32 MPa.

Adding the three components above yields an estimated total maximum isostatic pressure of around 48 MPa.

Glacial loads will also imply additional rock stresses. These could lead to creep movements and possibly convergence of the deposition hole. This effect is assumed to be of minor importance, but needs to be further elucidated. Another possible minor contribution is an increased buffer swelling pressure due to long-term build-up of copper corrosion products near the canister surface, leading to a reduced volume for the buffer. During buffer swelling, the load on the canister can be uneven, but these effects were demonstrated to be negligible in the SR 97 analysis /SKB, 1999a/.

As described in section 6.3.1, full scale tests indicate that the collapse pressure of the cast iron insert designed for BWR fuel is at least 120 MPa. Therefore, it is provisionally concluded that there is a considerable margin relative to collapse loads for the highest pressures that can be expected in the repository.

7.9 Data for radionuclide transport calculations

The analyses presented above are mainly related to the isolating potential of the repository, although some of the properties, like the density and hydraulic conductivity of the buffer and the tunnel backfill, are also related to its retarding potential. As mentioned in section 6.4, it is, in general, not possible to formulate criteria for properties related to radionuclide transport, rather the implications of different conditions need to be evaluated in integrated assessments. It is however essential to identify all the relevant data at an early stage, so that they can be properly qualified.

Table 7-6 shows input data types for radionuclide transport and dose calculations in SR-Can. Input data uncertainties for all data types listed will be characterised in the SR-Can Data report. The transport and dose analyses to be carried out at later stages of the project, of which examples are provided in chapter 12, will include comprehensive sensitivity analyses of results obtained using the SR-Can input database.

Table 7-6. Input data types for radionuclide transport calculations in SR-Can. Preliminary values for SR-Can are provided in the SR-Can Interim data report and are summarised in chapter 12.

Radionuclide inventory

Instant release fraction of inventory

Time for canister failure

Time between failure and onset of radionuclide transport

Time between onset and complete loss of transport resistance in canister

Fuel dissolution rate

Solubilities

Buffer porosity

Buffer diffusivity

Buffer sorption coefficient

Backfill diffusivity and sorption coefficient

Rock porosity

Rock diffusivity

Rock sorption coefficient

Groundwater flow in tunnel/EDZ

Equivalent flow from deposition hole to fracture(s)

Rock transport resistance, F

Rock advective travel time, t_w

Rock Peclet number, Pe

Maximum penetration depth in rock matrix, D_{Pen}

Biosphere effective dose conversion factors, EDF

Sensitivity studies of the probabilistic results of radionuclide transport and dose calculations carried out in the SR 97 project /SKB, 1999a/ and subsequent analyses based on essentially the same data set /Hedin, 2002b, 2003/, have systematically identified a few input data types that dominate the output total dose uncertainty. These are listed below.

- The number of defective canisters as a function of time. This quantity will be derived from analyses of the isolating potential. Preliminary accounts of important aspects of such analyses have been given above.

- Temporal data for the evolution of canister defects after penetration. This is a highly uncertain area that can however be handled by pessimistic assumptions.

- The fuel dissolution rate. A report /Werme et al, 2004/ compiling relevant experimental data and recommending data for use in SR-Can will be the basis for assessing this quantity.

- The transport resistance in the host rock (the F factor). The F factor will be calculated probabilistically in hydrological site-specific models and depends on a number of factors related to groundwater flow and transport in the host rock. This complex topic is addressed in chapter 9 and will be covered in the SR-Can data report. A preliminary account will be given in the Interim Data report /SKB, 2004d/.

- The ecosystem-specific effective dose conversion factors, EDFs. The EDFs, which depend on the ecosystem under consideration, are determined probabilistically in separate calculations, see the discussion in Appendix C. Input data used in deriving these factors will be included in the SR-Can Data report.

Secondary to the above, sensitive input data as regards total dose are the flow at repository depth, the instant release fraction as well as solubilities and buffer and rock diffusivities of dose-dominating radionuclides. In the SR 97 assessment, total doses were almost always dominated by I-129 and Ra-226.

7.10 Conclusions

A number of preliminary conclusions regarding the repository function have been drawn and are summarised below. Many of the data used in the evaluations need to be qualified. A number of issues to be evaluated in subsequent, more detailed, analyses have are identified.

A general reservation concerns the fact that the analyses have been made for reference initial state conditions. Deviations from these conditions have not been systematically analysed. These types of deviations are discussed in the context of scenario selection in chapter 8.

Canister failure due to corrosion

- The likelihood of canister failure due to corrosion is very low during the assessment period, even when initial welding defects are taken into account.

- Data for the evaluation of corrosion of welding defects need to be qualified and results based on qualified data propagated to consequence calculations.

- Consumption of oxygen initially present in the buffer and backfill needs to be further studied.

- The possibility of penetration of oxygenated surface water to repository depths during glacial conditions needs to be further assessed.

Canister failure due to isostatic overpressure

- It seems to be possible to rule out this failure mode.

- However, because the highest overpressures, i.e. those potentially caused by a glacial overburden, would affect all canisters, this claim should be further substantiated. In particular, it is important to establish a reliable collapse criterion through laboratory tests and supporting strength calculations.

Canister failure due to rock shear at deposition holes

- The possibility of this failure mode, and the possibility of rock failure around the deposition hole due to significant ice sheet loading needs to be thoroughly evaluated in SR-Can.

Canister, buffer and backfill temperatures

- The buffer peak temperature is expected to be well below the 100°C criterion.

- Also the canister temperature is expected to be below its 100°C criterion, in particular since this criterion applies only when the canister is in contact with water. The gap between buffer and rock needs to be included in the calculations and the handling of inhomogeneous rock thermal properties needs to be further developed. Possibly, also initial shrinkage of the inner part of the buffer needs to be evaluated.

- The buffer and backfill minimum temperature requirement of 0°C needs to be evaluated against maximum permafrost depths.

Buffer density

- The initial swelling of the buffer has a marginal impact on buffer density.

- Buffer and backfill erosion for dilute groundwaters (glacial conditions) needs to be further evaluated, both as regards possible water compositions and the quantitative effects of dilute waters.

- The possibility of piping before rock resaturation should be assessed.

- A density criterion for the avoidance of canister sinking needs to be developed, see section 6.3.2

Buffer and backfill swelling pressure and hydraulic conductivity

- Both potential buffer materials are likely to fulfil the requirements on swelling pressure and hydraulic conductivity for both Na^+ and Ca^{2+} as adsorbed ionic species and for very saline groundwaters, provided that the buffer density is above 1,900 kg/m^3.

- The backfill material based on a mixture of clay and crushed rock is likely to fulfil the requirement on hydraulic conductivity for the expected range of repository conditions, provided that density is maintained. The swelling pressure criterion seems not to be fulfilled for this backfill material if Milos clay is used and only for low ionic strength groundwater if MX-80 clay is used.

- If the mixture backfill concept is to be further evaluated, it is important to study the effects of a collapsed backfill with a conducting zone at the tunnel ceiling in the consequence calculations.

- The backfill concept with Friedland clay remains to be evaluated as regards swelling pressure an d hydraulic conductivity (data are available).

The above conclusions primarily concern isolation. Section 7.9 points to input data for radionuclide transport and dose calculations and provides a brief discussion of sensitivities to the various categories of data.

8 Preliminary selection of scenarios

8.1 Introduction

As mentioned in section 2.2, a key feature in managing uncertainties in the future evolution of the repository system is the reduction of the number of possible evolutions to analyse by selecting a set of representative scenarios.

The selection must focus on addressing the safety relevant aspects of the evolution expressed at a high level by the safety functions isolation and retardation which are further characterised by reference to safety function indicators in chapter 6.

Guiding principles in the selection of scenarios is that they should be mutually exclusive and that together they 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, as discussed further in section 2.12.

This chapter presents a preliminary selection of scenarios to the extent possible at this stage of the assessment. The outcome of the analyses that are proposed in subsequent chapters may lead to conclusions that could warrant modifications of the scenario selection. The preliminary choice presented here will thus be re-evaluated at a later stage of the assessment.

8.1.1 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 therefore be possible to draw conclusions regarding risk.

SKI's regulations SKIFS 2002:1 require that scenarios be used to describe future potential 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 General 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. For these categories SKI's Recommendations state the following:

"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 on 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."

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."

SKI's Recommendations also state the following: "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."

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" and further: "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 SSI's background 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."

A first set of conclusions for the scenario selection can be drawn from the above:

- A main scenario should be defined in accordance with the definition above. A number of uncertainties will have to be handled within this scenario.

- Less probable scenarios will be selected to at least include future human actions that inflict damage on barriers. These will however be excluded from the risk summation, since the background comments to SSI FS 1998:1 state that the risk criterion "concerns a repository undisturbed by man". The extent to which also "alternative sequences of events" will be covered within the category of less probable scenarios depends on how exhaustive an analysis is undertaken of the main scenario.

- Residual scenarios will be selected to analyse e.g.
    - the significance of individual barriers and barrier functions,
    - consequences for intruders,
    - consequences of an unclosed repository that is not monitored,
    - possibly additional cases needed for the development of a design basis.

Scenario probabilities will be estimated to the extent possible, but it can already be concluded that these will often have to be pessimistically overestimated. A main purpose for estimating probabilities is to allow a risk calculation (see also section 2.12 for a discussion of scenario probabilities in the risk calculations).

8.1.2   Initial state, internal processes and external conditions

The system evolution depends on the initial state, the processes within the system and the external conditions described in more detail in chapters 3, 4 and 5, respectively. These three categories are also the "top level" building bricks when selecting scenarios.

Key barrier properties related to safety are presented in chapter 6 and a basic understanding of the traits of system evolution is given in chapter 7. Based on all this information, the next step of the analysis is to select scenarios to be analysed in more detail.

Regarding the initial state for the engineered barriers, the reference conditions with tolerances as described in chapter 3 as well as deviations from this state need to be considered. The FEP analysis, see further section 3.1.2, identified, regarding the initial state, also the case of an unsealed abandoned or monitored repository. Furthermore, it was noted that effects of phased operation need to be considered. This is part of the expected evolution of the repository, but not readily captured in the system of processes that describe the evolution of the system over time.

Regarding the initial state of the geosphere and the biosphere at the site, the base case model with uncertainties as well as alternative conceptual models (ACMs) must be considered.

Regarding internal processes, the entire process system for fuel, canister, buffer, backfill and geosphere must be characterised and assessed. Methods for representing these processes in the safety assessment, including the handling of uncertainties, are given in the Process report, see also chapter 5.

Regarding external conditions, the factors (mainly climate-related changes and future human actions) and associated uncertainties discussed in chapter 4 need to be managed.

In conclusion, each scenario will be defined by specifying:

- an initial state of the engineered barrier system,

- an initial state of the geosphere and the biosphere,

- a prescription for the handling of internal processes,

- a prescription for the handling of external conditions.

8.1.3 Variants and calculation cases

For 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.

Some aspects of the quantitative description of the evolution of a variant may require several calculation cases to appropriately evaluate all uncertainties that should be covered according to the definition of the variant in question. This is particularly the case for radionuclide transport and dose consequence calculations.

8.1.4 Scenario probabilities

With the definition of the main scenario as required by SKI FS 2002:1, several of the scenarios in SR 97 (used to take account of initial canister defects, climate changes and earthquakes) will now be included in the main scenario. Therefore, estimates of the scenario probabilities in these cases will be replaced by a probabilistic treatment of the occurrence of a feature (e.g. an initially defective canister) or events (e.g. earthquakes). The essence of the issue, i.e. establishing the probability estimates, is however unchanged.

Mutually exclusive scenarios or circumstances must be represented as separate scenarios or variants. This includes alternative:

- climate evolutions,

- process understandings,

- conceptual models of a site.

In many cases, it will be difficult to assign motivated probabilities to these mutually exclusive conditions. In a final risk summation, the problem can be handled by assigning unit probability to the condition giving the highest consequences and disregarding the other conditions. (If condition A would yield the highest consequences during a certain period and condition B during another, then the specific condition yielding the highest consequence will have to be chosen for each period, in order to bound the consequences in a strict sense.)

8.1.5 Conclusions

In summary:

- Scenarios will be selected in accordance with the regulatory requirements above, thus comprising the three main categories:
  – Main scenario.
  – Less probable scenarios.
  – Residual scenarios.

- The main scenario will, by definition, cover a large portion of the possible evolution pathways of the system and it will be divided into a number of variants;

- Scenarios and variants will be defined by specifying:
  - an initial state of the engineered barrier system,
  - an initial state of the geosphere and the biosphere,
  - a prescription for the handling of internal processes,
  - a prescription for the handling of external conditions.

8.2 Defining the base variant of the main scenario

8.2.1 Introduction

In accordance with the regulatory requirements, a main scenario covering "the most probable changes in the repository and its environment" will be selected. Within these limitations, a range of possibilities exists regarding e.g. alternative conceptual models of the site and possible external conditions that can not be excluded from the main scenario. The first step in selecting scenarios will therefore be to define a more restricted base variant of the main scenario. As the base variant of a scenario with high likelihood of occurrence, this variant should cover a considerable part of the range of possible outcomes of repository evolution.

8.2.2 Initial state of engineered barriers

It is emphasised that the reference conditions do not reflect an "ideal repository". Rather, the tolerances in the reference conditions do, by definition, include, e.g. buffer density variations that should allow for imperfections in deposition hole geometry and imperfections in the manufacturing process. Also, initial welding defects in the canister seals are included in the reference initial state.

Reference conditions

The initial state encompasses the entire repository with all 4,500 deposition holes. Since the main scenario, according to SKIFS 2002:1, "…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…", the base variant initial state should cover the conditions expected in the entire ensemble of deposition holes. This means, in simplified terms, that if one canister in a thousand is expected to have an initial welding defect, such that the minimum copper thickness is less than the target value of 15 mm, the most likely initial state would include around five such canisters. Furthermore, the range of buffer densities given in the initial state description should be such that it covers the expected conditions in the entire ensemble of deposition holes.

The intention with the reference conditions for the engineered barrier system given in section 3.2 is that they should meet this requirement. The reference condition of the canister includes welding defects and the tolerances of the buffer density have been defined taking imperfections in deposition hole geometry, variations in raw material composition and imperfections in the manufacturing process into account.

The initial state of the engineered barriers for the base variant of the main scenario will therefore be the reference conditions. However, at this stage of the repository programme, it can not be strictly shown that the reference conditions cover every possible mishap or design deviation with a high likelihood of occurrence.

Further management of initial defects/deviations

A detailed definition of the initial state for the engineered system components of the main scenario will require i) identification and description of all potentially safety compromising defects/deviations that could possibly occur and ii) for each defect/deviation *either* a substantiated reason for excluding it <u>or</u> a quantitative inclusion of it in the reference conditions (or, if the likelihood is considered extremely low, as a an alternative initial state).

Identifying deviations

There is a substantial basis for identifying such potentially safety compromising deviations:

- The reference initial state and the initial state FEPs as described in sections 3.2 and 3.5, respectively. The list of variables defining the state of a system component is also relevant in defining a structured approach to identifying such deviations.

- The function indicators identified in chapter 6 and the preliminary analyses in chapter 7 will both aid in determining what should be regarded as "potentially safety compromising deviations".

- Procedures, more or less well established, for how the manufacturing and deposition of the engineered parts should be carried out in a quality assured manner will aid in identifying potential causes of failure and in assigning probabilities to those failure modes that cannot be excluded from further analysis.

The intended function of the system will be maintained if all function indicator criteria given in Table 6-2 are fulfilled. To identify mishaps, deviations from the intended design etc that are related to the initial conditions and that could potentially compromise safety, it must be assessed which initial conditions could lead to an immediate or longer-term violation of a function indicator. The basis for such an assessment comprises the identification and characterisation of the function indicators presented in chapter 6, the results of the preliminary analyses described in chapter 7 and the general understanding of the system by the experts involved in the assessment.

Basis for exclusion or estimation of likelihood in the main scenario

The prime basis for exclusion or an estimation of likelihood is an understanding of the manufacturing and control procedures applied in the manufacturing and deposition of the engineered barriers in the repository. These will include:

- Manufacturing and quality control procedures for the cast iron insert.

- Manufacturing and quality control procedures for the copper canister.

- Procedures for the emplacement of fuel in the canisters.

- Sealing methods for the copper canister and quality control procedures for the seals.

- Procedures for transportation of the canister from manufacturing to emplacement in the deep repository.

- Control procedures for raw materials for buffer and deposition tunnel backfill.

- Manufacturing control procedures for buffer and deposition tunnel backfill.

- Procedures for the emplacement of buffer, canister and backfill in the deep repository.

The approach to handling these matters in SR-Can will be the following:

• A strict analysis of the likelihood of deviations from the reference initial state is not possible since the manufacturing and control procedures have not been defined.

• Based on the preliminary plans for the above mentioned manufacturing and control procedures, it is considered that the most likely case will be that all deposition holes will have engineered barriers characterised by parameter values within the reference ranges.

• This claim will be substantiated by documentation of the preliminary manufacturing and control procedures.

• Deviations of initial state from reference ranges of values for the engineered barriers will thus be excluded from the main scenario.

• A number of deviations will be analysed as residual scenarios. One aim with these analyses will be to determine the robustness of the repository to such deviations. The results of those analyses will be used as feedback to further design work.

Therefore, deviations from reference initial state will not in general be included in the risk summation in SR-Can. Based on the results of the analyses of the residual scenarios, a qualitative discussion will be given as to what likelihood a given deviation would have to have in order to influence the total risk substantially. A first attempt at identifying critical mishaps/design deviations is given in conjunction with the selection of residual scenarios in section 8.6.1.

This approach is in accord with that adopted in many other industrial applications, where, even during operation when the system is well known, an absolute quantification of risk is not seen as realistic. Rather, analyses of the effects of deviations/mishaps etc are used to claim that the likelihoods are acceptably low and to focus further risk reduction work. This is, e.g. the case in probabilistic risk assessments of nuclear power plants.

Finally, it is again noted that many uncertainties are handled within the reference evolution. Regarding, e.g. the peak canister temperature, uncertainties/variability in rock thermal conductivity are handled within the reference evolution, whereas an unintentionally high initial power is regarded as a mishap and included in the variants of the initial state.

8.2.3 Geosphere and biosphere initial state

The initial state for the geosphere and the biosphere will be the base case model (with uncertainties) as described in section 3.3. The site-specific layout will be that described in section 3.4.

8.2.4 Process system

The system of processes governing the evolution in the repository system will be handled according to the information given in the Process report. Uncertainties in process understanding and/or model representation will be handled within the main scenario or, if they impact evolution considerably, be allowed to generate variants as the analysis of main scenario proceeds.

8.2.5 External conditions

Regarding external conditions in the base variant of the main scenario, the climatic reference evolution must encompass all the climate domains and possible transitions between them, as discussed in section 4.2.3. Uncertainties including their causes will be handled as part of the base variant using the method outlined in section 4.2.3. The outcome of the climate analyses relating to the base variant could warrant the generation of additional variants of the main scenario.

As mentioned in section 4.2.1, it is currently not possible to predict the future climate evolution. Neither is it possible to describe an evolution that can be said to be the most likely. It is though very likely that the potential repository sites in a long time perspective will experience periods of all the identified climate domains and all the associated transitions. The reference evolution in the main scenario will, therefore, have to include periods of temperate/boreal conditions including shore-level displacement, both regression and transgression, at different rates, as well as permafrost and glaciation of different extent and also the possible transitions between the domains. A known evolution including all the mentioned components is the Weichselian glacial including the Holocene, i.e. the evolution from about 115,000 years ago to present time. This glacial cycle has been chosen to represent a reference evolution of climate-related conditions in this assessment.

The present climate conditions with a decreasing rate of isostatic uplift are assumed to prevail the first 10,000 years after repository closure. Changing sea levels would also have to be considered. Thereafter, a repetition of the Weichselian glacial cycle as it evolved from 115,000 years ago until the present day is assumed. (115,000 years ago the climate conditions were similar to the present.) For the remainder of the assessment period this evolution is assumed to be repeated.

The reason for choosing the Weichselian as the reference evolution in the main scenario is twofold. Firstly it is the best known of the past glacial cycles and many of the issues of importance for repository performance can be quantified by reference to associated geological information. Secondly the available geological information makes it possible to verify the supporting analysis and modelling efforts aiming at process understanding and studies of the often complex coupled processes related to climate changes.

As mentioned in section 4.2.3 the evolution will be described both in a quasi-stationary manner as a time series of climate domains and as a continuous evolution as the variation of at set of key parameters. For each domain the duration and extreme values of key parameters will be determined and for each transition between domains the importance of rate of change will be investigated. Uncertainties regarding evolution, magnitude of key parameters and rates of change and their causes will be discussed. An example is human-induced warming which may yield an extremely long period of temperate/boreal conditions in comparison to the most recent geological past.

Future human actions other than human induced climate change will be excluded from the base variant and treated as less probable scenarios, see section 8.5.

8.2.6 Summary of main scenario base variant

In summary the base variant of the main scenario is defined as follows:

- Initial state for engineered barriers: Reference initial state (with tolerances).

- Initial state for rock and biosphere: Base case model (with uncertainties).

- All processes handled according to Process report, uncertainties handled within the scenario or allowed to generate variants as analysis of the main scenario proceeds.

- External conditions: Reference conditions, uncertainties handled by sensitivity studies after analyses of reference conditions have been completed. The outcome could warrant more variants.

8.3 Analysis of base variant of the main scenario

8.3.1 General evolution

The base variant of the main scenario will be analysed in two steps:

1. The general evolution of the system with all processes relevant to intact canisters will be analysed.

2. The development, including consequence calculations, of a system in which canister isolation is breached, but with the general evolution as in step 1.

The first step will result in a description of the general system evolution with bounds on the temporal evolution of the state of the system. The following uncertainties will be taken into account:

- Tolerances in EBS reference initial state.

- Process uncertainties handled according to the Process report.

- Data uncertainties in accordance with the Data report.

- Variations/uncertainties in external conditions based on repeated glacial cycles.

Uncertainties in, e.g. the groundwater chemical evolution will result in bounds on the extent of ion exchange in the buffer and backfill which will in turn influence the limits within which the buffer swelling pressure is expected to be found in the long-term.

Should the various uncertainty analyses performed in the integrated assessment of the base variant of the main scenario indicate critical divides in evolution pathways for the system, these phenomena will be considered as variant generating factors meaning that the base variant could be split into several distinct variants. One possible such example, however not expected to be explored, based on results of earlier analyses, is the quantitative evaluation of the erosion process for buffer and backfill. However, if considerable erosion cannot be excluded in the above analyses, the base variant could be split into two where one includes erosion. Alternatively, erosion could be included probabilistically in the main scenario. The latter strategy is advantageous in that the number of variants becomes more manageable, facilitating e.g. the handling of combinations of variants, see below.

Further plans for the analysis of the base variant of the main scenario are given in chapter 11 regarding its general evolution. A first and simplified account of some basic traits of general evolution relevant to this variant is given in chapter 7.

As regards the second step, the development of failed canisters will be analysed with respect to water ingress, corrosion of the cast iron insert under gas generation and the fate of the generated gas. Also, the mechanical evolution of the canister/buffer system as a consequence of decreasing strength, due to corrosion, build-up of corrosion products and gas pressures, will be analysed.

Radionuclide transport and dose calculations will be performed for the barrier conditions resulting from the general evolution and from the evolution of the failed canister. Each variant should be associated with a probabilistic consequence calculation. Additional probabilistic calculation cases will be defined to cover uncertainties not included probabilistically in the base case calculation. Possible examples of such uncertainties are rapid radionuclide transport in the backfill, alternative fuel dissolution models and alternative conceptualisations of the internal evolution of a defective canister.

Further plans for the analysis of failing canisters and consequence calculations for the base variant of the main scenario are given in chapter 12.

8.4 Main scenario; other variants

8.4.1 Variant generating factors

The base variant of the main scenario will, according to the definitions given in the above sections, cover a large part of the system evolution. There are however some factors that should be covered in the "high likelihood" main scenario and that are not included in the base variant:

- Alternative designs options; the alternative backfill material motivates a variant, whereas the alternative buffer material does not. The preliminary analyses in 7.7 indicate that the long-term evolution of the alternative backfill material differs from that of the reference material, whereas this is not the case for the two buffer materials.

- Alternative models of the geosphere. See further section 3.3.19 for a discussion on the handling of alternative conceptualisations of the geosphere.

- Variants generated as the analysis of the base variant proceeds.

This last is obviously an outcome of the analysis of the base variant uncertainties and cannot be further elaborated at this stage. Possible examples of conditions that could be indicated by the analysis are: massive erosion of buffer or backfill during glaciation; massive oxygen penetration during glaciation; massive glacial upconing of highly saline water.

8.4.2 Analysis of variant and residual scenarios

The analysis of the base variant of the main scenario outlined in section 8.3 will constitute a major part of the safety assessment. It will serve as a basis for the analyses of other scenarios/variants which will utilise many of the results of the base variant and focus on the differences controlled by the variant under consideration.

The evolution of the alternative backfill material variant is likely to resemble that of the base variant in many respects with possible exceptions regarding resaturation of the buffer/backfill system, the mechanical interaction between buffer and backfill during swelling at the end of the saturation phase, differences in backfill response to saline water intrusion and in hydraulic properties for radionuclide transport calculations. Much of the evolution of this variant is thus expected to be handled by referring to the base variant.

The evolution of a variant with an alternative conceptual site model defined by an alternative conceptualisation of fracture distribution would resemble the base variant in many respects, with the important exception of details of the hydraulic and transport properties of the system with potentially large impacts on the consequence calculations.

The main case will also be used as a point of departure for the analysis of a number of residual scenarios.

8.4.3 Combinations of variants

For the scenario selection to be comprehensive, combinations of the variants within and across scenarios must be considered. This will be done when all the variants and residual scenarios have been selected and analysed. The number of possible combinations of two or more variant generating factors into more complex variants could become large, even considering that mutually exclusive variants, e.g. mutually exclusive site models, should not be combined, and a practical approach for handling such a situation will have to be found. The problem is further complicated by the fact that each variant may be investigated through a number of calculation cases.

8.5 Less probable scenarios; future human actions

8.5.1 General

According to SKIFS 2002:1, the less probable scenarios should 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. (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."

At the present stage of the analysis, it is not meaningful to separate between uncertainties analysed within the variants of the main scenario and less probable scenarios. Possibly such a differentiation will become meaningful at a later stage. For the calculation of risk it is however irrelevant if a variant is regarded as part of the main scenario or as being a less probable scenario, as long as it is included with its probability in the final risk summation.

Future human actions will be included among the less probable scenarios. The effects of such actions will be analysed as perturbations of the evolution of the natural system as described in the main scenario, and primarily in the base variant.

8.5.2 Future human actions; introduction

This section describes how future human actions (FHA) and in particular intrusion issues will be handled in SR-Can. The suggested handling is largely based on results presented in the safety assessment SR 97 /SKB, 1999a/.

The recommendations related 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…" and further: "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…"

8.5.3 Principles and methods for managing FHA

In principle, three different options are conceivable for managing hazardous waste:

- Dilute it to harmless concentrations and disperse it in the environment.

- Convert it to a harmless form.

- Collect it and keep it isolated from man and the environment.

In Sweden, the last principle is applied to the spent nuclear fuel, as well as to the major part of other radioactive wastes generated by society. The spent nuclear fuel is planned to be encapsulated and placed in a repository deep in the bedrock. This means that the radioactive substances will be collected in one place. If humans disable the repository's barriers, they may be exposed to large quantities of the radiotoxic material. This potential risk is a direct consequence of the chosen disposal principle.

Man is dependent on, and influences, the environment in which he lives. Human actions affect the biosphere and thereby migration pathways for any toxic substances that are present. Human actions – such as irrigation, land drainage, construction of dams and canals – can affect the hydrological boundary conditions for a deep repository. By drilling and building in the rock, or constructing dumps and landfills or carrying out weapons testing on the surface above the repository, humans can affect the mechanical conditions of the rock. The thermal conditions can be affected by extraction/storage of heat from/in the rock.

The list of human actions that could influence the conditions on a repository site can be made very long. Since the future development of human society is basically unpredictable, it can never be made complete. The safety assessment covers only actions:

- that influence the performance and safety of the repository system and that can lead to or affect radiological consequences, and

- that are performed without knowledge of the repository and/or its function and purpose, i.e. inadvertent actions.

The idea of only taking inadvertent actions into account has been discussed and affirmed within the OECD/NEA (Organisation for Economic Co-operation and Development/ Nuclear Energy Agency). They support the principle that the society that produces the radioactive waste should also bear responsibility for developing a safe disposal system. In developing such a system, as much consideration as possible should be given to future generations. However, society today cannot protect future societies from their own actions if the latter are aware of the consequences /NEA, 1995/.

Based on the above, 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 also 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 greenhouse gases are also excluded from the treatment but will be addressed elsewhere in SR-Can.

The background comments to SSI FS 1998:1 state that "it is not necessary, in connection with an application, to investigate issues concerning intentional intrusion into a repository which is sanctioned by society". 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 or the consequences of the action are unknown.

8.5.4 Method

Human actions can affect the repository in different ways. Many factors of differing character such as settlement pattern, type of society, and level of knowledge and technology are of importance for human actions at the repository site. For the purpose of providing as comprehensive a picture as possible of different human actions that may impact the deep repository as well as their background and purpose, the following systematics have been used /Morén et al, 1998/:

A. Technical analysis: Human actions that could influence the performance of the repository are identified.

B. Analysis of societal factors: Societal factors and conditions of importance for whether human actions that influence the safety of the repository will take place are described.

C. Choice of representative cases for scenario construction: The results of the technical and socio-economic analyses are put together and one or several cases that illustrate how some future human actions may affect the repository are chosen.

D. Consequence analysis of chosen cases.

The three first steps are based on work carried out in conjunction with the safety assessment SR 97 /SKB, 1999a/ and summarised below; the last step will be accounted for in the final SR-Can report.

Evaluation of future human actions that may influence the safety of a repository include, considerations of both technical aspects and questions relating to the evolution of society and human behaviour. Examples of such questions are:

- How will technology and science develop?

- What will the future society look like?

- What will human living conditions be?

Answers to these types of questions cannot be found by means of conventional scientific methods. It is, for example, not possible to predict knowledge that doesn't exist today, and knowledge is deemed to be a key factor in this context. To formulate scenarios based on human actions, we have to rely on current knowledge, gathered from people who are alive and active today. An ambition has been to incorporate experience from people with expert knowledge within a wide spectrum of relevant fields. To achieve this, steps A and B above – technical analysis and analysis of societal factors – have been dealt with at work sessions to which experts with different backgrounds and knowledge have been invited /Morén et al, 1998/.

8.5.5 Technical analysis

To carry out step A – Technical analysis – a group of engineers with good knowledge in the fields of geotechnics, geology, geohydrology, chemistry, systems analysis and risk analysis was selected. The technical aspects of human actions on the repository site were addressed at a work session /Morén et al, 1998/. The purpose of the session was to

- Use of basis of current technical knowledge to draw up a list of human actions that could impact the repository system, and

- describe and explain those actions in technical terms.

The human actions in question were to be ones that influence repository performance and are feasible and credible from a technical viewpoint. In order to obtain a systematically structured and relatively complete list of actions, thermal (T), hydraulic (H), mechanical (M) and chemical (C) influences on the repository were systematically analysed.

An inventory of conceivable actions within each category was developed. The actions are presented in Table 8-1. It should be mentioned that most human actions that fit the above description lead to influences within several of the categories T, H, M and C.

Based on the potential influences on the repository, it was also judged which of the identified actions has the greatest influence on the performance and safety of the repository. It was found that actions that include drilling and/or construction in rock are those with the greatest potential influence on the repository system.

A technical assessment of the suitability of the repository site for the actions in Table 8-1 was that it is more favourable for building a heat store or heat pump plant than other places, due to the heat generated by the spent fuel. For the other actions, the repository site is equivalent to, or less favourable than, other places with similar bedrock. Regarding the ore potential of the site, the site investigations and subsequent analyses led to the conclusion that the candidate area can be described as sterile from an ore viewpoint, see further section 3.3.18.

Some other aspects of human actions at the repository site that have to be taken into account are that:

- The possibility of future human actions that might impact the repository has been considered in the repository design and site selection processes.

- In order for an action to be carried out, someone must be willing to pay for it, or it must be expected to yield a profit that covers the costs of carrying it out.

- Both costs and potential profits are coupled to technological progress and overall societal evolution.

- The utilization time for man-made facilities that involve some kind of continuous operation may be from tens to hundreds of years.

Table 8-1. Human actions that can affect a deep repository classified into the categories T, H, M and C /Morén et al, 1998/.

Category	No.	Action
Thermal influence (T)	T1	Build heat storage plant*
	T2	Build heat pump plant*
	T3	Extract geothermal energy*
	T4	Build plant that generates heat/cold on the surface above the repository
Hydrological influence (H)	H1	Drill well*
	H2	Build dam
	H3	Change surface water body's (watercourse, lake, sea) course, size and connections with other water bodies
	H4	Build hydropower plant*
	H5	Build drainage system
	H6	Build infiltration system
	H7	Build irrigation system*
	H8	Change conditions for groundwater recharge by change in land use
Mechanical influence (M)	M1	Drill in the rock*
	M2	Build rock cavern, tunnel, shaft, etc*
	M3	Excavate open-cast mine or quarry*
	M4	Construct dump or landfilling
	M5	Bomb or blast on the surface above the repository
Chemical influence (C)	C1	Dispose of hazardous waste in the rock*
	C2	Construct sanitary landfill (refuse tip)
	C3	Acidify air and land
	C4	Sterilize land
	C5	Cause accident leading to chemical contamination

*) Includes, or may include, drilling and/or construction of rock caverns.

8.5.6 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 /Morén et al, 1998/. A work session was held with experts in the fields of cultural geography, history of science and technology, and systems analysis. So called framework scenarios that describe plausible societal contexts for future human actions with an influence on the radiological safety of the deep repository were formulated /Morén et al, 1998/.

The framework scenarios were developed by means of morphological field analysis /Morén et al, 1998; Ritchey, 1997/, a group- and process-oriented interactive method for structuring and analyzing complex problem fields that are non-quantifiable, contain non-determinable uncertainties and require a judgmental approach.

From the study of societal aspects, it was concluded that it is difficult to imagine inadvertent intrusion, given a continuous development of society and knowledge. Owing to the long time horizon, however, it is not possible to rule out the possibility that the repository and its purpose will be forgotten, even if both society and knowledge make gradual progress. Nor is it possible to guarantee that institutional control over the repository site will be retained in a long time perspective. With a discontinuous development of society, where the development of society and technology contains a sudden, large change, it seems likely that knowledge will be lost and institutions will break down. It is also reasonable to assume that knowledge is lost if society degenerates.

8.5.7 Choice of representative cases

It is probable that the repository site will be used by people in the future. Human actions that influence radiological safety and are carried through without knowledge of the repository and/or its purpose are taken into account in the safety assessment. Actions that influence the isolation of the spent fuel are of the greatest importance for safety, followed by actions that influence the repository's capacity to retain and retard radionuclides if the isolation for some other reason has been breached. Changes in the biosphere influence the doses to which human beings may be exposed if the repository contains leaking canisters.

The repository will be situated 400–700 metres deep in the rock. The reason for this is the wish to locate the repository in an environment where the isolation of the fuel will be retained even in the event of extensive changes on the surface. Changes that have been considered are natural changes and changes caused by man. Examples of natural changes are change of the repository's location in relation to the sea, and the presence of permafrost and ice sheets. Natural changes influence man's opportunities to use the repository site.

Large uncertainties are associated with the development of technology and society. It is not possible to say that any of the actions in Table 8-1 is more representative or plausible than any other. For the same reason, it is not possible to provide detailed technical descriptions of future installations, or to describe the society and living conditions of the future. The choice of scenarios is therefore based on present-day knowledge and experience.

All actions in Table 8-1 influence the migration of radionuclides in the biosphere. However, actions that are performed on or near the surface, down to a depth of a few tens of metres, are judged not to be able to affect the technical barriers and the isolation of the fuel. This applies to the actions T4, H2, H3, H4, H5, H6, H7, H8, H9, M3, M4, C2, C3, C4 and C5 (though some of them could include drilling of relatively deep wells). Activities near the surface that belong to categories M and H are deemed to have less influence on the repository than natural changes in conjunction with future climate change. Of the actions that entail a chemical influence (C2–C5), acidification of air and land (C3) has been studied in most detail. In realistic cases of acidification by atmospheric sulphur and carbon dioxide, the environment at repository depth is not affected /Nebot and Bruno, 1991; Wersin et al, 1994/. Soil layers and bedrock are judged to work efficiently as both filter and buffer against other chemical compounds as well.

Bombing or blasting on the ground surface above the repository (M5) cannot affect the isolation of the waste, except if blasting is done with a powerful nuclear weapon. Such an event is in itself deemed to be highly improbable; moreover the consequence of the blast itself would be much greater than the consequence of leakage from the repository.

Some of the actions in Table 8-1 can – besides influencing radionuclide transport – indirectly influence the isolation of the waste if they render the environment at repository depth unstable. Such actions would have to be performed directly above or near the deep repository and include drilling and/or construction in the rock (M1, M2). These categories include actions that have to do with heat extraction (T1, T2, T3), well drilling (H1) and disposal of hazardous waste in the rock (C1). Hydropower plants (H5) and open-cast mines and quarries (M3) may also involve drilling or rock works at great depth. Before a rock facility is built, drilling is carried out to investigate the rock. What all of these cases share is therefore that – if present day technology is applied – they involve drilling in the rock.

Large rock facilities adjacent to the repository are deemed to be completely out of the question in a short time perspective, i.e. within a few hundred years, for several reasons. For example, the deep repository is itself a large rock facility – the only one of its kind in Sweden – that is very unlikely to be forgotten over such a short time span. Institutional

control can be expected to endure on this timescale. The enumerated actions that encompass major rock works are less likely, based on current technology and economics. In a slightly longer time perspective, i.e. a few or several hundred years or more, it is difficult to predict how knowledge, technology and society will develop, and thereby how and why rock facilities will be built. If construction of deep rock facilities should become commonplace, however, it can be assumed that both construction and investigation methods will have improved compared with current technology. Expanded construction of deep rock facilities would thereby also lead to an increased probability that the repository will be discovered during construction.

Of the actions in Table 8-1, "Drill in the rock" is judged to be the only one that can directly lead to penetration of the copper canister and breach of waste isolation, while at the same time being inadvertent, technically possible, practically feasible and plausible. "Drill in the rock" is furthermore a conceivable action in the light of the results of the societal analysis. Even if it is possible to build a rock cavern, tunnel or shaft or to excavate an open-cast mine which leads to penetration of the copper canister, doing so without having investigated the rock in such a way that the repository is discovered, i.e. without knowledge of the repository, is not deemed to be technically plausible. The case "Canister penetration by drilling" has therefore been selected as the most severe human-caused situation with consequences that are further explored. The consequences on transport pathways in the rock of other human actions will also be considered.

8.5.8   Analysis of FHA cases

The analysis of the drilling case consists of three parts;

- Purpose and realisation of the case;
  Background to why and how the action is carried out.

- Probability that the case will occur;
  Discussion 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. 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.

Also, the effects on radionuclide transport through the host rock will be analysed in a stylised cases. In section 12.6.2 a bounding case, disregarding geosphere retardation, is calculated. This is seen as a useful way of bounding the consequences on radionuclide transport of future human actions involving rock facilities.

8.6   Residual scenarios

According to SKIFS 2002:1, 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."

8.6.1 Mishaps/Initial design deviations outside reference initial state

As mentioned in section 8.2.2, to identify mishaps, deviations from the intended design etc that are related to the initial conditions and that could potentially compromise safety, it must be assessed which initial conditions could lead to an immediate or future violation of a function indicator. The basis for such an assessment are the function indicators presented in chapter 6, the results of the preliminary analyses of chapter 7 and the general understanding of the system by the experts involved in the assessment. A first result of such an assessment is presented in Table 8-2. The result will be used to select residual cases for analysis.

Table 8-2. Examples of deviations from reference initial state to consider in selection of residual scenarios.

Function indicator affected	Potential cause related to initial state	Basis for assessing likelihood	Approach to consequence assessment
Canister			
1. Minimum copper thickness	Welding process outside "process window" on which reference conditions are based. Consider all seals.	Welding procedures and non-destructive testing.	i) Alternative minimum copper thickness distribution as input data for canister corrosion calculation. Propagate to analysis of internal evolution of penetrated canisters.
			ii) Bounding case where all canisters fail at given point in time.
2. Minimum copper thickness	Higher than reference buffer pyrite content.	Manufacturing and control procedures for buffer.	Sensitivity analysis of pyrite content for canister corrosion. Propagate result, in terms of number of failed canisters over time, to consequence calculations.
3. Isostatic pressure on insert	Undetected mishap in casting procedure.	Manufacturing and control procedures for insert.	Sensitivity analysis of canister collapse load for evolution in main scenario. Propagate result, in terms of number of failed canisters over time, to consequence calculations.
4. Isostatic pressure on insert	Higher than reference swelling pressure	Manufacturing, control and deposition procedures for buffer.	See line 3 above.
5. Maximum canister temperature	Higher than intended initial power in one canister.	Procedures for fuel deposition.	Calculate peak canister temperature. Assess consequence of exceeding criteria at canister/buffer interface etc. Assume early failure of this canister in consequence calculations.
Buffer			
6. Hydraulic conductivity	Other than intended material composition	Manufacturing, control and deposition procedures for buffer.	Assess magnitude of deviation required to cause effect on transport properties. Assume canister corrosion with advective transport in buffer and estimate likelihood of failure. Propagate to consequence calculations, assuming advective transport in buffer also for these.
7. Hydraulic conductivity	Lower than intended density	See line 11.	See line 11.
8. Swelling pressure	Other than intended material composition	See line 6 above.	Assess impact on isostatic pressure on canister (if high swelling pressure) or on homogeneity and thereby transport properties (if low swelling pressure).
9. Swelling pressure	Lower than intended density	See line 11.	See line 11.
10. Maximum buffer temperature	Higher than intended initial power in one canister (handled above)	Based on outcome of corresponding canister issue, line 5.	(Probably not an issue, since max canister temperature is a more restrictive requirement.)

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	Function indicator affected	Potential cause related to initial state	Basis for assessing likelihood	Approach to consequence assessment
11.	Buffer density around entire canister	Lower than intended initial dry density of buffer blocks	Manufacturing, control and deposition procedures for buffer.	Calculate or estimate mass distribution in buffer after swelling. Evaluate consequence of each function indicator related to density, e.g. canister sinking to bottom plate, microbially mediated corrosion etc. Propagate to corrosion calculations and further to dose consequence calculations as appropriate.
12.	Buffer density around entire canister	Mishap in deposition sequence	See line 11 above.	See line 11 above.
13.	Buffer density around entire canister	Unrepaired and unfilled fallout in deposition hole	Procedures for handling rock fallout.	See line 11 above.
14.	Buffer density around entire canister	Less than intended backfill deposited above deposition hole (consider both deposition methods)	Manufacturing, control and despoition procedures for backfill.	See line 11 above.
15.	Buffer density around entire canister	Unrepaired and unfilled fallout in deposition tunnel	Procedures for handling rock fallout.	See line 11 above.
16.	Buffer density around entire canister	Buffer saturates and swells before backfill	Criteria for accepting deposition holes and tunnels.	See line 11 above.

Backfill in deposition tunnels

17.	Compressibility	Other than intended material composition	Manufacturing, control and despoition procedures for backfill.	See line 11 above.
18.	Compressibility	Less than intended backfill deposited	See line 17 above.	See line 11 above.
19.	Hydraulic conductivity	Other than intended material composition	See line 17 above.	Assess transport properties, propagate to radionuclide transport calculation case
20.	Hydraulic conductivity	Less than intended backfill deposited	See line 17 above.	See line 19 above.
21.	Swelling pressure	Other than intended material composition	See line 17 above.	See line 19 above.
22.	Swelling pressure	Less than intended backfill deposited	See line 17 above.	See line 19 above.
23.	Limited alkalinity	Construction concrete unintentionally left in deposition tunnel after completed deposition	Procedures for preparation of deposition tunnel.	Assess consequences on long-term stability of buffer and further consequences should the buffer fail.
24.	Limited alkalinity	Unintended composition of concrete in deposition hole bottom plate	Manufacturing and control procedures for bottom plate.	See line 23 above.

8.6.2 Bounding calculations

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. For example, the consequences of omission of a canister-damaging process could be given an upper bound by hypothetically assuming that all canisters fail at a given point in time, e.g. after 10,000 years. A maximum consequence of ineffective geosphere retardation could be established 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.

Examples of cases that could be considered include:

- No geosphere retardation.

- No solubility limits inside canister.

- No backfill, no buffer.

- All canisters fail at time t_1, t_2, etc.

- Unsealed repository.

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

8.6.3 Calculations to develop a design basis

The recommendations to SKIFS 2002:1 state the following: "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, such as 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 thus are not necessarily included as variants of the initial state. Additional calculations cases may therefore be needed to develop the design basis.

8.7 Summary of scenario selection

Table 8-3 summarises the result of the preliminary scenario selection carried out as described in this chapter. As mentioned, the selection of scenarios will be developed as the safety assessment project progresses.

Table 8-3. Results of the preliminary scenario selection. Green cells denote conditions for the base variant of the main scenario, red cells denote deviations from these conditions.

Scenario	Variant	Initial state EBS	Initial state Site	Process handling	Handling of external conditions
Main	Base	Reference ±tolerances	Base case model (with uncertainties)	According to PR	Reference climate + uncertainty analyses No future human actions (FHA)
Main	ACM1 ACM2 etc	As base variant	ACM1* ACM2* etc	As base variant	Reference climate
Main	Alternative backfill material	As base, but alt. backfill mtrl	As base variant	As base variant	Reference climate
Less probable	FHA1, 2, 3…	As base variant	As base variant	As base variant	Reference climate + FHA1, 2, 3…
Less probable	Process alternatives?	As base variant	As base variant	Alt. handling	Reference climate
Less probable	Alternative external conditions?	As base variant	As base variant	As base variant	Alternative conditions
Residual	Open, pumped repository	As base, but open, pumped transportation tunnels etc	As base variant	As base, modified according to IS	Reference climate
Residual	Open, deserted repository	As base, but open, deserted transportation tunnels etc	As base variant	As base, modified according to IS	Reference climate
Residual	EBS initial deviations (several cases)	As base variant	As base variant	As base variant	Reference climate
Residual	Exploration of safety functions	Extreme variations	Extreme variations	Extreme variations	Extreme variations
Residual	Design basis calculations	Possibly additional cases	Possibly additional cases	Possibly additional cases	Possibly additional cases

*ACM: Alternative Conceptual Model (of the site)

9 Hydrogeology

9.1 Introduction

The methodology used for hydrological calculations is presented in this chapter along with illustrative results. The provided information is essential for understanding the results in subsequent chapters. In the SR-Can Final report, much of the corresponding material will appear in supporting reports.

The information in this chapter serves two purposes; first, it is a status report on the development work outlined in the SR-Can Planning report /SKB, 2003a/, and second, some illustrative and site-specific results for use in safety assessment applications for the Forsmark site are presented. The chapter does consequently not follow the structure of the previous and some of the later chapters; rather, it should be seen as an independent account of the hydrogeological and radionuclide transport modelling necessary for further safety assessment analyses within SR-Can. The structure of the chapter mainly follows the one in the SR-Can Planning report.

The groundwater flow and radionuclide migration modelling carried out in SR-Can is a direct extension of the modelling carried out in the framework of the Site Descriptive Modelling of the respective sites /e.g. SKB, 2004e/. The site properties, e.g. the distribution of permeable features and present boundary/initial conditions, are taken directly from the site-descriptive models. Also, some of the modelling teams carrying out the Safety Assessment hydrogeological modelling presented in this chapter, as well as the software products used, are also directly involved in developing the site-descriptive models.

9.2 Flow modelling for open repository conditions

The starting point for the safety assessment is when repository construction begins. Thus, the effects of construction, operation, and transition back to near-virgin conditions after repository closure need to be addressed. Considering groundwater flow, the effects of an open repository need to be analysed, and the time needed for re-saturation after closure needs to be estimated.

The main issues identified for these analyses include, but are not limited to, the following:

- Inflow of groundwater to the tunnel system. Different grouting efficiencies according to specifications from Repository Engineering will be assessed.

- Near-surface drawdown effects such as the maximum influence area due to the open repository. Concerning these effects, there are some unresolved model and numerical implementation issues; specifically, if the drawdown is to be calculated, the models need to be able to handle surface boundary conditions that represent this phenomenon in a relevant manner. Furthermore, additional issues concerning coupling between deep and near-surface groundwater flows may have to be addressed.

- Upconing effects due to the open repository, i.e. the upward movement of water with a higher salinity.

- The turnover of surface water in the upper bedrock. The term turnover is here meant to reflect how many water volumes will be exchanged in the vicinity of the repository during the operational phase. An exchange of water implies that water with a possibly different chemistry will be introduced.

- The re-saturation time for the repository, i.e. how long will it take to return to stable conditions (concerning pressure and salinity fields). It is noted that these conditions not necessarily are identical to those prior to the operational phase. The re-saturation assessment also provides information on initial conditions for the long-term simulations of groundwater flow (specifically, is there a need to consider repository induced effects in these simulations, or are the time scales of these processes short enough to be neglected).

All issues above will be addressed and handled in SR-Can to some extent.

In the SR-Can Interim report, preliminary simulations of generic nature have been carried out. A new CONNECTFLOW model implementation of the Beberg site from SR 97 has been used to address various aspects of an open repository /Jaquet and Siegel, 2004/. Specific objectives have been to study the feasibility of setting up these types of models, and to estimate pressure and salinity effects related to the operational and re-saturation phases of the repository life time.

The strategy for modelling the impact of the repository has been divided into the following four steps:

- At repository scale, a discrete fracture network (DFN) representation of the fractured rock is first made. Stochastic simulation and upscaling of hydraulic properties from repository scale to a continuum representation at local scale are subsequently made.

- Stochastic simulation of hydraulic conductivity at local scale is performed. Replacement of stochastic conductivity values within the repository domain by a uniform equivalent value or by spatially variable equivalent values based on the underlying DFN model is performed. These two alternatives represent different repository implementations in the model, see below.

- Implicit integration of fracture zones is performed; i.e. the effect of deterministic fracture zones are incorporated into all elements intercepted by fracture zones.

- Modelling of density-driven flow in the local model for the repository phases of operation and post-closure is performed.

For the post-closure phase, the repository was assumed to be instantaneously back-filled with a material with specified and homogeneous hydraulic conductivity. The repository was included in the model in two different ways, either as a slab or as individual tunnels, see Figure 9-1 below. For the case with the repository represented as a slab, the slab was surrounded by a repository domain characterised by a single equivalent hydraulic conductivity value. For the case with individual tunnels, the repository domain was characterised by a spatially variable equivalent hydraulic conductivity. For the case with the repository modelled as a slab, two different hydraulic conductivity values of the back-fill were assessed (10^{-10} m/s and 10^{-8} m/s, respectively).
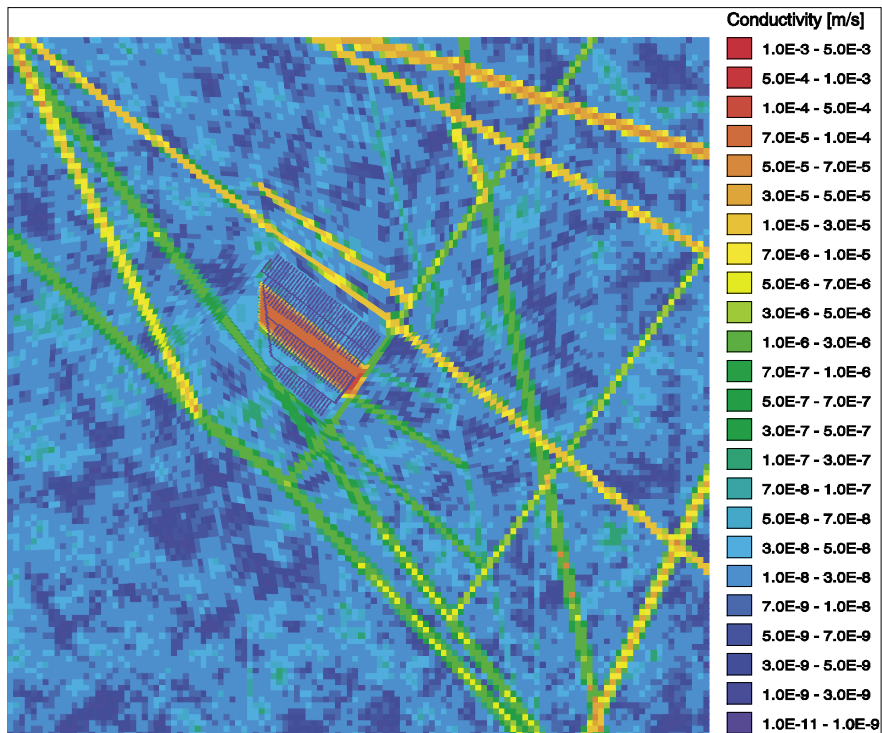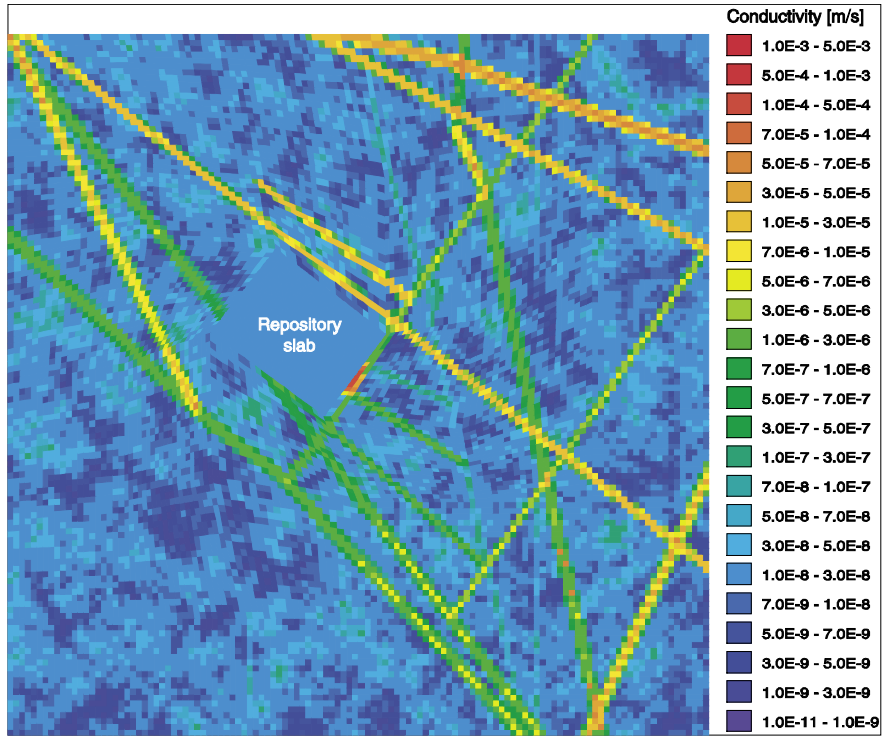
Figure 9-1. *Hydraulic conductivity field (Z-component) with implicit fracture zones for i) reposi-
tory slab within repository domain with uniform conductivity (note that the repository domain
coincides with the slab in the horisontal plane) and ii) repository with tunnels within repository
domain with variable conductivity. Horizontal cut at repository level.*

Three different performance measures were evaluated, namely re-saturation time (in terms of pressure changes), maximum salt concentration at repository level, and total inflow to the repository during the re-saturation phase.

The study showed that it is possible to model a tunnel system at atmospheric pressure in a heterogeneous rock mass using CONNECTFLOW. Specific results from the present study are that a model with the repository included as a slab has a more pronounced impact on resulting pressure and salinity fields. This is due to the fact that the slab constitutes a larger volume than all the individual tunnels summed together. Furthermore, the study indicates that the re-saturation times are short, on the order of twenty years. Increasing the hydraulic conductivity of the backfill has no significant effect on the re-saturation time since the water inflow is controlled by the hydraulic conductivity of the surrounding rock. An explicit description of the tunnels for the repository leads to a reduction of the re-saturation time (corresponding to a period of ca 15 years). This reduction is caused by the reduction of the repository volume which decreases the impact of the repository on the flow field.

The total inflows are calculated assuming no skin factor. The results indicate that the inflows are already steady a few years after repository closure, due to the relatively large hydraulic diffusivity. The salt concentrations at repository level are affected by up-coning during the de-saturation phase, but with the closing of the repository, the up-coning effect gradually disappears and the concentrations are then related to the unperturbed density-driven flow field, see Figure 9-2.

It is important to note that the modelling study performed was a feasibility study using data from a site not included in the site investigation process. Thus, the relevance of the quantitative results may be low; it is rather the methodology that is of interest for further analyses.

Site-specific modelling of an open repository is planned to be performed for both sites within SR-Can. This modeling is to be based on the experience obtained in the study by /Jaquet and Siegel, 2004/. Furthermore, an assessment of modelling capabilities needed for adequately addressing issues related to an open repository will be performed within the time frame of SR-Can. However, some of the expected outcomes of such an assessment will be developed only on a timescale suitable for incorporation within SR-Site.
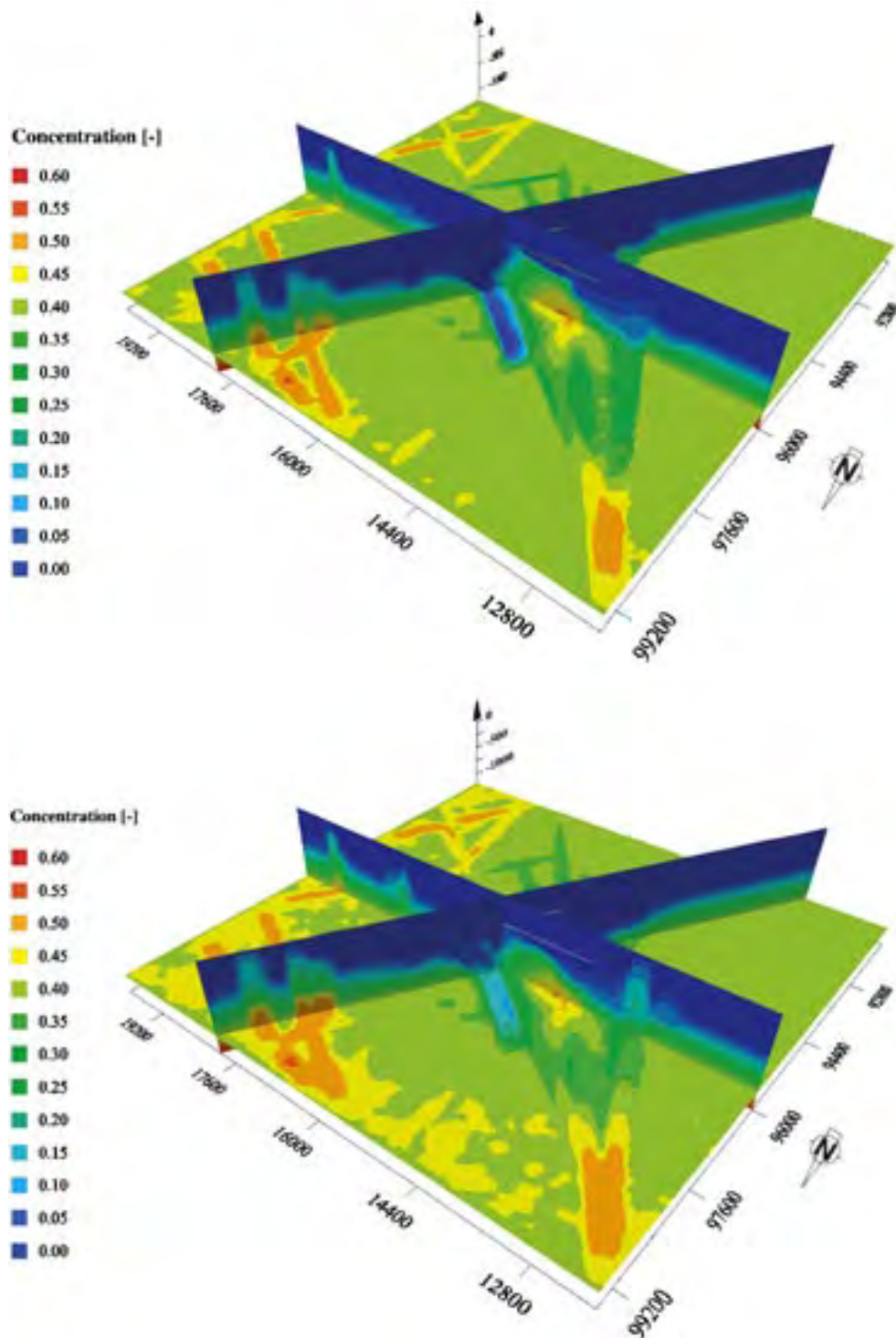
Figure 9-2. *Relative salt concentration after 100 years of de-saturation and 200 years after repository closure. The repository is indicated by a horizontal line in the cuts located between 400 and 420 m below sea level.*

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9.3 Flow modelling for current climate conditions

9.3.1 Strategy for the modelling of long-term flow evolution at Forsmark

In this section, a situation is considered where boundary conditions and included processes reflect the expected development of the geosphere from conditions relevant for a re-saturated repository 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 salinity field development need to be addressed due to the proximity of Forsmark to the Baltic Sea.

Several scales are of interest for the flow modelling, from the regional (length scale 10–100 km), via the local (length scale 1–10 km) and repository scale (length scale 10–1,000 m) down to a canister scale (length scale 1–10 m). Flow modelling is to be performed at all scales for the SR-Can applications.

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 (F-factor) and advective travel time along the flow paths.

The initial state of the geosphere for this modelling is provided through the site-descriptive modelling where results are expressed through the RVS tool and accompanying reports. The historical development of the groundwater flow regimes and salinity distributions are of prime interest in these analyses.

In SR-Can Interim, all groundwater flow modelling is based on the tool CONNECTFLOW /Marsic et al, 2001, 2002/. In /SKB, 2003a/, a number of shortcomings in SR 97 and previous safety assessments are discussed. CONNECTFLOW has been developed and applied to overcome these shortcomings. The main developments in functionality pursued with CONNECTFLOW since SR 97 can be summarised as follows:

- Nested models on all relevant scales can be used. There is the 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 can freely continue in the regional-scale model. Also, the nested modelling approach automatically ensures mass balance.

- There is the possibility to perform transient, density dependent simulations in nested continuum models (but not in discrete models).

- There is the 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/canister scales. Specifically, more detailed input to the near-field transport model COMP23 can be obtained (i.e. equivalent flow rates for the Q1 and Q2 paths in COMP23).

- 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.

These features and functionalities have been used to set up models based on the Forsmark version 1.1 site-descriptive model /SKB, 2004e/. Specifically, in order to demonstrate the groundwater flow and transport methodology outlined in /SKB, 2003a/, a set of nested models has been constructed in order to assess issues on various key scales /Hartley et al, 2004/. These nested models are listed below:

- A regional-scale continuum porous medium (CPM) model containing representations of deterministic large-scale fracture zones, with site-scale hydrogeological properties based on and consistent with an underlying discrete fracture network (DFN) data description. The DFN description has been provided by the site-descriptive modelling project, and is not further discussed here.

- A local-scale DFN model nested within the regional-scale CPM model to assess far-field transport pathways, but also capture the detailed transport pathways through the DFN immediately around the canister deposition holes.

- A CPM representation of the deposition holes, engineered damage zone (EDZ) and tunnels nested within a repository/canister-scale DFN model. This model is used to perform detailed calculations of groundwater fluxes in the DFN adjacent to canisters and in the EDZ, and for input to near-field source-term models.

The strategy outlined above rests on the following assumptions and simplifications:

- Density driven flow can only be handled in the regional CPM model. When flow and transport are modelled in the local-scale DFN, the density needs to be held constant. To ensure that the correct driving force for flow is used in the DFN part, the residual pressure in the DFN model is equated to the environmental pressure in the CPM model at the interface.

- Transport is modelled for "snapshots" in time; i.e. transport is assumed to occur for steady state flow conditions even if transient boundary conditions result in a time-evolving flow field.

- Fracture heterogeneity is not explicitly modelled. No information on intra-fracture heterogeneity is available through the present site-descriptive model /SKB, 2004e/. Instead, flow channelling is indirectly accounted for by using a scaling factor when transport resistance values are used for radionuclide transport calculations; for details, see the Data report /SKB, 2004c/.

- In SR-Can interim, retention in tunnels is not taken into account.

The first issue above can be handled in future analyses also by using the flow code DarcyTools /Svensson et al, 2004/, where the fracture network at all scales is transformed into an equivalent CPM before flow and transport calculations are performed.

The second issue can be handled using models where flow and transport are modelled simultaneously in the same code; an example of such a code is CHAN3D where a first application of transport in a transient flow field has been performed /Moreno et al, 2003/. Supporting calculations to bound the effects of the "snapshot in time" assumption are planned for SR-Can.

Concerning the third issue, generic research on how to best incorporate aperture hetero-geneity into flow models on multiple scales is on-going. However, increased channelling eventually reaches some limiting value after which the effects on transport no longer imply a reduced transport resistance. This is due to the fact that with increased channelling, also the fraction of stagnant water in the fracture plane increases, which in turn effectively increases the matrix access for the solutes.

Concerning the fourth point, retention in tunnels may have to be incorporated into the safety case if site conditions in future analyses imply extensive tunnel transport (not the case in the example in the SR-Can Interim report).

9.3.2 Example results

In this section, some example results based on the developed methodology are shown for illustrative purposes. All results presented below are based on the base case DFN represen-tation of the Forsmark version 1.1 model /SKB, 2004e/. For a comprehensive description of all analyses conducted, the reader is referred to /Hartley et al, 2004/.

Calculation of effective large scale permeability

For the regional scale CPM model, effective permeability values are needed. In SR-Can and SR-Site, large-scale permeability values will also be required by Repository Engineering.

The permeability values are obtained from the underlying DFN model assuming some cut-off truncation value of included fractures. The methods used to assess truncation are i) looking at the resulting distributions of up-scaled conductivity values (or rather equivalent permeabilities) at given block sizes for various truncation values, and using ii) matrix block size statistics. When the first method is used, the desired truncation is obtained when distributions attain stable forms for additionally included shorter fractures. The matrix block size method is based on identifying the directional spacing between fractures at different truncations. When a spacing which is within the chosen numerical block size (element size) is obtained, a reasonable truncation has been found. The final truncation chosen is based on the outcome of the two methods combined.

Figure 9-3 shows how the distribution of up-scaled permeability values depends on fracture length cut-off used.
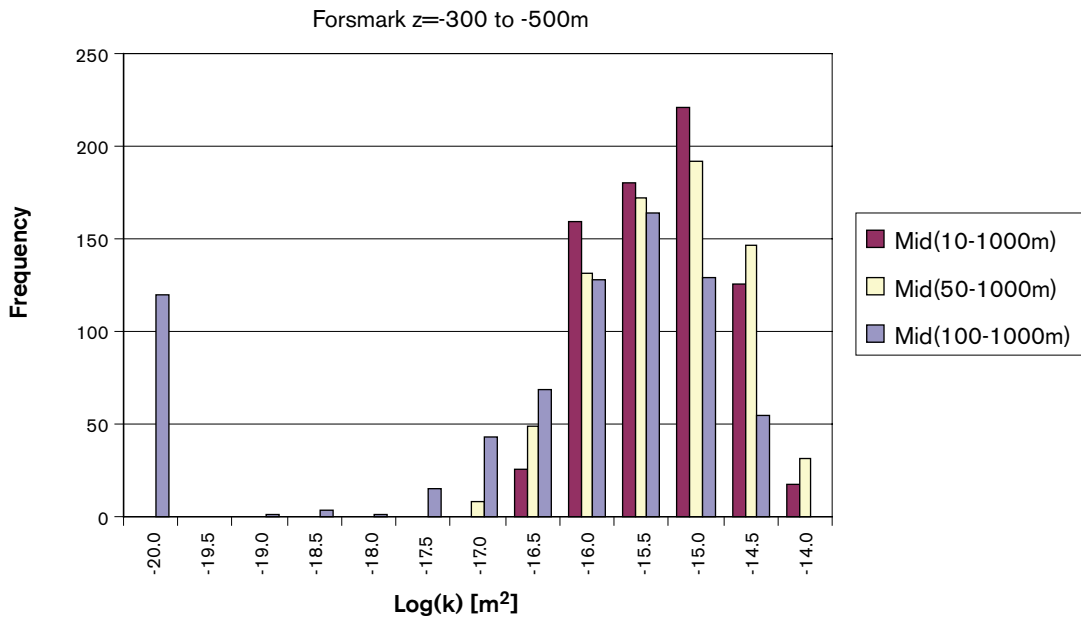
Figure 9-3. *Distribution of upscaled permeability for the middle of the DFN model between z = –500 m and z = –300 m on 100 m blocks. Here, the geometric mean permeability is used as a scalar quantity. Three series of data are shown for the cases with all fractures of lengths 10–1,000 m, 50–1,000 m, and 100–1,000 m.*

Time evolution of groundwater flow and salinity

The main objective of the regional scale model is to describe the time evolution of the flow and salinity fields; i.e. a forward modelling of paleohydrological processes. The salinity field provides, e.g. information on conditions relevant to the repository, see 11.2.6, whereas the pressure field can provide boundary conditions for DFN models where salinity is not explicitly taken into account.

In Figure 9-4, the salt mass fraction plotted on 4 vertical slices through the model domain is shown for two different points in time.
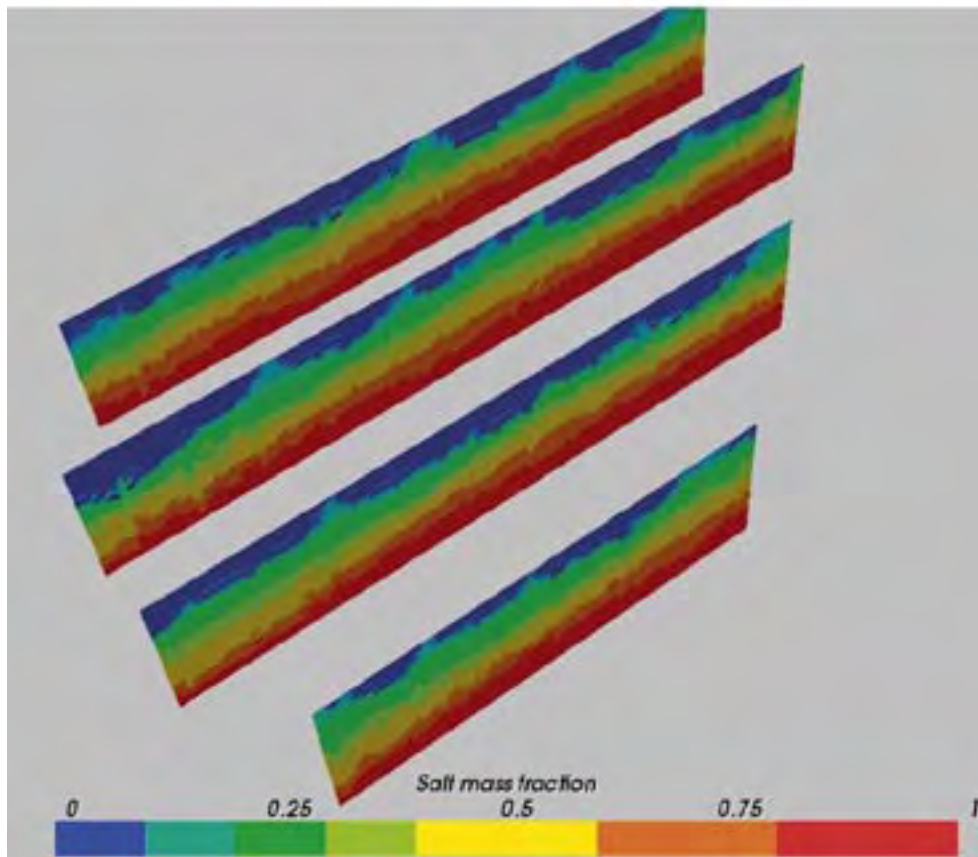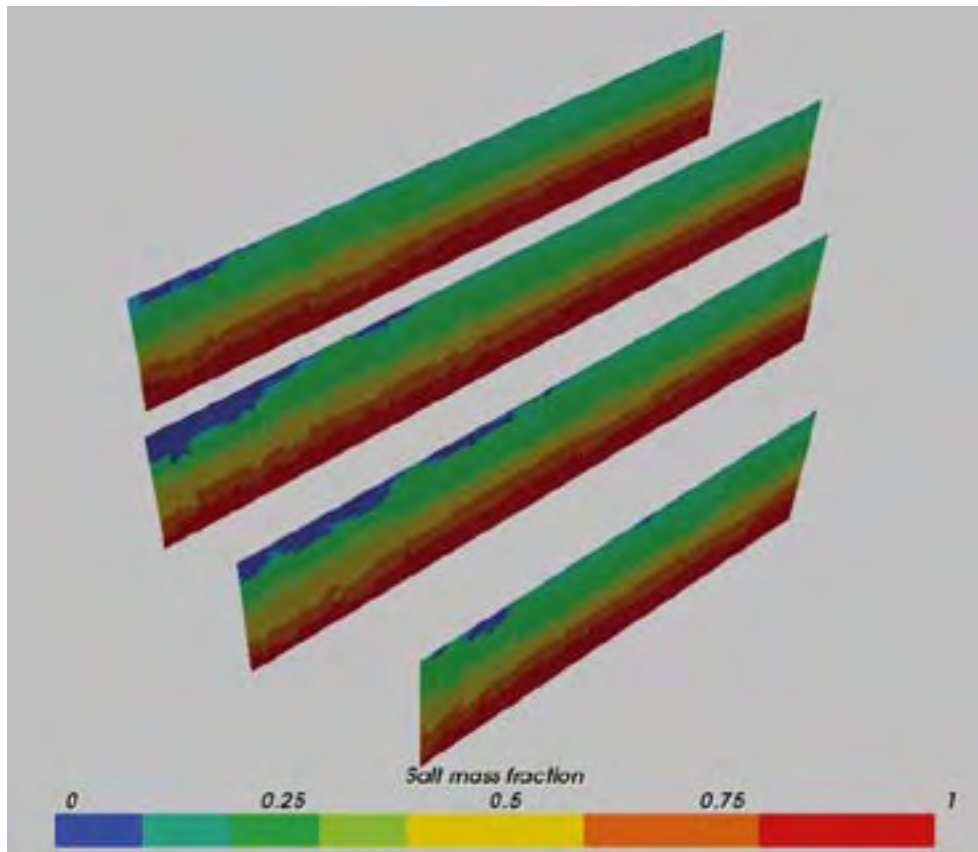
Figure 9-4. *Salt mass fraction on four vertical slices in the CPM model at 2,500 and 12,000 AD.*

Regional-scale migration paths and properties

A CONNECTFLOW DFN model 1,000 m thick (3,800 × 5,200 m in the horizontal plane), and with extra repository-scale fractures in a 60 m thick layer around the repository footprint has been set up.

The repository tunnels are included in the DFN region as vertical fractures with an equivalent transmissivity to represent a backfilled tunnel of specified hydraulic conductivity and cross-sectional area. Using this representation, it is possible to track particles released from designated areas of the repository, initially through the fractures close to the repository and then through the equivalent CPM portion of the grid.

A number of snapshots in time have been generated to assess the sensitivity of transport pathways as time evolves. The important idea is to identify 'critical' times when either repository fluxes or transport pathways show a significant change, e.g. flow in the repository is predominantly up instead of down, or the saline interface drops below the repository.

In Figure 9-5, the nested regional-scale CPM and local-scale DFN model are visualised.

The nested CPM/DFN model is used to carry out particle-tracking calculations for a full set of 5,026 canister locations. Information on discharge location coordinates are subsequently used in the biosphere modelling, see Appendix C.

A complete summary of statistical results for the different variants analysed is presented in the Data report /SKB, 2004c/.
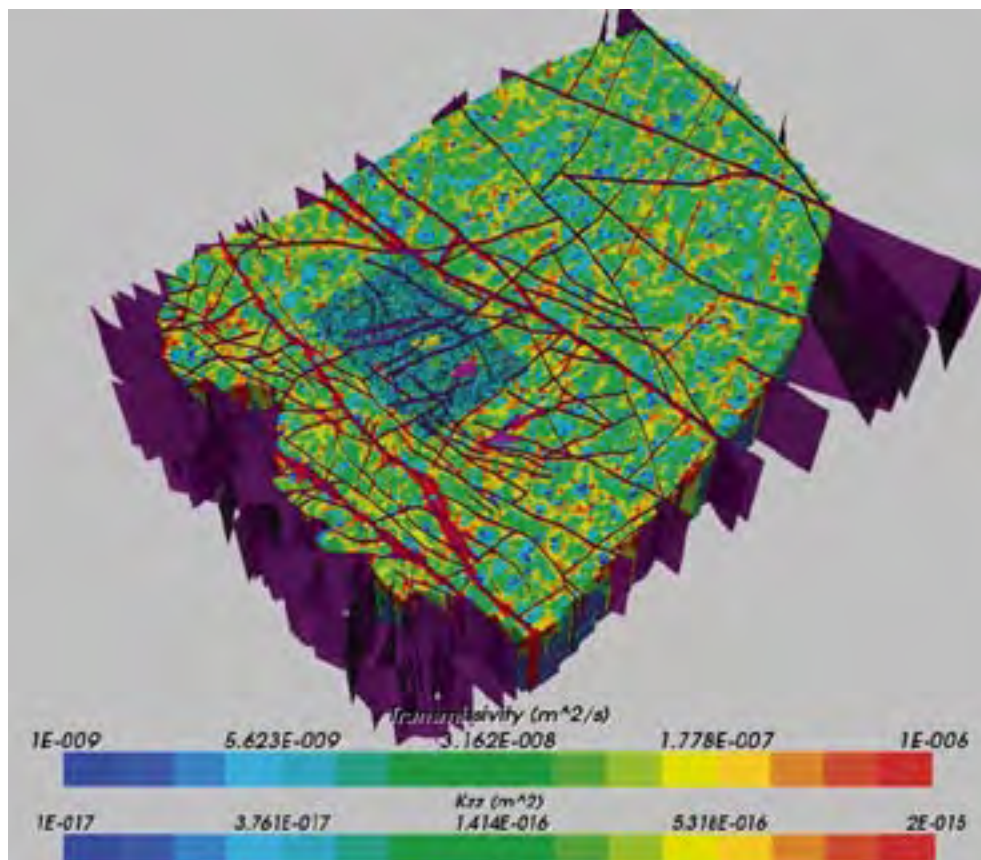
Figure 9-5. *The nested model with the top 2 layers removed to show the central DFN sub-area with the deterministic fracture zones superimposed. The CPM model is coloured by vertical permeability (kzz). For the DFN model, fractures are coloured by transmissivity.*

Canister-scale migration properties

The objective of this step is to construct a repository/canister-scale DFN model with a nested CPM representation of tunnels, deposition holes and the EDZ. In order to demonstrate the methodology, the DFN model has been restricted to a sub-region of the repository at the south-eastern corner containing 604 canisters. The CONNECTFLOW model consists of a CPM model describing the repository structures (tunnel, deposition holes) within a DFN model.

The purpose is to calculate two pathways for each canister: one starting in a fracture intersecting the deposition hole (corresponding to the Q1 path in COMP23), and one in the tunnel immediately above the canister (corresponding to the Q2 path in COMP23). For each path, initial fluxes are calculated and then transformed into the equivalent flow-rates used by COMP23.

The modelling is again based on steady-state calculations, but with environmental pressure boundary conditions transferred from the regional transient CPM model at appropriate times. The entire model is 100 m thick and covers an area of 590 m × 410 m.

The key issue with this model is to develop an understanding of the canister fluxes. The repository structures surrounded by the repository/canister-scale DFN model are shown in Figure 9-6.
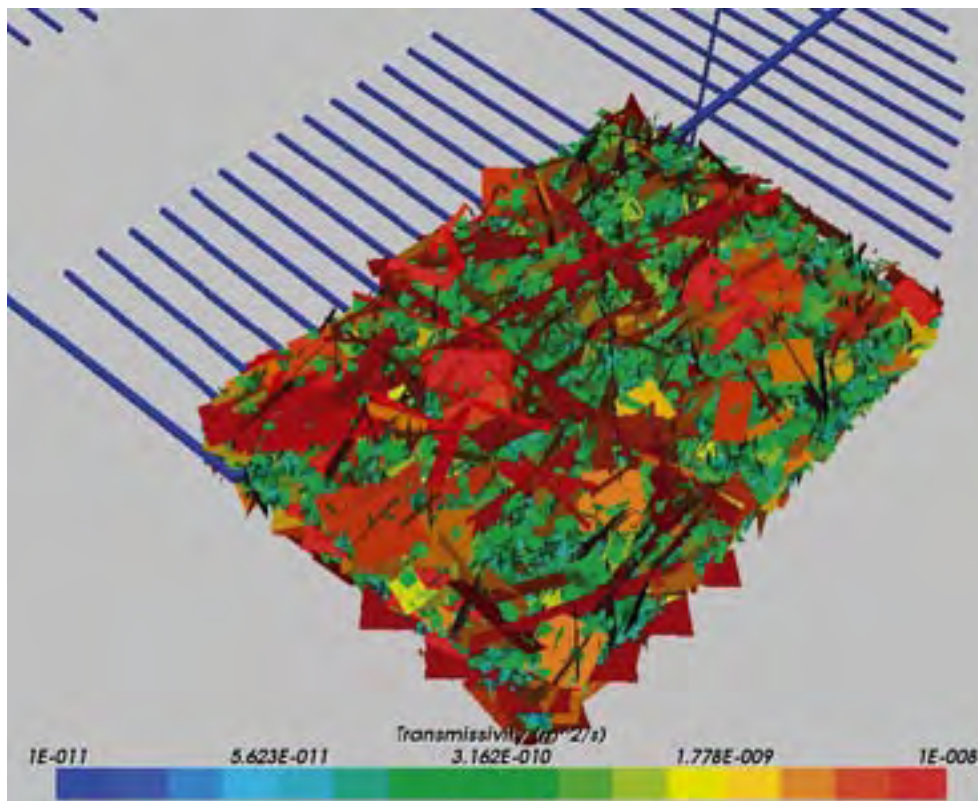
Figure 9-6. *The DFN sub-model for the nested repository/canister-scale model. The fractures are coloured by transmissivity, and part of the repository tunnels is shown in the background.*

The results from the groundwater flow calculations, i.e. the pressure distributions, are used to calculate particle tracks through the repository/canister-scale model.

Figure 9-7 shows a plot of particle tracks for particles released at all 604 canister locations and transported by the flow field calculated for 2,500 AD. The tracks are coloured according to travel time in the regional-scale nested model. The plots show two broad groups of pathlines arising from the south-east corner of the repository. The first group comprises paths that rise almost vertically to the surface, discharging above the repository in less than 100 years (red coloured paths in the south-east of the plot). The second group comprises paths that are transported a significant distance within the fracture network, eventually discharging to the sea bed after on the order of 10,000 to 100,000 years (blue paths to the north of the model).
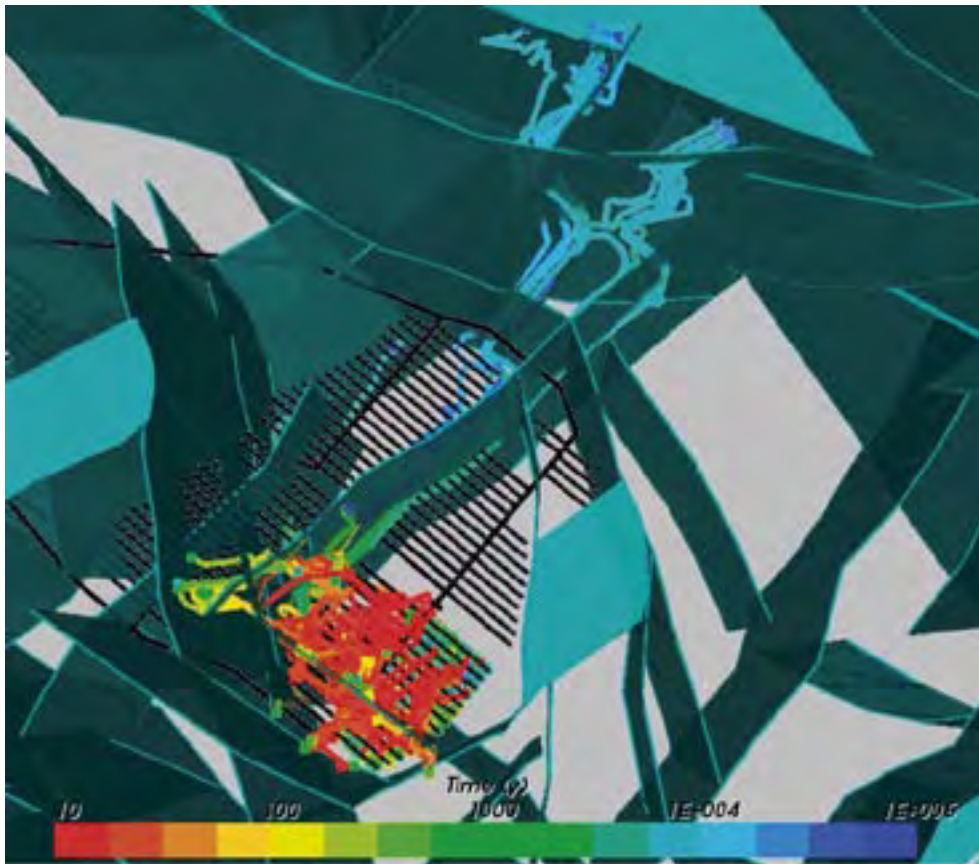
Figure 9-7. *Particle tracks in the nested model for particles starting in the 604 canisters in the south-east corner of the repository at 2,500 AD. The paths are coloured by travel time along the path in the regional/local-scale nested model.*
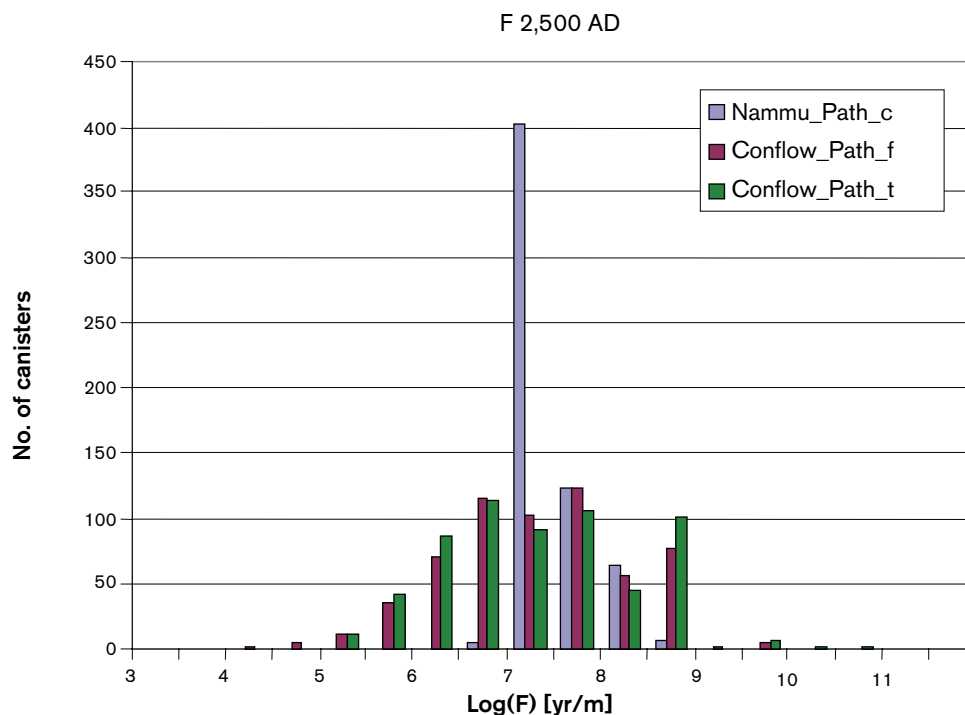
Figure 9-8. *Distribution of F-factor in the nested model with a release from 604 canisters at 2,500 AD. The three cases shown are for the CPM model (denoted Nammu_Path_c), nested model for the Q1 path (denoted Path_f), and the nested model for the Q2 path (denoted Path_t).*

In Figure 9-8 above, the resulting transport resistance is shown for the two different paths (Q1 and Q2), and for a path calculated in the regional CPM model. The pure CPM model path corresponds to the type of results obtained in previous assessments where nested models and DFN representations were not used.

It is clearly seen in Figure 9-8 that the CPM model provides a much narrower distribution of F-factors. That is, the new methodology provides both smaller and larger values of F, whereas the central value does not change much.

Summary of findings in the example calculations

In the original DFN interpretation of the Forsmark version 1.1 model /SKB, 2004e/, the fracture network connectivity is relatively good. The most important conclusions for this case are as follows:

- A cut-off in fracture length of about 50 m can be used for deriving the equivalent CPM permeability distribution for 100 m blocks.

- Fractures down to about 3 m have to be included on the canister-scale to adequately represent the near-field flows.

- Natural transients have a significant effect on results due to differences in head and salinity at 2,500 AD and 12,000 AD. Future freshwater conditions imply shorter paths.

- The developed methodology provides greater probability of many canisters being in 'safe' areas away from high permeability features.

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- The two paths considered (paths starting in fractures and in the tunnel, respectively) are similar. This is likely due to fractures being the dominant pathway, and so particles starting in the tunnel tend to enter the fracture system after only a short distance.

- Higher hydraulic conductivity backfill focuses more flow through the repository, reflected in higher flow rates.

For the updated DFN interpretation, the fracture network connectivity is relatively poor. The general conclusions for this case are listed below:

- A cut-off in fracture length about 20 m can be used for deriving the equivalent CPM permeability distribution for 100 m blocks.

- Fractures down to about 1 m have to be included on the canister-scale to adequately represent the near-field flows.

- Natural transients have a secondary effect on results. Flow rates and pathways are more determined by the local fracture connectivity around the deposition tunnels.

- The tunnel provides a dominant local pathway for transport even with a low backfill conductivity of 10^{-10} m/s. As well as providing a major conduit for flow, the tunnels also connect up localised fracture clusters that would otherwise be inaccessible to site-scale flows.

- Only about 60% of canisters are intersected by the connected fracture network.

- There is little difference between the two paths in terms of far-field results.

- Also for this case, the developed methodology provides greater probability of many canisters being in 'safe' areas away from high permeability features.

Future development needs

The methodology should not be viewed as entirely complete. It is suggested that in the next phase of SR-Can the following issues, in addition to the issues related to assumptions listed at the beginning of the chapter, should be addressed:

- The Engineered Damage Zone (EDZ) should be modelled explicitly in the canister-scale model and greater mesh resolution should be used to resolve transport in the tunnels especially for poorly connected networks where the tunnel dominates local flow and transport.

- The canister-scale models should include all canisters explicitly.

- Consideration has to be given to alternative fracture conceptual models and interpretations.

- The sensitivity to the structural model in terms of confidence of structures needs to be addressed.

- A verification of the pathways and transport statistics against a refined CPM model at the local-scale would be valuable to support the approximation of solving for constant density in the DFN model but coupled to environmental pressure.

- An approach needs to be found that is more robust for handling transport in the dead-end fracture clusters that occur in sparse networks.

- If CPM models are still to be propagated through the safety assessment then the spatial distribution of fracture porosity and flow-wetted surface area should be derived from upscaling DFN models in a similar way currently adopted for permeability.

9.3.3   The geosphere-biosphere interface zone and treatment of wells

The geosphere-biosphere interface zone (GBIZ) refers to the zone where a coupling of near-surface and deeper groundwater flow models needs to be accounted for. The zone is overlapping in the sense that models for the deep groundwater flow cover a domain all the way up to the ground surface, whereas biosphere and surface hydrological models extend to some depth into the soil and bedrock. The zone is also characterised by steep gradients in chemical and biological conditions, which in turn may require special attention in the modelling of this zone. However, these latter aspects are typically handled in the biosphere models in the SR-Can Interim application.

In the following, a conceptual model is presented for how the GBIZ will be handled from a hydrogeological point of view in SR-Can. Essentially two different types of discharges are considered; namely into a waterbody or the terrestrial environment, and into a well.

Discharge into a waterbody or into the terrestrial environment

Various studies suggest that the discharge from the repository is confined to a limited number of discharge areas at topographical low points, generally water bodies such as lakes, the sea and wetlands e.g. /Holmén et al, 2003; Holmén and Forsman, 2004; Brydsten, in prep/. Furthermore, the water bodies and wetlands usually are correlated to the location of major deformation zones in the bedrock /Brydsten, in prep/.

Figure 9-9 displays a conceptual picture/model of how the discharge of radionuclides from the deep rock enters the biosphere and mixes with surface waters and shallow groundwater.

An implication of the studies by /Holmén et al, 2003; Holmén and Forsman, 2004/, as summarised in /SKB, 2003a/, is that the horizontal movement in the near-surface groundwater zone is of minor importance for the location of the discharge points, i.e. the exit point results of the deep groundwater modelling can be used directly for biosphere modelling (no separate near-surface groundwater flow model is needed for the transfer of information). However, there is a need for a surface hydrological flow model to estimate surface and near-surface groundwater flows and thus mixing and dispersal in the biosphere.

The further migration in the biosphere of the discharging radionuclide flux depends essentially on the properties of the bottom sediments of water bodies, primarily lakes but also the sea. If the bottom of the water body is pervious, the discharge will pass through the bottom and enter the water body, see Figure 9-9. In this case, the GBIZ is handled numerically such that an intermediate radionuclide concentration in the water body is first calculated as the ratio of the radionuclide flux to the volumetric flow rate of the water body. Different accumulation reactions in the sediments, e.g. sorption, precipitation and biological uptake, are subsequently handled in the biosphere models, for details see Appendix C. These reactions will influence the calculated resulting radionuclide concentrations in the water phase of the water bodies.

If the bottom sediments are impermeable, the discharge will be diverted to the shore line where it will mix with the near-surface groundwater flow and surface runoff, see Figure 9-9. However, in some cases diffusion into relatively impermeable bottom sediments and/or into
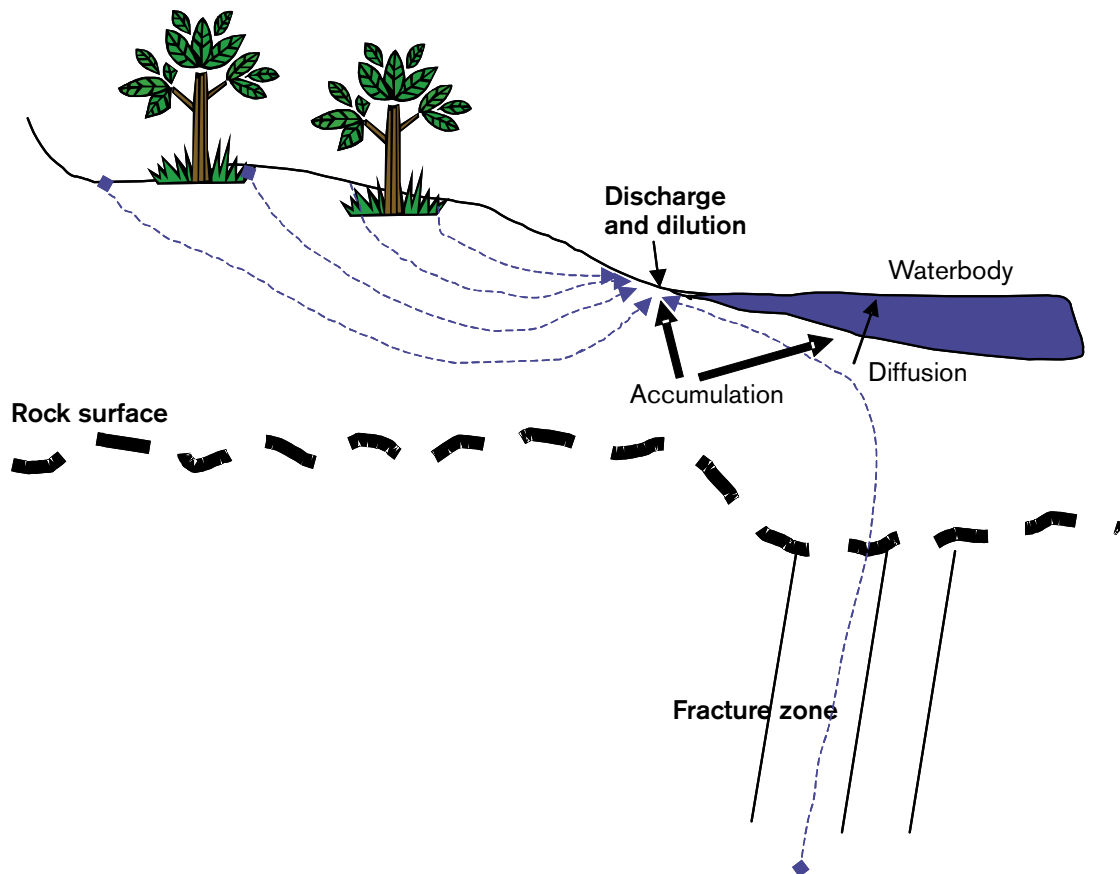
Figure 9-9. *A conceptual picture/model of how the discharge of radionuclides from the deep rock enters the biosphere and mixes with surface and near-surface waters.*

the water body through the bottom can be significant for radionuclides /Elert and Argärde, 1985; Elert et al, 1988/. At the shore line, accumulation can occur through precipitation in an oxidising environment, sorption to organic material and uptake by plants.

To conclude, at the most simplified level the GBIZ is handled such that the radionuclide flux from the models for deep groundwater flow and transport are directly imported into the models for the biosphere where subsequent accumulation reactions (including possible later release if conditions change) are dealt with. The only additional information needed is the near-surface water discharge. This information is readily available from the type of surface hydrological models that will be developed during the course of SR-Can. However, in the SR-Can Interim report, the surface water component (runoff) at radionuclide discharge locations is estimated from GIS information only, see Appendix C.

The flow available for dilution at a point at the shore is thus approximated by the total flow in the local catchment area that is associated with a discharge at that point, i.e.

$$C_i = R_i / Q_{catchment}$$

where R_i is the radionuclide discharge from the rock (Bq/yr) and $Q_{catchment}$ the (hypothetical) runoff from the catchment area if there was no net infiltration to the deep rock. The assumption of no net infiltration will not be needed when more advanced surface hydrological tools are applied.

For the final version of SR-Can, the surface runoff will likely be estimated with greater precision using more advanced surface hydrological models, e.g. MIKE-SHE /DHI, 2003/. This type of model can also provide information on path line characteristics for radionuclides that are transported through the near-surface environment. Specifically, it may be possible to assess whether the simplified conceptual model proposed in the SR-Can Interim report is valid, or if horizontal transport in the quaternary deposits is of greater relevance than indicated by /Holmén and Forsman, 2004/. Also, it may be possible to incorporate retention processes such that some aspects of radionuclide fate in the quaternary deposits can be directly modelled in the surface hydrological tool.

Discharge into wells

Simulation of wells can be of interest for safety assessment for at least two reasons; first, the volume of rock influenced by a well (capture zone for migrating radionuclides) can be used to assess the risk for harmful intakes, and second, dilution in the well is of interest for calculating the resulting concentrations.

In the SR-Can Interim report, no flow simulations of wells will be performed. Instead, a simplified approach will be utilised.

Depending on the position and production of the well, it may capture more or less of the water released from the rock and thereby also capture more or less of the dissolved radionuclides. This means that the concentration of radionuclides in the well is given by:

$$C_i = R_i F(Q)_{capture}/Q_{well}$$

where R_i is the radionuclide release from the deep rock, $F(Q)_{capture}$ is the plume capture fraction, i.e. the portion of the release which also enters the well, and Q_{well} is the well abstraction rate.

Issues to determine are thus the capture and pumping (well production) rates. Conservatively, it is assumed in the SR-Can Interim report that the capture fraction is 1.0 for an individual canister. Surface hydrological modelling, as indicated above, may in due course provide additional information concerning this assumption. One may hypothesise that the capture rate in fact is much lower, but possibly also that releases from several canisters may be captured by a single well. The pumping rate needs to be determined from consideration of maximum production rates for wells typical of the area, and considerations concerning daily usage (consumption) figures for private wells. It can be expected that the capture fraction is strongly dependent on where the well is installed, on its flow rate relative to the net infiltration, and on local topographic and hydrogeological conditions.

In the SR-Can Interim report, values for maximum production will be used for calculating the relevant well water concentration. For the SR-Can Final report, additional information is to be summarised on well usage in the site investigation areas.

9.4 Transport modelling for current climate conditions

Radionuclide transport in the geosphere is calculated in SKB safety assessments using the code FARF31 /Norman and Kjellbert, 1990; Elert et al, 2004/. 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 (including decay chains). The scientific reasoning and motivation for both included and disregarded processes will be provided in the Process report to be published as part of SR-Site. It is noted that on-going and planned research /SKB, 2004f/ addresses the basis for possible additional retention processes to be included quantitatively in the Safety Case.

A number of conceptual issues related to the one-dimensional stream tube concept are discussed in the SR-Can Planning report /SKB, 2003a/. No changes in concepts or methodological development have taken place since the planning report; hence, no additional information is provided here.

9.4.1 Colloid-facilitated migration

In SR 97, colloid-facilitated migration was not included as a transport mechanism for radionuclides. The reason for disregarding this was mainly that the concentrations of colloids in Swedish groundwaters are low enough for the effect of colloids to be negligible. However, based on transport data from the SR 97 assessment and colloid migration data from the Nevada test site (where rapid migration of relatively immobile plutonium has been suggested to be caused by colloid facilitated migration), /Klos et al, 2002/ conducted a study where the potential effects of colloids on transport for Swedish conditions were shown. In order to better understand the effect of colloids under Swedish repository conditions, the conceptualisation used by the FARF31 code for radionuclide migration in the geosphere (advection and dispersion in a stream tube with transverse diffusion into the rock matrix) has been discretised /Vahlund and Hermansson, 2004/ using the finite volume method and colloids have been added as a transport mechanism.

Pending reliable input data, the new code (FVFARF) has been tested against FARF31 and Collage II (a corresponding code /Hicks, 2003/ that allows for colloid-facilitated migration to be included). Figure 9-10 shows the results (based on the Collage II C999 test case) for a case with colloid-facilitated migration and fast sorption/desorption rates between radio-nuclides on colloids and the solute. It can be seen that the agreement between the two codes is, in general, excellent, except at large times where there is a significant difference. This difference is related to how the codes treat the transverse boundary conditions. Whereas the FARF31 conceptualisation assumes a maximum distance that a nuclide may diffuse in the transverse direction, the penetration depth, the CollageIIPlus code assumes an infinite penetration depth.

For the SR-Can Final report, the impact of colloids will be further studied.
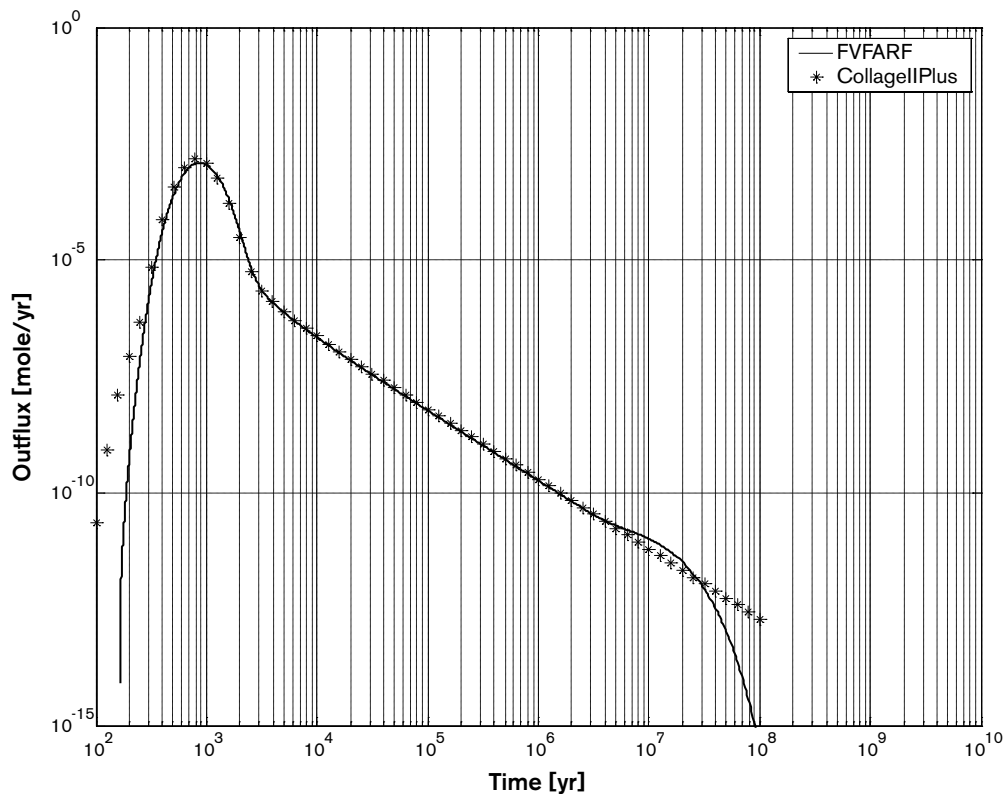
Figure 9-10. *Comparison between FVFARF and CollageIIPlus for a case with rapid sorption-desorption from mobile colloids ($\kappa_1=1$ y^{-1}) and slow sorption-desorption from immobile colloids ($\kappa_2=10^{-6}$ y^{-1}). Radionuclides enter the fracture in the solute phase.*

9.5 Groundwater flow and radionuclide transport modelling for climate scenarios

In the SR-Can Planning report /SKB, 2003a/, current tools and development needs concerning groundwater flow and radionuclide transport models are described 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. Below, planned activities for the SR-Can Final report are described. It is noted that no simulations are performed and no results presented for the SR-Can Interim report.

9.5.1 The temperate/boreal domain

The temperate/boreal domain is typically handled in most detail in current Safety Assessment studies (relative to the other two domains).

The simulations presented above, i.e. the developed methodology for the long-term evolution of the groundwater flow field, specifically addresses the conditions of the temperate domain. Thus, this domain is considered to be adequately handled through the development presented above.

9.5.2 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 a few hundred meters depth.

Other issues to consider include taliks where high solute concentrations may prevail, the dilution at the surface during summer periods, and the possibility of enhanced radionuclide concentrations in solution due to the expulsion of solutes, including radionuclides, from the developing ice.

In SR-Can, a modelling study will be conducted where the impacts of a permafrost region with a high salt concentration below the permafrost will be studied. The intention is to combine generic and some site-specific issues in the modelling study. Specifically, issues related to the time-scale of downward transport of salt from the bottom of the permafrost region to repository depth will be studied. Also, the resulting salinity field is of interest; the evolution of the salinity field mainly depends on the groundwater flow situation, which in turn depends on flow boundary conditions and hydraulic properties of the site.

A modelling study of permafrost depth evolution /Hartikainen, 2004/, see also section 11.4.1, will provide input data for the planned hydrogeological analysis.

9.5.3 The glacial domain

The changes in the geosphere and the geosphere's surroundings will be much greater for the glacial domain than for the permafrost domain. Two alternative options seem possible in order to handle this domain: a simpler version where changes are represented through alterations in parameter values and boundary conditions, or a more comprehensive analysis where the changes are directly simulated in the groundwater flow model.

The simpler option will be pursued in SR-Can, whereas the more comprehensive analyses remain research topics. With the simpler approach, the glacial domain primarily implies changes in parameter values 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. 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 is to obtain relevant boundary conditions reflecting the glacial environment. Large-scale ice-sheet models are developed in order to be able to provide the boundary conditions needed, see section 11.4.1.

A modelling study /Jaquet and Siegel, 2003/ has been performed with CONNECTFLOW where a slightly modified glaciation case from SR 97 was recreated. The analysis performed was mainly a feasibility study assessing the potential of the code to represent groundwater flow during a glaciation. This study will form a basis when up-dating the conceptual glaciation model with relevant, site-specific boundary conditions and parameters for the planned SR-Can analyses. The objective is to perform modelling studies for both the Forsmark and Oskarshamn sites. The modelling will likely be performed on a scale larger than the regional scale presently used in the site modelling projects.

9.5.4 Coupling between groundwater flow/transport and related disciplines

For issues related to coupled processes, specifically hydro-mechanical process coupling, the reader is referred to section 10.4.

Couplings between groundwater flow and geochemistry are possible to make based on the paleohydrogeological simulations presented in section 9.3.2 (Time evolution of groundwater flow and salinity). The geochemical evolution and its relation to groundwater flow are also discussed in section 11.4.8.

10 Handling mechanical and coupled hydro-mechanical issues

The impact of mechanical and coupled hydro-mechanical processes on the repository might range from slight alterations of the hydraulic properties of the geosphere to jeopardising the integrity of the canister. Some mechanical and/or coupled hydro-mechanical processes are initiated by the excavation of the tunnel system. Other processes initiate as a response to the deposition of canisters, which generate a thermal pulse. Yet others are the result of glaciations and plate tectonics.

Geomechanical processes might alter the retention capabilities of the geosphere, but the primary concern is the integrity of the canister. In particular, shear movements along fractures that intersect deposition holes have the potential to damage canisters. Therefore, the main focus in this chapter is rock shear movements and their potential impact on canister integrity.

The approach to handling this problem and other mechanical and hydro-mechanical coupled processes in the safety assessment SR-Can is described. However, much of the material presented is under development and, especially quantitative, conclusions are preliminary.

10.1 Rock shear movements at deposition holes

The function of the canister may be jeopardised due to shear displacement, i.e. faulting, along fractures that intersect deposition holes. Faults occur on all scales ranging from microscopic crystal dislocations to meter scale slip along regional deformation zones. However, only shear movements large enough to cause any damage on the canister or buffer are really of interest. The first subsection below aims at establishing this minimum slip of interest.

Reactivation of a deformation zone or fracture, regardless of scale, can in short be said to occur as a response to perturbations of the load (magnitude or direction) or changes in friction on the fracture plane. The faulting can either be seismic, where episodic slip attains mean velocities of the order of m/s, or aseismic where continuous slip may attain velocities of the order m/year. An earthquake occurs when strain energy, accumulated by tectonic or other processes active in the brittle crust, is suddenly released by shear motion along a planar discontinuity in the rock mass. The question is thus if such accumulation of strain energy can be anticipated at the candidate sites. Seismic events could be characterised as either natural earthquakes, i.e. tectonic- and glacioisostatic earthquakes or induced earthquakes, i.e. seismic events caused by the excavation and by the thermal pulse from the canisters. The following types need to be considered.

1. Seismic events, earthquakes, induced by underground excavation activities. These earthquakes are triggered by stress perturbations due to the presence of an underground opening and might occur in rock volumes with initially high stresses, usually at greater depth than planned for the repository, and in rock with a low degree of fracturing.

2. Seismic events induced by the thermal load.

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

4. Glacio-isostatic earthquakes. Such earthquakes, commonly referred to as "post glacial faults", are anticipated to occur during or shortly after any future deglaciation.

These different causes for earthquakes and shear movement are further discussed in subsequent subsections.

The KBS-3 system is designed such that canister positions are avoided within, or in the immediate vicinity of, major deformation zones capable of accommodating significant slip. Such structures are to be av, therefore, not the primary concern in SR-Can. However, an earthquake, regardless of origin, occurring on a deformation zone near or within the repository might trigger reactivation on smaller scale structures nearby. The final subsections of this section will explore respect distances from structures along which the earthquake could be located, "primary faults" and the resulting potential slip in fractures, "target fractures", which could intersect deposition holes. This will allow assessing the likelihood of shear movements potentially damaging the canister.

10.1.1 Behaviour of canister and bentonite exposed to faulting

The need to be able to assess the extent and likelihood of faulting on fractures crosscutting the deposition hole, evidently would depend on how much slip the buffer and the canister could accommodate without impairing their isolation functions. Numerical simulations have been carried out to address this particular issue.

The effects of faulting on buffer, copper shell and cast iron insert along a fracture intersecting a deposition hole have recently been analyzed numerically /Börgesson et al, 2004/. Laboratory tests were performed to determine relevant material properties for the buffer for the modelled situation.

The finite element code ABAQUS was used for the calculations. Figure 10-1 shows the resulting deformation after 20 cm rock displacement of the entire model, which consists of three different parts (bentonite buffer, copper canister and cast iron insert). The rock is not modelled but assumed to be completely stiff.

Shear rates up to 1 m/s, buffer densities up to 2.1 g/cm³ and net slips up to 20 cm were simulated, i.e. covering a much wider and tougher range of conditions than in SR 97. The results from the study indicate that the consequences of faulting across a deposition hole depend strongly on the density of the bentonite, but also on the location of the fault in relation to the centre of the canister. A fault intersecting at canister mid-height has less severe effects than a fault located off centre. However, immediate failure of the cast iron insert or copper canister predicted was not predicted even in the most extreme conditions studied.

The analysis provides the stress and plasticization state of the copper shell, the insert and the buffer immediately after shearing. A summary of the results is given in Table 10-1. The table shows the maximum plastic strain ε_p in the copper tube (excluding the lid), the rock shear displacement δ_p when the plasticization of the cast iron insert starts and the maximum plastic strain ε_p at three different slips (5, 10 and 20 cm).
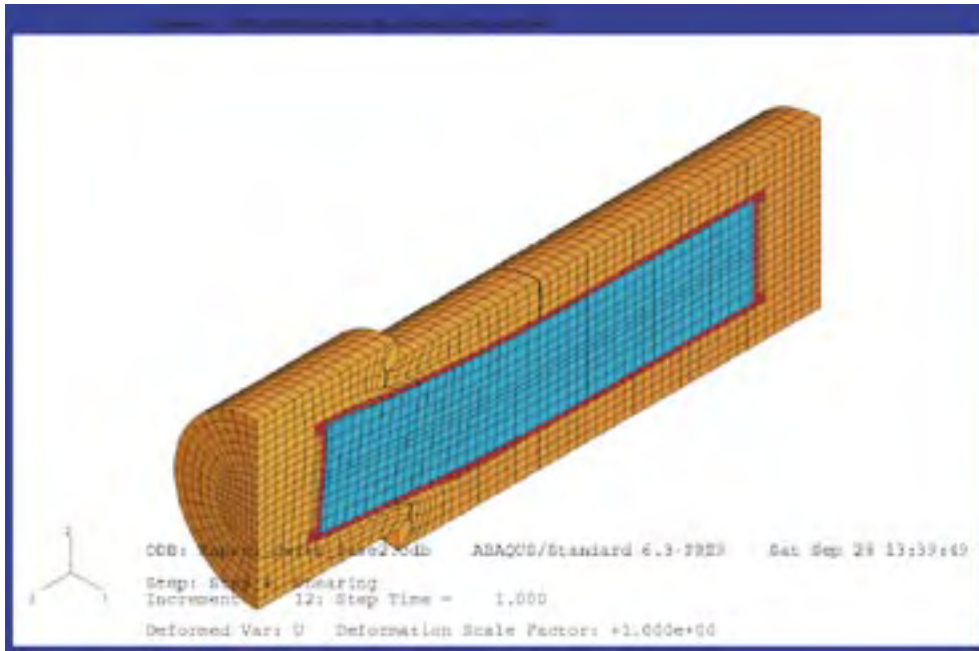
Figure 10-1. *Deformed structure after 20 cm rock displacement showing buffer, copper shell and cast iron insert /Figure 5-1a, in Börgesson et al, 2004/.*

Table 10-1. Calculated maximum plastic strain εp in the copper envelope surface and cast iron insert at different rock displacement δ (ec=shear of end sections c= shear of central parts, δ_p =start plasticization).

Shear plane location/	Copper tube	Rock	Cast iron insert		
Density (kg/m³)	Max ε_p (%) at		ε_p (%)	ε_p (%)	ε_p (%)
	δ=20 cm	δ_p (cm)	at δ=5 cm	at δ=10 cm	at δ=20 cm
ec/1,950	6	3	0.1	0.7	2.7
ec/2,000	8	2	0.4	1.6	4.4
ec/2,050	15	2	0.8	2.4	6.2
ec/2,100	24	2	1.2	4.1	10
c/1,950	4	-	0	0	0
c/2,000	6	4	0.01	0.08	0.17
c/2,050	16	3	0.5	3.6	11
c/2,100	26	2	3	9	19

The results in Table 10-1 were obtained for a shear velocity of 1 m/s, which is a realistic estimate in the primary fault of an intermediately sized (M = 5-6) earthquake /e.g. Madaragia and Olssen, 2002/. However, the shear rate in secondary slip fractures induced by such an earthquake is much less. Larger primary earthquakes would nevertheless not create larger than but M5 secondary slip in fractures intersecting deposition hole, since such large event can only occur in fracture zones larger than km scale, see section 10.1.7. The shear rate used in the numerical simulations is thus conservatively high.

The current specifications for the copper canister state that copper material must have a ductility of at least 40% and a creep ductility of at least 10%. For the cast iron insert, the ductility must be at least 11%. The criterion is that the canister must resist a 10 cm rock displacement for a bentonite density of 2,000 kg/m^3. As can be seen in Table 10-1, this is achieved with sufficient safety margin. Even for a 20 cm rock displacement and a bentonite density of 2,050 kg/m^3, the plastic strain in the cast iron insert will not exceed the specifications. For a non-design basis rock displacement of 20 cm at a bentonite density of 2,000 kg/m^3 the strain levels are well inside the specifications. Based on the data in /Börgesson et al, 2004/, a rock displacement even of 20 cm may, therefore, be acceptable.

It remains to be critically evaluated if the imposed strains could lead to canister failures of any type during the further course of events. A conceivable cause for later failure would be creep failure during creep relaxation of the stresses in the copper shell as a consequence of the deformations caused by the faulting. The relatively low strain levels indicate that the stresses induced must also be relatively low and are, therefore, not expected to have any influence on the creep properties of the copper. It should be pointed out that in SKB's ongoing creep test programme the initial loading of the specimens led to a pre-strain comparable to those calculated by /Börgesson et al, 2004/ before the creep data were recorded. The creep properties of the copper after being exposed to a rock shear movement are, therefore, not expected to be much different from creep properties measured in the laboratory. However, as a distinct issue the effects of future increased isostatic loads on canisters affected by an earthquake 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 the case of cementation.

For the SR-Can interim report the (potential) failure criterion of 10 cm is used in the assessment of repository evolution. In view of the current knowledge cited above, this criterion is certainly robust and possibly overly pessimistic.

10.1.2 Liquefaction

Although not directly related to faulting across the deposition hole – another potential consequence of seismic activities could be rapid changes of the groundwater pressure /Pusch, 2000/. Shaking or rapid changes of water pressures, due to earthquakes, could potentially cause the buffer to liquefy, see the SR-Can Interim Process report /SKB, 2004b/.

The liquefaction of the buffer turns the material from a solid state into a liquid state that could create a risk that the canisters tilt or sink. SKB has treated this issue in a previous report /Pusch, 2000/, with the conclusion that the necessary prerequisite for liquefaction of buffer may exist, but that the density of buffer and the range of stress conditions that will occur practically eliminates the risk for liquefaction, assuming earthquakes up to magnitude 7–8 with normal duration time. Further, /JNC, 2000/, studied seismic stability of the engineered barriers during an earthquake. Numerical models, used for subsequent analyses, were first verified and validated against engineering-scale models (scales 1:10 and 1:5) of the canister and buffer, which were shaken according to a well-defined earthquake

spectrum. In a numerical model accounting for pore water pressure in the buffer, no rise of pore water pressure in the buffer material could be demonstrated, and the possibility of liquefaction in the buffer was considered remote. Liquefaction due to earthquake shaking will therefore not be further considered here.

As further discussed in the process report /SKB, 2004b/ another liquefaction type phenomenon has been observed during compaction of bentonite blocks at very high water ratio. If the bentonite is compacted at very high stress to a state where the bentonite is completely water saturated, all further increase in stress is taken by the water, and the bentonite behaves like a liquid. This phenomenon has been observed during uniaxial compaction when liquid bentonite has squirted from the mould, but the process requires very high pressures and is unlikely to occur in a deposition hole. The issue may still require some further analysis in coming safety assessments.

10.1.3 Seismicity induced by rock excavation

It has long been recognised that mining activities can induce seismicity. Induced seismicity can be classified into two types: "Triggered earthquakes" that are caused by tectonic stresses but triggered by man and "induced earthquakes" that are purely antropogenic in nature. Here, we denote both types "induced earthquakes" for simplicity.

The majority of induced earthquakes are very small (M < 3) but in some rare cases the magnitude has exceeded M 5.0. /e.g. Martin and Chandler, 1996; Durrheim, 2001; Ortlepp, 2001/. Though such an earthquake is still considered small, a fracture plane capable of hosting an earthquake of this magnitude can, based on empirical relations between magnitude and slip /e.g. Wells and Coppersmith, 1994; Vakov, 1996/, accommodate slips that approaches the failure criteria of the canister/bentonite system.

The prerequisites for induced earthquakes are high stresses and high excavation rate, paired with low degree of fracturing. Such conditions can occur during mining, see section 10.1.8, but are less probable for the relatively small excavation rates and rock stressed expected in the repository. Furthermore, the events will occur during excavation, i.e. before waste emplacement, but could possibly be of concern for already deposited waste in other parts of the repository. However, these already deposited canisters would be protected by the same respect distances as applied for protection against post-glacial earthquakes, see section 10.1.7. Consequently, induced seismicity will not be further assessed in this Interim report, but is of still of potential interest.

10.1.4 Shear displacement induced by the thermal pulse

The heat load may cause shear displacement on fractures. The displacement may occur aseismically or be released seismically. The issue of canister damage caused by thermally induced fracture shear displacement has been constituently addressed since the appearance of SR 97 /Hakami and Olofsson, 2002/. Generally, even for large fractures, the displacement magnitude will be much below the 10 cm critical value.

10.1.5 Tectonic seismicity

/Wahlström and Grünthal, 2000a,b/ estimated the seismic hazard for Scandinavia by computing the probabilities of various peak ground accelerations (PGA) in a 50 year perspective. Their results indicate that the risk for large PGA, implicitly major earthquakes, is remote for this time period in the part of Fennoscandia that contain the sites.

However, predicting earthquakes in a much longer, 100,000 year, perspective, from previous and current seismicity, is particularly difficult in Fennoscandia because, amongst many other factors, the mechanisms that trigger the earthquakes change with time. Currently, the effects of ridge push dominate over the remnant effects of the previous glaciation(s). Though it is theoretically possible to compute the probability of the occurrence of large earthquake near or within the sites over the next 100,000 years, using, e.g. the well-known Gutenberg-Richter relations, such calculations are very uncertain. Based on estimates of Gutenberg-Richer parameters (a and b values) for various domains in Sweden /Kijko et al, 1993; La Pointe et al, 1999/ computed for each domain the number of expected earthquakes in a 100,000 year perspective. These earthquake probabilities were used in SR-97.

Most of the recorded earthquakes used to estimate the Gutennberg-Riche parameters, are probably due to NW-SE ridge push forces from the North Atlantic Ridge /Skordas, 1992; Skordas and Kulhánek, 1992; Kijko et al, 1993/. There is also some component of isostatic recovery. However, for the climate evolution assumed for the main scenario, where the next 100,000 years includes a glacial cycle, the role of rebound and earthquakes triggered by the ice unloading is anticipated to be far more important. Studies of the previous glaciation of Fennoscandia suggest that the majority of seismic activity related to ice unloading occurred immediately after (0–2,000 years) the deglaciation /Johnston, 1987, 1989; Muir Wood, 1989; Johnston, 1991; Muir Wood, 1993; Dehls et al, 2000; Firth and Stewart, 2000; Fjeldskaar et al, 2000; Arvidsson, 2001/. After that period, the tectonic forces appear to have dominated the seismic activity.

The number of large (M > 6) earthquakes predicted by /La Pointe et al, 1999/ was small, but still not negligible. However, there are reasons to believe that the probability of tectonic earthquakes is much less than assumed in SR-97:

- Studies have shown /e.g. Ahjos et al, 1984; Ahjos and Uski, 1992/ that there is often an upper limit to the magnitude that occurs within a particular region. This value was determined for Finland by /Ahjos et al, 1984/ who concluded that the maximum magnitude earthquake for Finland is M = 5.0 and a similar value would be expected for southeastern Sweden.

- The analysis by /La Pointe et al, 1999/ is based on various earthquake catalogues, that include pre-instrumental (pre ca 1904 in Sweden) historic events. Various records of intensity have been transformed to equivalent magnitude. However, recent findings /Kebeasy, 2003/ have shown that the historic seismic events, glacio-isostatic faults excluded, are probably overestimated by about one order of magnitude.

For these reasons, tectonically induced earthquakes larger than M6 will be neglected in the SR-Can Interim report. Evidently, further studies are required to substantiate this position.

10.1.6 Evaluation of the occurrence of post-glacial faulting

As noted in the previous section it appears that the majority of seismic activity related to ice unloading occurred immediately after (0–2,000 years) the deglaciation. However, the likelihood that a fault will occur at a particular site in a given post glacial situation depends on a number of circumstances mainly related to the development of the glacial load which in turn depends on the location of the repository site.

A number of large faults in northern Scandinavia, such as the Pärvie, Lansjärv and Stuoragurra faults with lengths up to 150 km and offsets of tens of meters in places, have been confirmed to be of post (or rather end-) glacial origin /e.g. Lagerbäck, 1979; Olesen, 1988/. It is widely accepted that they were formed as the result of large earthquakes

/Johnston, 1989; Muir Wood, 1989, 1993; Arvidsson, 1996/, and there is also general consensus that the fault movement took place as reactivation of existing fracture zones, rather than the creation new faults /Stanfors and Ericsson, 1993/. Hypotheses as to why the large scale faulting occurred only in northern Scandinavia include higher tectonic strain accumulation due to longer ice coverage and enhancement of tectonic stresses by asymmetrical unloading in the deglaciation process.

Research project on glaciation/deglaciation and implications for faulting

Although there are a number of studies on the fault stability effects of a glaciation /e.g. Johnston, 1989; Wu et al, 1999/, the detailed mechanisms behind the post(end) glacial faults in northern Sweden have so far not been thoroughly investigated. As the mechanisms are not fully described, the possibilities to evaluate the future occurrence of post(end) glacial faults at the candidate sites are limited. A research project with the overall objective to understand and quantify the effect of glaciation/deglaciation on the crustal stress field and its implications for the occurrence of post(end) glacial faulting has been initiated. The project will utilize numerical modelling (finite element analysis) and has been divided into the following:

- **Basic investigations to understand the physical relationships:** 2D simulations of the response of rheologically different Earth models to simple ice load models. The influence of factors such as crustal thickness, crustal and lithospheric rheology, material failure criteria, pore pressure and initial stress state on the resulting state of stress will be analyzed. The response of the models to surface and Moho topography and inclusion of weak zones will also be tested.

- **2D simulation of northern Scandinavia:** Construction of a realistic 2D Earth model based on data from northern Scandinavia. Investigations of the importance of ice sheet geometry and evolution, failure criteria and pore pressure on the formation of postglacial faults. Sensitivity tests and validation against available stress and surface displacement data.

- **3D simulation of northern Scandinavia:** Similar to the 2D simulation but in 3D in order to model the strong 3D effects in the loading and unloading of the ice sheet.

- **Site-specific 3D simulations:** Site-specific data, such as mapped faults and rock stresses will be used together with realistic ice models to investigate the local evolution of the crustal stress field and its implications for the occurrence of postglacial faulting.

The observation that deglaciation can produce stress states capable of releasing very large earthquakes warrants a detailed investigation of the underlying mechanisms. Basic building blocks in any such realistic study of the evolution of the stress field is the composition, and thus rheology, of the Earth in the study area, the hydraulic conditions in the crust, the properties and temporal evolution of the ice sheet and the large scale tectonic stress field. The first step of the modelling project described above is under way and preliminary results from the simulations have been incorporated into the description of the building blocks below, together with results from /Klemann and Wolf, 1998; Lambeck et al, 1998; Wu et al, 1999; Kaufmann et al, 2000; Milne et al, 2004/.

For the purpose of glacial rebound and crustal stress modelling, the Earth can be described as an elastoplastic plate, crust or lithosphere, on top of a viscoelastic mantle. The accumulation of shear stress in the plate depends on the thickness of the plate, its elastic properties and the viscosity of the underlying mantle. Considering the large variations in crustal and lithospheric thickness in Scandinavia, stress concentration is likely to vary significantly in the region.

Obviously, the properties of the ice sheet, such as duration, thickness, basal conditions and ice surface topography, governs the evolution of the state of stress in the Earth. The evolution of the Scandinavian ice sheet is discussed in section 11.4. The stress field modelling will depend crucially on the chosen evolution of the Scandinavian ice sheet and it will be appropriate to test alternative ice sheet evolutions in order to assess their significance for the results.

Hydraulic conditions in the brittle crust and the initial state of stress do not influence the modelling of the contributions to the stress field from the ice sheet, however, they significantly influence the assessment of crustal stability. Increased pore pressure reduces the normal stress on faults, driving them closer to failure. The magnitudes of the stresses induced by the ice sheet are small compared to the lithostatic stresses at depths below a few kilometers and cannot on their own bring the crust to failure. However, in conjunction with an initial state of sufficiently deviatoric stresses, however, the additional stress from deglaciation may push particular faults into failure.

The first step of the ongoing research project aims at determining which properties of the Earth and ice sheet have the greatest influence on the evolution of the crustal stress field and the occurrence of endglacial faulting. Based on these results and results from field experiments on the properties of the lithosphere in northern Scandinavia, an Earth model will be set up in the second step of the project. Simulations of the evolution of the stress field will be performed using the reconstruction of the Weichselian ice sheet described in section 11.4, together with other reconstructions of the Fennoscandian ice sheet. This will make it possible to calibrate and validate results from the simulations against data from northern Scandinavia.

Results from the basic investigation and from the 2D analysis of northern Scandinavia will be at hand for the SR-Can final report. These results should yield a basic understanding of the mechanisms that have caused the endglacial faults observed in northern Scandinavia. While understanding the causes of faults we know to have occurred does allow prediction of the likelihood of post glacial faulting at the candidate sites in the future, it is nevertheless anticipated that the results from this work will be a sound basis for quantitative discussions of the possible occurrence and timing of endglacial faults at the candidate sites.

Results from steps three and four, the 3D simulations of northern Scandinavia and of the candidate sites, will yield a more comprehensive understanding of the evolution of the crustal stress field and endglacial faulting. It will be possible to make quantitative estimations of which structures at the sites can be expected to be the most exposed to shear movement due to future loading and unloading of an ice sheet. Such analysis are planned to be included in the SR Site safety analysis.

Conclusions

Although the ongoing research project may show that the probability for post (or end) glacial faulting is very limited in South Sweden, such a statement could currently not be further substantiated. Consequently, the potential occurrence of post glacial faulting needs to be considered in the assessment calculations. However, results from the ongoing research may alter this conclusion, and in time for SR-Site a substantiated estimate of the probability of end glacial faulting will be made.

10.1.7 Secondary slip on fractures induced by nearby earthquakes

/Munier and Hökmark, 2004/ have reported a number of simulations of secondary faulting induced by earthquakes, using different models. In particular, the simulations addressed the following question: "If a deformation zone near or within the repository reactivates seismically, how far from the source fault is the secondary slip on target fractures within the limits of the canister failure criterion?" One aspect of the work is that it can be used to assess whether it is possible to avoid faulting across deposition holes by applying a mechanical "respect distance" with the following definition:

> "The respect distance is the perpendicular distance from a deformation zone that defines the volume within which deposition of canisters is prohibited, due to anticipated, future seismic effects on canister integrity".

The results of /Munier and Hökmark, 2004/ have also been used to define respect distances to be used in repository engineering and design. However, although such respect distances are applied in the layout work performed by Repository Engineering, Safety Assessment also needs to consider the uncertainty of the analysis and of the layout. Potentially, some deposition holes will experience faulting, despite the applied respect distances, and it is important to estimate the probability that this will occur.

Simulation results

A number of simulations using different models have been performed to address this issue. The models included a source fault, target fractures and boundary conditions as schematically illustrated in Figure 10-2. Despite differences in conceptualisation, limitations and capabilities in the various simulation codes used, all simulations were set up on the basis of these principles.

Table 10-2 shows an overview and results of the modelling work that has been performed.

Some aspects of the earthquake modelling conducted in SR-97 /La Pointe et al, 1999/ were questioned, in particular the way individual earthquakes were represented. The main concern was that the modelling approach did not take into account the dynamic effects of earthquakes. SKB therefore initiated a series of simulations, using different tools and different simulation approaches, taking the dynamic aspects into consideration /Munier and Hökmark, 2004/.

An important finding of these dynamic numerical simulations is that the dynamic effects are relatively unimportant at small distances. For target fractures, the static, residual, effects of the energy release overshadow effects of the dynamic load for all distances of any concern for the deep repository. This is in support of the static calculation scheme used in the seismic risk analysis in SR 97 /La Pointe et al, 1997, 1999/.

The reference target fracture used the dynamic analyses conducted is 100 m in radius. According to the simulation results of /Munier and Hökmark, 2004/, the numerically computed respect distance from the deposition hole to a primary fault, capable of accommodating an M6 event, would be 200 m given that it will be possible to detect and avoid fractures larger than 100 m in the deposition holes. If it proves feasible to reject canister positions intersected by 50 m radius fractures, the respect distance between deposition holes and the primary fault can be reduced from 200 m to approximately 100 m.
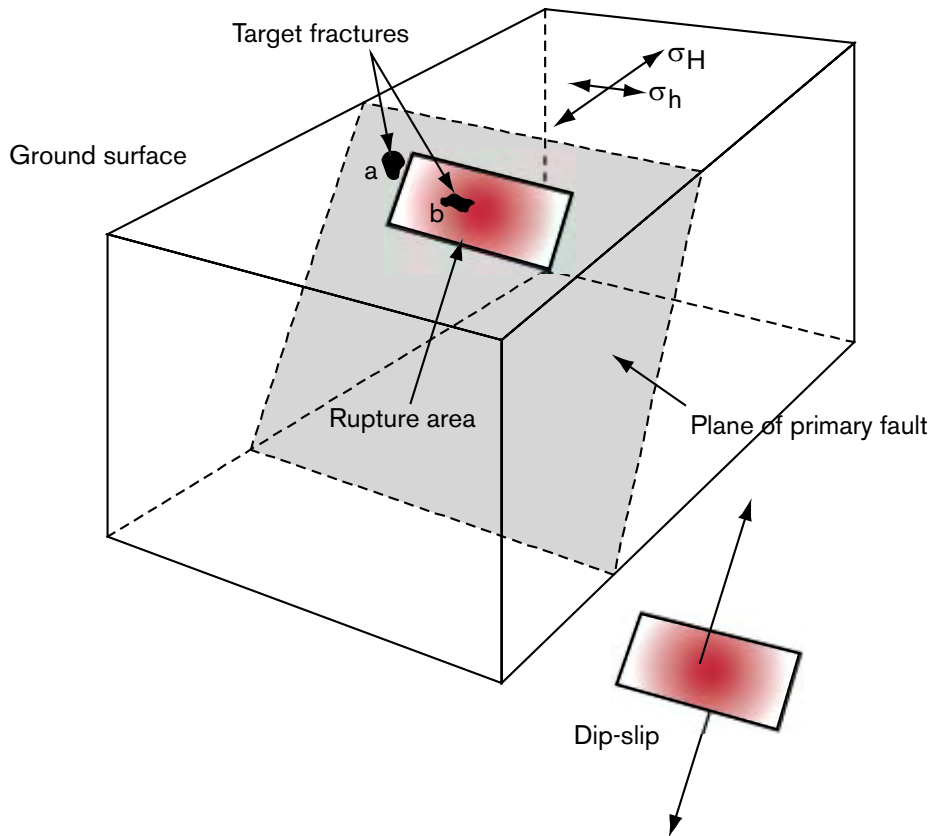
Figure 10-2. *Schematic cartoon of the numerical problem addressed, which is to find the maximum induced displacement on target fractures located at different distances from earthquakse that can be of different magnitude and originate at rupture areas of different size and shape. The primary fault movement is assumed to be dip-slip along steeply dipping fault planes that are potentially unstable because of the high horizontal stress in the fault dip direction. Target fractures may be located close to the edge of the rupture area (a) or close to the hypocentre (b).*

/Munier and Hökmark, 2004/ applied a reference magnitude of M6 in the primary fault. However, the stress drop, i.e. the change in static shear stress on the earthquake fault, was set at a conservatively high value, representative of intraplate events in general, in the dynamic numerical models. The stress drop, rather than the magnitude, is the key quantity for estimating the residual, static, effects of fault movements. The implication of this is that the numerically calculated induced displacements along reference target fractures probably are representative also of larger events, such that the computed respect distance does not need to be larger for M7 and M8 events than for reference M6 events. In conclusion, a respect distance of 100 m from the plane of the potential primary fault will probably be defensible from the computational point of view. This conclusion is based on the notion that stress drop is a magnitude-independent quantity /Scholz, 1990/.

The idealized representation of the source-target interaction used in the numerical models sets bounds to the range of distances that can be considered. Earthquake faults were represented by planar features in all models and seismic events were modelled as idealized and schematic relative movements along these planes. Attempting to analyze effects on target fractures at very small distances would not be meaningful, since details of the fault geometry and of the source mechanism will become important in the vicinity of the fault.

Table 10-2. Summary of different sets of results /from Munier and Hökmark, 2004/.

Code/ study	Type of result	Event	Target fracture	Main limitations of code/ study	Reference
Poly3D	Induced displacement on target fractures	All types of events	All sizes, all orientations frictionless	Dynamic effects not considered. Statistical approach makes direct derivation of respect distances difficult. No account of initial stress field.	/LaPointe et al, 1997/ /LaPointe et al, 1999/
FLAC3D step 1	Induced displacement on target fractures	M = 6, Dip-slip on vertical fault	100 m radius frictionless	Static effects not considered. Oscillations approximated by plane wave. No account of initial stress field.	/Munier and Hökmark, 2004/
FLAC3D step 2	Induced displacement on target fractures	M = 6, Dip-slip on vertical fault	100 m radius friction 15° friction 30°	Static effects not considered. Oscillations approximated by plane wave. No account of initial stress field.	/Munier and Hökmark, 2004/
Wave step 1	Velocity records to be used as boundary conditions in FLAC3D step 1 and step 2 models	M = 6, Dip-slip on vertical fault	No target	Faults must be either vertical or horizontal. No account of initial stress field.	/Munier and Hökmark, 2004/
Wave step 2	Induced displacements on 200 m fractures	M = 6, Dip-slip on vertical fault	100 m radius frictionless, friction 15° friction 30°	Faults can only be either vertical or horizontal. Target fractures must be either horizontal or vertical. No account of initial stress field.	/Munier and Hökmark, 2004/
FLAC3D step 3	Induced displacements on 200 m fractures	M = 6, Dip-slip on 70 degr dipping fault	100 m radius frictionless, friction 15°	Preliminary study with few results.	/Munier and Hökmark, 2004/

At small distances it is, for instance, not relevant to distinguish between induced displacements on target fractures and displacements on components of the seismogenic fault itself. Distances that are smaller than the measure used to describe the zone half-width should probably be considered too small in that respect.

To defend respect distances smaller than 100 m for M6 events and larger, the general conservativeness in the elastic stress/deformation model for rock fractures must be taken into account. Support for small respect distances is found in a study conducted by /La Pointe et al, 2000/ addressing the effects of fracturing in the regions of the tips of a slipping target fracture, using fracture propagation criteria based on stress intensity factors derived by /Shen, 1993/. The results of that study suggested that the maximum possible amount of induced shear displacement on a given fracture is determined by the size of the fracture and is independent of the load on the fracture, i.e. the stress drop, the earthquake magnitude and the distance to the earthquake fault. For fractures of 50 m radius, the maximum displacement was found to be only a few millimetres. However, this result is not conservative,

since the maximum displacements were calculated without consideration of the change in geometry that will follow from the processes around the fracture tips. Still, qualitatively the study points to the effects of strain energy being expended on fracturing rather than on elastic deformations and indicates that induced displacements will be significantly smaller than those obtained from the elastic source to target analyses. Taking full account of the results in /La Pointe et al, 2000/ means that earthquake-induced displacements on fractures transecting deposition holes will not be an issue for the determination of respect distances.

Respect distances

Due to anticipated, future reactivations, canisters will not be positioned within, or in the immediate vicinity of, local deformation zones or larger (i.e. deformation zones larger than ca 1,000 m). However, there is a general problem in defining which part of the rock that can be considered part of a deformation zone; the volume of rock affected by the presence and kinematic history of the deformation zone is generally much larger than can be estimated by macroscopic observations /e.g. Morad and Aldahan, 2002/.

It has long been recognised /Atkinson, 1982; Jamison and Stearns, 1982; Ingraffea and Wawrzynek, 1985; Sibson, 1985; Chester and Logan, 1986; Sibson, 1986; Labuz et al, 1987; Koestler, 1994; Vermilye and Scholz, 1994; McGrath and Davison, 1995; Vermilye and Scholz, 1998/ that the rock in the immediate surroundings of a deformation zone displays characteristics such as microfracturing, kink bands, cataclastic bands, etc in a volume usually termed the "process" or "damage" zone. Though many studies have targeted the tip of the structure, i.e. in-plane propagation, from a respect distance perspective, the out-of-plane growth, by linking adjacent fractures and widening the zone /e.g. Martel, 1989/ is of more immediate interest. In the geometric definition of deformation zones in our 3D models, we include the width of this zone, termed the "transition zone" in SKB nomenclature /Munier et al, 2003; Thunehed and Lindqvist, 2003/, because any future reactivation of the zone can, in principle, be located anywhere within the transition zone though it is far more probable that the main fault plane will reactivate /Scholz, 1990/.

Though the primary faulting through the canister can be avoided by locating canisters beyond the transition zone, secondary faulting might be triggered some distance away. Though our simulations have addressed the latter aspect, the notion of transition zone width must be included in the definition of the respect distance.

Table 10-3 shows a summary of the findings discussed above and should be read as follows: For each zone of a certain size the transition zone is calculated. If the transition zone exceeds the seismic influence distance, then the respect distance equals the transition zone width, otherwise the respect distance equals the seismic influence distance.

The respect distance estimates in Table 10-3 can all be reasonably well defended, but are not yet proven to be 100% safe. Some further work is needed to gain sufficient confidence in the general validity of the calculation-based conclusions. For layout planning purposes, an appropriate strategy may be to use the minimum respect distance and then, if permitted by available rock volumes, increase the respect distance for zones with half-widths that are larger than that first estimate.

Table 10-3. Seismic influence distance and Transition Zone half with in relation to zone length using various assumptions. If the transition zone exceeds the seismic influence distance, then the respect distance equals the transition zone width, otherwise the respect distance equals the seismic influence distance /from Munier and Hökmark, 2004/.

Zone size	Seismic influence distance estimated from dynamic analyses of source to target interaction (calculated induced displacement should be < 0.1 m)		Seismic influence distance estimated by, /La Pointe et al, 2000/ (induced displacement is not an issue, distance set at fracture diameter)		Transition zone half width estimates	
	If > 100 m radius fractures avoided	If > 50 m radius fractures avoided	If > 50 m radius fractures avoided	If > 25 m radius fractures avoided	W/L Ratio 2%	W/L Ratio 1%
> 3 km	—[1]	—[1]	—[1]	—[1]	0 m – 30 m	0 m – 15 m
3 km – 10 km	200 m	100 m	100 m	50 m	30 m – 100 m	15 m– 50 m
> 10 km	200 m	100 m	100 m	50 m	> 100 m	> 50 m

[1]Source movement does not exceed 0.1 m

Figure 10-3 shows respect distance estimates based on interpretations of results from the dynamic numerical analyses. The schematic zone is intended to represent a 10 km long zone with a transition zone half-width of 100 m (W/L ratio = 2%). A zone of such dimensions may accommodate a M6 event, or larger. If it is possible to detect and avoid fractures of 100 m radius, but not fractures smaller than that, the respect distance is 200 m (Figure 10-3a). If, on the other hand, it is possible to detect and avoid fractures with 50 m radius, the respect distance will be approximately halved (Figure 10-3b). Reducing the detection limit further, for instance such that 25 m radius fractures and larger can be safely detected and avoided, would, however, not automatically result in reduced respect distances. A canister position such as the one indicated in Figure 10-3c, for instance, would not be allowed because the idealized representation of the source to target interaction used in the numerical models does not allow conclusions to be drawn relevant to very close distances. Additionally, the canister position in Figure 10-3c is entirely contained within the transition zone of the fault and thereby excluded by definition.
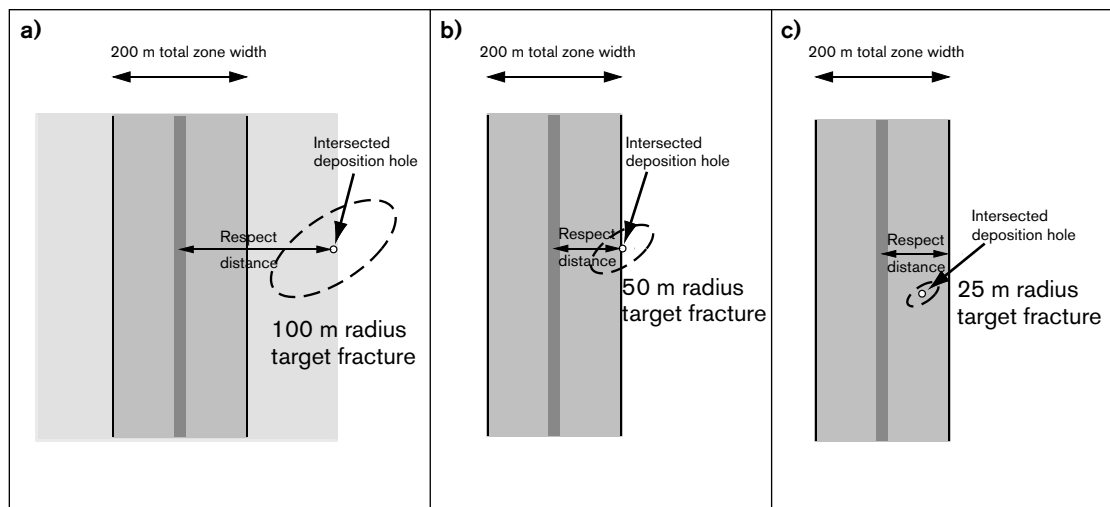

Figure 10-3. *Respect distances to 10 km zone based on the assumption that 100 m, 50 m and 25 m radius fractures can be safely detected.*

10.1.8 Observations of earthquake-induced damage on tunnels

One way of estimating possible mechanical effects on the repository is to examine documented cases of earthquake-induced damage on underground facilities, such as tunnels and mines. /Bäckblom and Munier, 2002/ have carried out a systematic and worldwide literature survey, including underground constructions at small distances from large earthquakes. The survey is also relevant for estimating the likelihood and impact of excavation induced seismic events, as noted in section 10.1.3.

Conclusions the literature survey suggest that, as a general rule, underground effects are insignificant compared with corresponding surface effects /Bäckblom and Munier, 2002/. There are two reasons for this, as summarised below:

- Oscillations have lower amplitudes at large depths. Because of wave reflections off the ground surface, mechanical oscillations are particularly intense close to and at the surface, due to superposition of incident and reflected waves.

- Underground constructions are less sensitive to dynamic loads. To damage an underground structure significantly, the disturbance must be powerful enough to rupture the surrounding medium, provided it is not too loosely coupled to the rock.

The repository will be at a much larger depth than most of the tunnels covered by the literature survey conducted by /Bäckblom and Munier, 2002/. Furthermore, the dimensions of the cross-sections of deposition tunnels and deposition holes are small compared to compared to the wavelength of seismic waves. In addition, the repository host rock will be of better quality than the rocks in the tunnel sections where damage was actually found and, as opposed to the tunnels in the survey, the repository cavities will all be backfilled. The literature survey included tunnels that intersected active fault zones on which earthquakes originated. In these cases, the damage was restricted to the immediate surroundings of the tunnel/fault intersection.

The study of /Bäckblom and Munier, 2002/ suggests that the respect distance, i.e. the distance between potential earthquake zones and deposition holes, may not have to be very large. This is because the large distances over which dynamic oscillations are known to propagate and cause damage to surface structures are not relevant to the problem of estimating respect distances which are to be applied to relatively deep (400–700 m) underground constructions. However, the general conclusions drawn from /Bäckblom and Munier, 2002/ need to be supported by quantitative respect distance estimates obtained by the use of numerical analyses. The main conclusions of Bäckblom and Munier are set out below:

- Damage due to shaking in an underground facility may occur if the peak ground acceleration (PGA) exceeds about 2 m/s². Sweden is located in the Baltic Shield that is seismically rather silent and will remain so over the foreseeable future. Seismic hazard analyses have been undertaken for Sweden and it is concluded that PGA greater than 2 m/s² is very unlikely the next coming 50-year period, in which the repository is planned to be constructed and operated.

- Damage due to shaking is very rare in deep underground facilities. Where such damage has occurred, the rock is either very poor or subject to very high stresses. Neither of these conditions will prevail in the Swedish repository. Most damage is also correlated to the presence of faults and the spent fuel will not be deposited in or close to important faults.

- Mining-induced earthquakes are known to cause local damage in the mines. At the repository site, it might be possible to experience local rock burst problems due to the spatially heterogeneous rock strength and the varying rock stresses. It is expected that these events, if they appear, will take place when the tunnels are excavated rather when the spent fuel is deposited. Additionally, the extraction ratio of the openings will be very low as compared to open stopes in a mine.

- There is also evidence for mines at great depth, that backfilling considerably lower the mining-induced seismic activity. However, backfilling is only effective in this respect if it is in intimate contact with the rock surfaces and has a reasonable stiffness compared to the rock mass stiffness.

- Brittle deformation of a rock mass will predominantly be through reactivation of pre-existing fractures. The data relating to faults intersecting tunnels show that creation of new fractures is confined to the immediate vicinity of the reactivated faults and that deformation in host rock rapidly decreases with the distance from the fault.

- Data from deep South Africans mines show that rocks in a environment with non-existing faults and with low fracture densities and high stresses might generate faults in an previously unfractured rock mass without any requirements for a pre-existing fabric of localised and concentrated micro-fractures in the intact rock. The Swedish repository will be located at intermediate depth, 400-700 m, where stresses are moderate and rock is moderatly fractured. The conditions to create such mining-induced faults will not prevail in the repository environment.

In summary, field evidence gathered in this study indicates that respect distances may be set considerably smaller than those based on numerical modelling.

10.1.9 Estimating the probability of secondary faulting induced by glacio-isostatic earthquakes

By avoiding canister deposition holes within certain distances from the deformation zones within which faults (of any cause) could occur, the likelihood of damaging shear movements can be significantly reduced or eliminated. The required sizes of these respect distances are being determined through a number of studies summarised in section 10.1.7. The distance depends on the properties of the deformation zone and is also based on the assumption that fractures above a certain size can be detected and avoided when locations of deposition holes are selected.

The method for avoiding damaging faulting is thus based on the assumption that target fractures exceeding a certain size can be detected. There is, however, a residual probability that such a fracture will go undetected and that it intersects a deposition hole.

By stochastic simulation of fractures, using site-specific data and tentative but realistic, site-adapted repository layouts, it is possible to compute the number of canisters that will be transected by a fracture large enough to host net slips that will exceed the failure criterion of the buffer/canister system. Further, it should be possible to provide a realistic estimate of the probability of detecting such a fracture so that the affected canister position may be abandoned. Combining these two probabilities would then result in the probability that a used deposition hole would be intersected by a too long fracture. Such probabilities will be calculated for SR-Can.

A more challenging task is to calculate the probability that any one of these structures will a) reactivate and b) slip more than 10 cm. This probability is certainly less than 1, and almost certainly much smaller than this. In fact, the observations of earthquake-induced damage on tunnels discussed in the previous section indicate that respect distances and damages may be considerably smaller than predicted by numerical modelling. This means even if there was a high magnitude earthquake, the probability of actually shearing a large fracture more than 10 cm, is much less than one. Substantiating this, low probability is not trivial, but will nevertheless be attempted in SR-Can.

10.1.10 Conclusions for consequence analysis

Since much of the methodology is under development, it is at this interim stage not possible determine whether calculation cases involving canister failure due to shear movement will have to be included in the probabilistic dose calculations and the final risk summation. In this interim report a radionuclide transport calculation case simulating such a failure will be included, see section 12.6.1.

10.2 Fracturing of the rock

There are two main modes of fracturing

- Formation of new fractures

- Propagation and coalescence of existing fractures

Formation of new fractures requires very high stresses. For most crystalline rock types the uniaxial compression strength is the range of 100–250 MPa. Stresses of these magnitudes are found only in the immediate surrounding of openings in rock with high initial virgin stresses. Numerous numerical studies have shown that the volumes that may fail as a direct response to rock exaction are very limited /Hökmark, 2003; Johansson and Hakala, 1995/. Future loads may increase the possibility of potential failure /Hakami and Olofsson, 2002/ but not in any drastic way.

The support provided to the excavation walls by the buffer and the backfill is likely to suppress further fracturing efficiently /Martin et al, 2001/. This phenomenon is presently being investigated and quantified in the APSE experiment /Andersson, 2003/. Taking full account of the likely findings of the APSE experiment will probably reduce the expected extent of future fracturing around openings very significantly.

Formation of new fractures will not affect canisters mechanically, since the rock volumes involved are too minor to alter the geometry of deposition holes. The possible importance of fracture formation from the safety assessment point of view is its potential to increase the permeability in limited annular regions around the repository openings (cf section 10.4).

Propagation and coalescence of existing fractures will change the fracture geometry. Similar to formation of new fractures, the process requires high stresses and will be found mainly in small regions around the repository openings. For the safety assessment the same issue arise as for formation of new fractures.

On the large scale, there is also the theoretical possibility that weak rock bridges between large fractures fail, and that the size of the resulting fracture is large enough to accommodate large shear displacement when subjected to future loads. However, this particular event can be important for the safety assessment only if it takes place extensively enough to dominate the uncertainties in the geometrical description of the fracture system.

In conclusion, it is likely that most fracturing will occur in conjunction with the construction work and will have relatively minor long-term implications. Nevertheless, new coupled hydro-mechanical calculations are planned for SR-Can, see section 10.4, in order to quantify the impact of fracturing due to excavation, thermal load and future loads caused by glacial episodes.

10.3   Time dependent deformation (creep)

The stress state in the Baltic Shield with the major principal stress being oriented NW-SE is largely determined by the Mid-Atlantic ridge push movements. Locally, the stress levels are limited and controlled by frictional sliding along nearby large deformation zones, meaning that additional tectonic strain will not result in much increased load on the repository host rock. Glaciations, however, will give an excess of mechanical load compared to present-day conditions. The nature of the glacial stress excess depends not only on the ice-load, but possibly also on crust/mantle interactions. Work is ongoing aiming at arriving at a better understanding of the relative importance of ice-load, crust/mantle interactions and large deformation zones to the stress field during glacial cycles (see section 10.1.6 above).

10.3.1 Convergence of deposition holes and tunnels

Theoretically, the repository host rock may deform as a function of time because of its inherent time-dependent material properties. Movements or deformations that take place slowly over long periods are called creep movements. Creep deformations can take place only if there are deviatoric stresses. Deviatoric stress states are, however, not sufficient to produce creep movements in crystalline rocks. The literature on creep in crystalline rock and along rock fractures gives extensive evidence of the existence of threshold stresses, or rather of thresholds of stress/strength ratios /Glamheden and Hökmark, 2004/.

For intact rock, the threshold may correspond to about 40% of the strength, meaning that it takes very high stresses to produce creep movements in intact rock. In addition, if the threshold stress/strength is exceeded, it will take small deformations to relax the stresses such that the stress/strength ratio drops below the threshold and the creep movement dies out.

Similar to intact rock, rock fractures deform slowly over time when subjected to stresses that exceed stress/strength thresholds /Glamheden and Hökmark, 2004/. The literature shows that the nature of creep is fundamentally different for different types of fractures: filled, clean, rough, smooth etc. As conservative, lower bound estimates, the threshold for unfilled fractures can be set at 30% of the fracture shear strength and to 10% for filled fractures. The concept of creep thresholds does not reveal any of the nuances and the complexity of creep in jointed rock masses, but it can be used to set bounds to creep-related convergence of the repository openings.

In SR 97 a simplistic technique was used to set extremely conservative upper bounds to the possible increase in mechanical load on a canister that could follow from rock creep. Creep-induced deformations of openings were assumed to continue until all shear stresses in the host rock had relaxed, i.e. the rock would behave as a viscous fluid. The final state would be that of a host rock with hydrostatic stresses. The deposition holes would have converged until the buffer compression had generated swelling pressures corresponding to the rock mean compressive stress. The present-day mean compressive stress at the repository level varies between the sites and may be around 20 MPa or more. However, if the rock actually would behave as a liquid in a very long time perspective, that stress would correspond only to the weight of the rock overburden and amount to about 14 MPa. With an additional ice-load of 30 MPa, the resulting pressure on the canister would be 44 MPa. This would give a small reduction of the deposition hole diameter. This conservative upper bound estimate is valid irrespective of the number of glaciation cycles expected to occur within the next million years, as long as the buffer keeps its mechanical properties.

The concept of creep thresholds will reduce the theoretically possible convergence to be much less than the convergence estimates obtained by use of the viscous fluid model. Quantitative estimates can be obtained by analyzing discrete fracture near field rock models. The strength of the fractures should be reduced in steps to represent the effects of creep, i.e. a successive relaxation of fractures shear stresses. Preliminary studies that are available now /Hökmark, 2003; Glamheden et al, 2004/ indicate that the convergence of openings will be very modest, a couple of millimetres for deposition holes and a few centimetres for tunnels.

10.3.2 Creep shear movements along fractures

In addition to the possibility of general convergence, there is also the theoretical possibility of creep shear movements across a deposition hole. Large creep-related movements along an individual fracture require a long fracture. In this respect, creep movements do not differ from any other shear movement (cf section 10.1 above).

10.4 Impact of mechanical processes on the host rock permeability

In SR 97, there was a general and qualitative discussion on how stress changes impact the permeability of the near field rock. However, for SR-Can 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 /DECOVALEX, 2004 in prep; Stephansson et al, 2004/. In same cases coupled THMC effects could affect rock permeability, although the changes may not always be very significant. For these reasons a special report on thermo-hydro-mechanical couplings is being prepared for SR-Can /Hökmark et al, in prep/. (Permeability changes due to chemical alteration are discussed in section 11.1.3 of this report).

The report will be based on literature surveys combined with numerical simulations of impact of, for example, rock excavation, thermal load and glacial load, at the tunnel and deposition hole scale for various rock properties and fracture geometries. These simulations are planned to be carried out using e.g. the 3DEC code /ITASCA, 2004/. At the time of producing this interim report the proposed calculations remain to be finalised and undertaken.

10.4.1 Transition from pre-mining permeability conditions to permeability at canister emplacement

In SR 97, the main pre-disposal mechanical effect considered was the development of an Excavation Damaged Zone. In SR-Can there will be increased attention to the pre-emplacement conditions, potentially along the following lines of reasoning.

Justification for consideration of M→H couplings only will be provided. Lessons learned from /DECOVALEX, 2004 in prep/ and the parallel EU project BENCHPAR will be utilised. There is a BENCHPAR Guidance Document that specifically discusses which THM couplings are more important and which are less important in modelling for radioactive waste disposal, and why. The document will be published as a paper in 2005 /Stephansson et al, 2005/.

The development and extent of an Excavtion Damged Zone (EDZ) will be assessed. An important source of input will be observations made at the ongoing "Äspö Pillar Stability" Experiment /Staub et al, 2004; Olsson et al, 2004/. Other available information as well as implications from international studies within the EU CLUSTER Conference /CEC, 2003/ and the ongoing DECOVALEX-4 project will also be considered.

Stresses in the near-field will be analysed. Particular attention will be paid to the extreme variants of the Forsmark and Simpevarp stress fields. The impact on extent of fracturing around deposition holes will be investigated.

For the rock outside EDZ possible relations between stress-change and permeability change and/or between deformations and permeability changes will be reviewed. This will then be used to bound the magnitude of such changes.

Requirements on precision in permeability disturbance estimates in relation to what is significant for safety will be explored. It will be discussed how these requirements can be reconciled with the findings regarding e.g. EDZ and stress redistribution effects.

10.4.2 Impacts at the tunnel ("near-field") scale

In SR-97 it was suggested that most post-emplacement loads (thermal load, glacial load) would increase rock stress and thus generally close existing fractures, i.e. decrease permeability. This view will be re-assed in SR-Can by considering:

- Stresses in the near-field with range estimates based on SKB and Posiva reports (and possibly others).

- Near-field stress change effects on fracture apertures (qualitatively: closure or expansion).

- Extent of additional fracturing due to future loads considering the importance of bentonite support pressure for stabilizing the walls of deposition holes.

Based on the findings obtained an approach for handling in the SR-Can final report will be suggested. This would start with a discussion on whether the general statements in SR 97 hold true.

10.4.3 Impacts at the repository ("far-field") scale

SR 97 qualitatively considered the impact of thermal expansion at the repository scale, but concluded that the reduction of horizontal stresses would not be large enough to be of any concern for permeability at repository depth. In SR-Can there will be a more thorough evaluation of M-H coupling in the far-field due to future mechanical and thermo-mechanical loads. The following should be addressed:

- Stresses in the far-field with range estimates based on SKB and Posiva reports (and possibly others).

- Review of stress vs. permeability models for fracture zones.

- Far-field stress change effects on deformation zone permeability.

Based on the findings obtained an approach for handling in the SR-Can final report will be suggested. This would start with a discussion on whether the general statements in SR 97 hold true.

10.4.4 Impact during glaciation

A subsequent chapter would address the two-way M-H couplings during glaciation, by reviewing ongoing hydro-mechanical glaciation studies. Issues to be considered include:

- Review of models for propagation of high pore pressures and their effects on ground-water flow and migration.

- Effects of high pore pressures on permeability.

- Effects of high pore pressures on rock mass strength (extent of pore pressure induced shear displacements).

- Extent of fracture opening due to high water pressures in fractures (hydraulic jacking).

- Effects of hydraulic jacking on permeability.

- Suggested approach for handling in SR-Can.

Based on the findings obtained an approach for handling in the SR-Can final report will be suggested.

In general, it appears that potentially remaining high pore pressures would have very little impact on the isolating or retarding properties of the rock mass. Remaining high pore pressures would only result if the rock permeability is very low in the first place.

The changed stress will certainly deform various fractures depending on their orientation. However, given the fundamental uncertainty in stress-strain and strain-permeability relations, numerical simulations may at best indicate in which fracture directions transmissivity ought to increase or decrease due to this effect.

10.4.5 Conclusions

Apart from addressing the development of an EDZ, SR-Can interim will not quantify mechanical impacts on rock permeability. Whether such impacts need to be quantitatively considered in the analysis of repository evolution will be judged depending on the outcome of the TMH-review /Hökmark et al, in prep/.

11 Analysis of the main scenario – general evolution; structure and some preliminary results

This chapter gives the structure for the presentation of the general evolution of the repository system in the main scenario of SR-Can, with a few preliminary results inserted where available. In the final SR-Can report, the corresponding chapter, then with considerably more results in place, will be a core element of the assessment.

The limited extent of the presentation in this interim report is in line with the scope of this report, where neither the integrity of the barrier system over long time scales nor the climate evolution is have been addressed in detail, see further section 1.3.1.

The focus is on canister integrity. The further evolution of canisters potentially ruptured as a consequence of processes occurring in the main scenario (or initially defective) is handled in the next chapter as are radionuclide transport for simplified barrier and biosphere conditions.

The repository evolution is followed from the start of excavation to the end of the assessment period, one million years into the future. The presentation is structured according to the relevant time frames for the assessment.

The excavation and operation phases are discussed in section 11.1.

The initial 1,000 years after closure are described in section 11.2, since this time scale is explicitly requested in SSI's regulations SSI FS 1998:1. Initial thermal, hydrological, mechanical and chemical transients caused by the presence of the repository dominate the analyses. The development of the surface conditions is controlled primarily by a continuous, unidirectional shore-line displacement. Today's climate is assumed to prevail.

The evolution for a continued temperate climate is discussed in section 11.3. The analyses cover development up to about 10,000 years into the future, although the duration of the present temperate period is highly uncertain. The period is characterised by steady state conditions regarding most aspects at depth whereas the surface conditions are controlled primarily by ongoing shore-line displacement.

Modelling of the reference glacial cycle, an assumed repetition of the Weichselian as described in section 4.2.3, is presented in section 11.4. The situation 115,000 years ago, when the temperature was similar to the present, is assumed at the start of this period. The Weichselian is then modelled as if it were to occur of the next 115,000 years. In accordance with the defined scope of this SR-Can Interim report, the resulting consequences for the repository are not analysed in detail.

Subsequent glacial cycles are briefly mentioned in section 11.5.

Following the analyses of the main scenario for reference climate conditions, sensitivity analyses related to uncertainties associated with the reference climate are described in section 11.6 according to the plans in section 4.2.3, focussing on key properties for safety and including a discussion on the effects of human-induced climate change.

11.1 The excavation and operation phases

This section discusses the evolution during the excavation/operation phase. Starting with the undisturbed, natural conditions as given by the site descriptive model, the mechanical and hydrochemical changes caused by the disturbance on the host rock by the excavation and operation of the repository are discussed.

11.1.1 Mechanical evolution of near field rock due to excavation

The rock mass at repository depth is under a pre-stressed condition, i.e. the in situ rock stress. Repository excavation, i.e. removal of rock, thus implies a major, but essentially local, rock mechanics impact. This raises several issues of concern for the construction work, like risk of fallouts into excavated volumes, spalling or key block stability. These engineering-related rock mechanics issues are evaluated within the framework of the repository design work carried out by Rock Engineering and will, in time for SR-Can, be reported separately. However, since most of these impacts concern phenomena that occur during construction, i.e. long before waste emplacement, they do not directly impact long-term safety, but the properties of the excavation-peripheral rock may after excavation differ from the properties inferred from the Site Descriptive Model based on pre-excavation site data. From a safety point of view, the issue is whether the excavation phase would affect the safety functions of the rock mass.

Development of an EDZ and other impacts on rock permeability

The main pre-disposal mechanical effect of concern to safety is probably the potential development of an Excavation Disturbed Zone (EDZ). The EDZ is defined as the remaining impact, i.e. after resaturation, on the hydraulic properties from the tunnelling. The EDZ basically originates from:

- excavation damage (i.e. from blasting or the TBM if this is used) and

- the changes of the stress field resulting from the changed stress boundary conditions compared with the undisturbed situation.

During the excavation phase itself additional disturbances are expected due to changes of the hydraulic regime through the zero pressure boundary condition in the tunnel and the potential development of a skin zone. However, these changes will not remain after resaturation.

As discussed in section 10.4.1, it is planned to explore, by literature survey and new simulations, the transition from pre-mining permeability conditions to permeability at canister emplacement in more detail than in SR 97. Issues to be discussed include, the EDZ, secondary stresses in the near-field with particular attention to extreme variants of the Forsmark and Simpevarp stress fields, and the impact on extent of fracturing around deposition holes as well an assessment of potential permeability changes in the rock outside the EDZ. As discussed in the Interim Data report /SKB, 2004c/ forthcoming analyses are likely to suggest that the EDZ would be limited in extent and that this extent can be controlled by the tunnel design and excavation technique.

Induced seismicity

As discussed in section 10.1.3, the excavation activities may also, in theory, induce seismicity. However, as discussed there, the prerequisites for induced earthquakes are not anticipated to prevail at repository depth. Furthermore, the events will occur during

excavation, i.e. before waste emplacement, but could possibly be of concern for already deposited waste in other parts of the repository. Nevertheless, such unlikely events could be easily observed and judgements could be made whether mitigating actions would be necessary.

11.1.2 Hydraulic evolution

The hydraulic evolution during this phase is illustrated by a calculation for an open repository inserted into the undisturbed hydrological regime, i.e. transient effects of the gradual excavation are not included. See section 9.2 for methodology and example results.

11.1.3 Chemical evolution in and around the repository

During the excavation and the relatively long operational period, groundwater will suffer substantial changes in composition around the repository. The presence of the repository will induce some significant groundwater changes, and shoreline displacements and climatic variations may cause additional, more limited, alterations. It is essential to understand the chemical status of the repository system at closure in order to describe its immediate geochemical evolution after closure. Important issues to consider are listed below.

- Effects of drawdown (increased meteoric water influx) and up-coning of saline waters. This is addressed using hydrological models (see section 9.2). During the operational phase, inflow of groundwater into the tunnel and mixing of groundwaters of different origin within rock fractures will probably result in precipitation of $Fe(OH)_3$ and $CaCO_3$. Grouting and shotcreeting will also influence these processes. Results of numerical simulations using, e.g. PHREEQC will be used to quantify the effects of both grouting and of precipitation/dissolution due to drawdown/upconing. The possible influence of thermal effects in the vicinity of the deposition tunnels should also be considered.

- Organic materials (including tobacco, plastics, cellulose, hydraulic oil, surfactants and cement additives) may be decomposed in microbiolocially mediated reactions, and therefore add reducing capacity to the near-field of the repository. However, these materials might also be detrimental in enhancing the potential for radionuclide transport in groundwater. In SR-Can the possible effects of these materials will be reviewed from a chemical and microbilogical standpoint.

- An important question concerns the expected evolution of the microbial population during operation and through the resaturation phase. Changes in microbe populations could potentially induce increased colloidal and organic matter concentrations. Some microbes will take advantage of the changing conditions during operation and resaturation, and consume part of the organic materials in the buffer and backfill, as well as the stray organic compounds left in the repository during the operation phase. An overview of these processes and their consequences is needed when discussing other non-microbial processes occurring during operation and the time immediately after closure.

- The reducing capacity of the backfill is 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. A model coupling chemical processes consuming oxygen with the hydrodynamic saturation of the backfill will be used to estimate the time scale for reaching anoxic conditions in the tunnels of the repository. In addition, any available results from the prototype repository at Äspö (groundwater and gas analyses) will be used to evaluate the relative importance of chemical and microbiological oxygen consumption in the backfill.

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11.1.4 Repository conditions at the end of the operational phase

In the SR-Can final report, the repository conditions at the end of the operational phase will be summarised, and the status of the function indicators discussed.

11.2 The first 1,000 years

This section discusses the evolution from repository closure through the first 1,000 years. For many developments at an individual deposition hole, the time of deposition is however a more natural starting point for the description. The starting points will therefore vary slightly depending on the nature of the analysis presented.

The present temperate climate is assumed to prevail. In general, the external conditions are therefore assumed to not change. An exception is however the shore-line, the change of which will impact the hydraulic and biosphere conditions.

11.2.1 Biosphere

The development of the shore-line will induce changes of the internal biosphere conditions such as biosphere succession (mire and forest development) and sediment redistribution (sedimentation and resuspension/erosion). The future shore-line displacement and sedimentation processes are inferred from the historical development of the site as determined by the site investigation programme and compiled by the analysis group. The estimated rate of shore-line displacement is 0.006 m/year /Hedenström and Risberg, 2003/ and thus 6 m during the next 1,000 years, see Figure 11-1.

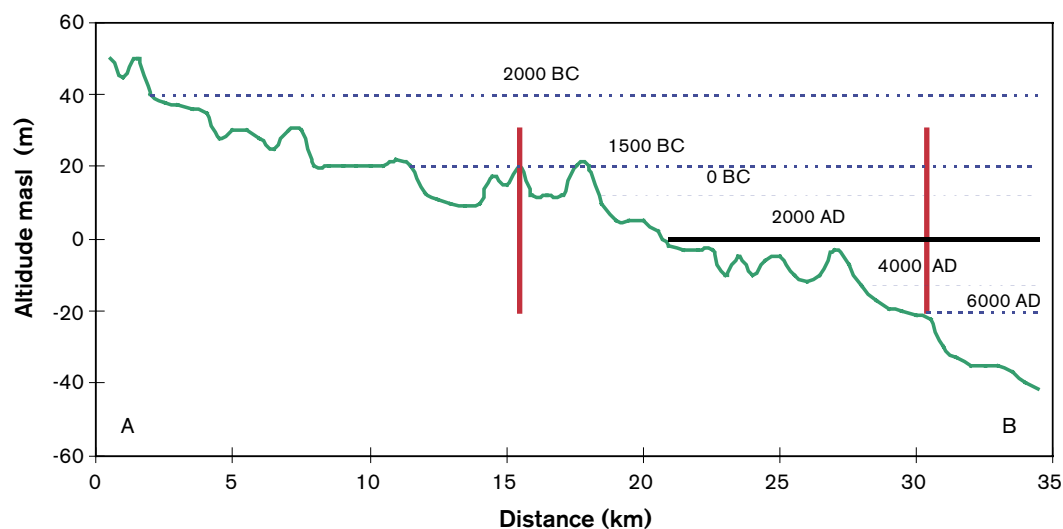***Figure 11-1.*** *Topographic relief along a line transverse the shore (A=1620000, 6683000 and B=1639000, 6713000). The horizontal blue lines show the sea level at c 2,000 BC, 1,500 BC, 0 BC, 2,000 AD, 4,000 AD and 6,000 AD. The vertical red lines indicate the location of the upstream and downstream vertical sides of the Forsmark regional model area. From ver 1.1. Preliminary site description Forsmark area /SKB, 2004e/.*

For the future ecosystem, vegetation and associated fauna will gradually migrate following the shore-line displacement. Some processes will interact, e.g. peat development and forest succession, which can also be inferred from the existing data. There are still gaps regarding the understanding of regolith processes and regolith-vegetation interactions. These gaps will not be filled until the completion of the SR-Site assessment.

The expected effects of shore-line displacement on the landscape by 1,000 years after closure are shown in Figure 11-2. In the area above the repository, the shore-line is displaced some 100 meters from its present position. This means that some of the bays, e.g. Äsphällsfjärden, are transformed to land and some larger islands appear. However, the main part of the regional modelling area is still a marine environment, with shallower bays.

The infilling of lakes and transformation to mires will be further analysed in SR-Can based on the rates estimated in this area. In this interim report, it is assumed that lakes shallower than 2 m are transformed to mires after 1,000 years. Since all present lakes above the repository are very shallow, they will all transform into mires. New lakes are continuously being formed at the coast, but the implications for the future landscape at the site have not yet been analysed.

Other expected changes of importance during the coming 1,000 years are human exploitation of the sites and climate change. Predicting human behaviour is always uncertain, but the detailed description of the current conditions of the biosphere at the site, historic land use and the catchments likely to develop during the coming 1,000 years provide constraints

Figure 11-2. *The Forsmark region in 1,000 years. Today's shoreline is marked as a grey dotted line. Darker shades of green represent more elevated areas.*

on human settlement, food and water supply etc. Future human exploitation of the environment at the sites in terms of e.g. farming, fishing, hunting, collecting berries and mushrooms, is thus estimated by the prediction of availability of suitable soils and water and their productivity. Moreover, old cadastral maps are used for analysis of previous land use of the area. The maps developed for the coming 1,000 years will contribute to estimating the constraints on possibilities for using the area for different purposes, e.g. agriculture. In this interim report, the only assumption made is that all wetlands are drained by ditching for use in agriculture. For the final SR-Can report, the use of the wetlands will be constrained based on the further analysis of the Quaternary deposits which will indicate that some areas with e.g. large boulders are unsuitable for farming.

Climate change or variability due to greenhouse gas-induced warming over the coming 1,000 years, considered in variants of the main scenario, is also expected to influence important parameters in the biosphere such as the hydrological cycle, sea level, and salinity of the Baltic Sea. However, climatic alterations are difficult to put into the context of a continuously changing environment, because the rate of change and variability cannot be defined. The implications of potential climate change on the hydrology and oceanography, e.g. sea level and salinity, will be described based on e.g. /Gustafsson, 2004/.

In summary, the biosphere at the site during the next 1,000 years is assumed to be quite similar to the present situation. The most important changes are the natural infilling of lakes and slight withdrawal of the sea with its effects on the coastal basins.

11.2.2 Thermal evolution of the near field

The thermal evolution of the near field of the repository is calculated and discussed in section 7.3, with a focus on peak temperatures on the canister surface and in the buffer. These are the key quantities to determine in the safety assessment. Note that all calculations of peak temperatures in section 7.3 are based on the pessimistic assumption that no water uptake occurs in the buffer after deposition. Long-term results are given in Figure 7-7. The thermal evolution of the host rock on a larger scale can be calculated with the same model. This is not of primary importance for safety and has not been done for this SR-Can Interim report, see however the SR 97 report /SKB, 1999a/ for an example of such results.

11.2.3 Mechanical evolution of near field rock

After canister emplacement the most significant new mechanical load on the system will be the thermal expansion caused by the heat generated from the spent fuel. As further explained in chapter 10, the stress state in the Baltic Shield with the major principal stress being oriented NW-SE is largely determined by Mid-Atlantic ridge push movements. Locally, the stress levels are limited and controlled by frictional sliding along nearby large deformation zones, meaning that additional tectonic strain will not result in much increased load on the repository host rock.

Potential for seismicity and faulting

As clarified in section 10.1.3, repository induced seimicity, if it occurs at all, is connected to the rock excavation. It needs not be considered a possibility after repository closure. The possibility of significant faulting or other fracture shear displacement induced by the thermal pulse is also judged to be very limited, see section 10.1.4. Furthermore, as discussed in section 10.1.5, the likelihood of significant (i.e. M > 6) tectonically induced earthquakes is also extremely remote during the first 1,000 years after emplacement and

need not be considered in the consequence analysis. In summary, there will be no significant, i.e. 10 cm or more, displacements of fractures intersecting deposition holes during the first 1,000 years.

Fracturing of the rock

As further discussed in section 10.2, it is likely that most fracturing occurs in conjunction with the construction work, and with relatively minor long-term implications. Nevertheless, new coupled hydro-mechanical calculations are planned for SR-Can, see section 10.4, in order to further substantiate the impact of fracturing due to excavation, thermal load and future loads caused by glacial episodes.

Potential for creep deformation

As discussed in section 10.3, the stress changes caused by ridge push and local heating would not be sufficient to overcome creep thresholds. Before the next period of glacial loading, creeping of the rock mass may be neglected.

Mechanical Impacts on rock permeability

As discussed in section 10.4, it was suggested in SR 97 that the thermal load would increase rock stress in the vicinity of the deposition holes and thus generally close existing fractures, i.e. decrease permeability. Although this is may be generally true, this conclusion will be re-assessed by literature survey and new simulations. This assessment will also explore whether there would be any possibility of significant shear movement on the fractures in the near-field. However, experience from the DECOVALEX III project /e.g. Nguyen and Jing, 2003/, suggests that such shear movement would be very limited and of no consequence to the isolating or retention properties of the rock.

As discussed in section 10.4.3, SR 97 qualitatively considered the impact of thermal expansion at the repository scale, but concluded that the reduction of horizontal stresses would not be large enough to be of any concern for permeability at repository depth. In SR-Can there will be a more thorough evaluation of M-H coupling in the far-field due to future mechanical and thermo-mechanical loads. However, it is expected that the conclusions drawn in SR 97 will still be valid.

11.2.4 Hydrogeological evolution

The hydrogeological evolution of the saturated rock is modelled over a 10,000 year perspective for the changing boundary conditions due to shore-line displacement. See section 9.3, for methodology and results. Density dependent flow and the development of the salinity field are handled by the model. The resaturation phase of the rock is, however, not explicitly modelled.

The results are used in the modelling of the geochemical conditions, see section 11.2.6 and for radionuclide transport calculations, section 12.4.

11.2.5 Saturation of buffer and backfill

The following is a preliminary account of an on-going project aiming at quantifying the saturation process of the buffer and backfill for a range of different conditions.

The water saturation of the backfill and the buffer are determined by coupled 3D THM-processes influenced by several properties of the buffer/backfill materials and the hydraulic conditions of the rock. Two-phase flow conditions also have to be represented. The analysis was done in three steps:

- Investigation of the influence of the backfill properties and wetting conditions on the water saturation phase of the buffer as an update of the wetting calculations /Börgesson and Hernelind, 1999/ for the SR 97 assessment.

- Influence of the rock conditions on the wetting phase of the backfill in the deposition tunnels for three different backfill types.

- Influence of entrapped air on the wetting phase of the backfill in the deposition tunnels.

The mechanical interaction between the buffer and the backfill, in particular due to the buffer swelling at the end of the saturation process has not been considered in this study. This aspect is discussed in section 7.4.1 and in /Börgesson and Hernelind, 1999/.

Influence of backfill properties and wetting conditions on buffer saturation

In the calculations done for the SR 97 assessment, the main supply of water was assumed to be through a fracture intersecting the deposition hole and the influence of the backfill was not studied in detail. Almost all calculations were done under the assumption that the backfill was water saturated from the start and that the buffer could suck water without limitation from the backfill. In reality the supply of water depends both on the initial conditions of the backfill and on the supply of water to the backfill, i.e. the wetting rate of the backfill. Therefore, the following new cases were studied in a number of variants.

1. The backfill is assumed not to supply any water to the buffer. By comparing the results with the SR 97 calculations where unlimited water was supplied, the influence of the backfill can be evaluated.

2. A situation where the rock around the deposition hole has a hydraulic conductivity of only $K=10^{-14}$ m/s and the buffer has a free supply of water through the backfill.

3. An extreme case where no water is supplied to the buffer by the rock. Two backfill types (30/70 bentonite/crushed rock and Friedton) and assumptions regarding water supply to the backfill varied from cases were only initial water was available to a situation where the backfill was water saturated at all times and a water pressure of 5 MPa was supplied through the backfill.

The calculations show that there is a strong influence of wetting from the backfill if the rock is rather dry ($K_{rock} < 10^{-13}$ m/s), whereas the influence is low if the hydraulic conductivity of the rock exceeds 10^{-12} m/s.

A completely dry rock yielded very long times to saturation (up to 2,000 years in the case of a 30/70 mixture with an initial water content of 12%) when water was supplied only by the backfill. The buffer will thus eventually reach a very high degree of saturation with water provided by the backfill even if there is no water supplied by the rock. The only exception is the calculation for Friedton with a low initial water content, which yielded drying of the buffer due to the low water content of the installed backfill. The result implies that a backfill material with a high initial suction should be avoided in a very dry rock.

The calculations are based on an MX-80 buffer. A Milos buffer is expected to behave similarly, since its swelling pressure and hydraulic conductivity are close to those of MX-80 at buffer density.

Influence of rock and backfill properties on the water saturation phase of the backfill

The calculations of the saturation phase of the buffer with varying backfill water supply described above show that the backfill has a major influence on the wetting when the rock matrix hydraulic conductivity is lower than 10^{-12} m/s. The backfill conditions and the rate of backfill wetting are thus vital for understanding buffer wetting under those conditions. Therefore, a number of calculations of the wetting rate of different backfill types under several rock conditions have been performed. The following factors were combined into a number of cases:

- Two different backfill materials: 30/70 crushed rock/bentonite and Friedton.

- Fracture distance (1–24 m between the fractures intersecting the deposition tunnels).

- Fracture transmissivity (T = $5\cdot10^{-8}$–$5\cdot10^{-11}$ m²/s).

- Rock matrix hydraulic conductivity (K = 10^{-13}–10^{-12} m/s).

- With and without a piping zone.

- Distance to water supplying hydraulic boundary (25–100 m).

These calculations show that the backfill will be saturated on a time frame of 0.5–150 years (30/70 mixture) or 3–200 years (Friedton). The longer saturation time for Friedton is explained by its lower hydraulic conductivity. There is generally a strong influence of the distance between fractures on the saturation time. The effects of fracture transmissivity, rock conductivity and distance to the hydraulic boundary are quite small. A permeable zone between the backfill and rock (due to piping effects) will give substantially shorter saturation time.

The calculations were based entirely on generic rock conditions. The water inflow to the tunnel in the different cases ranged from 0.00017 to 2.05 litres/(min·metre). For all these conditions, it is clear that the backfill will be saturated considerably faster than calculated for the buffer in the "dry rock" cases reported in the previous section.

The calculations for the 30/70 mixture were done for the MX-80 material. For the Milos material, the difference in properties will mainly be a lower suction potential and a higher hydraulic conductivity. The time to saturation for the Milos material is expected to be considerably lower, since the wetting is mainly controlled by the hydraulic conductivity of the backfill.

Analysis of trapped air in backfill

The influence of trapped air in the backfill on the water saturation process was analysed with Code_Bright version 2.2, which is a finite element code for thermo-hydro-mechanical analysis in geological media. A 1D, axially symmetric model including a backfilled tunnel and a portion of the host rock was analysed. At the model's outer boundary, the hydraulic pressure was set to 5 MPa and the water supply to the backfill was varied by varying the rock permeability. The rock was kept saturated, thus the air in the initially unsaturated backfill had to escape by diffusion through the rock. In addition to the cases where the gas pressure was calculated as part of the solution, cases with a constant gas pressure assumption (no trapped air) were analysed. In Table 11-1 the times for reaching a backfill saturation degree of 99% in the different models are given.

Table 11-1. Time for reaching backfill saturation of 99%.

K_{rock} (m/s)	Time for reaching 99 % saturation (years)	Comment
$5 \cdot 10^{-9}$	2.9	
$5 \cdot 10^{-11}$	4.3	
$1 \cdot 10^{-12}$	78	
$5 \cdot 10^{-9}$	0.45	Constant P_g = 0.1 MPa
$1 \cdot 10^{-12}$	75	Constant P_g = 0.1 MPa

It is concluded that air trapped in the backfill could have a considerable effect on the saturation time if there is plenty of water available in the rock. The saturation times are however small in such cases, also when the entrapped air is taken into account. With little water in the rock, the effect of the entrapped air is small, which mean that the air has little effect on the saturation time of the backfill.

Conclusions

The calculations in this section show that the buffer will be saturated in a period of a few to some hundreds of years (a few thousand in the most extreme, unrealistic cases). The longest calculated saturation times are of the same order of magnitude as those for repositories in clay, e.g. /Nagra, 2002/. The length of this period is expected to have no significant impact on the buffer performance.

A long saturation time means that no corrosion or radionuclide transport can take place for that period. However, the saturation time is still too short for this to have any significant positive impact on the overall performance of the repository. The temperature in the repository will be higher with a long saturation time, but no credit for water in the rock is taken in the calculation of the peak temperatures (that typically occur after 10 years), see section 7.3. The buffer properties are not expected to be affected by a long time of partial saturation. The bentonite has been exposed to partially saturated boundary conditions for millions of years /Smellie, 2001/.

Application to hydraulic conditions at the Forsmark site

The Forsmark Site-Descriptive model version 1.1 /SKB, 2004e/ provides information on two alternative DFN descriptions on a local scale. The model with lower fracture intensity and higher transmissivity values is believed to more accurately reflect actual site conditions.

The derived relationship between fracture length and transmissivity is for this model given as

$$T = 1.13 \cdot 10^{-10} \, L^{1.791}$$

where L is in m and T in m^2/s. Thus, for fractures in the length interval 1–10 m, the transmissivity will vary between 1×10^{-10} and 7×10^{-9} m^2/s.

An evaluation of the proposed DFN model for hydrogeological simulation purposes is provided in /Hartley et al, 2004/. Here, the total P32 value (fracture surface area per volume) for fractures of length 1 to 10 m in the depth interval –300 to –500 m is given as 0.336 m^{-1}. Assuming that this P32 value represents conductive fractures only, this value can be transformed into a conductive fracture frequency, e.g. /Andersson et al, 1998/. The resulting

Table 11-2. Saturation time for the backfill as a function of fracture spacing and transmissivity. First value is for a 30/70 mixture, second for Friedton

Fracture spacing/ Transmissivity	5×10^{-9} m²/s	5×10^{-10} m²/s	5×10^{-11} m²/s
2 m	0.8/6.5 years	1.2/6.7 years	3.4/11 years
6 m	2.2/19 years	3.0/20 years	9.5/31 years
12 m	5.5/44 years	6.9/46 years	19/63 years

conductive fracture frequency (CFF) is half the P32 value or CFF = 0.17 m⁻¹. This implies fractures with a mean distance of 1/0.17= 6 m.

These values fit well within the boundaries of the calculations described above. The calculated saturation time for the backfill is in the range of 1-65 years, Table 11-2.

11.2.6 Chemical evolution in and around the repository

During the first 1,000 years after closure, 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 groundwater around the repository. It is expected that the meteoric water and perhaps the Baltic water components in the ground-water will increase during this period.

One of the questions to be addressed for this period is whether the initial geochemical conditions are re-established after repository closure. The important parameters are redox properties and salinity. Evidence from the Äspö laboratory and from open Swedish mines show that reducing conditions prevail in the host rock even at a short distance from the tunnel walls. Air will be entrapped in the buffer and backfill, but anoxic conditions are expected to be established in the resaturated tunnels shortly after closure, see section 11.1.3. The salinity distribution will be initially affected by the perturbation caused during the operation period, and the further evolution of salinity will be studied using hydrological models, as discussed in section 9.3.

The successions of events at the site (e.g. shore displacements and changes in annual precipitation) are some of the input data for the hydrological modelling. The salinity distribution as a function of space and time is partly determined by the influx of meteoric waters and/or Baltic waters at repository depth. The calculations of salinity evolution are performed both within hydrological models (by particle tracking) and by adjusting mixing proportions of reference waters (looking at conservative chemical species, such as chloride) and the results compared.

The effects of groundwater mixing are seen in the behaviour of conservative species such as chloride, sodium, ¹⁸O, etc, whereas chemical processes such as precipitation, dissolution and redox reactions affect non-conservative parameters, e.g. pH and alkalinity. The extent of chemical reactions is governed by the overall compositional changes due to mixing. In SR-Can, the evaluation of the mixing proportions will be followed by the modelling of the chemical speciation and evaluation of mineral dissolution/precipitation reactions. For example, the result of mixing present-day groundwater at repository depth with increasing amounts of precipitation (rain water) will result in a mixture that is either super- or under-saturated with calcite. As calcite reacts at a relatively fast rate, the mixture of waters is allowed to reach equilibrium with calcite, and the new equilibrium composition produces new values of pH, alkalinity and calcium concentrations. These calculations will be performed with the PHREEQC code.

11.2.7 Buffer chemical evolution

Unsaturated phase

The geochemical processes will be the same before and after saturation. No modelling of the chemical evolution during the saturation transient is undertaken in SR-Can. Rather, the initial pore water is taken to be instantly mixed with groundwater /Domènech et al, 2004/.

Phase of elevated temperatures after saturation

The temperature gradient in the buffer may cause dissolution-transport-precipitation of some of the impurities in the buffer. The most important are calcium sulphates, calcite and SiO_2 /SKB, 2004b/. The magnitude of this process will be calculated with an integrated geochemical model for the near field described in /Domènech et al, 2004/. Impurities enriched in hot or cold sections of the buffer could potentially have an effect on the rheological properties.

Elevated temperatures have an effect on the montmorillonite in the buffer, mainly due to increased silica solubility. The extent of this is calculated with a kinetic expression /SKB, 2004b/.

11.2.8 Canister evolution

During the initial 1,000 years, the canister is expected to experience elevated temperatures, an increasing water pressure as the rock resaturates, differential pressures from the swelling bentonite and corrosion mainly due to sulphide and initially entrapped oxygen.

All these aspects have been covered in chapter 7, either as preliminary calculations (corrosion, section 7.2; peak temperature, section 7.3) or as brief references to earlier studies (e.g. differential swelling pressures, section 7.8).

The final SR-Can report will contain a more detailed account of these phenomena.

11.2.9 Repository conditions 1,000 years after closure

In the SR-Can final report, the repository conditions at the end of the 1,000 year period will be summarised, and the status of the function indicators discussed.

11.3 Evolution for continued temperate climate

In this section, the evolution of the repository system for an assumed continuation of the present temperate period is analysed. As mentioned, the duration of this period is highly uncertain. Here, most of the analyses are discussed in a 10,000 year perspective. Several of them have been discussed in this longer time perspective already in the previous section, since the respective model studies do not distinguish between the two time periods.

Many of the transients characterising the evolution during the first 1,000 years are not relevant for the continued evolution. The thermal and hydraulic conditions in the host rock will have more or less returned to the situation prior to excavation of the repository, modified however by the changing hydraulic boundary conditions due to land-uplift.

11.3.1 Biosphere

The continued shore-line displacement will influence the local biosphere and eventually result in a situation where the site is located inland rather than at the coast (Figure 11-3). This will in turn influence the positions of the potential discharge areas for radionuclides. Shore-line displacement and subsequent ecosystem development will also change the possible exploitation of the ecosystems. Previous lakes will, e.g. have become agricultural areas. Moreover, erosion of the regolith can change the topography and consequently the potential discharge areas for radionuclides.

During the series of transitions dependent on shore-line displacement and succession, several important stages can be identified. In this interim report, only the final "land case" is identified as substantially different from the "coast case". In the final SR-Can report, the aim is to systematically look at the transitions of the coastal region to lakes, rivers and terrestrial environments during intermediate critical development phases.
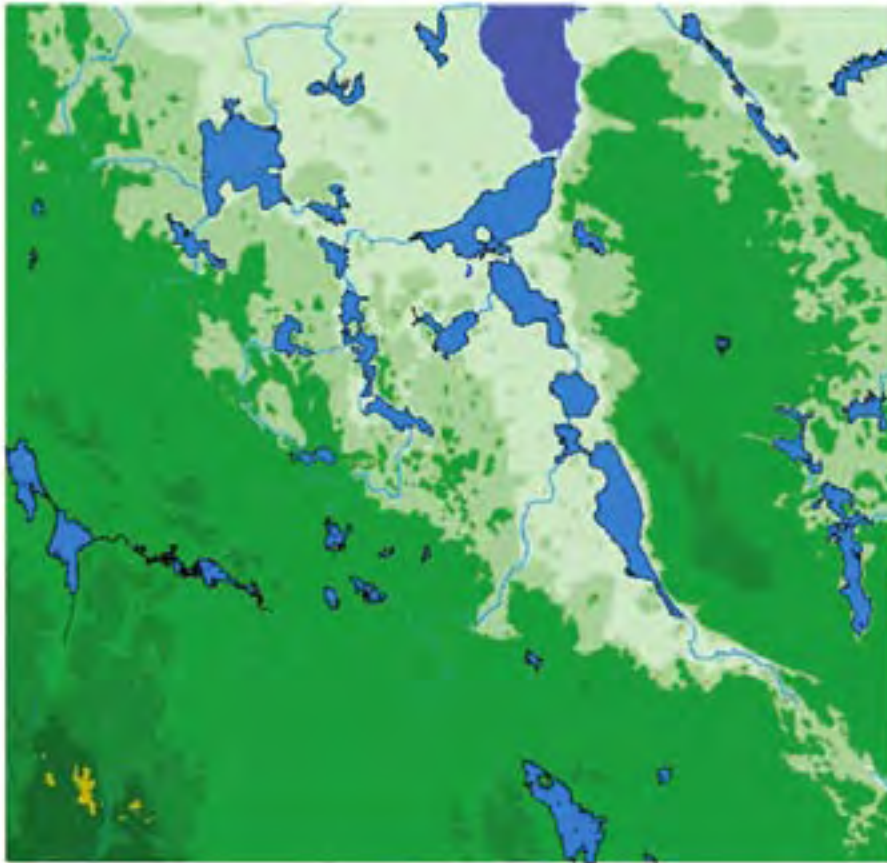

Figure 11-3. *The expected biosphere characteristics of the Forsmark region at 7,000 AD. The entire area is terrestrial and some large deep lakes are situated along the shoreline of the former island of Gräsö. Darker shades of green represent more elevated areas.*

11.3.2 Thermal evolution

The thermal evolution for this phase is discussed in section 11.2.2.

11.3.3 Rock mechanics

A continued temperate climate would not imply any additional mechanical loads compared to the situation in the first 1,000 years. Furthermore, the thermal load from the spent fuel would reach its peak and start to decline, even though some thermal output from the waste would still remain. As the thermal pulse gradually decreases during this period, the rock stress levels may eventually go back to those of the pre-waste-emplacement stage. This also means that there will be little change in the rock mechanics state during this period. In particular, the probability of significant tectonic earthquakes will remain low, rock fracturing or creep deformation of deposition holes or tunnels will be limited. Decreased rock stresses, as the thermal pulse diminishes, may in theory imply some effects on permeability, but these effects could not be larger than the impact from the thermal load on the original permeability field. Ongoing work, see chapter 10, will further substantiate all these claims.

11.3.4 Hydrogeological evolution

As mentioned in section 11.2.4, the hydrogeological evolution of the saturated rock is modelled in a 10,000 year perspective for the changing boundary conditions due to shoreline displacement. See section 9.3, for methodology and results.

11.3.5 Geochemistry

The methods for studying the geochemical conditions during a temperate period have been described in section 11.2.6. It is expected that most of the initial chemical perturbation caused by the operation of the repository have, after 1,000 years, a negligible influence on the geochemical conditions at the site. However, climate variations, affecting the relative infiltration of precipitation and sea water, can have on the other hand a larger impact on the overall geochemistry of the site.

11.3.6 Buffer and backfill

The chemical evolution in the buffer and backfill will continue over all repository timescales. This is calculated with the integrated geochemical model for the near-field described in /Domènech et al, 2004/. The model takes into account:

- Diffusive transport in the bentonite domain.

- Diffusive and advective transport in the backfill domain.

- Diffusive and advective transport in the granite domain.

- Precipitation-dissolution of accessory minerals in bentonite and granite.

- Precipitation-dissolution of secondary minerals in bentonite and granite.

- Cation exchange in the bentonite.

- Surface acidity of the bentonite.

- Cast iron insert corrosion.

- Thermal gradient.

The most important processes are ion-exchange and the dissolution/precipitation of calcite. The montmorillonite mineral is currently not included in the model for the near-field. Transformation of montmorillonite to less-expandable minerals will be calculated with a combination of a kinetic expression and a transport model for silica.

11.3.7 Canister

For continuation of a temperate period beyond 1,000 years, the canister temperature will be approaching that of the host rock background temperature, the water pressure and the bentonite swelling pressure are expected to be maintained at their values after the initial hydraulic transients and corrosion is expected to continue, mainly due to sulphide initially in the buffer, see further chapter 7, sections 7.2 and 7.3, for a preliminary account.

The final SR-Can report will contain a more detailed account of these phenomena.

11.3.8 Repository conditions at the end of a continued temperate period

In the SR-Can final report, the repository conditions at the end of this period will be summarised, and the status of the function indicators discussed.

11.4   Evolution for the reference glacial cycle

11.4.1 Reference long-term evolution of climate related conditions

This section gives a brief account of the modelling of the reference evolution of climate-related conditions, i.e. essentially a reconstruction of the Weichselian glacial cycle, with emphasis on the conditions at the Forsmark site.

The extent of the Scandinavian ice sheet is of principal importance in determining the extent of the glacial domain, which in turn affects the extent of the permafrost and temperate/boreal domains. The most important basis for the presented evolution of climate-related conditions is the results from a numerical modelling of the evolution of the Scandinavian ice sheet during the Weichselian. In order to calculate shore-level displacement, yielding boundary conditions for hydrological and geochemical analysis, a global isostatic adjustment (GIA) model is coupled to the ice-sheet model. The third main component in the modelling is a permafrost model, yielding permafrost depths. The main data flows between the ice sheet, GIA and permafrost models are shown in Figure 11-4. There will also be separate, more detailed, hydrological and mechanical analyses and modelling to provide a solid basis for analysis of the impact of ice sheets on repository evolution.

In this interim report, preliminary results from the ice-sheet model are presented. There are currently no results from the GIA modelling. Instead, the shore level as simplistically calculated by the ice-sheet model is given as an example. Permafrost results from 1D scoping calculations are available. The limitations of using these simplified models to generate the boundary conditions are discussed below.
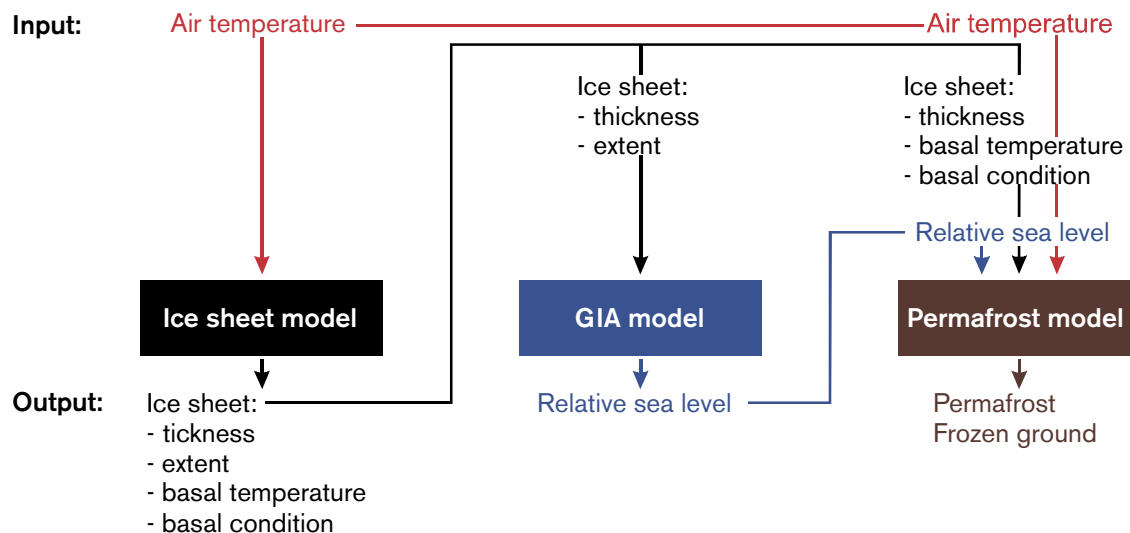
Figure 11-4. *Models used to provide boundary conditions for analysis of the impact of climate-related changes on the repository. Only input and output data shared between the models used to generate the boundary conditions are shown.*

11.4.2 Ice-sheet and GIA modelling

The ice-sheet model is dynamic and capable of simulating realistic ice sheets which are typically not in balance with the climate. Derived ice temperatures, together with density variations with depth, control ice hardness and ice flow. The thermodynamic calculation accounts for vertical diffusion, vertical advection, and heating caused by internal shear. The model has been developed over an extended period /Fastook and Chapman, 1989; Fastook, 1994; Fastook and Holmlund, 1994; Johnson and Fastook, 2002/ and results agree with other major ice-sheet models /e.g. Payne et al, 2000/.

Inputs to the dynamic ice sheet model are:

- Topography, including existing glaciers and ice caps.

- Thermo-mechanical properties of ice.

- Annual air temperature at sea level.

- Geothermal heat flux.

- Global sea level.

- Isostatic properties of the earth crust.

The ice thickness at each node in the model is a function of local ice velocity and mass balance. The mass balance is determined from an empirical relationship constituting a simple parameterization of the ice sheet's effect on local climate /Fastook and Prentice, 1994 based on Fortuin and Oerlemans, 1990 and Braithwaite and Olesen, 1989/. The climate input, forcing the ice sheet evolution, is the variation of the mean annual air temperature at sea level and local temperatures are determined from height over sea level and distance from the pole. In absence of a long-term palaeo-temperature climate curve from Scandinavia, the simulation of the Weichselian ice sheet over Fennoscandia was controlled by the temperature curve from the GRIP ice core, central Greenland /e.g. Dansgaard et al, 1993/, a typical method used in ice-sheet modelling of the Weichselian glacial cycle.
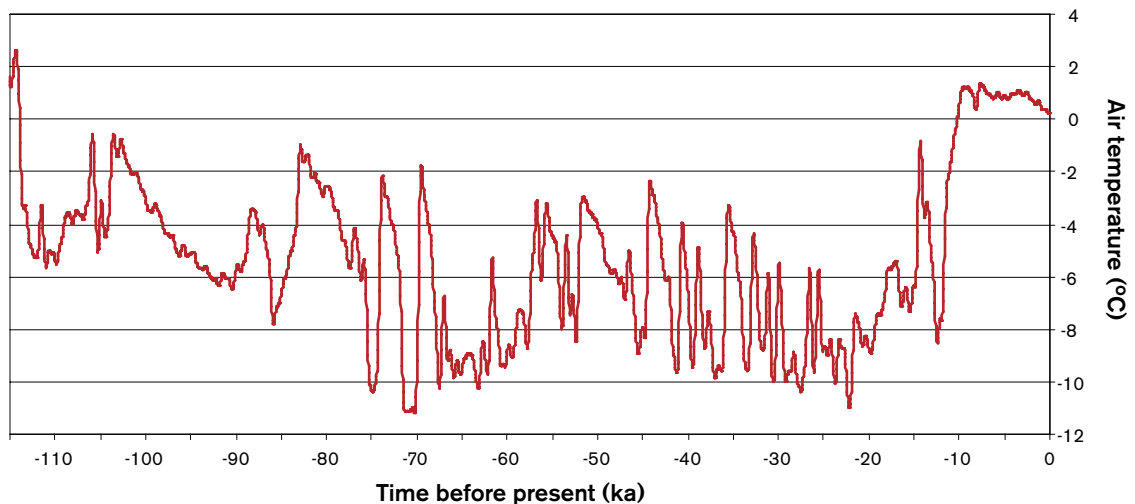
Figure 11-5. *Temperature reconstructions based on $\delta^{18}O$ in the Greenland ice core /from Dansgaard et al, 1993/.*

A new set of geothermal heat flux data has been compiled for Sweden and Finland based on national high resolution measurements of gamma emission /Näslund et al, submitted/. The data set is illustrated in Figure 11-6. Comparisons of calculations using a constant or spatially varying geothermal heat flux have shown that when studying the conditions at a smaller scale or in a specific area, the variations in geothermal heat flux are of importance for defining basal conditions, especially basal ice temperatures and melt rates.

The eustatic component of shore-level displacement (lowering of the sea surface due to accumulation of water in continental ice sheets and glaciers) is given as input to the ice-sheet model. There are several proxies and methods to reconstruct the eustatic evolution available in the literature /Shakleton, 1987; Lundberg and Ford, 1994; Fairbanks, 1989/. However, in the reconstruction of the Wechselian presented here, a model simulation of global ice sheet volumes has been used to estimate a eustatic curve.

The altitude of the ice surface is directly affected by isostatic changes of the earth's crust. Consequently, in order to adopt a proper climate input to the model, an isostatic model is required. The isostatic representation included in the ice sheet model is a simplified elastic plate model. This is considered adequate to adjust the ice sheet surface climate input for the modified topography, but is not intended for reconstructions of the shore-level.

As mentioned above, there are no Swedish climate archives covering the entire Weichselian. Various geological information such as end moraines, basal till distribution, interstadial and interglacial deposits do, however, provide information on the glacial history of northern Europe. Geological information on the Weichselian glaciation history of Scandinavia have been compiled /Lokrantz and Sohlenius, in prep/.

In numerical modelling of ice sheets, there is a need to calibrate the model, i.e. to determine values of unknown parameters in the ice-sheet system, for instance related to basal processes or anisotropic composition of ice. In the calibration process, the behaviour of the modelled Weichselian ice sheet was fitted against the known geological information of ice marginal positions. Information on Early and Middle Weichselian ice-sheet distributions as well as Last Glacial Maximum and deglaciational ice margin positions was used in the calibration process. The climate input to the ice-sheet model was locally modified so that the model results were compatible with the geological information on ice marginal positions and evidences of ice-free conditions.
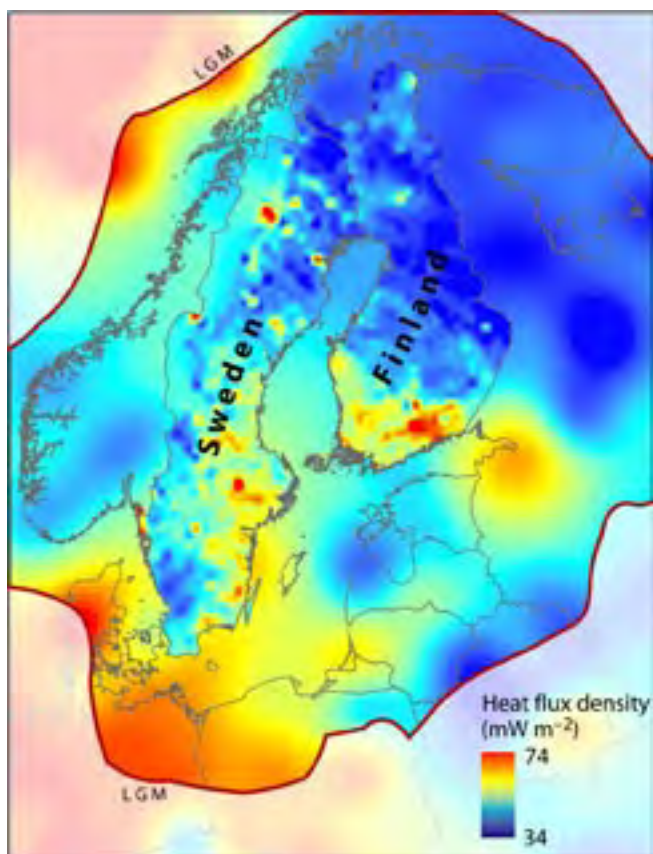
Figure 11-6. *Data set on geothermal heat flux within the area covered by ice at the last glacial maximum (LGM) /from Näslund et al, submitted/. High resolution data for Sweden and Finland based on gamma-emission measurements were complemented with coarser data on observed geothermal heat fluxes from drill holes /Pollack et al, 1993/.*

The modelled Weichselian total ice volume and total ice covered area for the calibration run are shown in Figure 11-7. The figure also shows the calibration points for the reconstruction and the corresponding marine isotopic stages (MIS, see also Figure 4-3) and the names of stadials and interstadials. Calibration of this particular model reconstruction was made against the Weichselian scenario as described by /Lundqvist, 1992/. Calibrations against alternative geological interpretations will also be performed.

The evolution at the Forsmark site depicted as a time series of climate domains and submerged periods is illustrated in Figure 11-8. Climate domains with a calculated duration shorter than 200 years are not resolved in this quasi static overview.

The eustatic input and simplified isostatic model included in the ice sheet model have, in this example, been used to determine whether the site is submerged or not. As mentioned above, the purpose of this isostatic model is not to predict shore-level displacement but merely to correct for changes in modelled ice sheet surface temperature and accumulation rate due to altered elevation. Therefore, this description of whether the site is submerged or not should be regarded as illustrative only. In this example, the site is considered submerged when the grid cell in which Forsmark is situated lies below the sea surface and the Öresund and Bält straits are open. If the straits are closed the site is assumed to be submerged by a lake as long as there is a remaining isostatic depression. If the site actually was submerged by a lake depends on the topography generated not only by the Scandinavian part of the ice sheet but also by associated parts of the Eurasian ice sheet in the northeast, and on the
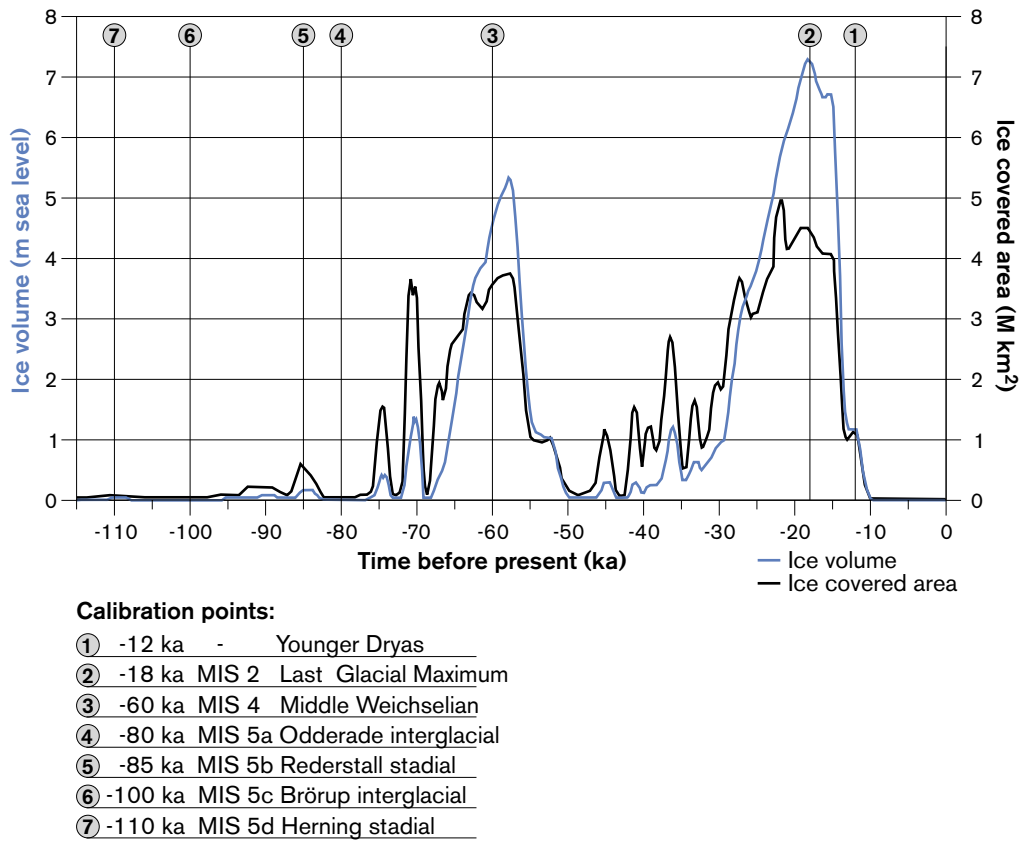
Figure 11-7. Reconstructed total ice volume and ice covered area throughout the Weichselian, and the calibration points for the reconstruction.
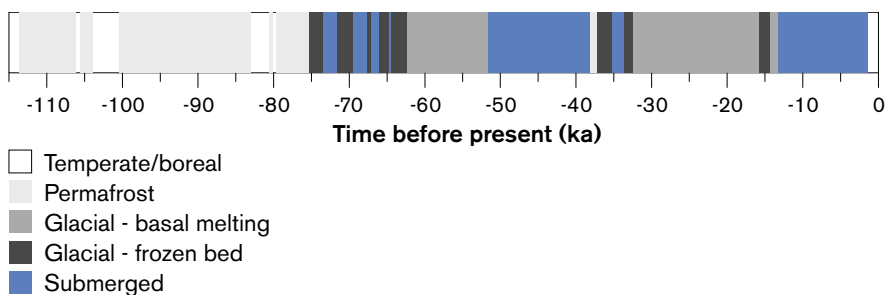
Figure 11-8. Time series of climate domains and submerged periods for the Weichselian at the Forsmark site.

run-off from the drainage area it generates. The examplified eustatic and isostatic evolutions and assumed submerged periods are shown in Figure 11-9. Proper studies of shore-level displacement considering key factors and processes will, in future assessments, be performed by means of GIA-modelling.
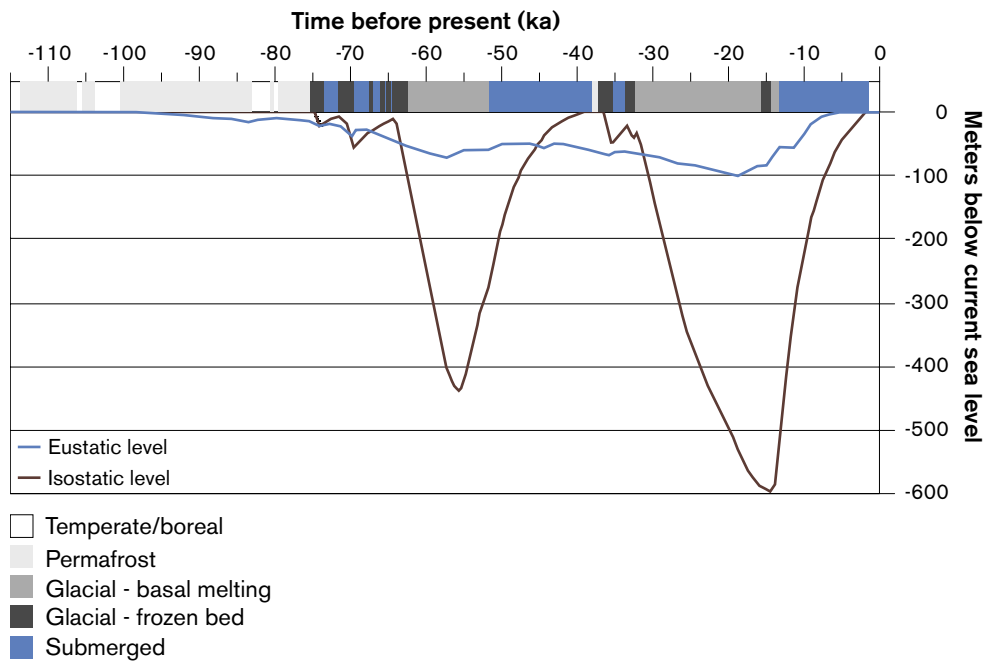
Figure 11-9. *Time series of climate domains and submerged periods and simplified eustatic and isostatic evolutions from ice sheet modelling.*

11.4.3 Permafrost modelling

The evolution of permafrost and frozen ground are investigated by means of modelling. Periglacial permafrost develops during cold periods when the area is ice free or lies above the level of the surface of the sea or large water bodies. Subglacial permafrost develops under a cold-based ice sheet. Calculations of the development of permafrost and frozen ground have been performed using a model developed at the University of Helsinki /Hartikainen and Mikkola, 2003/. For the purpose of estimating the possible depth of permafrost and frozen ground for this interim report, a 1D approach is considered to be sufficient /Hartikainen, 2004/.

The inputs to the permafrost model are:

• Temperature at the ground surface.

• Ice-sheet thickness.

• Groundwater head (set to 0.9 times the ice thickness during periods of basal melting and zero otherwise).

• Geothermal heat flux.

• Soil cover (depth, material, hydraulic properties).

• Bedrock (thermal, mechanical and hydraulic properties).

• Groundwater composition.

The temperature input used for calculations of depths of permafrost and frozen ground is shown in Figure 11-10. For ice-free periods it is that used in the ice-sheet modelling. For periods when the site is ice covered, basal temperatures given by the ice-sheet model have been used. For periods when the site is submerged by the sea, the temperature at the bottom is set to zero if the temperature at the sea or lake surface is below zero. If the temperature

Figure 11-10. *Time series of climate domains, submerged periods and temperatures. Surface temperature during ice free, non-submerged periods is that at the bed surface and during submerged periods that at the sea or lake surface (red). During ice-covered periods both the temperatures at the ice surface (red) and at the ice/bed interface (yellow) are shown. Assumed temperature at the sea/lake bed is show in purple.*
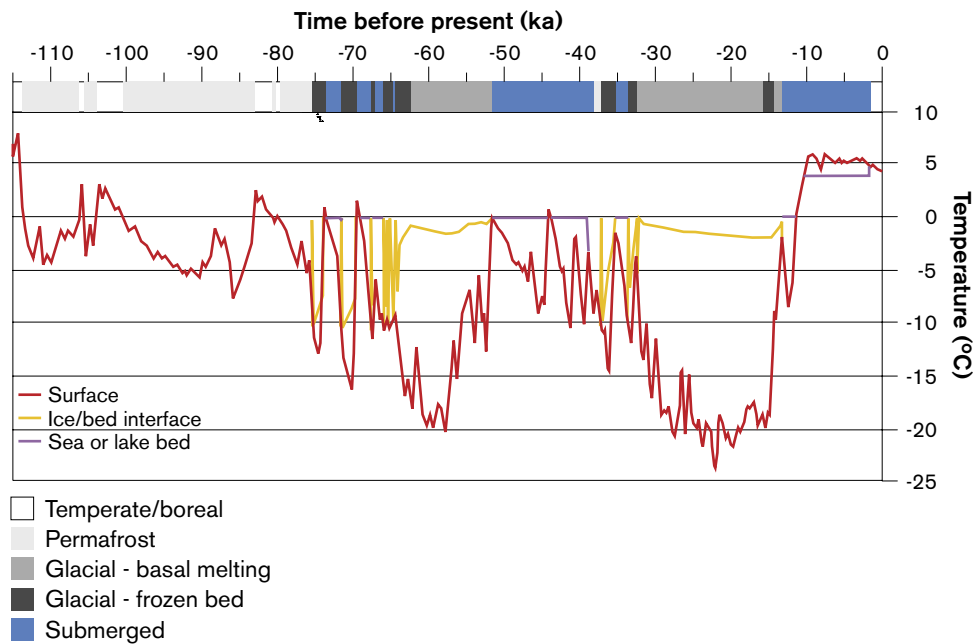
at the surface is above zero but below 4°C the temperature at the bottom is set to the same temperature as at the surface, and if the surface temperature is above 4°C the bottom temperature is set to 4°C.

Ice thickness and basal conditions for the Forsmark site, extracted from the ice-sheet model and used in the permafrost modelling are shown in Figure 11-11, other input to calculations of permafrost were obtained from the site descriptive model. The results of the one-dimensional calculations of depths of permafrost and frozen ground are shown in Figure 11-11 /Hartikainen, 2004/. The impact of sea or lake water covering the site on the development of permafrost and frozen ground is not included in the modelling. From current areas of permafrost it is known that permafrost does not exist under large water bodies, and that larger lakes do not freeze to the bottom during winter. There are examples of sub-sea permafrost, but these are believed to be relict and the result of permafrost evolution from times when these sea beds were not submerged /Allen et al, 1988 in Vidstrand, 2003/. Sub-sea frozen beds may also develop in supercooled Artic waters /Vidstrand, 2003/. In the 1D-calculations of permafrost depth, the effect of water coverage is illustrated by the assumed sea/lake bed temperatures. This simplified example indicates that the presence of sea or lake water affects the evolution of permafrost and needs to be considered (see Figure 11-11).

So far, only one-dimensional scoping calculations of permafrost depth have been carried out. To model the lateral extent of permafrost and the effects of factors such as topography, varying soil depth and properties, presence of lakes and water bodies and varying properties of the bedrock, 2D and/or 3D modelling is required. A sensitivity analysis to identify the most important factors affecting the calculated permafrost depths will be performed. The identified factors will then be taken into account in site-specific modelling of occurrence of permafrost and frozen ground.
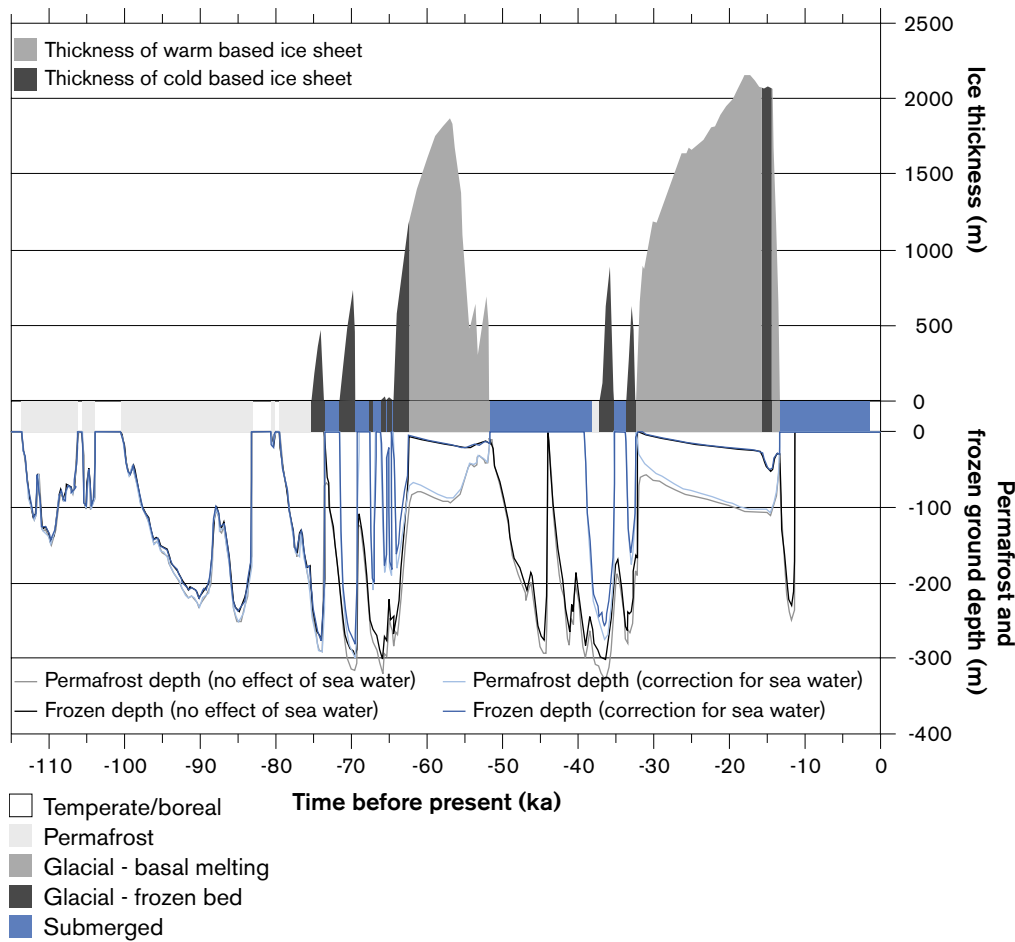
Figure 11-11. *Time series of climate domains, ice thickness and depth of permafrost and perennially frozen ground (as permafrost is defined by temperature the occurrence of permafrost does not always mean that the ground is frozen).*

11.4.4 Further analyses

The evolution of the shore level is, in addition to estimations of permafrost, used as input to hydrological analysis and analysis of groundwater composition. The example curve shown in Figure 11-9 is the above described output from the ice-sheet model. The plan for SR-Can is to use a GIA model to calculate the relative shore level. This will give a more detailed topographic picture including information on whether, and how, the Baltic is connected to the sea, which will provide a basis for estimates of salinity.

The evolution of the ice sheet and its basal conditions, including the production of basal melt water, and the occurrence of permafrost and frozen ground are also input to more detailed analyses of subsurface hydrological and mechanical conditions. As discussed in section 9.5.3, the interactions between climate, ice sheet and subsurface generating the hydrological system associated with a continental ice sheet are complex and not fully understood. An example is the formation of ice tunnels and other conductive features at the ice/bed interface and their importance for determining pressures and flows. Data from ice sheet, GIA and permafrost modelling will also be used when analysing the effects of glaciation on the crustal stress field and implications for postglacial faulting.

11.4.5 Biosphere

Permafrost conditions

The permafrost and tundra situation will be described and discussed in a separate report for SR-Can. Parameters and processes of importance for potential transport of radionuclides to and within the biosphere during this period are the properties of the geosphere/biosphere interface (e.g. formation of taliks), erosion processes and human exploitation of the environment (e.g. in defining exposure pathways). As part of SR-Can, the method for handling these conditions will be established.

Glacial conditions

During glacial conditions, the surface ecosystems are expected to contain few species and food chains and the human population is likely absent or sparse. Therefore, the doses from potentially discharged radionuclides are expected to be very low. These assumptions need to be described and supported.

A report describing glaciated and ice-margin surface ecosystems and their human exploitation will be compiled for SR-Can in order to give some basis for the inclusion or exclusion of dose calculations for this period.

Next interglacial period

The Forsmark area has earlier been submerged by the sea or very large freshwater lakes. The sea has likely experienced periods with higher salinity than today /Westman et al, 1999/, and, immediately after deglaciation, also freshwater periods. After a future glaciation, the shore-line displacement is expected to gradually make the Forsmark area less submerged and eventually the first land in the area will appear, maybe 10,000 years after the ice retreat. The sediments are expected to be eroded by strong, wave driven resuspension forces /Brydsten, 1999a/ during this period, before transformation to a terrestrial environment occurs. Only some limited areas along Gräsö are expected to have continuous accumulation bottoms over the following 10,000 years (Figure 11-12). Thereafter, as in the present situation, a period dominated by a coastal environment is expected to take over, followed by a terrestrial period when lakes, rivers and mires will be formed.

In general, the ecosystem processes during the next interglacial period are expected to be similar to those occurring during the present interglacial. There will be a Baltic Sea basin, with a lower salinity than ocean water. Rock outcrops and depressions with till and bays, lakes and bogs will probably be located at approximately the same places as today, since their location is essentially controlled by the underlying geological structures which have persisted for several millions of years. However, eskers cannot be generalised in this way. Humans will probably be able to exploit the sea, the lakes and the land in similar ways as today, and their needs are assumed to be the same. Thus, the description of the next 10,000 years and the historic description of the biosphere can serve as a general "model" for all future interglacial periods.
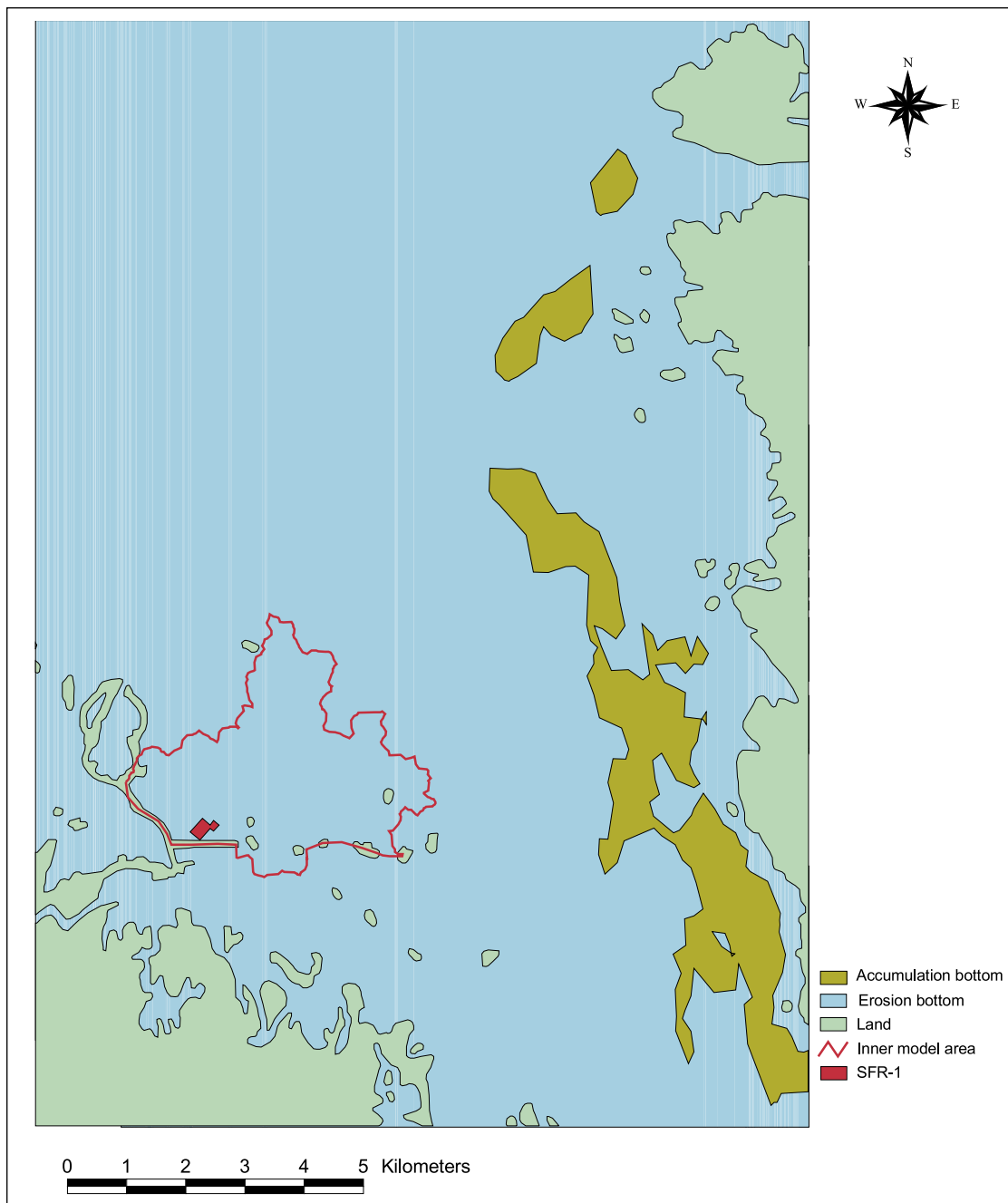
Figure 11-12. *Areas close to Gräsö island that are expected to have continuous accumulation bottoms over the next 10,000 year /Brydsten, 1999a/.*

11.4.6 Rock mechanics

Glaciations, will give an excess of mechanical load compared to present-day conditions. The nature of the glacial stress excess depends not only on the ice-load, but possibly also on the crust/mantle interaction. While estimating the added vertical stress component is relatively straightforward, it is more complex to assess the shear component as this will depend on the nature of the interactions between the ice, the rock and the mantle. Work is going on to arrive at a better understanding of the relative importance of ice-load, crust/ mantle interaction and large deformation zones to the stress field during glacial cycles (see section 10.1.6).

Seismicity and faulting

As discussed in section 10.1.6, it is currently not possible to exclude the possibility of post (or end) glacial faulting. However, results from ongoing research may alter this conclusion, and in time for SR-Site a better substantiated estimate of the probability of end glacial faulting will be made.

Even if earthquakes occur, this does not necessarily imply a hazard to the repository. As discussed in section 10.1.1, damage to the canister would only result if the shear movement across the deposition hole was larger than at least 0.1 m. Furthermore, shear movement would only occur on larger fractures, see section 10.1.7. During construction of the repository such fractures will be avoided by applying proper respect distances and deposition hole acceptance criteria, but there will remain a possibility that some "unsuitable" deposition holes will be accepted. In SR-Can, estimates will be provided, see section 10.1.9, on the joint probability that a used deposition hole would be intersected by too long a fracture and that this fracture would shear by more than 10 cm. However, for this interim report a case with one such canister is analysed in order to illustrate the effects, see section 12.6.1.

Fracturing of the rock

As discussed in section 10.2, it is likely that most fracturing will occur in conjunction with the construction work, and with relatively minor long-term implications. Nevertheless, new coupled hydro-mechanical calculations are planned for SR-Can, see section 10.4, in order to further substantiate the impact of fracturing due to excavation, thermal load and future loads caused by glaciations.

Potential for creep deformation

As further explained in section 10.3, a simplistic technique was used in SR 97 to set extremely conservative upper bounds to the possible increase in mechanical load on a canister that could follow from rock creep. Creep-induced deformations of openings were assumed to continue until all shear stresses in the host rock had relaxed, i.e. the rock would behave as a viscous fluid. The final state would be that of a host rock with hydrostatic stresses. The deposition holes would have converged until the buffer compression had generated swelling pressures corresponding to the rock mean compressive stress. For a mean compressive stress of 14 MPa and an additional ice-load of 30 MPa, the resulting pressure on the canister would be 44 MPa. This would give a small reduction of the deposition hole diameter. This estimate is valid irrespective of the number of glaciation cycles expected to occur within the next million years, as long as the buffer keeps its mechanical properties.

The concept of creep thresholds reduces the theoretically possible convergence to be much less than the convergence estimates obtained by use of the viscous fluid model. Quantitative estimates can be obtained by utilising discrete fracture near-field rock models. The strength of the fractures should be reduced in steps to represent the effects of creep, i.e. a successive relaxation of fractures shear stresses. Preliminary studies that are available now /Hökmark 2003; Glamheden et al, 2004/ indicate that the effects, i.e. the convergence of openings, will be very modest, a couple of millimetres for deposition holes and a few centimetres for tunnels.

Mechanical Impacts on rock permeability and other MH-coupled effects

As discussed in section 10.4.4, SR-Can will address the two-way M-H couplings during glaciation, by reviewing ongoing hydro-mechanical glaciation studies complemented by numerical analyses. No account of such effects is given in this interim study.

11.4.7 Hydrological evolution

The methodology for handling hydrological issues during a glacial cycle is described in section 9.5. MH couplings are discussed in section 10.4.

11.4.8 Geochemical evolution

The successions of temperate, permafrost and glacial climate domains will greatly affect the flow and composition of the groundwater. There will be a constant evolution between climate domains, and there is no clear boundary between them. For example, during a temperate domain, temperatures may slowly decrease such that permafrost regions slowly develop within parts of the region. It is, however, not meaningful to perform detailed, time-dependent hydrological calculations, so there will be no such basis for an analysis of the geochemical evolution.

Therefore, the geochemical modelling will be restricted to using separate specifications for the different climatic domains. It is expected that different groundwater compositions will prevail around the repository as a result of the different types of climate domains and their corresponding hydraulic conditions.

Permafrost

The onset of permafrost might induce the formation of saline groundwaters due to the exclusion of salt during groundwater freezing. However, these more saline waters will be formed on top of the original groundwater, which will be less saline and therefore less dense. Gravitational effects will cause a gradual downward movement of the salinity to reach depths of similar groundwater density. In SR-Can, the movement of the salinity will be studied by numerical hydrological modelling, and the effect of a regional groundwater gradient below the permafrost will also be investigated.

Field investigations of sites affected by permafrost are not simple; for example saline drilling fluids must be used to avoid freezing. A study of a mine located in permafrost in Canada has been conducted in collaboration with Posiva and Nirex. The data suggest the presence of an undersaturated zone under the permafrost, probably due to the draw-down created by the mine. Although methane emanated from several boreholes, no evidence of methane ice has been found at the mine.

Glaciation

The penetration of diluted waters and upconing of saline waters under continental glaciers has been described for example in /Jaquet and Siegel, 2003/. Two extreme groundwater types may be inferred from the model: the "saline ice-front" and the "non-saline melting zone". The saline waters of the ice front occur as a consequence of hydraulic upconing effects. Converesely, dilute meltwaters penetrate the geosphere as a consequence of high hydraulic pressures beneath the ice-sheet. The effect of the upconing is largest in front of the ice margin, where salinities as high as 50 g/L are predicted at repository depth, see Figure 11-13.
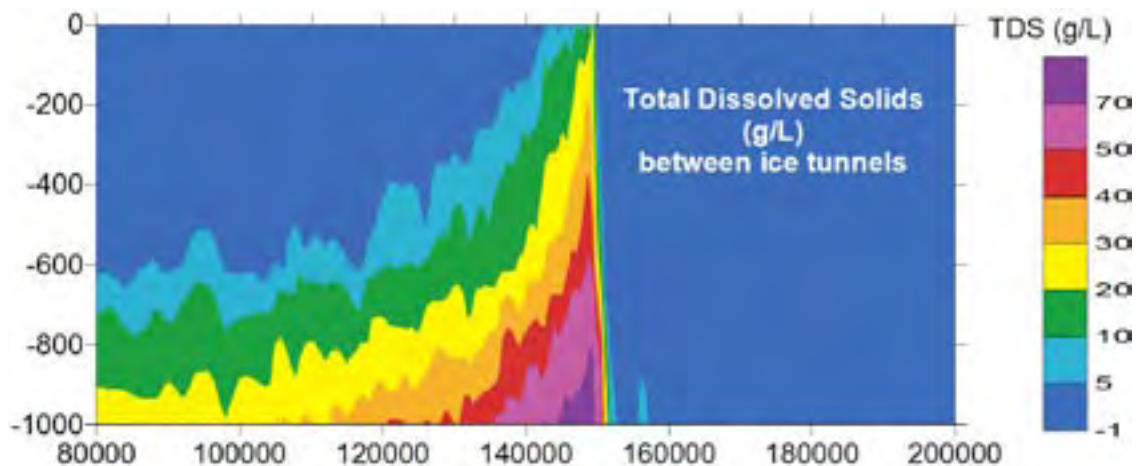
Figure 11-13. Calculated distribution of groundwater salinity in a profile perpendicular to the ice margin of a glacier (see SKB-R-03-04). In this model the ice margin is located at coordinate 150,000 m. Due to the up-coning effect the salinity increases in front of the ice margin: up to TDS = 50 g/L at repository level (−500 m).

The reactions between oxygen-rich melt waters with minerals present at the sites will be calculated within SR-Can. Preliminary results show that the waters become slightly alkaline and anoxic. The results are however influenced by the hydraulic characteristics of different fracture zones.

11.4.9   Effects on engineered barriers

The effects of climatic evolution on the engineered barriers are not analysed in detail in this interim report. Several crucial issues to consider have, however, been mentioned in the preliminary analyses, chapter 7, e.g.

- Buffer erosion.

- Effects of salinity on the buffer.

- Isostatic pressure on canister.

- Penetration of oxygenated water.

- Shear movements at deposition holes.

11.4.10 Repository conditions after the reference glacial cycle

In the SR-Can final report, the repository conditions at the end of this period will be summarised, and the status of the function indicators discussed.

11.5   Evolution for subsequent glacial cycles

For the reference climatic evolution, the first glacial cycle is simply assumed to be repeated until the end of the assessment period, i.e. for one million years. With a cycle period of around 115,000 years, this means about nine repetitions of the Weichselian type of glacial cycle.

This will e.g. mean that the surface, thermal and hydraulic conditions are expected to be, to a first approximation, cyclic whereas chemical alterations like ion exchange in the buffer and canister corrosion will continue over the entire period as will long-term mechanical processes like tectonic effects and creep.

11.5.1 Repository conditions at the end of the assessment period

In the SR-Can final report, the repository conditions at the end of this period will be summarised, and the status of the function indicators discussed.

11.6 Sensitivity to assumptions in reference climate

In the SR-Can final report, this section will contain a sensitivity analysis, as outlined in section 4.2.3.

11.7 Conclusions

Following the analyses presented in this chapter, conclusions regarding isolation potential and barrier conditions for the main scenario will be drawn. Canister failures resulting from the evolution will be analysed in the next chapter, for the barrier conditions representative of the main scenario evolution.

12 Analysis of failed canisters; example calculations of radionuclide transport

12.1 Introduction

This chapter demonstrates some aspects of the analysis of failed canisters, both for the main and other scenarios. The main purposes are to:

- Give an account of the current understanding of the internal evolution of a failed canister.

- Demonstrate how the evolution can be expressed as input data for radionuclide transport calculations.

- Give an example of a base case probabilistic radionuclide transport and dose calculation, including sensitivity analyses of the calculation results to input data uncertainties.

- Demonstrate a number of variant calculations of the base case, handling uncertainties not covered by the base case, and examples of extreme, unrealistic "what if" cases demonstrating understanding of system function.

The external conditions for all situations considered in this chapter are assumed to be today's climate and biosphere. These simplifications are in line with the scope of this Interim report, see further section 1.3. Furthermore, a temperate climate will likely give rise to the highest doses for a given release from the repository, although this remains to be strictly shown.

The database for the calculations is far from complete. No attempt to draw conclusions regarding safety for the Forsmark example site will be made, although the "best possible" input data available at this stage for the engineered barriers and for the Forsmark Site Model version 1.1 have been used.

Failure modes

A canister is considered as failed when the copper shell is penetrated, i.e. when there is an open connection between the interior and the exterior of the copper shell. The basic failure mode of canisters considered here is due to corrosion in which penetration of the copper shell occurs where the shell thickness is reduced due to assumed initial welding defects. Other potential failures due to corrosion, e.g. by oxygen assumed to penetrate during glacial conditions could be treated similarly, should the full analysis of the main scenario and its variants not allow exclusion of this phenomenon. A calculation case for estimating consequences of failures that could potentially be caused by rock shear movements at a deposition hole will also be presented. Whether such cases would be included in a final risk summation would depend on the results of the analysis of the likelihood of this failure mode, see further section 10.1. A failure due to isostatic overpressure is considered highly unlikely, see section 7.8, but the implications of such failures could also be calculated with the models used in the example calculations presented here.

Number of failed canisters as a function of time

The failure of canisters due to corrosion of the copper shell is described by the preliminary modelling results in section 7.2.2. The average number of failed canisters increases linearly with time as determined by the weld defect statistics and the concentration and transport properties of the corroding sulphide impurities in the buffer. In the base case calculation shown in section 7.2.2, on the average one single canister in the deep repository is penetrated at the end of the one million year assessment period. Although this result is preliminary, it provides an important background time frame for the discussion of the evolution of a failed canister in the following section.

12.2 Evolution of failed canisters

12.2.1 Introduction

The evolution of a failed canister is complex and depends on a number of uncertain factors. Water is likely to intrude into the canister, causing corrosion of the cast iron insert with hydrogen gas generation. The build-up of gas pressure in the canister can be considerable and lead to the suppression of further water entry and also to gas release through the buffer. As corrosion proceeds, corrosion products, occupying a larger volume than the corresponding amount of metallic iron, will exert mechanical pressure on the copper canister, potentially leading to an expansion of the original defect in the copper shell. The corrosion also causes a weakening of the cast iron insert, making the canister more vulnerable to isostatic pressure. This could also lead to expansion of defects.

The evolution will also be influenced by external factors like the external mechanical load on the canister and by the thermal conditions. Based on preliminary results in previous chapters, no failures are expected during the initial 1,000 years when elevated temperatures will prevail in the repository.

In the radionuclide transport calculations, the canister interior is pessimistically assumed to possess no transport resistance and no sorbing capacity. Rather, as soon as the canister is filled with water, a continuous pathway between the spent fuel and the canister exterior is assumed and the canister interior is represented as an inert water volume in which radionuclides are dissolved and diffuse freely. Transport resistances or barrier functions of the inner structural parts of the canister and the fuel, including the fuel cladding, are thus disregarded once the transport pathway is established.

Key issues for the transport calculations are therefore reduced to the following:

- After canister failure, when will a continuous water pathway between the spent fuel and the canister exterior be established?

- What is then the size of the passage through the copper shell (the only transport resistance taken into account) and of the void volume in which radionuclides are dissolved?

- How will the defect size and the void volume evolve over time?

In section 12.2.2, different possibilities for the internal evolution of the canister are sketched, and, based on these, assumptions regarding the key parameters for the transport calculations are formulated in section 12.2.4. Gas transport through the buffer is addressed in section 12.2.3.

A further issue to consider is the possibility of nuclear criticality in the interior of a failed canister. This is discussed in section 12.2.5.

12.2.2 Possible internal evolutions

General

In the SR 97 assessment /SKB, 1999a/ the internal evolution was modelled in two separate studies /Bond et al, 1997, Takase et al, 1999/. Uncertainties regarding both understanding of the involved phenomena and data were considerable. The following is a discussion of the problem complex, based on the results of the two SR 97 studies and on some new experimental data.

Once the copper canister has been penetrated, water can intrude. The intrusion rate of water will be determined by the difference between the groundwater pressure and that in the interior of the canister, since the flow resistance of the hole is much smaller than that of the bentonite /Bond et al, 1997; Takase et al, 1999/. At e.g. a pressure difference of 4.9 MPa, corresponding to 5 MPa hydrostatic pressure and 0.1 MPa pressure in the canister, the rate of water inflow will be $3 \cdot 10^{-5}$ m^3 per year for a 6 mm diameter hole /Bond et al, 1997/.

In /Smart et al, 2002a,b/ a series of different corrosion experiments are reported. Part of the study was to investigate the influence of corrosion products and water chemistry on the corrosion rates. Some of the experimental results are, therefore, not directly applicable to the situation in the repository. The mean corrosion rates were low and generally less than 1 μm per year. In high ionic strength water at pH 7 to 8, the corrosion rate for cast iron was measured as 0.1 μm per year whereas at pH 10.5, the rate was as low as 0.01 μm per year. It is difficult to judge what can be considered as a pessimistic upper bound for the corrosion rate. The measured rates span nearly two orders of magnitude, although most data indicate a rate of less than 0.1 μm per year. Based on /Smart et al, 2002a,b/, a realistic rate of anaerobic corrosion of cast iron can be set to be less than 0.1 μm per year, corresponding to a hydrogen production rate of about 0.2 litres/(m^2·year) /Smart et al, 2002a,b/. This corresponds to a water consumption of 2.4 g/year, if the corrosion occurs over the full cast iron area (about 14.4 m^2). This can be compared with the water inflow rate of 30 g/year. The galvanic coupling between the cast iron and the copper will have a very limited influence on the corrosion rate. Recent experimental results indicate that the galvanic corrosion rate in de-aerated groundwater is as low as 0.02 μm per year, i.e. within the uncertainty of the anaerobic corrosion rate for cast iron /Smart et al, 2004/. The corrosion rate will, therefore, be too low to consume all the water that initially enters through corrosion reactions and as a consequence, the corrosion will also take place over the full cast iron surface area since the corrosion rate is the same in water vapour as it is in liquid water /Smart et al, 2002a,b/.

It should be pointed out, however, that the annulus between the canister and the insert at the time of the failure of the copper canister will most likely have closed due to the swelling pressure of the bentonite /Knuutila, 2001/. In these circumstances, the corrosion will take place over a much reduced area. The creep deformation of the copper shell as a result of the build-up of the bentonite swelling pressure will be further studied and the result may modify the possible scenarios for the development of a failed copper canister.

In the following, four different possibilities for the further evolution are sketched.

Base case: Corrosion in filled annulus ceases, tight insert

There will be a net inflow of water into the annulus. This inflow will decrease with time as the hydrogen counter pressure builds up and finally come to an end when the hydrogen pressure equals the hydrostatic pressure. After that, the corrosion reactions will consume the remaining water inside the annulus and corrosion will continue by water vapour. The area on the surface of the insert that will corrode will be determined by the rate at which the water is consumed, i.e. the corrosion rate, and the rate at which water diffuses into the annulus. The corrosion rate will drop with time as the magnetite layer thickens and its transport resistance increases. After 10,000 to 20,000 years depending on the manufacturing tolerances between the copper canister and the insert, the annulus or part of the annulus will be filled with magnetite. At that time no or very little water will enter the annulus and the subsequent corrosion will be controlled either by the very low supply of water or, alternatively, by the transport of iron to the original hole in the copper shell. In either case, the corrosion will most likely then drop to a very low rate. With this evolution, there will be no release from the canister until the cast iron insert fails. The strength of the insert has been shown experimentally to withstand the extra load during a glaciation and the only conceivable mechanical overload that could cause canister failure would be a massive rock shear movement.

Alternative case I: Corrosion in filled annulus continues, Cu shell expands, bentonite creep relaxation

An alternative evolution would be that, when the annulus is filled with corrosion products, corrosion will not cease but continue at the same rate over at least part of the surface area of the cast iron insert. The growth of the corrosion products will cause the copper canister to expand its radius through creep. The creep ductility of the copper is specified to be at least 10 percent. At a corrosion rate of 0.1 μm/year, this strain would not be reached for about 475,000 years and would require that the whole insert wall thickness had been corroded away. (The corrosion of 0.1 μm of iron produces approximately 0.2 μm of magnetite.) The expansion of the diameter of the copper canister would also lead to an increased bentonite density. The swelling pressure increases very rapidly with the increase in density, see section 7.7. It seems reasonable to assume that the bentonite would "relax" by creeping/ extruding into the space above the canister as the canister radius expands, limiting the swelling pressure in the gap between the canister and the rock wall to a value not too far from the original pressure. While this happens, the mechanical strength of the insert is continuously lowered and it will, at some point, fail. A rough calculation indicates that the insert's strength has been halved when the wall thickness is reduced to 35 mm. This would happen after 150,000 years at a corrosion rate of 0.1 μm/year. The actual strength of the insert remains to be determined, see further section 6.3.1. Once that has been established, it might be fruitful to perform some calculations for varying wall thicknesses to establish the failure pressure and also the mode of failure, i.e. what does the canister look like after failure. It seems, however, reasonable to assume that sometime during a future ice age, the canister insert will collapse due to the increased water pressure. Whether this would also result in failure (cracking) of the outer copper shell is not obvious and if such a failure should occur, the size and shape of the resulting hole in the canister would be highly uncertain. A possibility would be the opening of a millimetre wide axial crack over the major part of the canister length.

The above development indicates that there will be no releases until a major glaciation, which occurs in roughly 100,000 year cycles. Then, possibly, a defect of a size that remains to be determined would occur. It would furthermore be difficult to take credit for any transport resistance from the canister for this defect.

Alternative case II: Corrosion in filled annulus continues, Cu shell expands, bentonite compression

A second alternative evolution would be that the bentonite would not through creep relax the increased swelling pressure due to the expansion of the corrosion products. This evolution is, in fact, in most respects identical to the one described above. The insert's failure would, however, happen earlier and might not even require an ice age for failure within a period of hundred thousand years.

Again this evolution indicates no release until the large failure, which might, however, occur earlier than with creep relaxation.

Alternative case III: Corrosion in filled annulus ceases, corrosion continues inside insert

A third alternative evolution would be that although the cast iron in the annulus has ceased to corrode, corrosion is still possible inside the insert, in the fuel deposition channels. This corrosion would be caused by water vapour (see above). The rate is, also in this case, assessed as 0.1 μm/year. The corrosion will lead to a gradual weakening of the insert's mechanical stability until it, most likely under the increased load during an ice age, collapses. The failure would be similar to those described above.

Further development after a large defect

After a larger defect (hole) in the copper canister has developed, the corrosion of the insert will continue at the same rate as previously and the iron in the canister insert will be gradually replaced by magnetite. The copper corrosion will be very limited during this period and its rate will depend on the supply of sulphides from the rock, and the buffer and backfill. This process will continue for some additional few hundred thousand years after the larger failure developed. The exact time will depend on the volume of iron remaining after the larger failure. During that time, there will be substantial amounts of hydrogen present in the near field. There will also be relatively small void volumes inside the copper/magnetite canister. It also seems reasonable to assume that the magnetite will extrude into the original crack in the copper canister.

12.2.3 Gas transport through the buffer

The corrosion of the insert will generate hydrogen according to:

$$3Fe + 4H_2O \rightarrow Fe_3O_4 + 4H_2$$
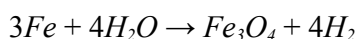
A corrosion rate of 0.1 μm/year will generate 0.42 litres (STP) of hydrogen per m^2 of iron surface per year.

A gas pressure build up is expected within the canister since the surrounding water-saturated bentonite is impermeable to gas flow. Transport by diffusion of hydrogen dissolved in the buffer pore water for different conditions has been estimated by /Wikramaratna et al, 1993/. A small defect in the copper would give a transport capacity for diffusive transport which is much lower than the expected production rate, meaning that the gas pressure in the canister will increase.

The understanding of the mechanisms behind gas migration through a water-saturated bentonite is incomplete. The treatment of the process in SR-Can is essentially based on experimental observations.

At a certain pressure, the bentonite will open and allow the gas to pass through. In SR 97 this pressure was assumed to be the sum of the swelling pressure and the hydrostatic pressure. However, recent experiments have shown that the entry pressure for gas into bentonite can be substantially higher than this /Harrington and Horseman, 2003/. Based on the experimental interpretation by /Harrington and Horseman, 2003/, at the peak pressure a fracture will open in the buffer and the peak pressure could be expressed as:

$$p_g \text{ (peak)} = T + 2\sigma_{eff} + p_w$$

according to the 'classic theory' of hydrofracture /Haimson and Fairhurst, 1967/, where T is the tensile strength of the clay, σ_{eff} is the isotropic effective stress outside the region of stress concentration and p_w is the porewater pressure in the clay. For a water-saturated bentonite, the isotropic effective stress is equal to the swelling pressure. For the experiment, the calculated value for the peak pressure of 21.4 MPa agrees fairly well with the measured value of 22.1 MPa. Maximum gas pressures in the range of 20–25 MPa can, therefore, not be ruled out. A build-up of such pressures would take at least 14,000 years with a corrosion rate of 0.1 μm/year if the entire surface of the insert is available for corrosion. The effects of such pressures on the host rock need to be evaluated.

After gas breakthrough the pressure will fall to a value which is equal to the total stress:

$$p_g \text{ (post peak)} = \sigma_{eff} + p_w$$

The fractures generated by the gas will stay open as long as there is gas production within the canister. The experiments show that the gas transport leads to no or very little desaturation of the bentonite. The buffer is therefore expected to retain its properties throughout the gas transport period. When gas production ceases, the fractures are likely to close and seal. The gas transport is therefore not expected to lead to an increased hydraulic conductivity of the buffer.

The formation of a gas phase could push water out of the canister if the defect is located in the lower part of the canister. This situation should be considered in the formulation of calculation cases for the final SR-Can report.

Based on current understanding, the hydrogen gas from corrosion would have no negative effects on the performance of the buffer. The gas pathways are not expected to lead to a loss of the diffusion barrier. However, high pressures can be expected in the near-field and contaminated water may be pushed out by the gas under certain conditions.

12.2.4 Conclusions for consequence calculations

The above two sections demonstrate that there are considerable uncertainties regarding the internal evolution of a failed canister. Conceivable outcomes range from situations where the full isolation potential is essentially maintained to those where a water pathway is established within thousands of years and the initially small damaged area expands to a larger region in tens or hundreds of thousands of years.

In order to include uncertainties related to the canister evolution in the overall quantification of consequences, the following simplified treatment is adopted:

- The small defect is assumed to be circular and have a radius of 2 mm. This is rather large given the observed distribution of pore sizes from electron beam welding.

- Following failure in the form of a small penetrating defect due to corrosion, it is assumed that at least 1,000 years will elapse before a continuous aqueous transport path between the fuel and the canister exterior is established. This assumption is based on the slow water ingress rate, further decreased by the gradual build-up of an internal counter pressure due to hydrogen gas formation, as well as on the barrier functions of the cast iron insert and of the fuel cladding. Any one of these factors is likely to provide more than 1,000 years of delay.

- The further development is assumed to eventually lead to a large failure of the copper canister, potentially to the extent that the canister offers no transport resistance to radionuclides. Based on the different possibilities for the evolution sketched above, it is assumed that this may occur at any time between 1,000 years and 100,000 years after failure. A uniform distribution of this additional time required for a large failure to develop is therefore assumed. No transport resistance for the canister is assumed when the large defect has developed. This is the most pessimistic case and will be reconsidered in the continuation of the SR-Can project.

Through the above assumptions, the uncertainties related to internal canister evolution are incorporated in the probabilistic calculations. The assumptions are, however, not based on qualified data in the same strict sense as for many other data.

Since both data and conceptual uncertainties are considerable, it is difficult, from a strict compliance calculation point of view, to claim any safety properties of a failed canister, other than an initial delay of radionuclide transport if the original failure is small. A case where all transport resistance from the canister is lost 1,000 years after failure is, therefore, also analysed. This is based on available information at this stage of the analysis and may be reconsidered. Also, the effects of assuming a finite transport resistance after a large failure will be explored in variation cases.

12.2.5 Criticality

The possibility of nuclear criticality in the canister interior has been dismissed in a number of studies, see e.g. the SR 97 report /SKB, 1999a/. The issue has recently been analysed by /Agrenius, 2002/. Those 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. Consideration of additional actinides and selected fission products gives a larger margin of safety. There is, therefore, no need at present for more data in this field. The results will be discussed in the SR-Can Process report.

The risks for criticality as a result of redistribution of material has been analysed by /Behrenz and Hannerz, 1978/ and /Oversby, 1996/. In both cases the conclusions were that criticality outside the canister has a vanishingly small probability, requiring several highly improbable events.

12.3 Models for radionuclide transport and dose calculations

Figure 12-1 shows the models and data used in the radionuclide transport and dose calculations. In the following, a brief description is given of the near-field model COMP23, the far field model FARF31 and the biosphere as represented by separately calculated ecosystem specific effective dose conversion factors. The hydrological model CONNECTFLOW is discussed in chapter 9.

Radionuclide transport and dose consequences for many of the variant and residual cases will, in these example calculations, be calculated with a simplified, analytical model that yields similar results to the numerical models. The analytical model is briefly explained in section 12.3.4.

Separate modelling of colloid-facilitated transport in the geosphere is discussed in section 9.4.1.
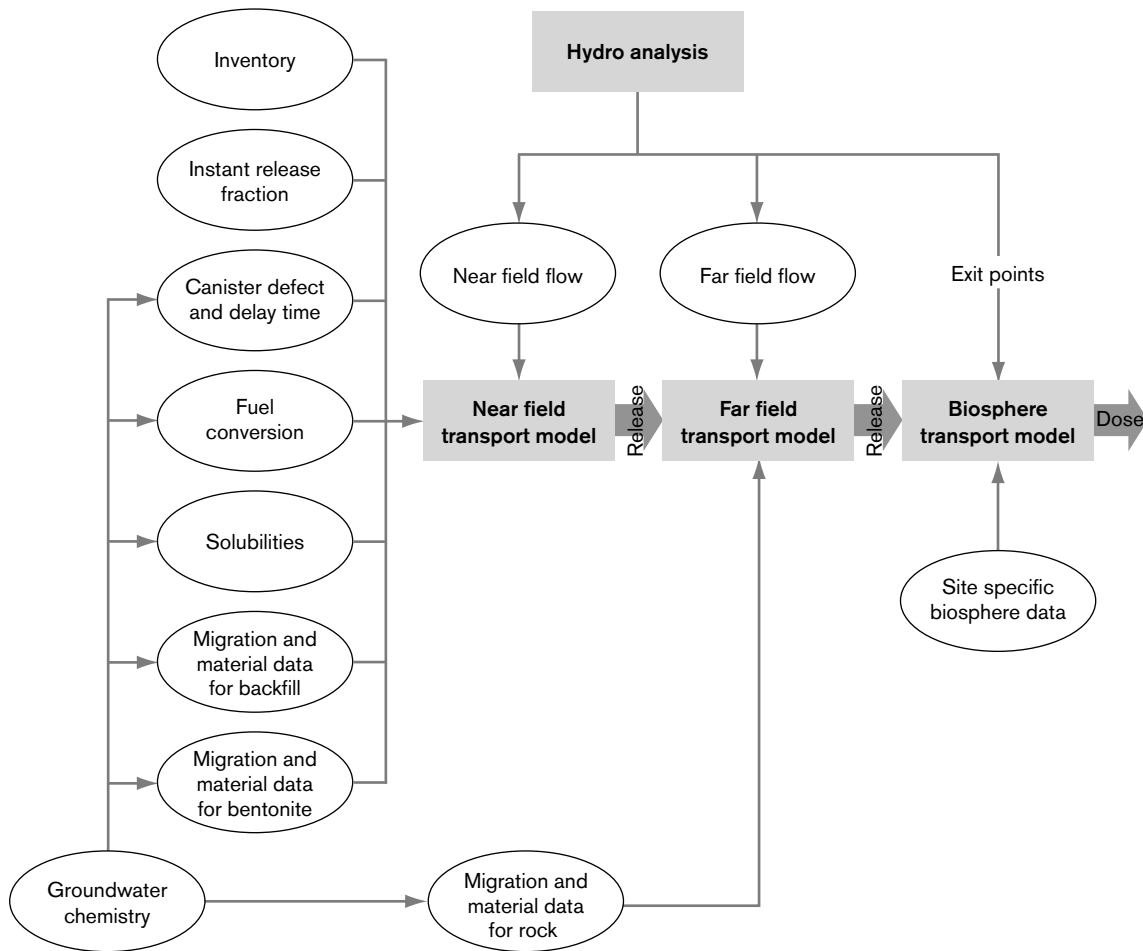
Figure 12-1. *Models and data for the consequence calculations.*

12.3.1 The near field model COMP23

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; Cliffe, 2004/. COMP23 is a multiple-path model that calculates transient nuclide transport in the near field of a repository by use of a network of coupled resistances and capacitances 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 enhance calculation speed. Whereas the COMP23 model used in SR 97 was only able to handle nuclide transport through diffusion, the present version has been modified so that advective transport can also be simulated. A further development since SR 97 is that all nuclides of a specific element can now share the elemental solubility inside the canister, where solubility limitations are imposed on radionuclide concentrations.

Figure 12-2 shows the canister deposition hole and the backfill and how it is modelled by COMP23 in SR-Can. Two exits from the near field are included: a fracture intersecting the deposition hole at the vertical position of the canister lid, denoted Q1, and an excavation damaged zone, EDZ, in the floor of the deposition tunnel, Q2. (In SR 97 two additional pathways were modelled, but only Q1 and Q2 gave significant contributions.) In the

Figure 12-2. *The near field and detail of its model representation as compartments B1-B6, C1-C3 and E in the model COMP23. The transport paths Q1 and Q2 to a fracture and to the excavation damaged zone are also shown. (There is also a minor EDZ around the deposition, not shown in the figure.)*

hydrological modelling, the number of fractures intersecting a deposition hole and the properties of these fractures are determined statistically based on the DFN description of the rock, see further the Interim Data report /SKB, 2004c/. If more than one fracture intersec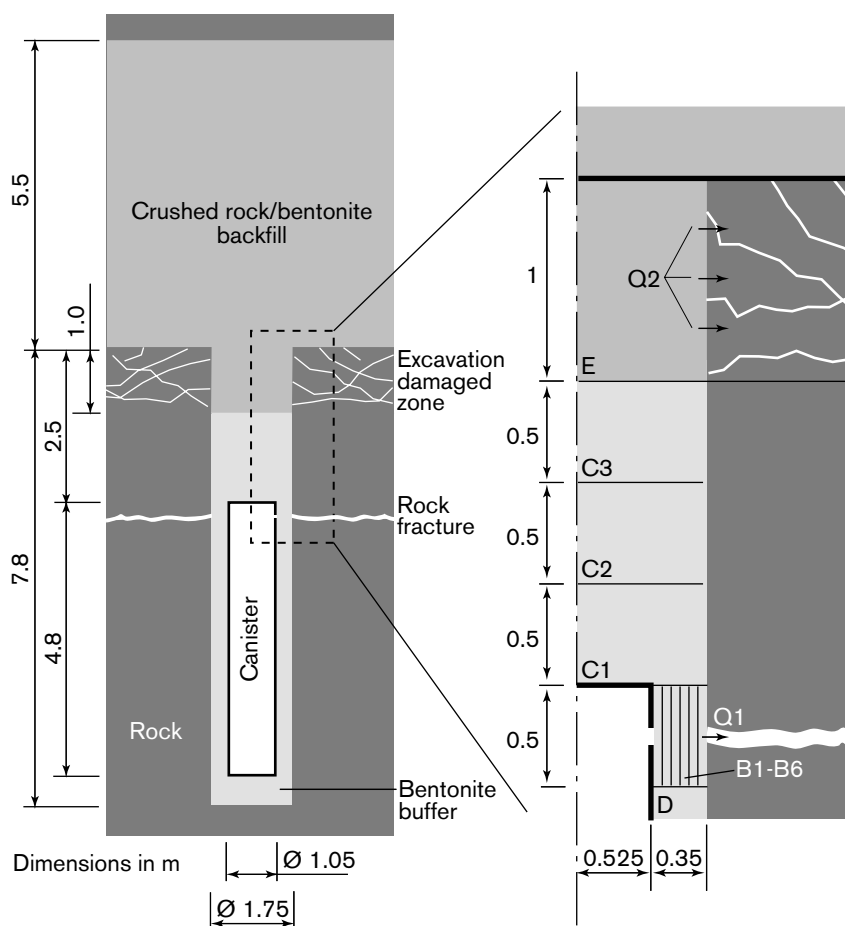ts a deposition hole, the transport capacity of the several fractures are added and pessimistically assigned to the single fracture modelled by COMP23. Furthermore, the flow rate, q, at the top of the deposition hole is determined in the hydrological calculations. Combined with generic data on the EDZ transport properties, q is used by COMP23 to calculate the transport rate through Q2.

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.

For the final SR-Can report, a model validity document for COMP23 will be produced. An example of such a document, for the FARF31 code presented below is provided in /Elert et al, 2004/.

12.3.2 The far field model FARF31

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; Elert et al, 2004/ is based on a one-dimensional stream tube concept, and includes the following processes: advection, dispersion, matrix diffusion with equilibrium sorption, and radioactive decay (including 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. See further section 9.4.1 for the handling of colloid transport in the geosphere.

12.3.3 Biosphere representation

Section 2.8 and Appendix C outline the handling of the biosphere in SR-Can. A more comprehensive, site-specific and realistic description of the biosphere development is envisaged in comparison to e.g. the safety assessment SR 97 /SKB, 1999a/. The highest doses are expected for those parts of temperate periods during which the site is not submerged.

As mentioned in section 2.8, the treatment of the biosphere in the consequence calculations aims at capturing two situations that are representative of the highest dose consequences that could reasonably occur during the assessment period, assuming that the biosphere and its use by humans resembles the present situation.

One of these is a mire being used for agriculture, representing a terrestrial ecosystem in which radionuclides may be accumulated over a long period but where exposure may be limited to a shorter period. The properties of the mire are, as far as possible, representative of the Forsmark site. The other is a self-sustaining farm obtaining drinking and irrigation water from a local well. For these two systems, ecosystem specific dose conversion factors integrated over 10,000 years have been calculated probabilistically, see further Appendix C. The ecosystem-specific dose conversion factor (EDF) distributions are used as input data in the radionuclide transport calculations, and used to transform the radionuclide releases from the geosphere to individual effective dose.

12.3.4 Simplified analytical model

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 using 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 /Hedin, 2002a; SKB, 2004f/. 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 corresponding calculation time for the numerical models is of the order of one minute.

The analytical model will be benchmarked against the numerical models for the base case calculation and used for many of the variant and residual cases. All essential consequence calculations in the final SR-Can report will however be carried out with the numerical models.

Apart from being a practical tool for massive probabilistic calculations, the use of two complementary sets of models, building on the same concepts and using the same input data, provide quality assurance for the handling of probabilistic calculations. The analytical model is also useful for gaining insights into the meaning of the calculated results.

Colloid transport in the geosphere is not handled by FARF31. This issue is addressed in section 9.4.1.

12.4 Base case calculation

This section presents the base case input data, calculation results, sensitivity analyses of the results and a number of variant calculations that explore uncertainties not included in the base case.

It is again emphasised that the material presented in this section is not to be regarded as a preliminary evaluation of repository safety at the Forsmark site. The results of the hydrological calculations are not representative of the site to the extent required for such an evaluation and several other input data sets remain to be qualified.

12.4.1 Input data

Input data for the radionuclide transport and dose calculations will be given in the SR-Can Data report. At this interim stage, an Interim Data report /SKB, 2004c/ has been produced, where migration data for the buffer are discussed in detail. Data uncertainties are discussed in a background report by selected experts in the field /Ochs and Talerico, 2004/. The uncertainty discussion follows a template designed in the safety assessment project, see section 2.7. Based on the findings in the background report, data for consequence calculations have been selected in the Interim Data report in collaboration between the experts and the safety assessment team. This handling of data uncertainties will be applied for also other important data for the consequence calculations in the final assessment. At this interim stage, most other data are however based on the SR 97 database /Andersson, 1999/ or improvements thereof.

For several SR 97 data types, the SR 97 Data report presents reasonable and pessimistic values. In the SR 97 probabilistic consequence calculations, the reasonable data were, somewhat arbitrarily, assigned a probability of 90 percent and the pessimistic values a

probability of 10 percent for many data types /SKB, 1999a/. In subsequent calculations, most of the discrete distributions have been replaced by lognormal distributions preserving mean values and standard deviations. The latter distributions yielded results similar to those of the SR 97 discrete distributions /Hedin, 2003/. A common approach when basing data on the SR 97 Data report will therefore be to construct lognormal distributions with mean values equal to the reasonable value and standard deviations such that data values more unfavourable than the pessimistic value cover 5 percent of the probability distribution. These continuous distributions thus include also data between the reasonable and pessimistic values and data that could be more favourable than the reasonable value. This is a simplified way of deriving input data distributions, pending the final, qualified, data.

The input distributions reflect both uncertainty due to lack of understanding of an issue (dominating for, e.g. the fuel dissolution rate or the input data related to canister failure) and variability (dominating in the cases of number of canister failures as a function of time and the statistical data obtained from the hydrological modelling). The two types of uncertainty, epistemic and aleatory, are thus mixed in the probabilistic calculations.

Table 12-1 gives an overview of the input data for the base case. The data are presented in some detail below and all data are tabulated in the Interim Data report /SKB, 2004c/.

Table 12-1. Input data types for radionuclide transport calculations in SR-Can.

	Nuclide/ Element Specific	Note
Radionuclide inventory	N	SR 97 data for 38 MWd BWR fuel
Instant release fraction of inventory	N	*
Time for canister failure	–	**
Time between failure and onset of radionuclide transport	–	1,000 years
Time between onset and complete loss of transport resistance in canister	–	Uniform (0, 10^5 yrs)
Fuel dissolution rate	–	Uniform ($5 \cdot 10^{-8}$/yr, $5 \cdot 10^{-7}$/yr)
Solubilities	E	*
Buffer porosity		**Anions: T(0.12; 0.17; 0.24) Cations: 0.43
Buffer diffusivity	E	**
Buffer sorption coefficients	E	**
Backfill diffusivity and sorption coefficient	E	*
Rock porosity		SR 97 data; Anions: 0.0005 Cations: 0.005
Rock diffusivity	E	*
Rock sorption coefficient	E	*
Groundwater flow in tunnel/EDZ	–	***
Equivalent flow from deposition hole to fracture(s)	–	***
Rock transport resistance, F	–	***
Rock advective travel time, t_w	–	***
Rock Peclet number, Pe	–	*
Max. penetration depth in rock matrix, D_{Pen}	–	**
Biosphere EDF factors well, correlations propagated	N	Calculated distributions for mire and

* Log-normal distributions based on reasonable and pessimistic SR 97 data.
** Triangular distribution based on SR-Can data.
*** Correlated distributions calculated by hydro model ConnectFlow.

Radionuclide inventory

The radionuclide inventory is that of the SR 97 assessment, i.e. calculated inventories for BWR fuel of a burn-up of 38 MWd thermal output. No uncertainty estimates for these data are provided in this Interim report, see however the SR 97 data report /Andersson, 1999/ for a discussion of uncertainties. In the final SR-Can report, uncertainties and other fuel types will be considered.

For the calculations to be presented below, the following nuclides were included, based on results from several earlier assessments: C-14, Cl-36, Ni-59, Ni-63, Se-79, Sr-90, Nb-94, Tc-99, Sn-126, I-129, Cs-135, Cs-137 and the 4n+2 and 4n+3 decay chains, i.e. those including U-238 and U-235 with relevant daughter and parent nuclides.

Instant release fraction of inventory

The estimate of instant release fraction, i.e. the fraction of the inventory assumed to be immediately dissolved when water contacts the fuel, is based on the SR 97 database. In the SR 97 Data report, reasonable and pessimistic data were estimated. Based on these, lognormal distributions are constructed for the SR-Can example calculation according to the procedure above.

Number of defective canisters as a function of time

The number of defective canisters as a function of time is based on the preliminary calculation of corrosion of canister weld defects presented in section 7.2.2. Based on assumed statistics of the seal thickness, canister penetration due to corrosion was calculated probabilistically, yielding a linearly increasing number of failed canisters as a function of time. For the two corrosion situations modelled, on the average considerably less than one canister in the entire repository at the end of the one million year assessment period was failed. For the example calculation it will be assumed that one canister fails and that the failure time is a triangular distribution over 0 to 10^6 years with its maximum at 10^6 years.

This is the only canister failure mode considered in the base case of this example calculation.

Data related to the internal evolution of a failed canister

The evolution of a failed canister is complex and includes many uncertainties as discussed in section 12.2. Input data related to the internal evolution, namely the delay time between failure and onset of radionuclide transport, the time of occurrence of a large failure and the sizes of the original, small failure and of the larger failure, are given in section 12.2.4.

Fuel dissolution rate

The basis for estimating the fractional fuel dissolution rate has recently been documented /Werme et al, 2004/. A uniform distribution ranging between $5 \cdot 10^{-8}$/yr and $5 \cdot 10^{-7}$/yr is recommended for use in SR-Can, corresponding to times for total dissolution ranging between 2 and 20 million years. This will be used for the base case.

The experimental basis is, however, limited. Therefore, several cases with fixed fuel dissolution rates covering a wider range will also be calculated, letting all other parameters vary as in the base case.

Solubilities

Solubility data will be based on the SR 97 database. In the SR 97 Data report, reasonable and pessimistic values were estimated. Based on these, lognormal distributions have been constructed for the SR-Can example calculation according to the procedure above. For a few elements, the ratio of reasonable to pessimistic data was several orders of magnitude, yielding extremely long distribution tails. In these cases, the upper tails of the distributions were truncated at a value of 1,000 times the pessimistic value in order to avoid numerical complications.

The SR 97 solubility data were site-specific, in that site-specific groundwater compositions were used to derive the chemical conditions for which solubilities were determined. The differences between the sites as regards solubilities are minor. The site data for Finnsjön (Beberg) are used in SR-Can, since this site is closest to the Forsmark site.

Buffer diffusivity, porosity and sorption data

The buffer is assumed to have a density of 2,000 kg/m^3 in the calculations (the design reference value).

Buffer diffusivities and sorption coefficients are given in the Interim Data report /SKB, 2004c/ and data uncertainties are represented by a likely value with a lower and an upper limit within which the "correct" value is expected based on scientific reasoning in the expert report /Ochs and Talerico, 2004/ discussing data uncertainties.

In situations where a most likely value can be established in addition to the range of possible values, triangular and log-triangular distributions can be considered as appropriate representations of data uncertainties /Mishra, 2002/. Triangular distributions have therefore been constructed, with the minimum and maximum values given by the lower and upper limits and the mode (peak value) given by the likely value. Log-triangular and uniform distributions will also be used to explore the importance of the assumed shape of the distributions.

The buffer porosity is given by /Ochs and Talerico, 2004/ as 0.43 for cations. For anions, to account for anion exclusion, an interval ranging between 0.12 and 0.24 with a most likely value of 0.17 is given. A triangular distribution for anion porosity is therefore assumed based on these data.

Backfill properties

Backfill density, diffusivity and sorption coefficients are based on the SR 97 database. In the SR 97 Data report, reasonable and pessimistic values were estimated. Based on these, lognormal distributions have been constructed for the SR-Can example calculation according to the procedure above.

Equivalent flow rate for fractures intersecting deposition holes

The equivalent flow rates for fractures intersecting the representative deposition holes are directly calculated in the hydraulic model. Statistics of this quantity correlated to other outputs from the hydraulic calculations are thus available and are used in the example calculation. This is an improvement compared to the SR 97 calculations where much of the handling of the equivalent flow rate was based on generic assumptions.

Equivalent flow rate for the excavation damaged zone, EDZ

According to /Moreno and Gylling, 1998/, the equivalent flow rate for the excavation damaged zone, EDZ, can be calculated according to

$$Q_{eq,EDZ} = 2W_{EDZ}\sqrt{4D_w q_{EDZ} L_{EDZ}\, \varepsilon_{EDZ}\, / \pi}$$

where W_{EDZ} is the extension of the EDZ, D_w the diffusivity in water, q_{EDZ} is the darcy velocity for the EDZ, L_{EDZ} the length of the EDZ in contact with water and ε_{EDZ} the flow porosity of the EDZ.

W_{EDZ} has recently been estimated at typically 0.3 and at most 1 m, but it is uncertain if the EDZ is an internally connected structure, i.e. whether it offers a continuous pathway from the deposition hole to a conductive feature of the rock. A triangular distribution T(0, 0.3, 1) is, therefore, used for this quantity.

Based on the SR 97 data report, a triangular distribution T(0.0001, 0.0003, 0.001) will be used for ε_{EDZ}. For L (given by the radius of the deposition hole) and D_w, the SR 97 values will be used. D_w is element specific but varies insignificantly between elements, and enters the expression as its square root, further diminishing the differences.

Rock porosity

Based on the SR 97 Data report, rock porosities of 0.005 and 0.0005 are assumed for cations and anions, respectively. In the final SR-Can report, these data will be re-evaluated and uncertainty estimates provided.

Rock diffusivity and sorption data

Rock diffusivity and sorption data are based on the SR 97 database. In the SR 97 Data report, reasonable and pessimistic values are estimated. Based on these, lognormal distributions are constructed for the SR-Can example calculation according to the procedure above. The sorption coefficient for Sn-126 was estimated to range between zero (pessimistic) and 0.001 m^3/kg (reasonable) in the SR 97 database. Since the zero value does not allow construction of a log-normal distribution as suggested above, the discrete SR 97 distribution was kept for Sn-126 meaning that the reasonable and pessimistic values are assigned 90 and 10 percent probabilities, respectively.

The SR 97 rock diffusivity and sorption data are site-specific. The differences between the sites are however minor in this respect. The site data for Finnsjön (Beberg) are used in SR-Can, since this site is closest to the Forsmark site.

Rock transport resistance, F, and advective travel time, tw

The rock transport resistance, F, and advective travel time, t_w, for the representative deposition holes are directly calculated in the hydraulic model for releases from both Q1 (a fracture) and Q2 (the tunnel or EDZ). Statistics of these quantities correlated to other outputs from the hydraulic calculations are thus available and are used in the example calculation.

The calculated F-values are divided by 10 to approximately account for channelling effects, see further the Interim Data report.

Rock Peclet number

Data for the Peclet number, Pe, are based on the SR 97 database. In the SR 97 Data report, reasonable and pessimistic values were estimated. Based on these, lognormal distributions are constructed for the SR-Can example calculation according to the procedure above.

Maximum penetration depth in rock matrix

Penetration depths are based on laboratory and field evidence in line with a draft report of an ongoing review of the current status of matrix diffusion research with implications for performance assessment. A triangular distribution T(0.05 m, 0.4 m, 3 m) is used.

The minimum value is based on the fact that laboratory studies clearly show penetration depths on the order of centimetres; thus, less penetration than 1–10 cm should not be expected.

Biosphere EDF factors

Probabilistically calculated biosphere EDF factors for a mire and for a well used at a local farm are used in the example calculation. All input data for the probabilistic EDF calculation have been reviewed and in a few cases revised, see Appendix C. In each realisation of the integrated transport and dose calculations, EDF data are sampled from the results of the separate EDF calculations. Correlations between EDF distributions for the different nuclides are hereby propagated, since EDF values for all nuclides for a specific realisation of the transport and dose models are taken from the results of a specific realisation of the EDF model. This is an improvement compared to the SR 97 calculations where uncorrelated statistics of the individual EDF distributions were used.

12.4.2 Release locations

Since the repository is distributed in space, the locations of radionuclide releases from the geosphere will also be distributed, as simulated by the hydrogeological model. Several local ecosystems will thus be potentially contaminated, depending on the locations of failed canisters and the transport pathways in the geosphere.

In this example calculation, the pessimistic approach of letting all calculated releases occur to the same representative ecosystem, either a mire with a size representative of the mires at the site or a single well, see further Appendix C, is taken. This approach is seen as pessimistic since preliminary evaluations suggest that releases from at most 10 percent of the canister positions would reach a single ecosystem. This approach will be reconsidered in the final SR-Can report. It would, e.g. also be possible to model the whole ensemble of release points and the corresponding ecosystems, and determine exposure of individuals making use of several parts of the contaminated environment.

12.4.3 Applicable risk criterion

As mentioned in section 2.12.2, there is a choice between calculating an average dose to individuals in a regional group on the one hand and to highly exposed individuals within that larger group on the other, and the risk criteria to be applied in the two cases are 10^{-6}/yr and 10^{-5}/yr, respectively. In section 2.12.2, it is argued that the larger, regional group should utilise an area of the order of many square kilometres.

Considering that a well or a mire used for agriculture at a particular location at the Forsmark site can reasonably be used for only up to a few hundred years during a temperate period and that such a well or mire can only support a very limited number of persons, see further Appendix C, it seems reasonable to use the higher risk-limit of 10^{-5}/yr (140 μSv/yr) in these cases. As mentioned, assessing compliance is not a concern in this Interim report. It is however important to clarify the principles for the use of the two risk limits at this stage of the SR-Can project.

12.4.4 Results of the base case calculation

The following is a brief description of the processes that are quantified in the transport models, as an introduction to the presentation of the results of the base case calculation.

1. No releases occur from the canister before a continuous water pathway has been formed between the fuel and the exterior of the failed canister. Radioactive decay reduces the radionuclide content and total radiotoxicity of the fuel.

2. As soon as a continuous water pathway has formed, the instant release fraction of the inventory dissolves in the water in the canister void. If the solubility limit is reached, the concentration of the dissolved nuclide in the water does not increase further. The nuclides dissolved in the water begin to diffuse out of the canister. The release of nuclides embedded in the fuel is determined by the fuel dissolution rate. Also here, the solubilities of the nuclides limit the concentration that can occur in the water.

3. The nuclides are sorbed with varying efficiency in the buffer and the diffusion and sorption properties determine the time for diffusion through the buffer. If this time is shorter than or comparable to the half-life of the nuclide, it passes out into the rock.

4. In the rock, the nuclide's sorption properties, together with the rock's transport properties, determine the time for transport through the rock to the biosphere. As in the buffer, the half-life of the nuclide determines whether it passes through the geosphere before decaying to a substantial degree.

5. In the biosphere, the nuclide gives rise to a dose that is dependent on its inherent radiotoxicity and its turnover in the biosphere type to which it is released. Both of these factors are included in the EDF value used.

In general, nuclides with a relatively high instant release fraction also tend to be readily soluble and relatively mobile in both buffer and rock. Several percent of the inventory of I-129, for example, is instantly released; iodine has a very high solubility and is not sorbed in either buffer or rock. Plutonium isotopes, on the other hand, lie completely embedded in the fuel matrix, have low solubility and are sorbed strongly in both buffer and rock. Isotopes of uranium, thorium and americium have similar properties to plutonium.

In the SR 97 assessment /SKB, 1999a/, a number of single realisation cases were presented and discussed, see section 9.11 of the SR 97 report. These cases are important for understanding the model system and the importance of single parameter variations. Such cases are not reported here, since the focus is on the probabilistic methods that have been developed since SR 97, such that data uncertainties can be analysed in an integrated, probabilistic fashion, both for understanding uncertainties in the overall probabilistic treatment and, in the final SR-Can report, to assess compliance.

Figure 12-3 shows the results of the probabilistic base case calculation for the two cases of a mire and a well recipient, calculated with both the numerical (red curves) and the analytic models. 5,000 realisations were calculated with input data sampled from the distributions described above using Latin Hypercube Sampling (LHS).
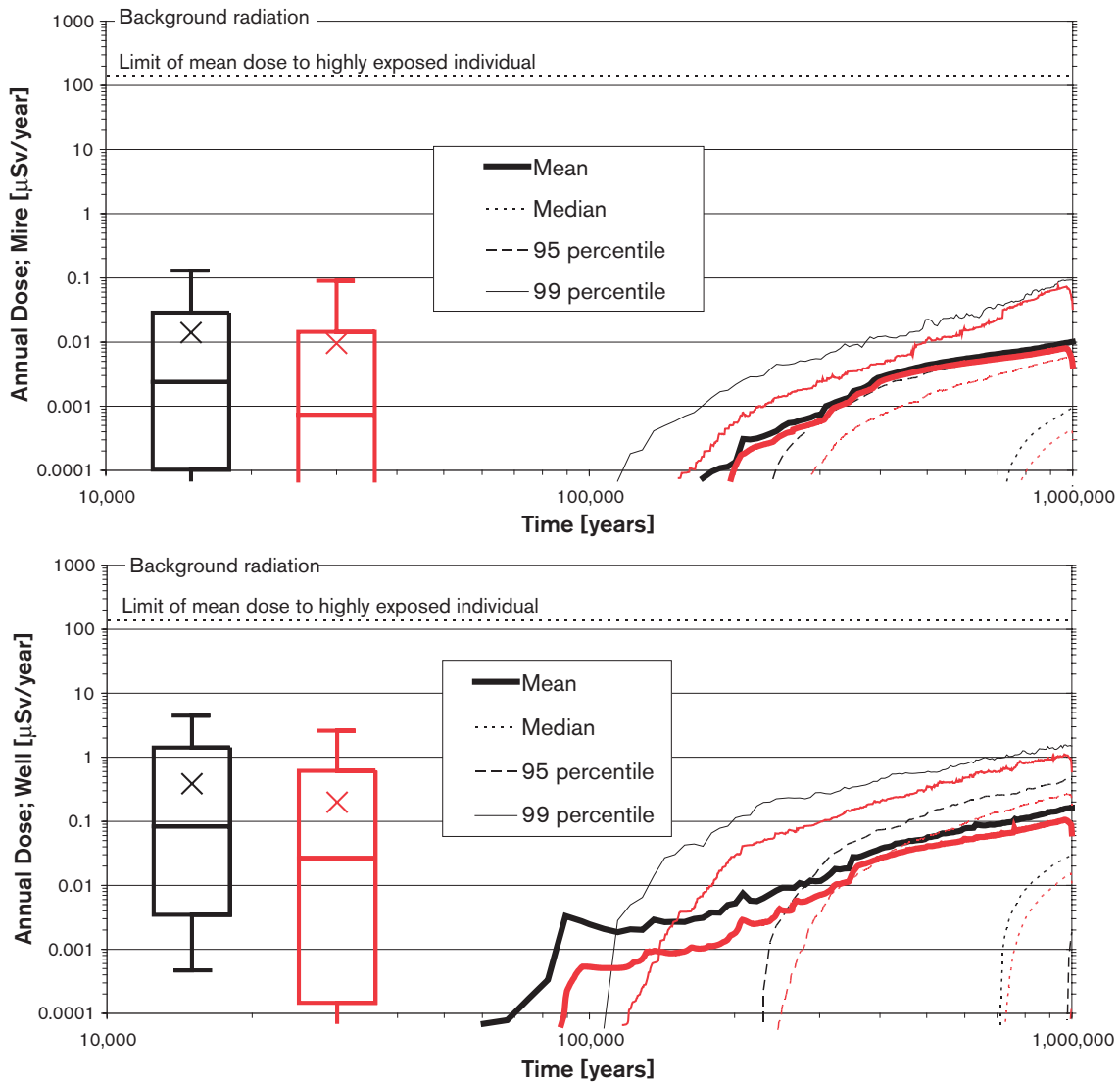
Figure 12-3. *The results of the base case probabilistic calculation for mire (upper) and well recipients. Red curves are results obtained with the numerical model, black curves are analytical results. The box-and-whisker plots to the left show the 99, 95, 50, 5 and 1 percentiles of the peak dose distributions; the crosses are the mean values from these distributions.*

As seen in the figure, the mean value is increasing at the end of the assessment period. This is a direct consequence of the fact that the number of failed canisters due to corrosion is increasing steadily. (The decrease in mean value of the numerical results at the end of the period is a numerical artefact.)

The distribution is highly skewed since the mean is close to the 95th percentile. This is essentially a reflection of the skewness of a few important input distributions, rather than of the transformation properties of the model. This also means that a considerable number of realisations are required in order to obtain a stable mean value. The number of realisations executed here, 5,000, has been found to be adequate for the SR 97 data, but this needs to be confirmed in the calculations for the final SR-Can report.

As discussed in section 2.12.2, so called risk dilution effects can be elucidated by comparing the peak of the mean dose, 0.076 μSv/yr (0.11 μSv/yr) for the mire (well), occurring at the end of the one million year assessment period in Figure 12-3, to the mean

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value of the set of peak doses collected from all the 5,000 realisations. Statistics of this latter quantity are shown in the box-and-whisker plots in Figure 12-3. The mean of the peaks is 0.096 µSv/yr (0.2 µSv/yr), i.e. a factor of less than 2 higher than the peak of the mean dose. It is, therefore, concluded that for this input data set, risk dilution effects are small. This is largely due to the fact that once a canister has failed, releases will continue essentially undiminished for a long period of time, so that similar peak doses are obtained irrespective of the canister failure time. The dispersive properties of the system and the fuel dissolution that causes releases for millions of years after failure, thus limit this type of risk dilution effects.

Decomposition of the base case results

The base case results have been decomposed with respect to the two dominant nuclides Ra-226 and I-129 and with respect to the two release pathways from the near field, Q1 and Q2, see Figure 12-4. Note that the calculated dose caused by Ra-226 includes, through the EDF factor for Ra-226, doses caused by its daughter nuclides generated through decay in the biosphere.

Ra-226 dominates the total mean dose as do releases through Q1. The sum of the Ra-226 and I-129 mean doses is indistinguishable from the total mean dose curve in the figure. Also, the mean dose caused by releases through Q1 (not shown in the figure) virtually coalesces with the total mean dose curve.

Practically all Ra-226 emerges from ingrowth within the canister, and is then transported through the buffer, to the rock through Q1 and further through the rock to the biosphere. Releases of Ra-226 through Q2 are negligible, as is ingrowth in the buffer and rock. Ra-226 emerging from the canister interior and released through Q1 thus practically determines the mean value of the dose as a function of time, at least for times beyond several tens of thousands of years when significant ingrowth has occurred. It should also be pointed out that the fuel dissolution, which determines the fraction of ingrown Ra-226 available for transport, is a key process for the Ra-226 releases.
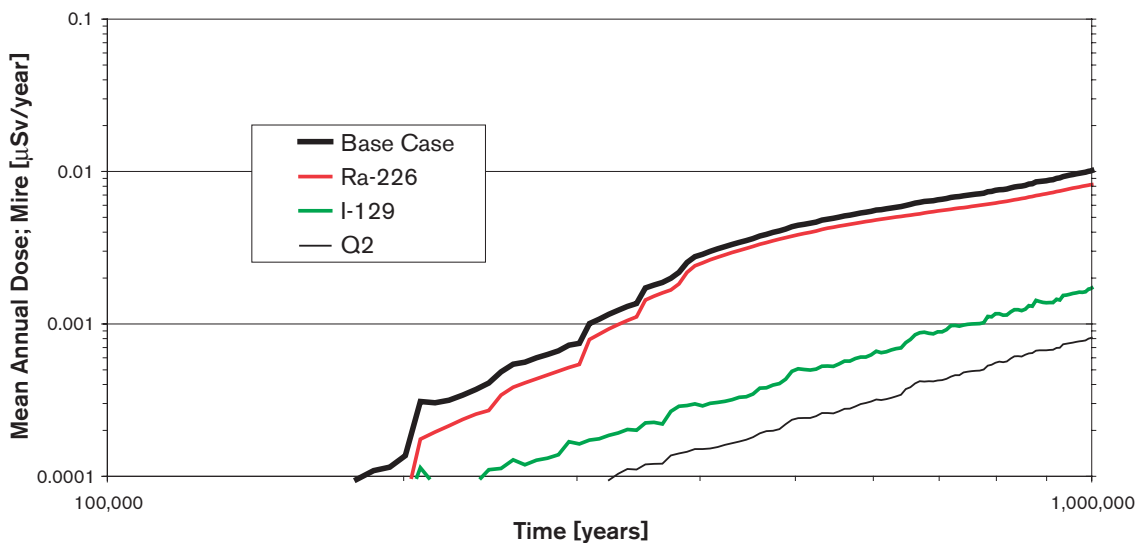

Figure 12-4. Decomposition of the base case mean dose into dominant nuclides and release pathways.
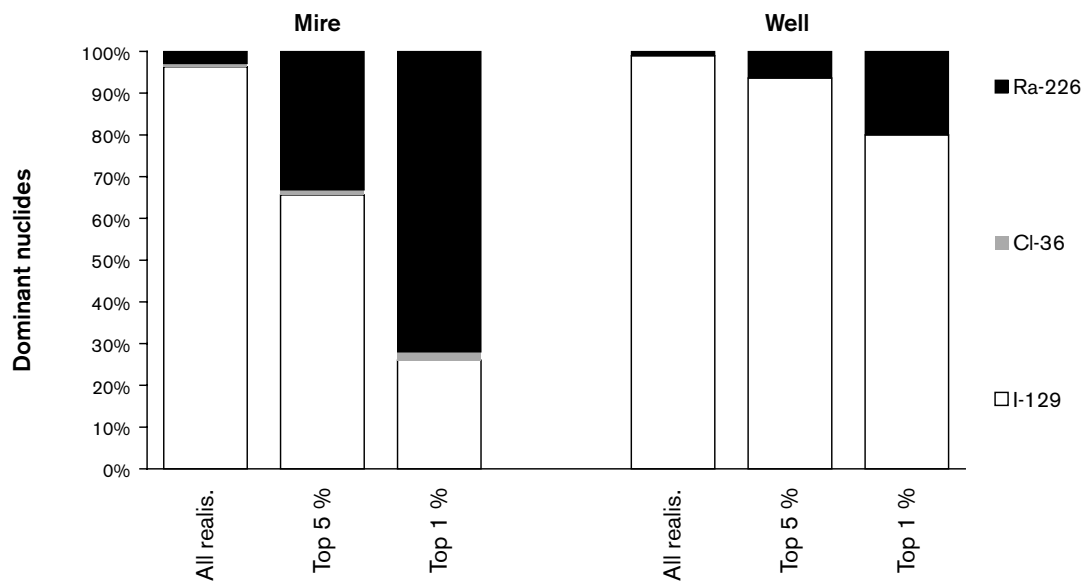
Figure 12-5. *Dominating nuclides. Virtually all realisations are dominated by either I-129 or Ra-226.*

Furthermore, the nuclide giving rise to the peak dose has been determined in each realisation of the base case, see Figure 12-5. Virtually all realisations are dominated by I-129 or Ra-226; in a few realisations for the mire biosphere, Cl-36 dominates.

If only the realisations yielding the highest doses are considered, the dominance of Ra-226 is more pronounced, see Figure 12-5. This, in combination with the fact that the distributions are highly skewed is another way of demonstrating that the mean dose is almost entirely caused by Ra-226.

Alternative safety indicator

As mentioned in section 6.4.1, the constraints on geosphere releases issued by the Finnish Radiation and Nuclear Safety Authority, STUK, will be used as an alternative safety indicator in SR-Can. Section 6.4.1 describes the constraints and their applicability. In Figure 12-6 the geosphere releases for the base case have been normalised, nuclide by nuclide, to STUK's nuclide-specific release constraints. The figure shows the sum of the normalised releases, which is not to exceed unity according to the STUK regulations. As seen, there is ample margin for the releases calculated in the base case. Even if the STUK constraint is applied directly to the near field releases, Figure 12-7, the margin is considerable.

It is noted that the margin to the release constraint, a factor of the order of 10^4, is similar in magnitude to that obtained for SSI's dose limit applied to the mire biosphere above.

Since Ra-226 dominates the mean value, it could be interesting to also use measured Ra-226 concentrations in mires and in wells or groundwater at the site as additional alternative safety indicators.
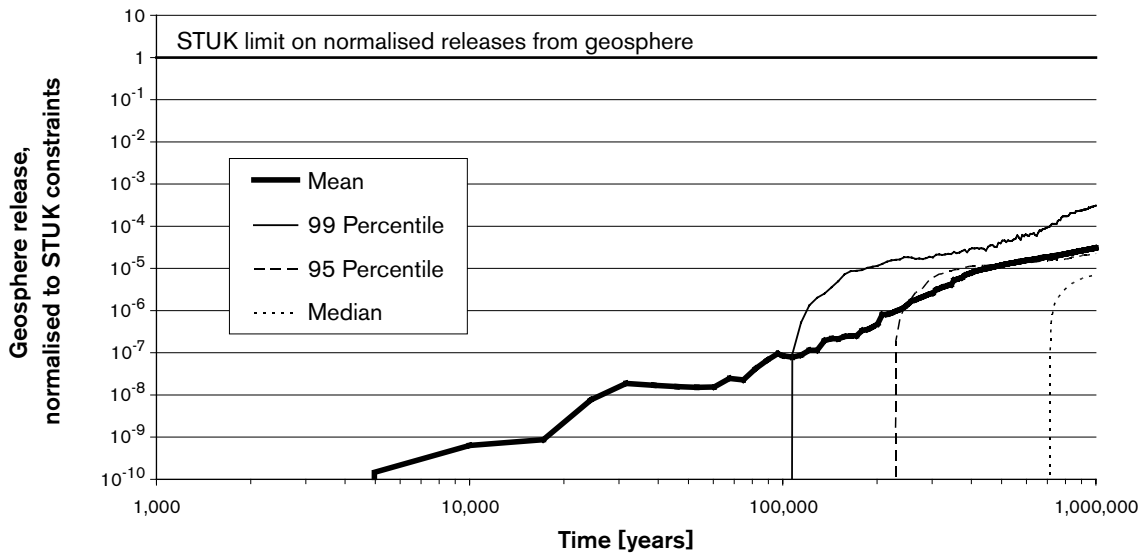
Figure 12-6. *STUK's release constraint applied to the base case geosphere releases.*
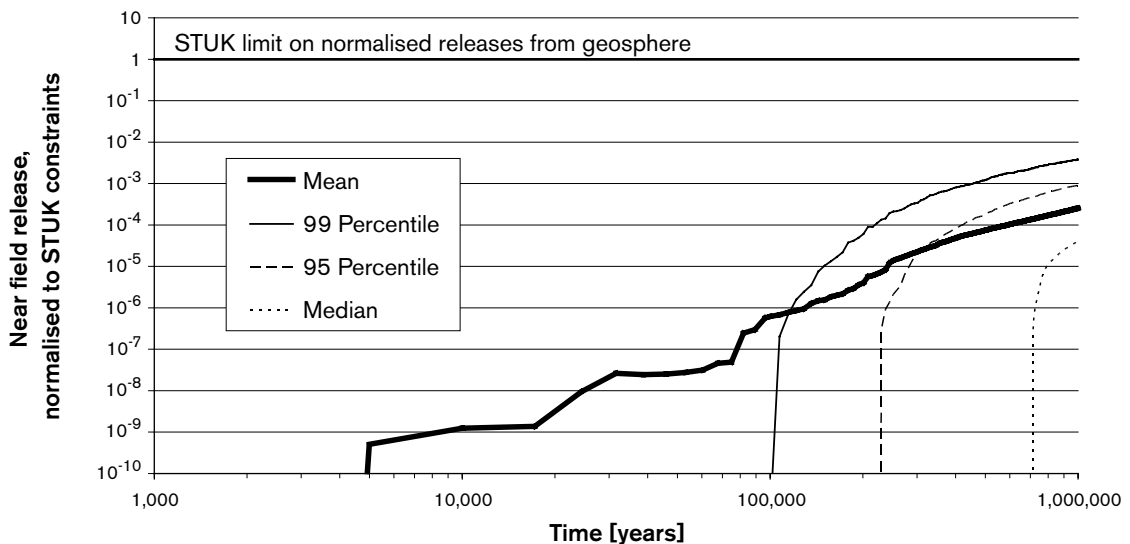
Figure 12-7. *STUK's release constraint applied to the base case near-field releases.*

Further benchmarking of the analytical model

In addition to the comparison between numerical and analytic models given in Figure 12-3, the peak doses calculated in the 5,000 realisations of the base case for the mire biosphere have been compared, see Figure 12-8. Results for the well case (not shown) are very similar.

The discrepancies are within a factor of ten (within the dotted lines) for the great majority of cases. The discrepancies are in general smaller for higher doses that have a dominating influence on the mean values.
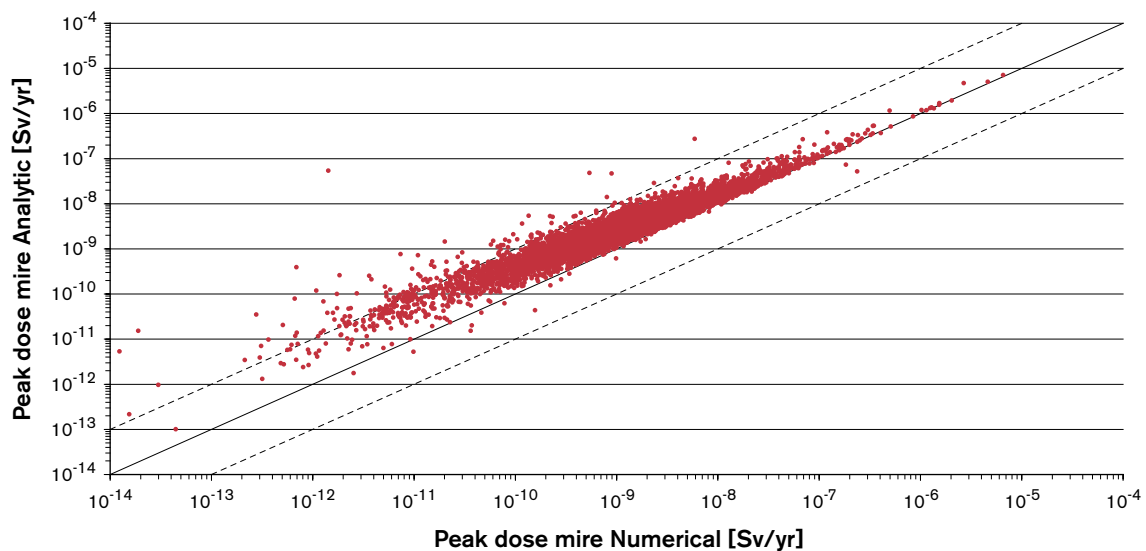
Figure 12-8. *Comparison of peak doses for the mire biosphere in 5,000 realisations calculated with the numerical and analytic models.*

The differences are mainly explained by the fact that the numerical model takes into account diffusion from the deposition hole to the tunnel, which thus accumulates radio-nuclides, whereas this effect is pessimistically disregarded by the analytical model where the top of the deposition hole is effectively treated as it was sealed. Conceptualising the numerical model in this latter way leads to discrepancies generally within a factor of three /SKB, 2004f/.

Based on these findings and the results of earlier benchmark exercises /Hedin, 2002a; SKB, 2004f/, the analytic model is used in the example calculations to follow, unless otherwise stated. As mentioned, all essential consequence calculations in the final SR-Can report will be carried out with the numerical models.

Further simplifications of transport and dose calculations

In /Hedin, 2003/ it is shown how the essential features of the probabilistic results of calculations based on the SR 97 input data can be reproduced with a further simplified analytic model consisting of a few analytic expressions. A probabilistic calculation evaluating 5,000 realisations could be completed in less than a minute.

The exercise has not been repeated for this Interim report, but should yield similar results also for this case, since the model conceptualisations are those used in the SR 97 calcula-tions and the input data are similar. The simplified representation provides insights into which parameters are the most essential for the calculation result and helps in explaining, in simplified terms, the essential features of the transport models.

12.4.5 Sensitivity analysis of base case calculation

This section presents sensitivity analyses of the probabilistic base case results with the purposes of determining:

- which uncertain input parameters give the most significant contribution to the width of the output dose distribution,

- which uncertainties have a significant impact on the mean value of the dose since the mean dose is directly proportional to the risk, i.e. the regulatory target, and

- which uncertain input parameters give the most significant contribution to the width of the output dose distribution for individual nuclides.

Global sensitivity analysis

The first purpose is thus to perform a so called global sensitivity analysis, i.e. to identify the input parameters that have the greatest influence on the spread of the results. The contribution to output spread depends on both the spread of the input parameter and the model's sensitivity to variations in that particular input parameter. A range of methods for this type of sensitivity analysis exists /Saltelli et al, 2000/, and suitable methods for the KBS-3 system have been selected in recent work /Hedin, 2002b; Hedin, 2003/, 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 monotonic function of the input variables /Saltelli et al, 1993; Helton, 1993; Hamby, 1994; Iman and Conover, 1979/. This applies also to the present non-linear and monotonic system /Hedin, 2003/, and the standardised rank regression coefficient (SRRC) is, therefore, used for identifying the most important variables contributing to dose uncertainty.

In the rank regression method, the data in each input and output distribution is replaced by its rank order within that distribution. Hereby, non-linear features of the distributions are "linearised". The rank transformed input and output data are then standardised, i.e. subtracted by their mean values and divided by their standard deviations, to obtain dimensionless quantities, independent of units in which the data are expressed. A traditional regression model, relating output data to input data, is then built on the standardised, rank transformed data. The so obtained regression coefficients are defined as the standardised rank regression coefficients, SRRC.

The SRRCs thus provide a measure of the monotonic change in the output vs. monotonic change in the input data over their sampled range and provide a method for identifying those input data that contribute most to the output uncertainties. If an input parameter has a large SRRC relative to other input parameters, then the variability of that input parameter causes comparatively large variability in model output. By ranking the input variables with respect to their SRRCs, the input parameters that are most important in a model simulation can be identified.

The SRRCs for the base case result was determined, using the commercially available software Statistica. The results are shown in Figure 12-9. Dominating variables are the ecosystem-specific dose conversion factor for I-129 (EDF I-129), the equivalent flow rate at the deposition hole (Qeq1), the delay time (tDelay), the fuel dissolution rate, the instant release fraction (IRF) and the geosphere transport resistance (F). This is in line with the findings in e.g. the SR 97 assessment.

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Figure 12-9. *SRRCs for the mire and well results. The calculation endpoint is the peak dose over the entire one million year assessment period. The same method can be applied at different specified points in time; an important uncertain factor appearing in that case is the time at which an initially small canister defect suddenly increases in size. The R^2-values are the goodness-of-fit values for the regression models built on the ranked data.*

The identified parameters are all related to the release of I-129. This is expected since Figure 12-5 shows that I-129 causes the peak dose in the great majority of realisations and it can thus be expected that parameters related to this release will show up in the importance ranking.

If input data are correlated, the interpretation of the SRRC importance measure is not straightforward. The influence of correlations on the importance ranking can be elucidated by determining also partial rank regression coefficients, PRRC /Hamby, 1994 and references therein/ and comparing the two importance measures. If the results differ, this indicates a strong influence of the correlations. Since several important input parameters are correlated in the case analysed here, e.g. Qeq1 and F in the above results, also the partial correlation coefficients were determined, using the same tool as above. The resulting numerical values of the two importance measures were indeed different, but the same important parameters were identified with both methods and the ranking order was almost identical.

The exact ranks or importance measures are of secondary interest. The aim is to identify the few variables whose uncertainties give the dominating contributions to the output uncertainty. It is therefore concluded that the SRRC results presented above give a relevant view of the dominating uncertain parameters for the base case. See also the verification exercise below.

Main risk contributors

The SRRC method is useful for identifying the parameters that cause the overall spread of the results in the consequence calculation. However, this is not the same as identifying the parameters or the parameter values that cause the highest risk. The top few percent of the realisations play an important role in determining the mean value and these realisations are dominated by Ra-226 according to the above. To determine which input variables contribute to 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 12-10 shows the α_{99} values for the base case results. All α_{99} values above 0.3 are included in the figure. Further details are given in /Hedin, 2002b/. All identified variables are related to releases of Ra-226, which is expected since this nuclide dominates the high dose realisations that determine the mean value.

Tailored regression model

In /Hedin, 2003/, it is demonstrated how, based on the understanding provided by the analytic model, a strongly simplified non-linear expression of input data can be derived that approximates the output (mentioned in section 12.4.4). The derived expression was used to build a "tailor made" regression model that explains almost all the variation in the results calculated with both the numerical and analytic models in /Hedin, 2003/.

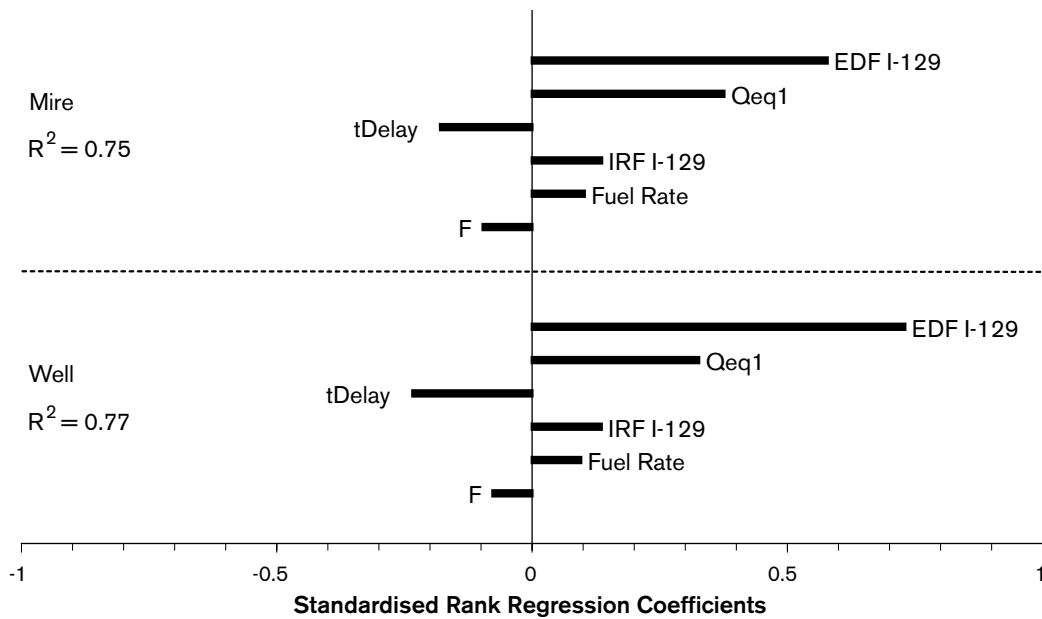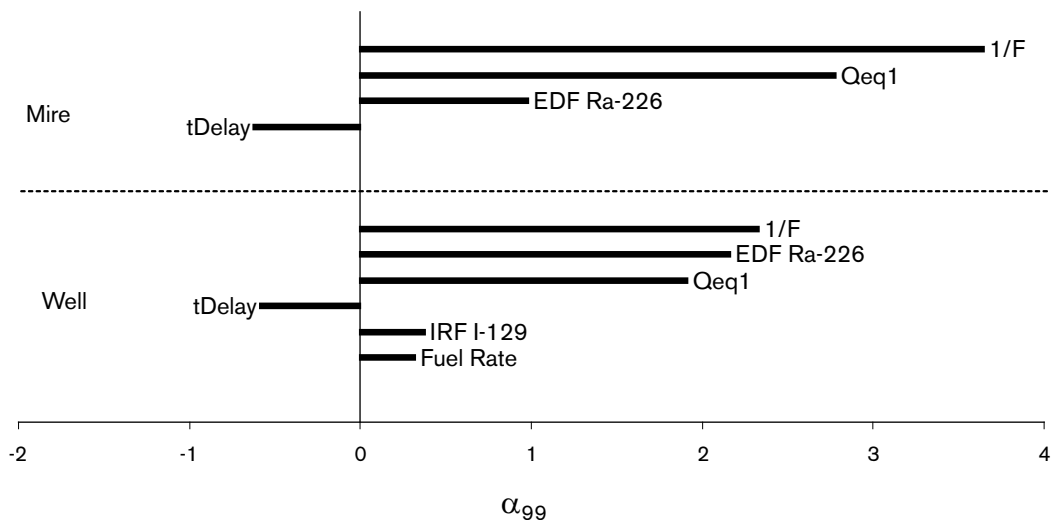**Figure 12-10.** *α_{99} values for the mire and well results. Note that the calculation endpoint is the peak dose over the entire one million year assessment period. The same method can be applied at different specified points in time; an important uncertain factor appearing in that case is the time at which an initially small canister defect suddenly increases in size.*

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Verification of global 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 studying 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.

Figure 12-11 shows the result of a verification of the sensitivity analysis of the peak dose distribution, i.e. the quantity for which the sensitive input parameters were determined above, using the SRRC method. The parameter to which the result was most sensitive, the EDF value of I-129, was fixed at its median value and all other parameters were varied as in the base case in 5,000 realisations. The result is shown in Figure 12-11, where the widest distribution is the base case result and the second widest is that with the EDF-value of I-129 fixed. The procedure was continued by successively fixing also the equivalent flow rate of path Q1 (Qeq1), the delay time (tDelay), etc, to their median values, in each step executing 5,000 realisations. The result demonstrates that the decrease in width in successive steps is moderate beyond the three most sensitive variables. The quotient of the 90th percentile to the 10th percentile decreases from about 66 for the full distribution to 7 when the three most sensitive parameters have been fixed. The corresponding reduction for the quotient of the 99th percentile to the 1st percentile is from about 7,500 to 11.

Sensitivity analyses for individual radionuclides

The rank regression method can be applied also to individual nuclides. Figure 12-12 shows rank regression coefficients for the two dominant nuclides, I-129 and Ra-226 for the mire case. Note that the result for I-129 is very similar to that of the peak total dose in Figure 12-9. This is consistent with the fact that I-129 dominates in 96 percent of the realisations. Note also that for Ra-226, all important parameters identified are related to rock properties. The EDF input data for Ra-226 vary as much as that of I-129, but is not ranked as an
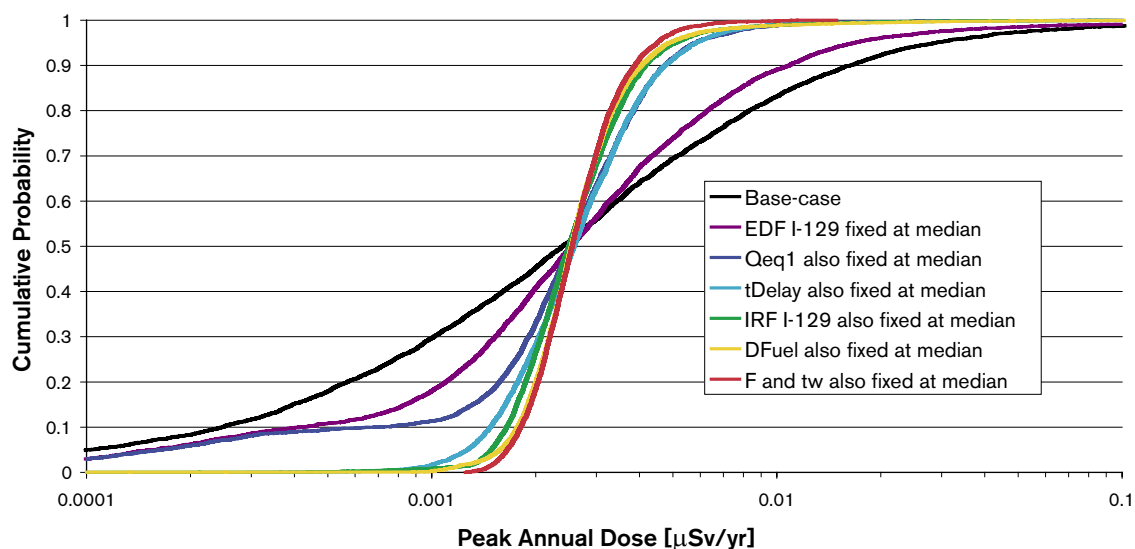

Figure 12-11. *The effect on peak dose distribution of successively fixing an increasing number of important parameters at their mean values. The decrease in spread in each step illustrates the relative importance of the parameter added to the set of fixed parameters in that step.*
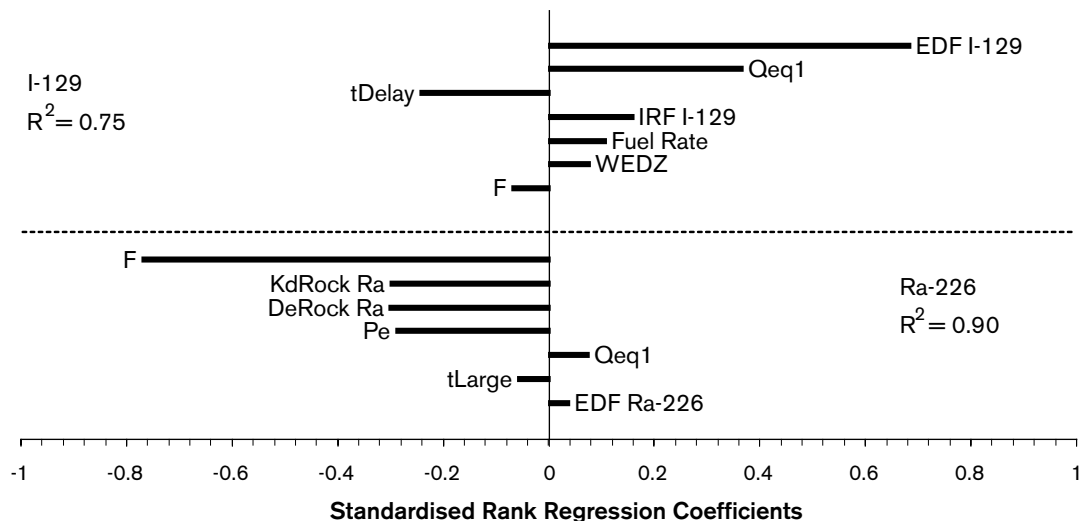
Figure 12-12. *SRRCs for the peak doses of I-129 and Ra-226 for a mire biosphere. The R^2-values are the goodness-of-fit values for the regression models built on the ranked data.*

important parameter in Figure 12-9, whereas the EDF of I-129 is the most important for that nuclide. The reason is that the varying rock conditions affect the overall result more than the EDF values for Ra-226; the SRRCs provide a relative, but not an absolute value of importance. In general, the peak doses associated with Ra-226 vary over almost ten orders of magnitude, whereas the spread of I-129 doses are limited to about two orders of magnitude. As is demonstrated in the next section, I-129 is readily transmitted through the geosphere, almost irrespective of the rock conditions.

12.4.6 Geosphere transmission

The retarding function of the rock can be analysed by using the rock transmission, T, defined as the fraction of a radionuclide release to the geosphere that passes through it without decaying. For the conceptualisation of geosphere transport used in the far-field model, T is given by an analytic expression involving the F-factor, the advective travel time and the Peclet number for the transporting fracture, the porosity, depth, diffusivity and sorption coefficient of the rock matrix and the half-life of the radionuclide /Sudicky and Frind, 1982/.

This expression was evaluated probabilistically for the base case input distributions of the geosphere transport parameters. The resulting cumulative T distributions for a selection of nuclides are shown in Figure 12-13. The figure demonstrates that non-sorbing nuclides like I-129 and Cl-36 are readily transmitted through the geosphere. A sorbing nuclide like Pu-239, on the other hand, is efficiently retarded by the rock.

The half-life of the nuclide is crucial for its transmission properties. A stable element has unit transmission irrespective of rock conditions. This is the reason for the relatively high transmissions of the strongly sorbing U-238, which has a half-life of $4.5 \cdot 10^9$ years. Ra-226, in contrast, with a half-life of only 1,600 years, has a low transmission despite being relatively weakly sorbed in the geosphere.

This type of transmission calculation is seen as a useful diagnostic tool by which e.g. distributions of rock transport parameters from variants of groundwater flow calculations can be quickly evaluated.
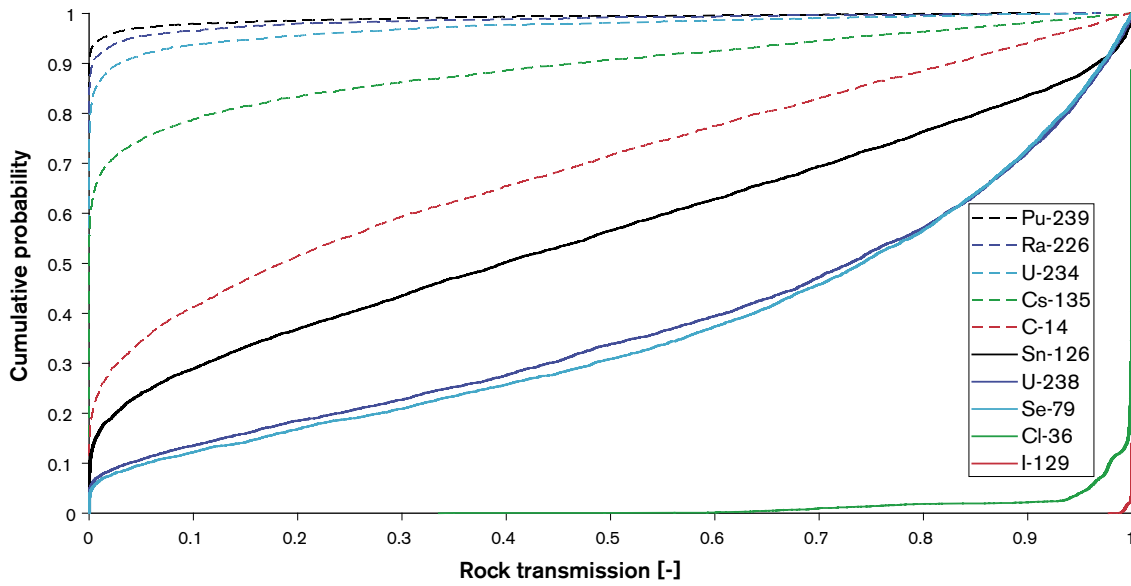
Figure 12-13. *Rock transmission distributions, T, for a selection of radionuclides, calculated probabilistically for the input distributions used in the base case.*

The sensitivities of rock transmission distributions to its input parameters can be determined with the rank regression method used above for dose sensitivities. Figure 12-14 shows the result of applying this method to the T distribution calculation for a selection of radionuclides. The F-value is the dominant parameter for all nuclides.
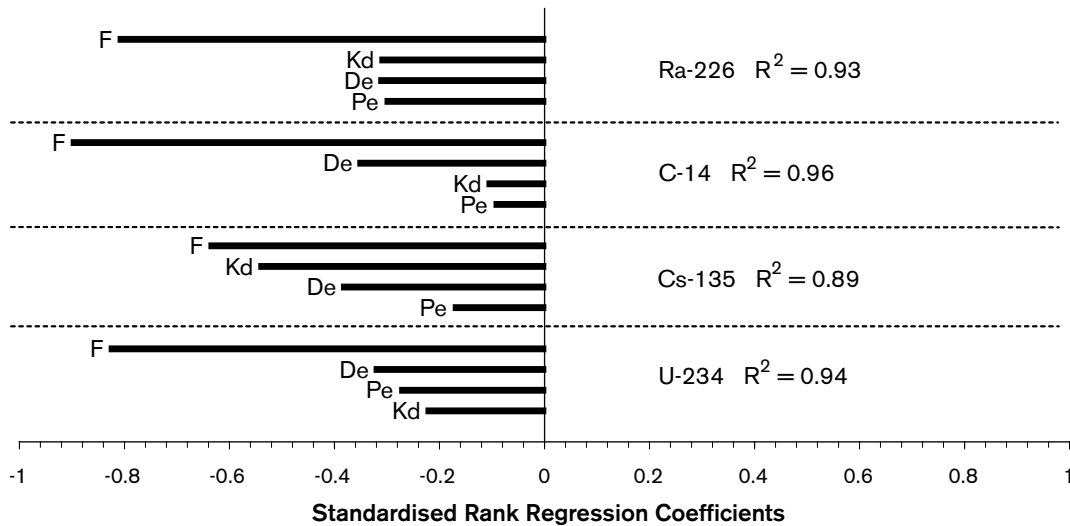
Figure 12-14. *SRRCs for the transmission distributions of four radionuclides. Note the high R^2-values, indicating the goodness-of-fit of the rank regression model.*

12.5 Variant case calculations

This section presents a number of variant probabilistic cases where alternative assumptions to those in the base case are made. In general, these cases represent alternative formulations of the base case that are of relevance for a compliance calculation. More drastic alternative assumptions, so called "what if" cases, that are not based on uncertainties in the underpinnings of the base case, but are rather formulated to understand the roles of the different parts of the system, are presented in section 12.6.

The two first variations concern general methodological issues in probabilistic calculations, namely the effects of input parameter correlations and of the form of selected input distributions. Thereafter, two cases are presented that elucidate conceptual uncertainties regarding the fuel dissolution and the internal evolution of a failed canister. Finally, a case exploring pessimistically neglected co-precipitation effects is set up. All cases are calculated probabilistically in 5,000 realisations, with all data except those specific to the variant case as in the base case. Thereby, the effects illustrated in the variant cases are evaluated in the overall context of data uncertainties.

12.5.1 Correlations

Several of the input data for the base case calculation take correlations into account: All probability distributions calculated by the hydrological model are correlated, i.e. the distributions of transport resistances, advective travel times, equivalent flow rates and Darcy velocities. Also the EDF distributions for different nuclides are correlated.

A main reason for correlations not taken into account in the base case concerns those related to the chemical environment in the repository. Uncertainty in the chemical conditions is one cause for uncertainty in the buffer and rock diffusivities and sorption coefficients and the radionuclide solubilities. These correlations are not reflected in the input distributions since all the concerned quantities are sampled independently.

In order to put a bound on the possible effects of this type of correlation, the sampled input data for each concerned parameter were sorted from the most favourable to the most unfavourable value, thus yielding a ranked table for each parameter. The base case calculation was the re-run, but with the parameters related to the chemical environment now fully correlated so that the data of the same rank from each table were drawn in a given realisation. The sampled data are thus favourable or unfavourable simultaneously. The results are shown in Figure 12-15.

The result indicates that the potential influences of geochemically related correlations on the overall calculation results are not important. This finding is consistent with the results of a similar test /Hedin, 2003/ made on the SR 97 data.
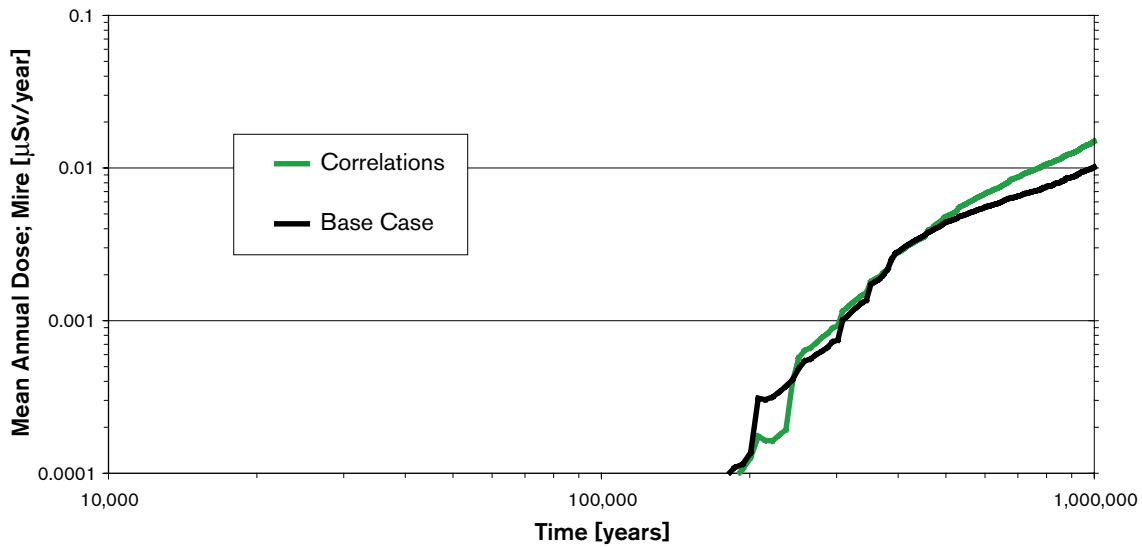
Figure 12-15. *Probabilistic results of calculations assuming full correlations of parameters influenced by the geochemical environment. Other data as for the base case.*

12.5.2 Input distribution shapes

Figure 12-16 shows the result of replacing all the triangular distributions, i.e. data for buffer diffusivity, sorption coefficient and anion porosity by either uniform or logtriangular distributions covering the same ranges. Cases where all these data are taken to be equal to the pessimistic and optimistic limits of their distributions are also shown.

The figure demonstrates that the influence of the tested input distribution shapes for these data is minor. This is consistent with the outcome of the sensitivity analyses, as none of the uncertainties associated with these data were identified as important. It is also consistent with the results of a similar test /Hedin, 2003/ made on the SR 97 data. That test covered also data related to solubilities and retardation in the geosphere.

Figure 12-16. *Probabilistic results of calculations with alternative input distribution shapes. Other data as for the base case.*

12.5.3 Alternative fuel dissolution rates

There are considerable conceptual uncertainties regarding the fuel dissolution rate. In the base case, the rate is uniformly distributed between $5 \cdot 10^{-8}$/yr and $5 \cdot 10^{-7}$/yr. Based on current understanding, it is possible that practically no fuel dissolution would take place during the assessment period, e.g. due to catalytic effects caused by the presence of hydrogen gas in a corroding canister insert. It is furthermore difficult to completely rule out also higher rates than assumed in the base case, since the experimental basis is still limited. It is, therefore, interesting to explore the influence of this factor on the overall results.

Figure 12-17 shows the effect of assuming different fuel dissolution rates ranging from no dissolution to an unrealistically high value of 10^{-3}/yr. All other data were sampled probabilistically in 5,000 realisations for each case, using the same input distributions as for the base case. The analytic model was used in the calculation.

For zero or very limited dissolution, only the instant release fractions of the inventory contribute and releases of I-129 dominate. At higher rates, the net influence is via the ingrowing nuclide Ra-226, however limited by the solubility of Radium. The results for the two highest rates are indistinguishable since they both imply complete fuel dissolution on short time scales compared to those of interest here. The early part of the mean dose curve in these cases is dominated by I-129. It is important to note that even the highest, unrealistic values have only a limited effect on the overall result, namely an increase of the peak mean dose by about a factor of 6.

The calculation was done with the analytic model, which has been benchmarked here for the base case dissolution rates and in other studies for dissolution rates up to 10^{-4}/yr /SKB, 2004f/.
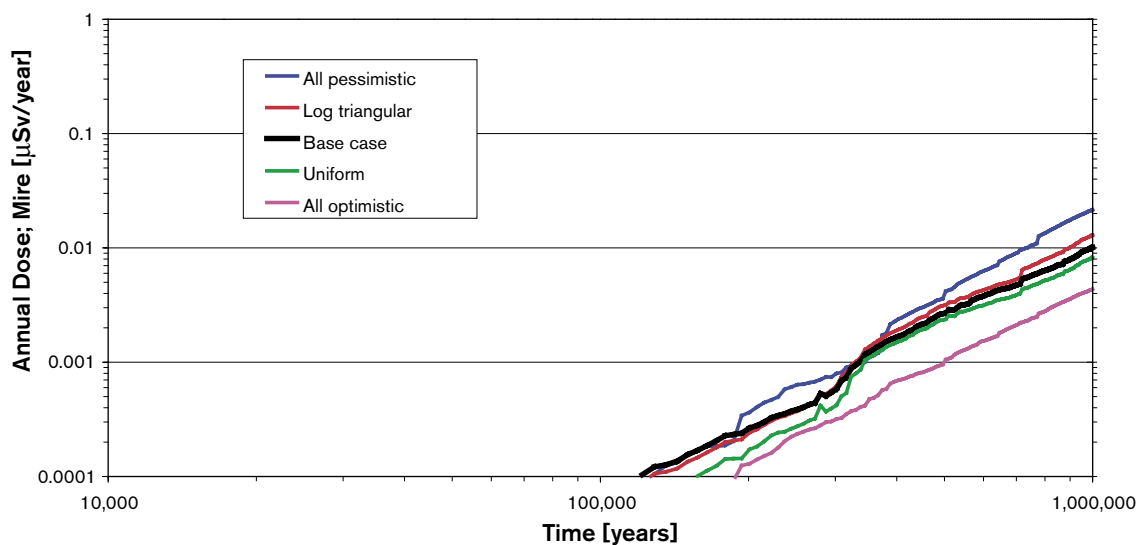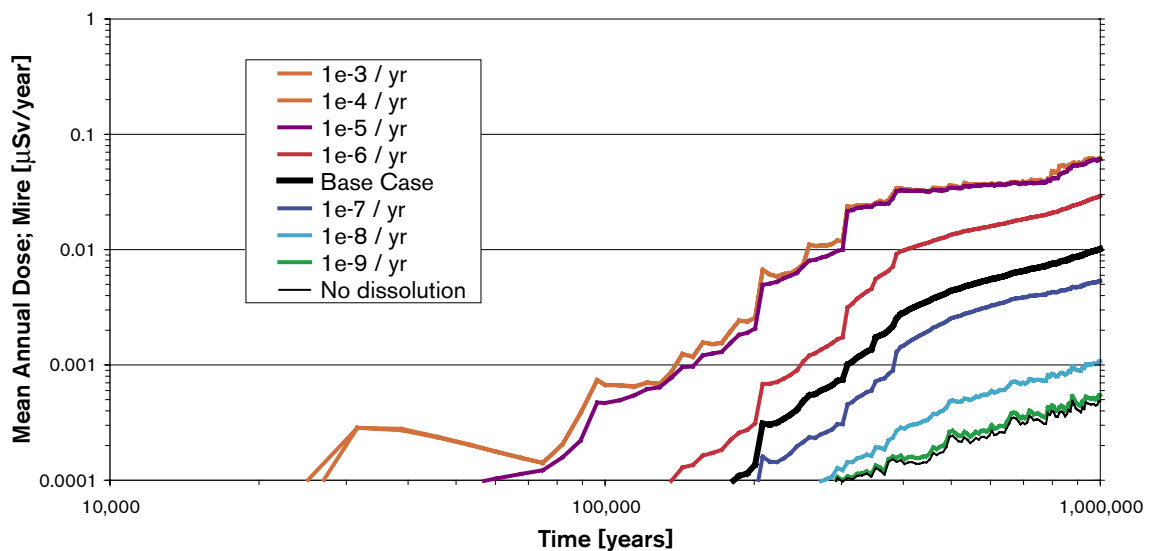

Figure 12-17. *Probabilistic results of calculations with alternative fuel dissolution rates. Other data as for the base case. Each alternative is studied in 5,000 realisations.*

12.5.4 Importance of transport resistance provided by the canister

As mentioned in section 12.2.4, several aspects of the scientific basis for judging the function of the canister after failure are highly uncertain. In particular, the time from an initial small failure to a development of a larger failure is difficult to estimate. As an alternative to the uniform distribution ranging between 0 and 100,000 years used in the base case, a robust assumption of an immediate development of the large failure is used in an alternative case presented in Figure 12-18. The size of the large defect is another uncertain key parameter. Figure 12-18 therefore also presents cases where this varies from the size of the initial, small defect (a circular hole with a radius of 2 mm) to the base case where all transport resistance of the canister wall is lost. All other data were sampled probabilistically in 5,000 realisations for each case, using the same input distributions as for the base case. The analytic model was used in the calculation.

The overall effect of assuming an immediate large defect is small compared to the base case, since the time scales covered in the calculation are longer than the times assumed for the large effect to develop in the base case. Going from a defect radius of 2 mm to a complete loss of transport resistance implies an increase in releases and doses of about an order of magnitude.
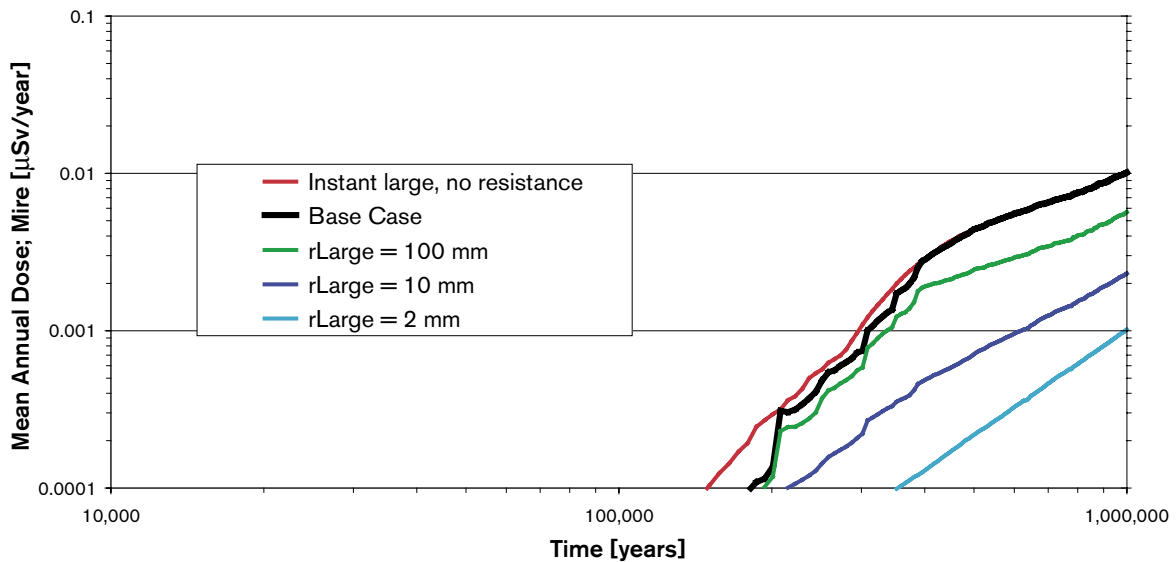
Figure 12-18. *Probabilistic results of calculations with alternative assumptions related to the internal development of failed canisters. Other data as for the base case. Each alternative is studied in 5,000 realisations.*

12.5.5 Co-precipitation of Radium

Co-precipitation of in particular Radium in the canister could lead to a lower solubility for this element. In the SR 97 assessment it was suggested that co-precipitation could lead to Ra solubilities that are three orders of magnitude lower than if this process is not taken into account /Bruno et al, 1997/. In the consequence calculations for SR 97, co-precipitation was however pessimistically neglected.

To elucidate the importance of co-precipitation, the base case was recalculated with 1,000 times lower Radium solubilities. The effect on the mean total dose for a mire is a lowering by a factor between 2 and 3 beyond 200,000 years. Ra-226 now dominates in 1.4 percent of the realisations compared to 2.9 percent for the base case (Figure 12-5).

Figure 12-19 shows the peak doses of Ra-226 for the base case and the case with lowered Radium solubility. In realisations where the results of the two cases are equal, the lowered solubility did not affect the release of Ra-226, i.e. Radium did not reach its solubility limit inside the canister even with the lower solubility. In some realisations, the peak doses differ by as much as a factor of 1,000. Here, the solubility limit of Radium was reached already in the base case, and the lowering of the solubility by a factor of 1,000 resulted in a corresponding lowering of Ra-226 release.
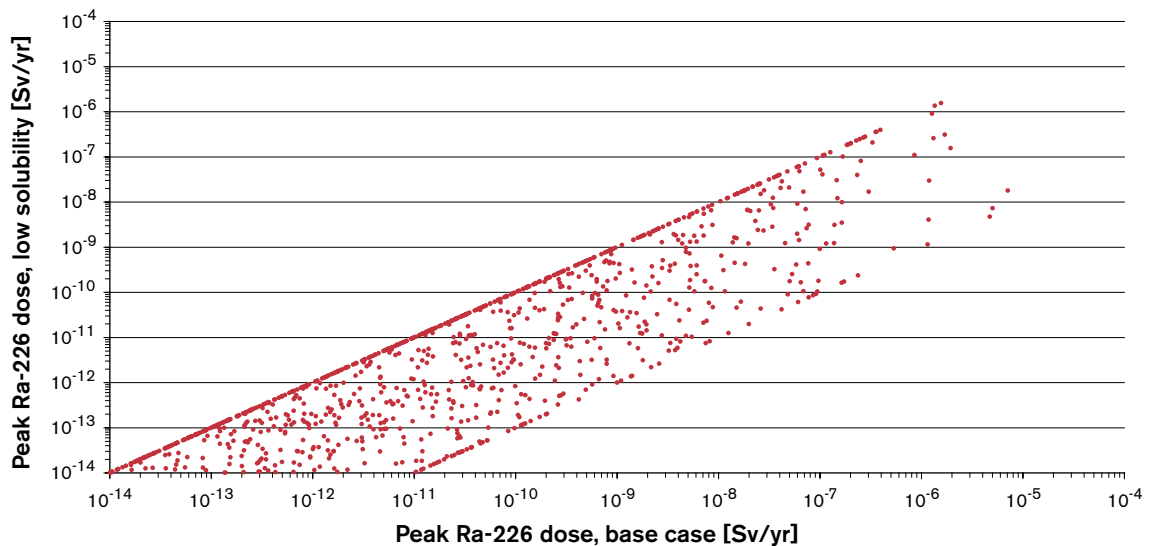
Figure 12-19. Comparison of peak doses of Ra-226 for the base case and for a case where the solubility has been lowered by a factor of 1,000.

12.6 "What if" cases

In this section, so called "what if" cases are formulated and analysed in order to elucidate various aspects of the function of the system.

12.6.1 Canister failure due to rock shear

The system design and repository layout is so as to avoid the possibility of rock shear, see further section 10.1. Since, at this stage of the analysis, it cannot be conclusively ruled out, it is interesting to analyse the consequences of such a case. It is furthermore a representative example of a so called common mode failure where a common cause leads to the simultaneous failure or impairment of several safety functions.

The calculation case is based on the following data and assumptions:

- The probability of a major earthquake in the immediate vicinity of the site is remote prior to, and during the next glaciation. The most likely time for a damaging fault would be shortly after the next major glaciation. The event is therefore assumed to occur 100,000 years from present.

- Only a very limited number of canisters would be affected since most would be protected by application of proper emplacement criteria. For illustration purposes one such failed canister is assumed.

- In the affected deposition holes the faulting is supposed to be so large that it causes massive failure of the canister, i.e. there will be no delay time and no credit from limited transport resistance in the canister.

- The shear-movement will not affect the buffer to the extent that its protection against advective transport will be impaired, but the effective amount of buffer between canister and the shearing fracture is reduced from 35 to 20 cm.

- The canister failure location is assumed to fully coincide with the location of the shearing fracture. Furthermore, the shear is assumed to increase the fracture transmissivity significantly. The Q_{eq} value for the intersecting fracture is therefore assumed to be the highest in the calculated distribution for the base case calculation (0.0355 m³/yr).

- The shearing fracture is very likely to be connected to a major fracture zone. Consequently the rock transport resistance, the F value, is assumed to be the lowest in the calculated distribution for the base case calculation (3,680 yr/m). The corresponding value of the advective travel time is used (2,220 yr). This means that the retardation potential of the geosphere is very small.

All other data and assumptions are handled probabilistically in 5,000 realisations as in the base case.

Figure 12-20 shows the result of this calculation. The peak mean dose is almost three orders of magnitude higher than that of the base case. Ra-226 dominates in 96 percent of the realisations, for all times.
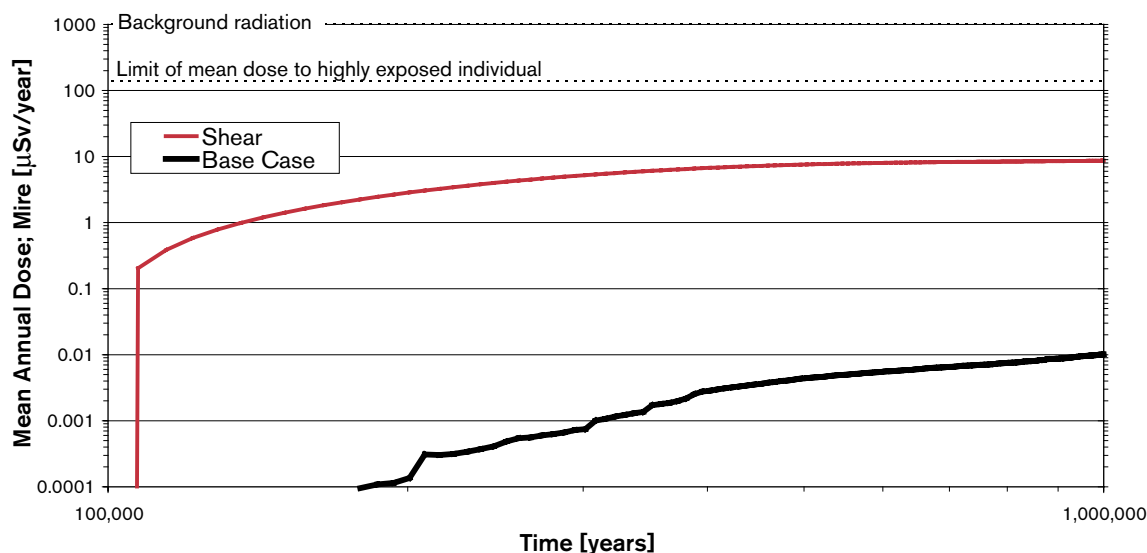
Figure 12-20. Probabilistic results of calculation assuming failure due to rock shear at a deposition hole.

Evidently, a canister failure due to rock shear may increase the mean annual dose significantly. However, it should also be remembered that the likelihood of such failures is very low. As discussed in section 10.1.9, a failure requires the combined event of a deposition hole being intersected by a too long fracture despite an application of an avoidance strategy, that there will be a M6 earthquake or larger and that the fracture intersection with the deposition hole will actually reactivate and slip more than 10 cm. The probability of any of these events is low – some are probably much less than one. In particular, observations of earthquake-induced damage on tunnels discussed in section 10.1.7, indicate that damages and, therefore, the required respect distances, may be considerably smaller than predicted by numerical modelling. This means that even if there really was a high magnitude earthquake, the probability of actually shearing a large fracture more than 10 cm, is much less than one. Substantiating this, low, probability will be attempted in SR-Can.

12.6.2 Role of geosphere retardation processes

To elucidate the role of the geosphere transport processes for radionuclide retardation, cases where different geosphere retardation processes were excluded have been calculated. Figure 12-21 shows three cases where i) sorption, ii) sorption and matrix diffusion and iii) all geosphere retardation, including the advective travel time of the groundwater, have been excluded. The last case thus implies direct releases from the near field to the biosphere. The geosphere flow rates at repository depth calculated by the hydro model, and used to calculate the releases from the near field are however unchanged in all cases. All other data were sampled probabilistically in 5,000 realisations for each case, using the same input distributions as for the base case. The analytic model was used in the calculation. The third case was calculated also with the numerical model, yielding an almost identical result, as also included in the figure. In these cases Ra-226 dominates in 64 percent of the realistaions, for most of the time period shown in Figure 12-21, and I-129 in the remainig realisations.

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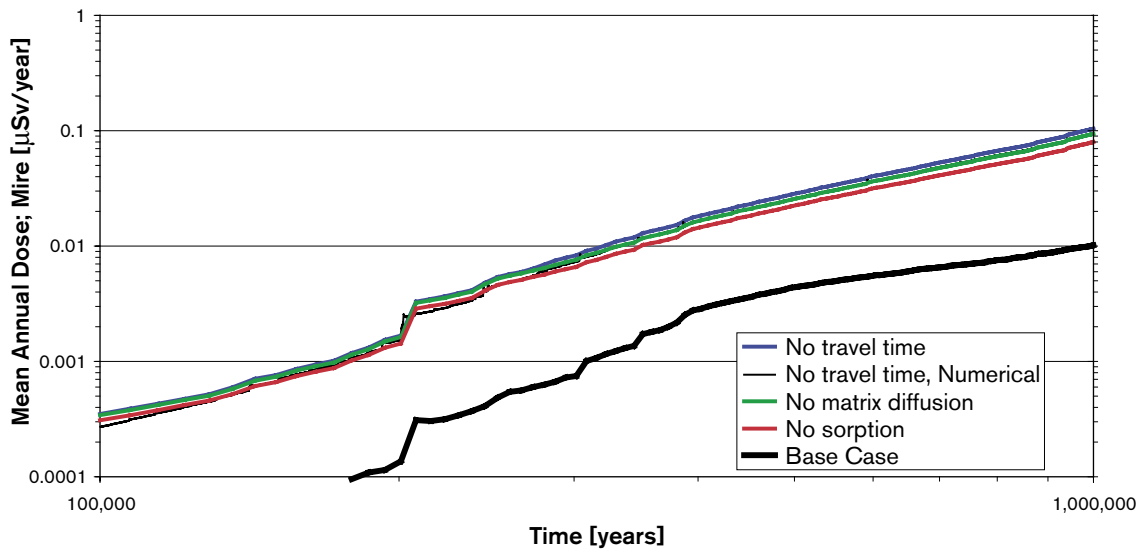
Figure 12-21. *Influence of geosphere retardation processes; "no travel time" indicates that all releases from the near field occur directly to the biosphere. Each alternative is studied in 5,000 realisations.*

It is noted that the overall effect of neglecting all geosphere retardation is an increase of total releases and doses by about an order of magnitude. This case puts a fundamental bound on the possible negative effects of uncertainties regarding colloid transport, simplified treatments of spatially varying retardation properties of the host rock, channeling effects in the geosphere, poorly sealed investigation boreholes, the impact of rock facilities on transport pathways etc. It further illustrates the role of the geosphere in the total system as far as its function as a retarding barrier is concerned.

It should also be pointed out that, in the modelling of the geosphere transport processes, there are aspects of geosphere retardation that have been pessimistically neglected, e.g. geochemical immobilisation. A more realistic treatment of these could demonstrate a stronger role of geosphere retardation in the overall system, and would also lead to decreased risks relative to the base case studied here.

12.6.3 Failure of all canisters

To illustrate the role of the canister in the system, three unrealistic cases where all the 4,500 canisters are assumed to fail at 1,000 years, 10,000 years and 100,000 years after deposition have been calculated, see Figure 12-22.

The increase of the doses over time when the failure time is fixed as in these cases, is mainly due to two factors: the time elapsed before the initially small defect suddenly increases (uniformly distributed between 0 and 100,000 years) and ingrowth of actinides, in particular Ra-226.

The increase in dose compared to the base case is obviously large. However, it is noted that not even with these assumptions, is the dose limit exceeded on the basis of these preliminary data. It is also noted that the releases from all the canisters are pessimistically assumed to reach the same relatively small mire, i.e. no credit is taken for the distributed repository.

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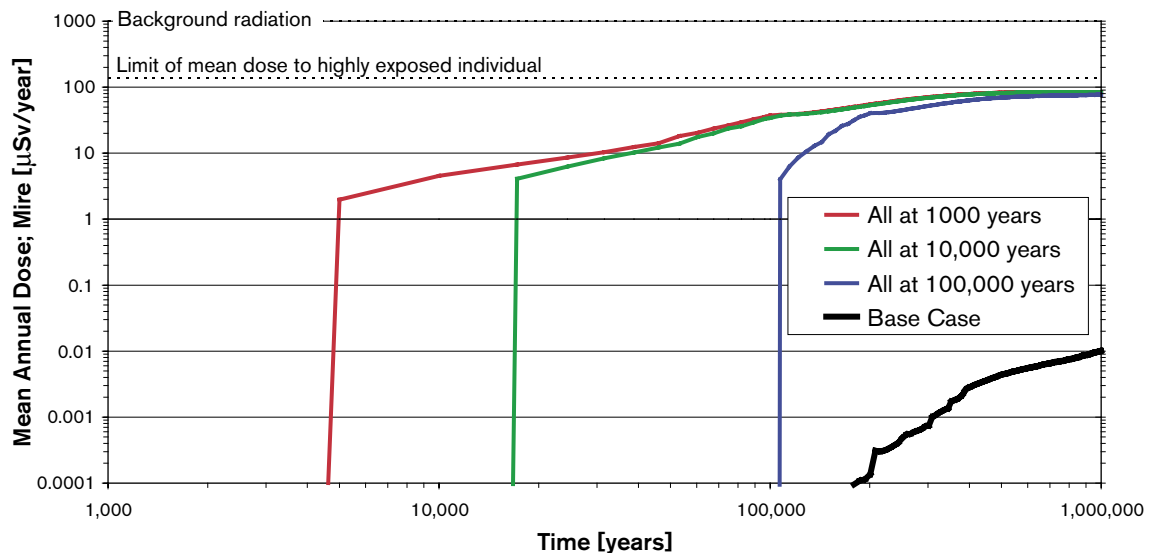
Figure 12-22. *Mean annual doses when all canisters are assumed to fail at 1,000, 10,000 or 100,000 years. All other data as in the base case. Each alternative is studied in 5,000 realisations.*

12.7 Summary and conclusions

This chapter has demonstrated methodology for the analysis of failed canisters for the assumptions that today's external conditions are essentially unaltered over time.

Several possible internal evolutions of failed canisters are sketched and input data for consequence calculations are derived from these.

Models for dose and risk consequence calculations are selected and references to model documentations are provided.

A probabilistic base case calculation, assuming canister failure due to corrosion, is developed. Derivation of input data is demonstrated, showing, through referring to the Interim Data report, an example application of the methodology for the handling input data uncertainties for buffer migration parameters. Probabilistic flow-related transport data for the rock from the Forsmark calculations are used.

A base calculation case is defined and used to demonstrate comparison to the risk criterion.

The results of the base case calculation are analysed and it is demonstrated that

- risk dilution effects can be quantified and that these are of minor importance,

- I-129 and Ra-226 are the dominant dose contributors,

- fractures intersecting deposition holes are the dominant release paths from the near-field

The base case results were subjected to sensitivity analysis using the method of standardised rank regression by which the parameters giving the highest contributions to the spread of the output quantity were identified. Variables contributing to high mean doses were identified by conditional mean analyses. Sensitivity analyses of results for dominant individual nuclides are also provided. Furthermore, the base case has been calculated with two different sets of models yielding similar results, thereby providing a quality assurance check regarding the handling of models and data.

Variant cases have been calculated probabilistically, exploring impacts of

- Correlations related to the geochemical environment that were not taken into account in the base case; it is demonstrated that such correlations are relatively unimportant.

- Alternative choices of subjectively determined input distribution shapes for buffer migration parameters, where the tested distribution shapes all yielded similar results.

- Conceptual uncertainty related to the canister internal evolution, demonstrating that the consequences of the base case are close to those of a pessimistic, bounding case.

- Conceptual uncertainty related to the fuel dissolution rate, demonstrating that the most extreme assumptions could lead to results differing from the base case by about an order of magnitude.

- The effects of including co-precipitation of Radium in the canister when determining the solubility of Radium; the effects on Ra-226 releases are considerable in many realisations whereas those on total mean dose are more limited.

Hypothetical extreme cases are analysed probabilistically to explore:

- The role of geosphere retention, including a case where geosphere retention is entirely neglected; this leads to a dose increase of about an order of magnitude.

- The importance of canister integrity by assuming that all canisters break at 1,000, 10,000 and 100,000 years; this leads, as expected, to considerable increases in dose consequences.

- Canister rupture due to shear movement across a deposition hole, demonstrating that this unlikely failure mode may have considerably worse consequences than a failure due to corrosion.

It is emphasised that the purpose of the calculations presented in this chapter is primarily to demonstrate methodology. The data selection used in the example calculations is not final.

13   Conclusions

This chapter discusses how the purposes of this report have been fulfilled in section 13.1 and elements that could be included in a concluding chapter of the final SR-Can report in section 13.2.

No conclusions regarding safety of the KBS-3 concept are drawn below, since the data used in this interim assessment are preliminary and since a number of issues have not been addressed. In general, it is though noted that the findings presented confirm earlier results regarding the safety of the KBS-3 concept.

13.1   Fulfilment of purposes of this Interim report

A methodology for the SR-Can assessment has been presented and, as far as possible at this interim stage of the project, exemplified. This is the main purpose of the interim reporting of the safety assessment SR-Can, as requested by SKI and SSI.

The authorities' expectations on the interim reporting of SR-Can are summarised in section 1.3.1. The items mentioned there are reproduced below, together with a brief description of where the issue in question is addressed in the report.

• The main purpose of the Interim report is to provide an account of the safety assessment methodology (facilitating feedback prior to the SR-Can main report).

An overview of the methodology is given in chapter 2 and the entire report with its supporting documents exemplifies and provides more detailed accounts of the methodology.

• Important steps in the safety assessment should be described and, as far as possible, exemplified.

See above.

• A structured account of how the methodology has been developed since SR 97 should be provided.

A brief such account is provided at the end of Appendix B.

• A discussion on how review comments by the authorities and by the NEA on SR 97 have been handled should be provided.

This is provided in Appendix B.

• The application of the authorities' regulations SSI FS 1998:1 and SKIFS 2002:1 should be described and, if possible, exemplified.

This is provided, as references to relevant sections of the main text, in Appendix A.

• Scenario selection including discussion on scenario probabilities and risk contributions should be included.

The principles for scenario selection are presented and a preliminary selection is carried out in chapter 8. Scenario probabilities and risk contributions are discussed in sections 2.12, 8.1.4 and 8.2.2. As mentioned in section 8.1.4, many factors that could be seen as scenario generating are probabilistically included in the main scenario. Examples of these probabilistic treatments are given, for initial canister defects in section 7.2.2 and in /Müller and Öberg, 2004/, and for earthquakes in section 10.1.9.

- Examples of FEP descriptions, initial state descriptions and process diagrams should be provided.

Overview descriptions of FEPs are given in the FEP database /SKB, 2004a/. The initial state and initial state FEPs are described in chapter 3 and in the Interim initial state report /SKB, 2004d/. Processes are described in chapter 5 and in the Interim process report /SKB, 2004b/. The roles of process diagrams and other tools, like process tables, for the representation of processes are also discussed in chapter 5.

- Examples of choice of models, documentation of models, choice of input data and of calculation cases (including "what if" cases) and sensitivity analyses should be provided.

This is provided in chapter 12, or through references therein, for dose and risk consequence calculations. Some models, data and sensitivity analyses for repository evolution are presented in chapter 7 and in other parts of the report.

- Consequence calculations for a scenario (or variant or part of a scenario) should be undertaken – for simplicity these may be without climate and biosphere changes (like the canister defect scenario in SR 97).

This is provided in chapter 12.

- Examples of reporting of results and evaluation relative to the risk criterion should be presented (with no requirement of completeness).

See the above item.

- The strategy for handling of uncertainties should be described (with explicit examples for judgement of the level of ambition).

This is presented in section 2.11. The handling of system uncertainty is primarily related to FEP processing (section 2.4 and the Interim FEP report /SKB, 2004a/) and to the selection of scenarios (chapter 8). Examples of handling of conceptual uncertainty on the individual process level are provided in the Interim process report /SKB, 2004b/. Examples of how conceptual uncertainties are handled by appropriate choices of parameter values in consequence calculations are given, for uncertainties related to fuel dissolution in section 12.5.3, and for uncertainties related to the internal evolution of the canister in section 12.5.4. The general handling of input data uncertainty is outlined in section 2.7. A more detailed account of that methodology and examples for buffer migration parameters are given in the Interim data report /SKB, 2004c/.

Methodology issues to be reviewed according to the terms of reference for the international review team of SR-Can are also listed in section 1.3.1. They are addressed as follows (most of them already mentioned above).

- Description of the initial state of the repository and its components.

See above.

- Description of features, events and processes (FEPs) that are relevant to repository evolution.

See above.

- Strategy for safety demonstration (e.g. allocation of safety to different barrier functions and the role of dilution).

The strategy is, in a general sense, closely related to the entire assessment methodology. The function indicators and function indicator criteria, see chapter 6, are essential components in the analyses of different barrier functions. The role of dilution is specifically addressed in section 6.2.

- Basis and methods for scenario selection and evaluation.

See above.

- Assessment of the model framework for consequence analysis and compliance evaluation.

See above.

- Methods for biosphere modelling including the transition zone from basement rock to Quaternary deposits and ecosystems.

The overall approach to biosphere modelling is presented in section 2.8. Details, including the transition zone, are provided in Appendix C. Hydrological aspects of the biosphere/ geosphere interface are treated in section 9.3.3.

- Methods for risk analysis, including the use of probabilistic methods, uncertainty and sensitivity analyses, estimation of probabilities, averaging of risk.

See section 2.12 and chapter 12.

- Quality assurance measures including handling of expert judgements.

Quality assurance measures are briefly described in section 2.11.3; handling of expert judgements in section 2.10.

13.2   Tentative contents of concluding chapter in final report

The following is a brief outline of some elements that could be included in the concluding chapter of the final SR-Can report.

13.2.1 Risk summation and compliance assessment

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 2.12 in order to reach a conclusion regarding compliance with the regulatory risk criterion.

An example risk summation is difficult to demonstrate, since the consequence calculations only handle the main scenario for simplified external conditions and only one failure mode. Several other contributions, if found significant, would be included in a total summation. The principles for risk summation are discussed in section 2.12.

13.2.2 General evaluation of safety

This section would include a general evaluation of the safety of the KBS-3 concept, bringing out the main arguments for safety as provided by the safety functions isolation and retardation. The multi-barrier concept would be discussed, including the regulatory requirement that "the necessary safety is maintained in spite of a single deficiency in a barrier". Conclusions from the results of comparisons to alternative safety indicators would also be included.

13.2.3 Feedback to site investigations, design development and R&D

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 and of the results of the comparisons with function indicators.

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 has implications for the actual investigations during continued site investigation.

In general, an evaluation will be made of the confidence in the 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 mixtures will provide feedback to site investigations on the level of ambition and approach for describing rock type variability.

- Earthquake analyses based on different alternative descriptions 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, 2002a/. 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.

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) which are defined through alternative initial states.

Also a discussion of the design basis, see section 8.6.3 in the light of the safety assessment results should be included in the feedback given to design development.

Feedback to Research & Development

The results of sensitivity analyses have implications relating to key 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.

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.

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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 retardation of dispersion of radioactive substances, either directly, or indirectly by protecting other barriers in the barrier system.

Handling in SR-Can: The ways in which the barriers contribute to safety is discussed in detail in chapter 6. Several of the calculation cases in chapter 12 address this issue directly. In general, most of the safety assessment is aiming at demonstrating barrier safety.

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[6], shall be reported to the Swedish Nuclear Power Inspectorate without delay[7]. 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.

Handling in SR-Can: The purpose of the safety assessment can be said to demonstrate this point.

6 § The barrier system shall be designed and constructed taking into account the best available technique[8].

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 are not seen as issues for a safety assessment by the authorities (section 3.3.6 of /SKI and SSI, 2001/). SKB shares this view and these issues will therefore not be addressed in SR-Can.

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 issue is addressed in many of the analyses. In particular, a set of calculation cases (residual scenarios) to illustrate this issue are discussed in section 8.6.2. Also some of the calculation cases in chapter 12 illustrate this point.

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.

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.

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[6] Cf Chapter 4. 2 § of the Swedish Nuclear Power Inspectorate's regulations (SKIFS 1998:1) concerning Safety in Certain Nuclear Facilities.

[7] Cf Chapter 2. 2 § of the Swedish Nuclear Power Inspectorate's regulations (SKIFS 1998:1) concerning Safety in Certain Nuclear Facilities.

[8] Cf Chapter 2. 3 § of the Swedish Environmental Code.

Handling in SR-Can: The systematic management in a database of the mentioned features, events and processes in SR-Can is discussed in section 2.4 and in /SKB, 2004a/. The detailed management of many of these factors is discussed throughout the report.

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 2.5.

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 5.2, the description of system evolution is a task for the entire assessment and will be discussed for each scenario, see e.g. chapters 7, 11 and 12.

• 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: A preliminary scenario selection for SR-Can is provided in chapter 8.

• 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 chapter 5 and section 2.7, respectively. Interim versions of these reports are provided in /SKB, 2004b/ and /SKB, 2004c/, 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 safety assessment. A plan for the management of uncertainties is given in section 2.11, sensitivity analyses are exemplified in chapter 7 and section 12.4.5.*

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 chapters 11 and 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 9 and 10 § and Appendix of SKI FS 2002:1, i.e. those sections that concern the safety assessment.

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 preliminary selection of scenarios is provided in chapter 8.*

The lack of knowledge and other uncertainties in the calculation conditions (assumptions, models, data) is denoted in this context as uncertainties[9]. 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,

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[9] This explanation of the term uncertainty only makes sense in Swedish where the same word (säkerhet) is used to denote both certainty and safety.

- 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 safety assessment. A plan for the management of uncertainties is given in section 2.11.*

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.

Handling in SR-Can: *This matter is addressed in the Process report, see further section 5.3, subheadings "Handling in SR-Can" and "Uncertainties". An interim version of the process report is provided in /SKB, 2004b/.*

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: *Deterministic and probabilistic model calculations are exemplified in chapters 7, 9, 11 and 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 8.1.4. This is an issue that will 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 8.6.3.*

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 12.2.5.

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 chapter 5 and section 2.7, respectively. The use of natural analogues is addressed in section 2.9. Interim versions of the process and data reports are provided in /SKB, 2004b/ and /SKB, 2004c/, respectively.

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 chapter 5 and section 2.7, respectively. Interim versions of the process and data reports are provided in /SKB, 2004b/ and /SKB, 2004c/, respectively.

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 2.5.

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.

(Compare SSIFS 1998:1 and SSI's comments on those regulations).

Handling in SR-Can: *The use of alternative safety indicators is discussed in section 6.4.1 and exemplified in section 12.4.4.*

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 are not seen as issues for a safety assessment by the authorities (section 3.3.6 of /SKI and SSI, 2001/). SKB shares this view and the issues in 4 § 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[10].

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 aimed at achieving this end-point. Issues directly related to the calculation of risk are discussed in section 2.12. Example calculations are provided in chapter 12.

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[10] 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.

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 2.8.4.*

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.

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 sections 4.3 and 8.5.*

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-Ca*n (11 § and 12 §):*** *The handling of different time scales are discussed throughout the report, e.g. in section 2.5 (time frame for the assessment), in section 2.8.1 (timescales for the biosphere treatment), in chapter 5 (time scales in process descriptions), chapter 11 (system evolution) and in section 12.2 (evolution of initial canister defects). The first 1,000 years are explicitly treated in the evolution of the main scenario. It is demonstrated that canister failures during the first 1,000 years are extremely unlikely. Furthermore,*

several aspects of the internal evolution of a failed canister imply that no releases will occur during the first 1,000 years after failure.

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:

$$\gamma \int P(D)DdD$$

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, γ (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 is 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 of 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 retardation. 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.

Methodological developments since SR 97 and handling of review comments on SR 97

This Appendix provides an account of how review comments on SR 97 have been handled. Section B.1 treats the review comments by SKI and SSI and section B.2 those by the NEA international review team, both with references to relevant sections in the main text. Section B.3 lists the main methodological developments since SR 97 without references to the main text since the developments are essentially covered by the preceding account of the review comments on SR 97.

B.1   Handling of SKI's and SSI's review comments on SR 97

The authorities have requested that, in the interim report, an account should be given of how their review comments on SR 97 have been handled, see section 1.3.1. In the overall evaluation of their joint review /SKI and SSI, 2001/ of the safety assessment SR 97, SKI and SSI summarise their findings under the four headings appearing below. The text from the review report has been copied and the developments in these areas since SR 97 are described in italics.

B.1.1   Data and Technical Premises for the Safety Assessment

The assumptions concerning the initial state of the engineered barriers are essential premises for the analyses presented in SR 97. In practice, SKB's assumption is that one of the canisters is deposited with an initial defect while the other canisters are intact at the time of deposition. Furthermore, in SR 97, it is assumed that the buffer is intact and that the evolution of the buffer surrounding each canister is the similar. Issues relating to the long-term evolution of the backfill and plugs are not dealt within SR 97.

Bearing in mind the fact that knowledge of the engineered barriers is incomplete and that there is a need to provide feedback to the development work on the engineered barriers, the authorities' opinion is that alternative types of canister damage and damage frequencies should have been more fully developed in SR 97. For the same reason, the authorities consider that SKB, in future safety assessments, should assess the importance of malfunctions of the buffer, backfill and plugs, particularly with respect to thermal effects during buffer resaturation.

In SR 97, SKB has used data from three previously investigated sites: Äspö (Aberg), Finnsjön (Beberg) and Gideå (Ceberg). Although the site data vary in scope and quality, depending on the site, the authorities consider the scope of the data to be reasonable in relation to the purposes of SR 97. Furthermore, in the authorities' opinion, the data provide a reasonable coverage of the conditions that can be expected at the sites that are being considered for SKB's planned site investigations. The biosphere modelling is based on the existing ecosystems at the three sites.

Canisters: A first step has now been taken towards coupling the assumptions regarding initial state of the canister to statistics from the actual test series of canister manufacturing. Descriptions of different types of defects etc are in progress and will be available for the final SR-Can report. Also, sensitivity analyses are performed to elucidate the sensitivity of the overall dose consequences to the number of defective canisters. The corrosion of defective canisters is analysed probabilistically and important parameters for this process have been identified.

Buffer: A first step has furthermore been taken in coupling the description of uncertainties of the initial state of the buffer to the manufacturing and emplacement procedures. The initial buffer density is e.g. described as a range that is propagated to some of the analyses in the assessment. Buffer malfunctions arising from variations outside that density range will be analysed as a "what if" scenario. The description of the knowledge of the early THM evolution of the buffer has been updated in the Process report. Modelling of buffer chemical evolution during the "thermal phase" has been performed since SR 97 and will be further developed in SR-Can. A preliminary account of more extensive resaturation calculations for the buffer is given in this Interim report and the consequences of an extended dry period are discussed.

The long-term evolution of the backfill is now included in the analysis. The backfill is treated in a dedicated chapter in the Process report, some preliminary analyses are performed in chapter 7, the consequences of increased backfill conductivity are analysed in the hydrological calculations and will be propagated to radionuclide transport calculations as the project progresses. Plugs are now treated as a part of the system in the Initial state report and will be included also in the Process report.

B.1.2 Demonstrate Safety Assessment Methodology

In the opinion of the authorities, SKB has demonstrated in SR 97 that it has access to qualified scientific data and the necessary tools and methods to assess the long-term safety of a repository for spent nuclear fuel. The safety assessment methodology presented in SR 97 has been developed, in several respects, in relation to previously presented safety assessments. For example, in SR 97, SKB has taken a first step to adapting its safety reports to the requirements of the authorities' regulations, including the presentation of the protective capability of the repository in terms of risk. The methodology of SR 97 also qualitatively meets the requirements on scope and content specified in SKI's draft regulations on safety in connection with final disposal (see Chapter 2) and, thereby, is a sound platform for SKB's further safety assessment development work.

At the same time, in their review, the authorities find that some parts of the methodology presented in SR 97 must be further developed and detailed prior to future licensing, as described below. Essential aspects of the criticism provided in this review have been communicated earlier, such as in connection with SKI's review of SKB's SKB 91 performance assessment /SKI, 1992/. In the authorities' opinion, some of the deficiencies found could have been avoided if SKB had, to a greater extent, taken into account in SR 97 the premises for the safety assessment that SKB itself formulated in SR 95 /SKB, 1995/. Examples include the discussions on completeness in connection with scenario selection, model validation and the evaluation of calculation results, taking into account various types of uncertainties.

The methodology for scenario selection has been considerably developed and adjusted to the regulatory requirements since SR 97. The robustness of the calculation results is evaluated by sensitivity analyses and a more extensive selection of calculation cases allows for the evaluation of various types of uncertainty regarding e.g. fuel dissolution rate or of properties related to the internal evolution of a defective canister.

Structure and Presentation

In the authorities' opinion, SR 97 is on the whole well-written and organized. SR 97 contains the components that, according to SKI's draft regulations concerning safety in connection with the final disposal of nuclear waste, should be included in a safety report.

The main criticism of the presentation of information in SR 97 relates to deficiencies in traceability and transparency with respect to different types of judgements made as well as deficiencies in documentation with respect to parts of the safety assessment methodology, such as scenario selection and risk analysis. Furthermore, the description of biosphere processes and biosphere models is inadequate in the SR 97 Main report and background reports. All essential information must be taken from sub-references. However, in the authorities' opinion, these issues can be dealt with in SKB's ongoing work on developing a basic structure for safety reports.

Handling of expert judgements in SR-Can is discussed in section 2.10. The risk analysis and the scenario selection methodologies have been developed as discussed in section 2.12 and chapter 8, respectively. Biosphere models are now described in the Main report and in background reports; no essential information will appear in sub-references.

Focus of the Safety Assessment

SKB states that, in SR 97, it has placed greater emphasis on analyses of the isolating functions of the repository, compared with previous safety assessments. In the opinion of the authorities, this should have led to a more in-depth analysis of the uncertainties associated with the engineered barriers and their evolution in the repository, particularly with regard to possible defects in and malfunctions of the canister and buffer as well as the importance of long-term chemical changes in the buffer. Such an evaluation of uncertainties is valuable in order to assess the barrier performance of the rock and in order to formulate performance requirements for the engineered barriers. These views have previously been expressed, for example in SKI's review of SKB's SKB 91 performance assessment /SKI, 1992/.

This issue is addressed through the introduction of function indicators and function indicator criteria, through the evaluation of these over time, and through the inclusions of barrier defects and malfunctions in the scenario selection.

System Description

In the authorities' opinion, the newly developed THMC diagrams are a good complement to previously developed methods for system description and for the visualization of processes in the repository. However, SKB should develop the method in order to improve the inclusion of time-dependent effects and structural changes. SKB should also continue its work on developing a systematic description of the processes in the biosphere.

SR 97 contains a systematic review of the processes and data used in the consequence analysis for the canister defect scenario. Although this documentation represents a major step, SKB should develop the methodology, mainly in view of supporting the reasons for eliminating unfavourable processes from the consequence analysis. Alternatively, these processes should be included in the calculations so that the risk contributions can be evaluated. Colloidal transport of radionuclides and the impact of microbes on canister corrosion are two examples of such processes that have been identified in this review.

The role of the THMC diagrams and the development of these to better suit the needs of the safety assessment are discussed in section 5.2. The systematic description of processes in the biosphere is described in Appendix C.

Criteria for exclusion of several unfavourable processes from the consequence analysis have been formulated. A more extensive treatment of the description of how each process should be handled in the safety assessment is given in the Process report. Several potentially unfavourable factors like microbial canister corrosion, buffer erosion, colloid-facilitated transport and penetration of oxygenated groundwater for glacial conditions will be further evaluated by analysing the scientific basis for their occurrence and in terms of "what if" calculations in order to establish their importance should they occur.

Scenarios

In the authorities' opinion, the scenarios analyzed in SR 97 provide an acceptable coverage of the internal and external events that could affect the protective capability of the repository. However, in future scenario work, SKB should ensure that these provide a good basis for, and are logically coupled to, both the system description and the risk calculations. One deficiency of SR 97 is that couplings between different events are not adequately analyzed. For example, SKB has not adequately investigated the impact that future climate changes could have on the engineered barriers, on radionuclide transport as well as on how the frequency and magnitude of earthquakes can affect the protective capability of the repository. In the authorities' view, SKB should consider analyzing more comprehensive scenarios that, in a more integrated manner, handle events and processes that can affect repository safety. SKB should also conduct a more extensive analysis of scenario uncertainties, such as climate evolution alternatives and alternative assumptions on defects in the engineered barriers.

Much of the above is covered in the methodology for the scenario selection described in chapter 8. The main scenario now includes climate change and earthquakes. The intended handling of the latter is described in section 10.1. The handling of climate evolution alternatives are discussed in section 4.2.3. Alternative assumptions on defects in the engineered barriers are largely handled as residual scenarios.

The example consequence calculations presented in this Interim report are however not strictly coupled to the scenario analyses at this interim stage. This is in line with the requirements on the Interim report, see further section 1.3.1.

Data and models

In the authorities' opinion, prior to conducting SR 97, SKB developed a comprehensive set of models for the needs of the safety assessment. However, the documentation and the justification of models must be improved in future safety assessments. The evaluation of alternative hydrogeological models in SR 97 is a valuable initiative for understanding model limitations and conceptual uncertainties. A similar approach should also be considered for other parts of the model chain, such as the evolution of the near field and radionuclide transport.

It is positive that SKB is attempting to gain an understanding of the complex processes that affect the evolution of defective canisters in the repository. However, the authorities consider that the models used in SR 97 must be evaluated and better supported by data prior to future safety assessments. The corrosion analysis for intact canisters must be better

validated against experiments and other corrosion models. Furthermore, SKB should take the canister weld joints into account in the corrosion analysis.

With respect to the selection of data, the authorities consider that the background report, "Data and Data Uncertainties" is a laudable initiative, even if data used in other contexts besides the consequence analysis for the canister defect scenario should have been documented in a similar manner.

In SR 97, SKB has taken a first step towards a more structured biosphere modelling by analyzing a number of exposure pathways in different ecosystems for the hypothetical repository sites, Aberg, Beberg and Ceberg. However, in the authorities' opinion, SKB should improve its understanding of radionuclide migration from the geosphere to the biosphere and develop its assessment of environmental protection in order to comply with the regulatory requirements. SKB should also take into account the possibility that several exposure pathways can lead to simultaneous exposure. For example, exposure via drinking water consumption must be studied together with other possible exposure pathways.

References to documentation of models used in this report are provided in the appropriate sections. No direct attempts to develop alternative conceptual models for radionuclide transport in the near-field or the geosphere have been made, since no obvious alternative conceptualisations suitable for the purpose of the safety assessment are available. A number of bounding calculation cases, putting bounds on the consequences of conceptual uncertainty are however presented.

Regarding evolution of defective canisters, the results in chapter 12 demonstrate how this can be treated with pessimistic assumptions, bounding the consequences of uncertainties related to this evolution for the few canisters that are expected to fail. Some new experimental data exist, but the overall understanding of the coupled system of processes involved does not allow the formulation of a detailed, unambiguous model. Rather, in chapter 12, a number of different possible evolutions are sketched and, based on these, input distributions with large uncertainties are derived for the consequence calculations. The pessimistically case mentioned above puts an upper bound on the effects of these uncertainties.

The corrosion analysis of intact canisters has been extensively reported in /King et al, 2001/. The canister welds joints are now included in the corrosion analysis, see section 7.2.2.

The scope of the SR-Can data report has been extended to include data other than those directly related to radionuclide transport, see further section 2.7 and the Interim data report /SKB, 2004c/.

Issues regarding the migration of radionuclides from the geosphere to the biosphere are discussed in section 9.5.4 and Appendix C. Environmental protection is briefly discussed in section 2.8.4.

Measures of the Protective Capability of the Repository

In the authorities' opinion, SKB has correctly interpreted SSI's health protection requirements in the SSI FS 1998:1 regulations /SSI, 1999/, which stipulate that the risk limit for large populations is 10^{-6} per year. In the authorities' view, SKB should justify, in greater detail, its selection of the individual or group with the highest dose commitment, since it is not clear how this individual/group stands in relation to a larger population.

The assessment of environmental protection in SR 97 is deficient. However, the authorities are aware that SKB is actively working on this issue. The authorities are expecting that SKB will initiate further work within this area, as is reflected in SSI's regulations /SSI, 1999/.

SKB states that it did not take into account the dilution of radioactive substances and migration in the biosphere as a safety function, with the explanation that it is difficult to predict the evolution of the biosphere. At the same time, dilution in the biosphere is a deciding factor in the assessment of the consequences of the climate scenario. In the view of the authorities, SKB should, in consultation with the authorities, define the role of the biosphere prior to future safety assessments.

SKB has only, to a limited extent, used alternative measures of the repository protective capability. In the authorities' view, alternative safety indicators, such as the flow of radionuclides from the geosphere to the biosphere, and radionuclide concentration in the environment, are essential complements to dose and risk and can be used to obtain information on differences between repository sites. A discussion on the results for Aberg with respect to alternative safety indicators would have been valuable.

The selection of the group with the highest dose commitment is discussed and justified in section 12.4.3. The assessment of environmental protection is briefly discussed in section 2.8.4. SKB's approach to dilution is accounted for in section 6.2. The flow of radionuclides from the geosphere to the biosphere is used as an alternative safety indicator in SR-Can.

Risk Analyses and Calculations

In the opinion of the authorities, in its canister defect scenario, SKB has developed a set of calculation cases that describe the interactions of the various barrier functions and illustrate the possible consequences of leakage from a defect canister. However, it should be possible to considerably develop the uncertainty and sensitivity analyses for example by including variations of more than one parameter or parameter group at a time as well as hypothetical examples that more stringently test individual barrier functions.

In the authorities' opinion, the risk calculations in SR 97 are a first step in adapting to the use of a risk criterion. However, SKB should develop a less arbitrary method of representing probabilities for the many parameters that are included in the risk analysis. Correlations between different parameters in the risk analysis should also be studied in greater detail, since these could have a considerable impact on the final result. In the view of the authorities, a specific account of the protective capability of the repository in the short term (0–1,000 years after closure), as stipulated in SSI's regulations on the final management of nuclear waste, is also lacking.

The probabilistic consequence calculations and the associated sensitivity analysis reported in chapter 12 is one type of multi parameter variation. Most of the variant cases are also probabilistic, meaning that the particular aspect explored in a specific calculation case is studied with all other data uncertainties included. There are also several examples of hypothetical cases that more stringently test various barrier functions.

Input data are derived with the new approach presented in the Data report, aiming, contrary to the case of SR 97, at assignment of input distributions rather than merely reasonable and pessimistic values. Correlations are propagated from separate hydrological and biosphere calculations to the consequence calculations. The effects of correlating also other parameter groups are studied in a variant of the base case, see section 12.5. The first 1,000 years are now explicitly treated in the evolution of the main scenario. It is demonstrated that canister failures during the first 1,000 years are extremely unlikely.

Furthermore, several aspects of the internal evolution of a failed canister imply that no releases will occur during the first 1,000 years after failure.

Expert Judgement

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

Plans for procedures for documentation and implementation of expert judgement are presented in section 2.10. Handling of expert judgements relating to process documentation and process handling, including modelling of processes, is described in chapter 5 and in the Interim process report /SKB, 2004b/. Quality assurance is briefly discussed in section 2.11.3. Concerning the integrated assessment level, this report has been reviewed by the SKB's international Site Investigation Expert Review Group, whose members have a profound expert knowledge of matters related to long-term safety.

B.1.3   Compliance with Safety and Radiation Protection Requirements

One overall purpose of SR 97 is to demonstrate that KBS-3 has good prospects of meeting the long-term safety and radiation protection requirements and to show that it is possible to find a site in Sweden that meets the requirements. In SR 97, SKB states that: "a safe deep repository for spent nuclear fuel, based on the KBS-3 method, can be constructed at a site with conditions similar to those exemplified in the three examples –Aberg, Beberg and Ceberg".

In their review of SR 97, SKI and SSI have not found any obstacles to prevent geological final disposal in accordance with the KBS-3 method from meeting the required safety and radiation protection requirements. Based on the review of SR 97 and the previous review of SKB's RD&D programme, the authorities consider that the KBS-3 method is a good basis for SKB's future site investigations and the further development of the engineered barriers. However, a detailed evaluation of the prospects of the KBS-3 method in meeting the requirements can only be made once detailed data have been obtained from the site investigations and when more extensive practical experience concerning manufacturing and testing the engineered barriers has been gained. Furthermore, SKB must supplement and develop its safety assessment methods, taking into account the findings of the regulatory review of SR 97.

A first step in incorporating detailed data from the site investigations and more experience from the manufacturing and testing of the engineered barriers, as well as in applying a developed safety assessment methodology is taken in this Interim report.

B.1.4   SR 97 as a Basis for Site Investigations and Function Requirements

SR 97 must also provide a basis for deriving the parameters to be measured in a site investigation and for specifying the factors for selecting sites for investigation. Furthermore, SR 97 must provide a basis for deriving preliminary function requirements with respect to the engineered barriers.

In the authorities' opinion, SR 97 has provided SKB with a basis for further work on the site investigation and function requirements. However, the authorities find that SR 97 does not contain any in-depth discussion of what the results of the safety assessment would mean for the site investigation programme and the function requirements for the engineered barriers. Instead, SKB states that the results from SR 97 will be dealt with in separate projects, including the project to develop the site investigation programme, the formulation of requirements and preferences with respect to the bedrock and the review of functional requirements and design basis requirements for the canister and the other barriers. Therefore, the authorities intend to return to these issues in connection with the regulatory review of SKB's supplement to RD&D Programme 98 and, at a later stage, in connection with the review of SKB's RD&D Programme 01.

In this review, the authorities have stated that SKB should conduct more comprehensive analyses of uncertainties in the assumptions used for the canister and buffer performance in order to better determine the importance of the rock barrier to safety and to thereby identify which parameters it is important to study in a site investigation. In the authorities' view, such analyses are also necessary for SKB to specify design requirements for the engineered barriers. It is important for SKB to evaluate the experience from SR 97, including the findings of the regulatory review, in its further development work on the site investigation programme and the engineered barriers.

As indicated above, these issues have been dealt with in other projects. More comprehensive analyses of uncertainties in the assumptions for the canister and buffer performance will be provided in SR-Can. Thereby, it should be possible to provide more useful feedback to further site investigations and to the development of the engineered barriers once the final results of SR-Can are available. Feedback to site investigations will also be given in the preliminary site evaluations mentioned in section 1.1.1.

It is also worth noting that there is presently a close link between site investigations and safety assessment on an informal day-to-day basis.

B.2   The NEA review of SR 97

The authorities have requested that, in this Interim report, an account of how the NEA review comments /NEA, 2000/ on SR 97 have been handled, see section 1.3.1. The conclusions made in the final chapter of the NEA report have been copied below and descriptions of the developments in these areas since SR 97 are inserted in italics.

"The KBS-3 disposal concept has the essential elements of a sound concept for the disposal of spent nuclear fuel in a geologic repository. It provides defence-in-depth through a set of passive barriers with multiple safety functions. The concept is based on well-established science and a firm technological foundation, is well defined, and appears to be implementable.

SR 97 provides a sensible illustration of the potential safety of the KBS-3 concept that takes account of the conditions in Swedish bedrock, based on data from three sites. The documentation is generally well written and the arguments well presented, but there is room for improvements in the completeness of arguments, traceability and transparency.

Given the current state of expertise of the SKB geoscience and engineering programmes and the favourable indications from SR 97, SKB's desire to move to a site-selection phase is well founded. This is reinforced by the observations that the performance of the geosphere

barrier is site-specific and data are needed from potential sites to better develop, focus and test the SKB assessment methodology.

The review has not identified urgent issues that must be resolved prior to proceeding to the investigation of potential sites. Several observations and recommendations are made that SKB and the safety authorities may wish to consider in the future development of the Swedish safety assessment programme for spent fuel disposal:

- A high-level, periodically updated document describing the SKB's safety strategy should be prepared. This would reveal the evolution of the KBS-3 concept and show how various technical studies have contributed to its development and to the understanding of the requirements for safety."

A first version of such a document appears in SKB's RD&D programme 2004 /SKB, 2004f/.

- "More frequent, iterative safety assessments would facilitate the timely evaluation of the significance of new scientific and engineering information and enhance the role of safety assessment as a means to integrate the programme. More frequent assessments would also develop and ensure the continuity of staff experience and skills required to conduct such assessments."

This Interim report, requested by the authorities, is partly motivated by the above recommendation.

- "A number of technical issues have been identified, the resolution of which would enhance the robustness and transparency of the descriptions and arguments that support the safety case. More important examples relate to:
  – documentation of the evidence and arguments leading to confidence in the maintenance of reducing groundwater conditions at repository depth,
  – improved understanding of the origin and evolution of groundwater solutes,
  – interpretation of the "flow-wetted surface" parameter including methods to provide field data necessary to support its use, and
  – definition of the expectations and requirements of biosphere modelling consistent with Swedish regulatory guidance and scientific constraints."

The evidence for the maintenance of reducing conditions will be updated in SR-Can, both through renewed modelling exercises and through more thorough argumentation regarding this issue. Also, the sensitivity to oxygen penetration of the isolating capacity of the repository is addressed in section 7.2. The developed methodology for handling groundwater solutes is discussed primarily in sections 11.2.6 and 11.4.8. The treatment of the "flow wetted surface" parameter is quite different from that in SR 97. An account can be found in chapter 9 and references therein. Biosphere modelling is described in Appendix C.

- "Better definition of SKB's strategy for scenario selection could clarify the representativeness and purpose of the different scenarios, and how they build to an integrated evaluation of safety. In future assessments, more formal scenario development or selection techniques would be preferable."

This is provided in SR-Can, in particular in chapter 8.

- "It would be beneficial to develop an integrated, and more comprehensive, approach to uncertainty and sensitivity analysis that covers a fuller range of parameter and model uncertainties and evaluates multi-parameter sensitivities. Improved transparency is needed in the selection of parameter values defined as "realistic" or "pessimistic" in SKB's current method. Methods that permit the construction of probability distributions from limited amounts of data should be reconsidered."

The probabilistic consequence calculations and the associated sensitivity analysis reported in chapter 12 is one type of multi parameter variation. Most of the variant cases are also probabilistic, meaning that the particular aspect explored in a particular calculation case is studied with all other data uncertainties included. There are also several examples of hypothetical cases that more stringently test various barrier functions.

Input data are derived with the new approach presented in the Data report, ensuring, contrary to the case in SR 97, assignment of input distributions rather than merely reasonable and pessimistic values.

- "Discussion is required between SKB, SKI and SSI on the interpretation of the Swedish regulatory requirements related to risk and probability, the authorities' expectations, and practical methods that might be employed to calculate desired endpoints while preserving statistical veracity. Discussion is also required with SSI regarding their expectations for assessing impacts to the natural environment and how requirements might be met."

SKB is awaiting response from SSI to a number of issues raised by SKB related to risk calculations. SSI is expected to issue general advice related to their regulation SSI FS 1998:1 in the near future. This is expected to resolve some of the issues.

- "In future safety assessments, consideration should be given to incorporating more realistic, as opposed to conservative, descriptions of the performance of the facility. The adaptation and completeness of the present scenarios to the conditions of specific sites should also be considered."

Several aspects of the description of the facility are more realistic in SR-Can. The backfill is incorporated in more detail as are plugs and borehole seals, see section 3.2 and the interim initial state report /SKB, 2004d/. The hydrological description of the near field rock is more realistic and detailed, see chapter 9. The corrosion analysis of initial weld defects is less pessimistic (section 7.2.2) and will, in the SR-Can final report be based on test data from the canister manufacturing. The scenarios are adapted to the site mainly through the use of the site descriptive models to account for the initial state at the site.

- "Incorporation of more comprehensive sensitivity and uncertainty analyses into the assessment methodology could help to guide site investigations, and specifically, to identify which site-specific data are most important to safety and potentially to be obtained during the site characterisation programme."

This issue has been dealt with in other projects, see SKB's comment in section B.1.4. Further feedback to site investigations will be given in SR-Can and in the preliminary site evaluations mentioned in section 1.1.1.

B.3   Methodological developments since SR 97

The main methodological developments since SR 97 have already been mentioned in the two preceding subsections of this Appendix. These include:

- An adaptation of the assessment methodology to recently issued regulations.

- Development of a new FEP database.

- The definition of a number of function indicators and function indicator criteria.

- A developed methodology for scenario selection.

- Methods for process documentation, handling input data uncertainties, probabilistic calculations and sensitivity analysis.

- Developed methods for analyses of technical issues relating to e.g. geosphere hydrology and transport, earthquakes, climate and biosphere.

- The development of simplified assessment models for the analysis of radionuclide transport and dose, allowing massive probabilistic evaluations, and of an integrated near-field evolution model for the assessment of several of the function indicators.

Approaches to biosphere assessment

In section 2.8 the biosphere methodology in SR-Can is described. The biosphere is represented as a set of objects that can be interconnected to form an integrated landscape model (cf section C.1). The landscape models represent different critical time periods as described in section 2.8 (Figure 2-4) and below in section C.2. This requires development of models of the objects, e.g. forest, costal area and lake, and further that these models can handle site specific data. Examples of the strategy for the analysis can be found in this Appendix.

The interconnection of the biosphere objects depends on surface hydrology and the locations of the discharge points, further described below. To be able to handle the hierarchical structure of models and inclusion of site data, new modelling tools have been developed /Jones et al, 2004/. This is briefly presented in this Appendix and exemplified with models for the different biosphere objects.

The main part of the material presented in this Appendix is recently developed concepts and models that was not used in the SR 97 assessment and that was only partially developed for the SAFE assessment /Karlsson et al, 2001; Kautsky, 2001/. There are several alternatives for modelling biosphere objects that need to be explored and tested before SR-Can is finalised. Several new results are presented as examples in this Appendix but will later appear in separate reports, e.g. in the Marholmen report /Lindborg and Kautsky, 2004 in manus/. Moreover, SKB's RD&D programme 2004 /SKB, 2004f/ explains how the long-term biosphere research supports various assumptions relating to the biosphere in SR-Can.

C.1 Integrated landscape model

In SR-Can the biosphere will be defined as a combination of specific biosphere objects. The objects have different spatial extension and properties. Each such object can be regarded as an ecosystem with an intrinsic turnover of matter. That is, instead of describing e.g. a lake as several 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 carrying radionuclides from the geosphere entering the same lake will be added. The positions of the discharge points (x, y, z) will be overlaid by the polygon describing the biosphere object.

After identification of the positions of the discharges and the associated ecosystem type, the accumulation of the discharged radionuclides downstream in the catchment will be modelled. If there are several stream-tubes entering the same catchment basin, but in different biosphere objects, these will be combined by connecting the different biosphere objects together based on site-specific maps. The maps not only describe how the biosphere objects are interconnected with each other, but also provide estimates of important parameters such as water turnover, accumulated runoff and information on how the biosphere can be utilised by humans. The procedure needs to be updated for each identified critical time period in the biosphere (cf section C.2 and section 2.8).

In this interim report, these methods are tested with site-specific data to identify data gaps or additionally required tool capabilities, and to provide further understanding of the site.

The discharge points of radionuclides from the geosphere to the biosphere, obtained from the geosphere modelling, section 9.3, were selected as an illustration of how the biosphere objects will be connected and positioned in relation to the discharge points. In section C.3 the role of the surface hydrology is described further.

In this preliminary analysis the release starting at 2,500 AD was projected on to the map of the site today since data on the hypsography and sediments of the sea are not available at this stage. In the modelling of the ecosystems the importance of the advective travelling time is shown. In this illustration, existing dose models from SR 97 and SAFE were used with recent improvements as described in later sections. Running water and forest, for which models are not yet available, were illustrated as objects in the layout, but modelled simply as a feed through for the radionuclides.

From the discharge points, the major biosphere types were identified (Figure C-1). This was straightforward for most points, i.e. points associated with the same lake, mire or sea area (e.g. area 1, 8, 15 and 16). However, fringing wetlands to lakes and sea were more difficult (e.g. area 5 and 6). Today they are two different habitats, but the border between them reflects their current stage of stage of development. To further analyse this requires more details on the geometry.
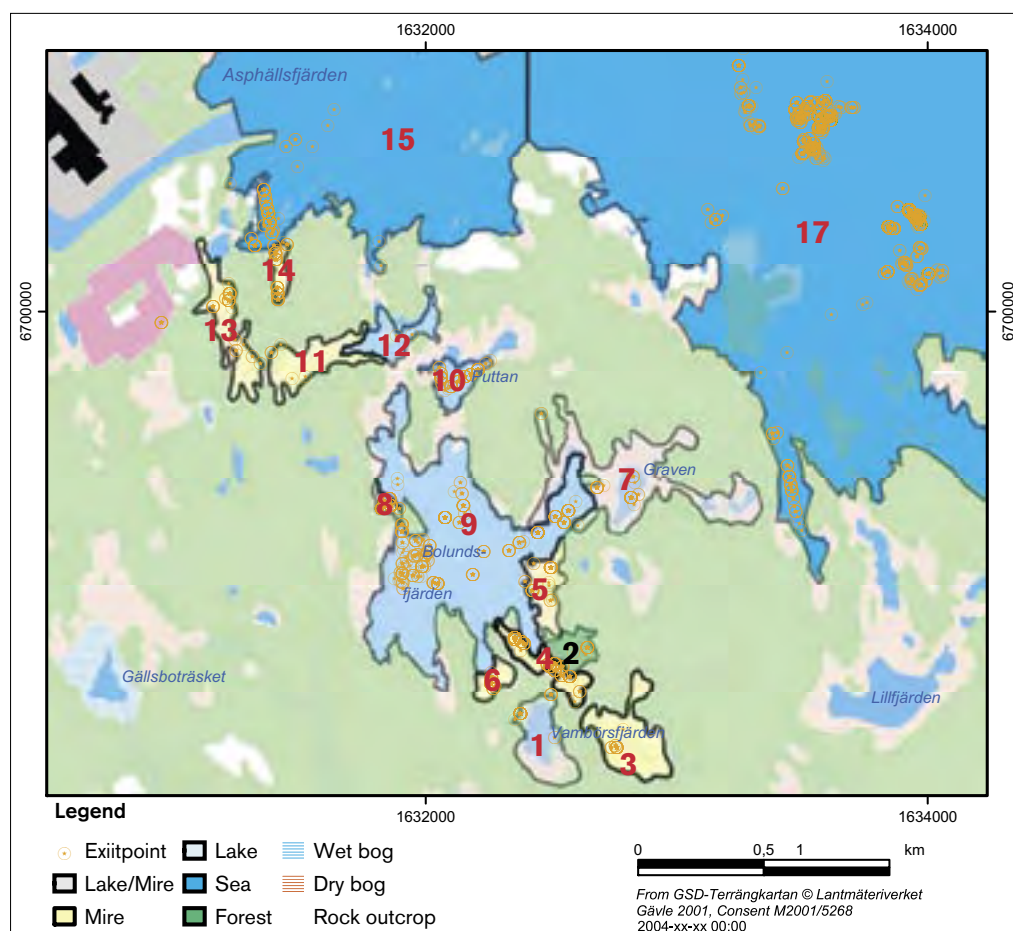

Figure C-1. Map with biosphere objects classified according to the exit points of radionuclides to the biosphere, cf legend. The objects are numbered. Sea object 16, 18 and 19 are outside the of the map area.

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There are some distinctive areas of release in the sea which requires further analysis of when releases occur (e.g. 18, 19). The advective travel times through the geosphere for these exits are more than 1,000 years and have a median of almost 10,000 years (Figure C-2). This means that these areas would not be coastal environments when the release occurs. Only a few of the discharge points are associated with forest (area 2). The statistics of number of exit points associated with different ecosystem objects from an early test calculation are presented in Table C-1. The actual transport times for different radionuclides to different discharge points are not estimated here, that analysis will made in the final SR-Can study.

The result from this preliminary analysis shows that more than half of the exit points are located at the coastal seafloor (Sea 17). Approximately 200 (5% of the total) have also advective travel times less than 1,000 years, i.e. still a coastal situation. Another large fraction (27%) of exit points are in lake Bolundsfjärden (area 9) and fringing mires (areas 4 and 8). For the majority of the points the advective travel time is less than 1,000 years (Figure C-2). That is within the projected persistence of Bolundsfjärden.

Notable from this exercise is that very few points are to terrestrial environments other than mire (only 3 that corresponds to 0.5%).

These findings from the preliminary data indicate that it is likely that the coast, lakes and fringing mires are the primary receivers of discharge from the geosphere. This confirms earlier analyses.

The identified biosphere objects were represented with corresponding dose-models and connected, see Figure C-3. The dose models are listed in Table C-1 and described in relevant sections later. As far as possible, site-specific data have been used in the different models (listed in Table C-1). Some data are taken from the SAFE study /Karlsson et al, 2001/.

A constant unit release of 1 Bq/year was applied to the most upstream object Varmbörs-fjärden (Mire1). Four hypothetical radionuclides with almost infinite half life and with K_d values in the range 1–1,000 m^3/kg respectively were simulated in the model over 10,000 years. The results are shown in Figure C-4 and Table C-2, where the total activities in various ecosystems are compared to the total amount of radio nuclides released to that time.

The results show that radionuclides with low K_d (1 m^3/kg) flowed through the network of connected ecosystems out into the sea. On the other hand nuclides with high K_d (1,000 m^3/kg), remained almost exclusively in the first three ecosystems nearest the discharge. The radionuclides with intermediate K_d values (10 and 100 m^3/kg) were found in the middle of the chain, in lake Bolundsfjärden. A considerable fraction of these radionuclides also left the system.

Although large fractions of the radionuclides with lower K_d values were transported downstream, the concentrations in water and particulate matter (i.e. peat and sediments) decreased several orders of magnitude due to the strong dilution in the ecosystems downstream (Figure C-5).
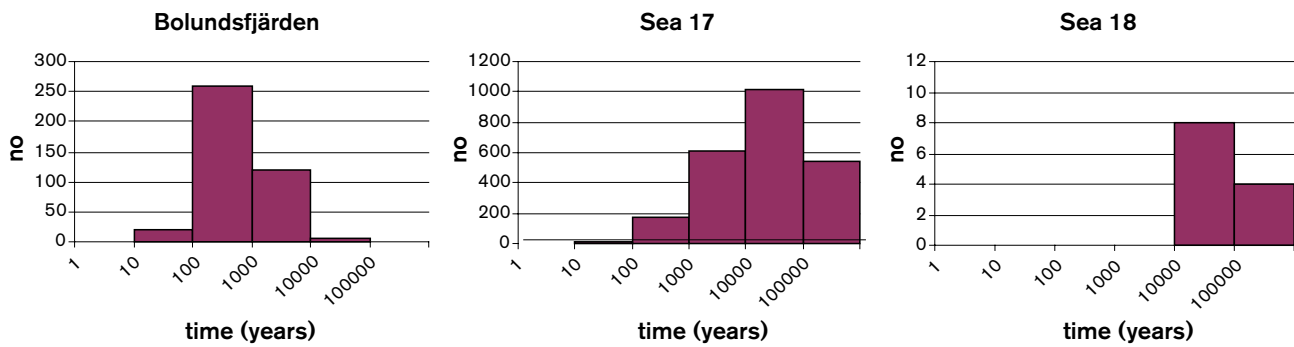
Figure C-2. *Examples of distribution of numbers of discharge points as a function of advective transport time in years (tw) to different ecosystem objects. Bolundsfjärden is a lake and Sea17 a coastal area receiving a large part of the discharges under present-day conditions. The coastal object Sea 18 is associated with only a few discharge points and have long advective transport times. Note different scales on the Y-axes.*
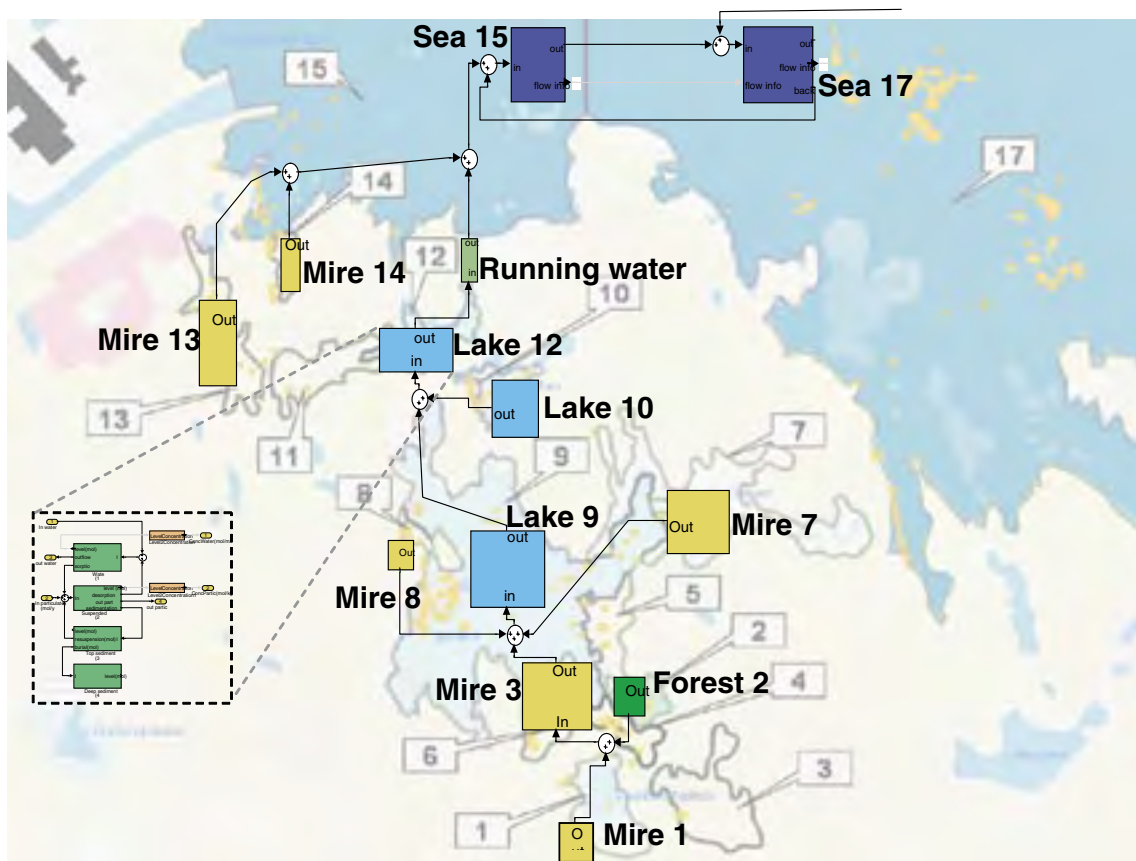

Figure C-3. *Screen shot of a part of the network model used that is located mainly over land. The objects mires, lakes, coasts ,running waters and forest are represented in different colours. For each object there is an underlying biosphere model as exemplified for Lake 12, left hatched panel.*

Table C-1. Classification and properties of ecosystem objects including statistics of discharge points to the biosphere and associated advective transport times.

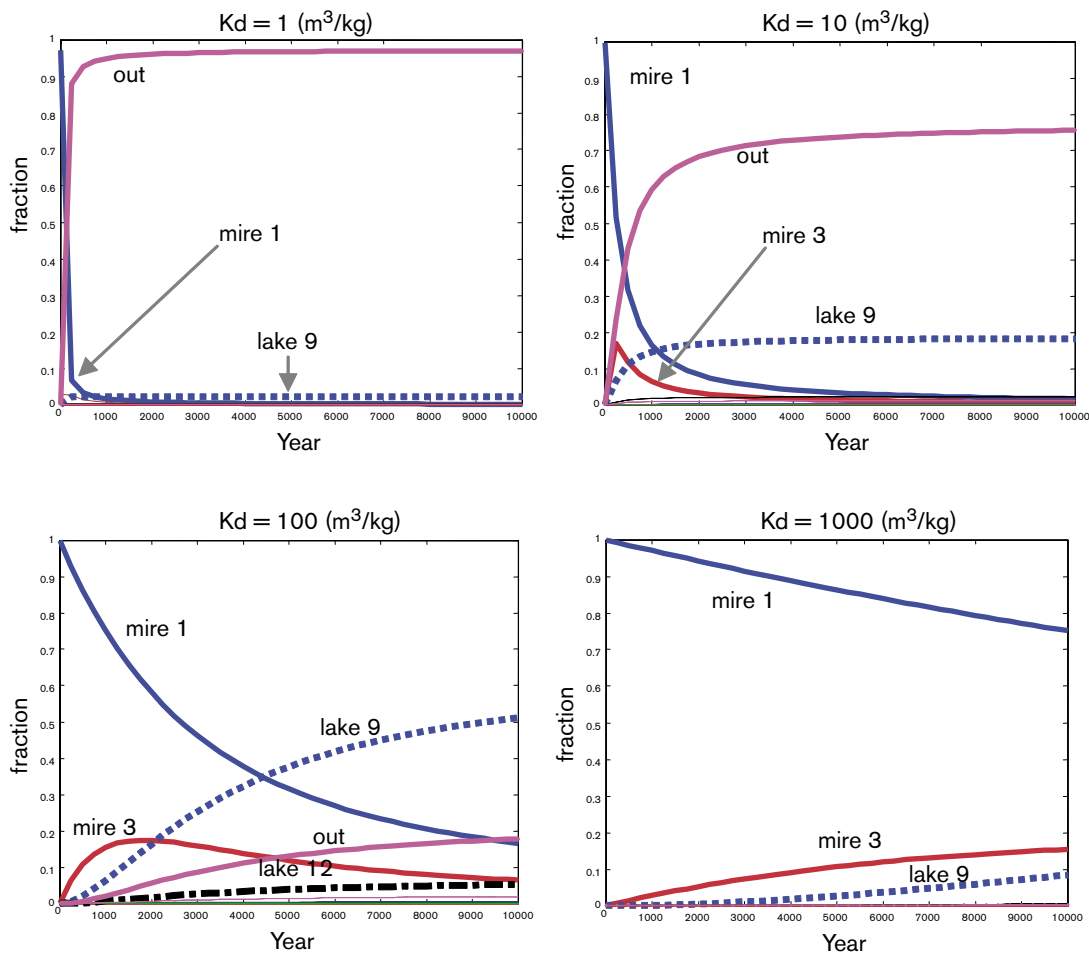| Name	Id	Ecosystem	Number of points (n)	(%)	Adv. Transp. time median (years)	Adv. Transp. time max (years)	Model	Object area (10³ m²)	Drainage area (10³ m²)	mean depth (m)	volume (10³ m²)	turn over time (years)
Vambörsfjärden	1	Mire/Lake	76	1.7	35	178	Mire1	56	484	0.4	21	0.19
Djupsundsdel.	2	Forest	22	0.5	37	510	Forest2	22	702			
	3	Mire	32	0.7	35	281	Mire3	70	695			
	4	Mire	367	8.2	35	12670	Mire3	32	1280			
	5	Mire	77	1.7	24	922	Mire3	36	1267			
	6	Mire	59	1.3	14	80	Mire3	16	63			
						tot	Mire3	154	2610			
Graven	7	Mire/Lake	53	1.2	32	184	Mire7	50	615	0.1	6	0.07
	8	Mire/Lake	419	9.3	26	3605	Mire8	7	26			
Bolundsfjärden	9	Lake	406	9.0	60	2440	Lake9	610	8003	0.6	374	0.21
Puttan	10	Lake	120	2.7	29	4361	Lake10	80	236	0.4	30	0.02
	11	Mire	7	0.2	4	18	Mire12	52	271			
N. Bassängen	12	Lake	2	0.0	3217	4321	Lake12	80	13440	0.3	24	0.01
	13	Mire	61	1.4	7	1187	Mire13	54	709			
	14	Mire	92	2.0	28	97830	Mire14	13	61			
Asphällsfjärden	15	Sea	207	4.6	26	2072	Sea15	1026		1.8	1856	0.002
	16	Sea	36	0.8	4327	10670	Sea16	1557		2.3	3550	0.002
	17	Sea	2343	52.1	3613	84410	Sea17	4465		3.8	17012	
	18	Sea	12	0.3	7932	30370	Sea17	4398		4.2	18340	
						tot	Sea17	8863		4.0	35351	0.002
	19	Sea	103	2.3	10250	57320	Sea19	11490		10.7	122943	0.002
Öregrundsgrepen		Sea	0	0	0	0	Sea	456000		11.2	5107000	0.033

Figure C-4. *Locations of radionuclides from an annual unit release to Mire 1. Relative amounts of radionuclides at different times in the different ecosystems are displayed. Results for Each K_d are shown in a separate panel.*

Table C-2. The locations of the radionuclides released over 10,000 years. Four different K_d-values have been simulated. Relative amounts (%) in different ecosystem objects are tabulated Note that concentrations are highest close to the sources shown in Figure C-5.

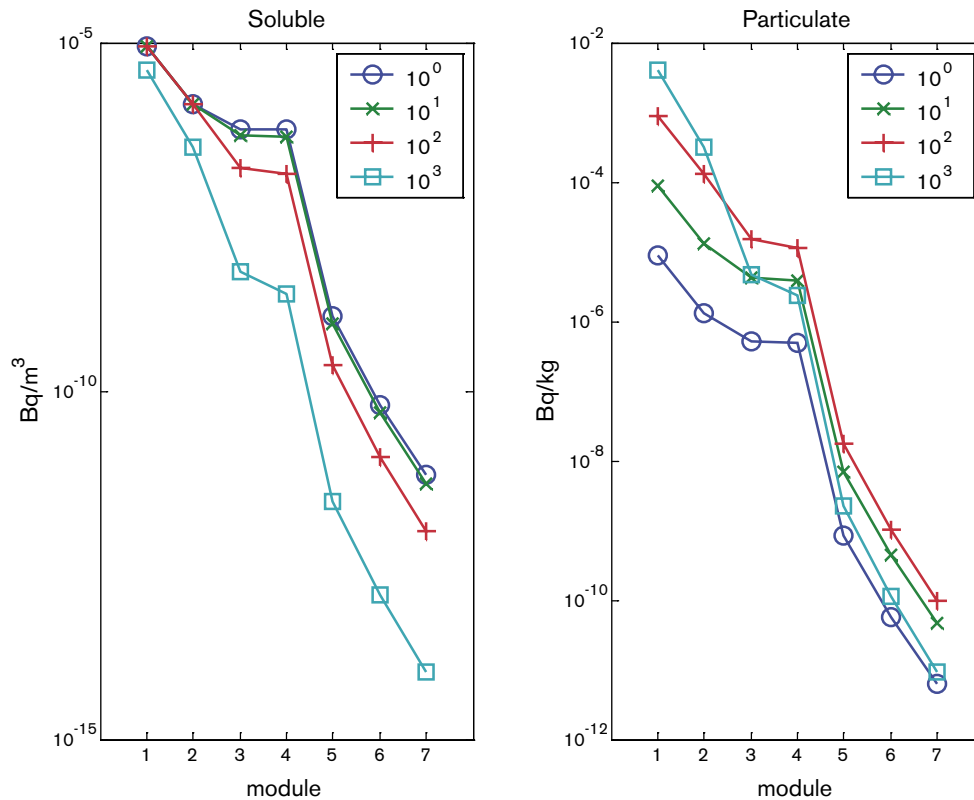| Model	Relative amount (%)			
	Kd = 1	Kd = 10	Kd = 100	Kd = 1,000
Mire 1 (Varmbördsfjärden)	0.2	1.7	16.6	75.1
Mire 3 (Djupsundsdelarna)	0.1	0.6	6.4	15.5
Lake 9 (Bolundsfärden)	2.3	18.3	51.2	8.4
Lake 12 (Norra Bassängen)	0.3	2.2	5.2	0.5
Sea 15 (Asphällsfjärden)	0.0	0.3	0.5	0.0
Sea 17	0.0	0.2	0.3	0.0
Öregrundsgrepen	0.2	1.1	1.9	0.1
Discharged to the Baltic Sea	97.0	75.6	17.8	0.3

Figure C-5. *Radionuclide concentrations in the water (left) and in the particulate phase (right) along the ecosystem chain for different K_d values (shown in the legend). The numbers on the horizontal axis represents ecosystems along the route of transport 1: Mire 1, 2: Mire 3, 3: Lake 9, 4: Lake 12, 5: Sea 15, 6: Sea 17, 7: Öregrundsgrepen.*

The preliminary results from this exercise indicate that:

- The methods and tools are available for landscape modelling.

- The model can handle all discharges properly in individual biosphere objects and can represent downstream accumulation.

- The model tool is capable of handling complex site information.

- Coastal ecosystems, lakes and some type of mires are the major receivers of discharges.

- The highest concentrations and the highest doses will arrive closest to the discharge points.

- The overall systems behaviour needs to be explored further in a variety of site-specific contexts as the capabilities of the various object models are enhanced.

In SR-Can, this method will be used and applied for the biosphere at the different periods dependent on availability of spatial data.

C.2   Development of ecosystems over time

The characteristics of the ecosystems will vary over time which is outlined in chapter 11. The most important long-term external factors are shore-line displacement and the glacial cycle. These factors affect the selection of models, e.g. terrestrial or marine or when a well can be drilled. For most contexts this is handled by selecting an appropriate configuration of ecosystem objects to provide a snapshot representation of the overall environment for each time period. A critical parameter is how long the ecosystem persists which affects the total amount of radionuclides accumulated in the system. For the marine ecosystem, which persists throughout the major part of the interglacial period, shore-line displacement has a significant effect on model parameters which affects calculated radionuclide concentrations. This can be handled as a continuous change in time of the parameters, as exemplified below.

Long-term internal development can also affect the persistence of the ecosystems. This is obvious for lakes, which transform to mires, but this can also be applied to wells, agricultural land and mires which also have constraints in life length and thus also a maximum time for radionuclide accumulation. Finally, the location of each discharge point from the geosphere is likely to vary with time.

Another example of how the coastal ecosystem is dependent on time is presented in the next section. In Figure C-6 a hypothetical example is provided of how the pattern of ecosystems may develop with time. For this SR-Can Interim report, examples of timing of drilling wells can be seen in the SAFE study in which well construction and use was restricted to newly formed land for approximately 1,000 years after the shore-line had passed /Kautsky, 2001/.
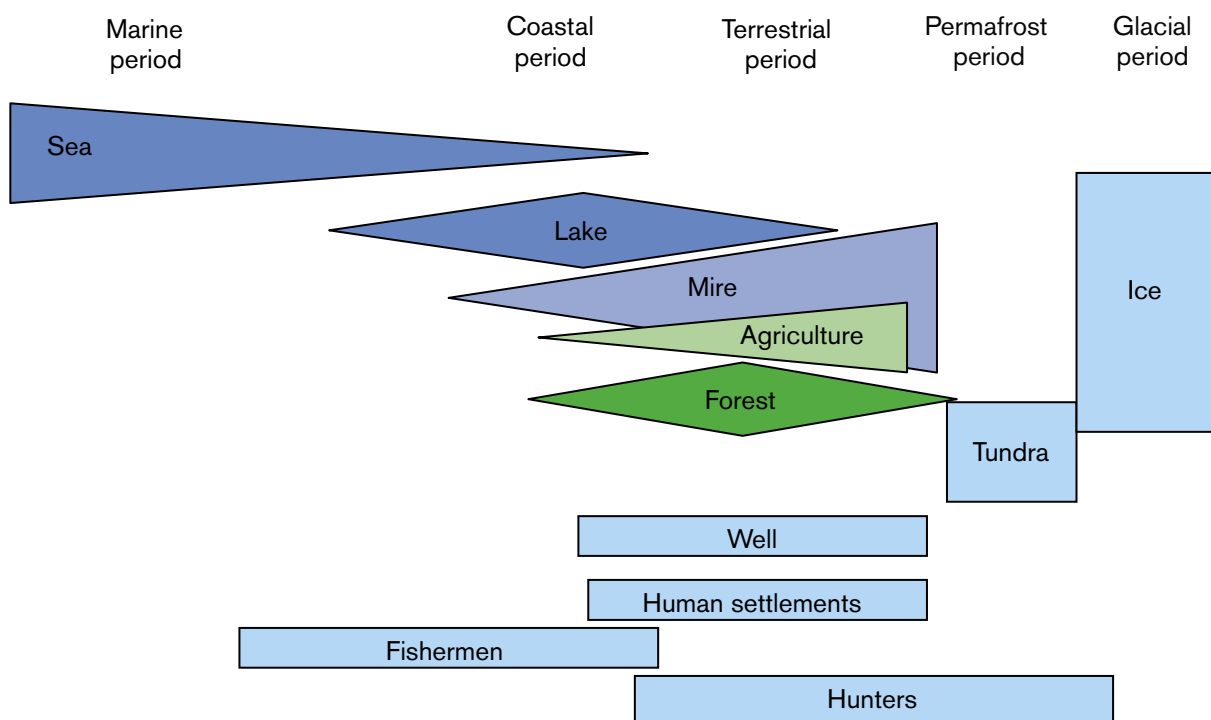

Figure C-6. *Hypothetical extension of different ecosystems and human settlement during an interglacial period at a site.*

C.2.1 Coastal ecosystem, example of time dependent ecosystem

The following example shows more realistic results for the radionuclide exposure in a coastal ecosystem than using EDF values for a 10,000 year period. Moreover, it shows how time-dependent processes can be handled.

In this example, the coastal model from the SAFE study /Karlsson et al, 2001/ with the same geographic delimitation and other parameters except those taken to be time dependent (see below) and nuclide-specific, which are from /Karlsson and Bergström, 2002/. The sediment discharge point is used as described in section C.4.1. The assumption for this example is that a marine ecosystem at Forsmark exists after the ice retreated following the last glaciation, from –8,000 AD to 4,900 AD when the model area, as defined in SAFE, is transformed to land and lakes. Thus, in the calculations, 4,900 AD is assumed to be end date for the coastal ecosystem as a primary receiver of discharges.

The time dependent parameters for this model are the start date for discharge, mean depth and area of the model area and Öregrundgrepen as well as the fraction of accumulation bottoms. They are based on the shore-line displacement and the current digital elevation data (DEM) for Forsmark and plotted in Figure C-7 and Figure C-8.

The fraction of accumulation bottoms is illustrated in Figure C-9. For the time-period outside the range –5,500 AD to 3,000 AD the boundary values were extrapolated to -8,000 AD and 4,900 AD, respectively.

Concentration and dose calculations over time

The immediate dose is calculated for the humans utilising the marine environment according to the assumptions in /Karlsson et al, 2001/. For the accumulated discharges in the sediments, it was assumed that humans would use the sediments for agricultural purposes in the future and the dose was therefore calculated according to the model representation of agricultural land in the SAFE study /Karlsson et al, 2001/. The concentration in the top soil used for farming was calculated from the total inventory of radionuclides in both the top and deep sediment.
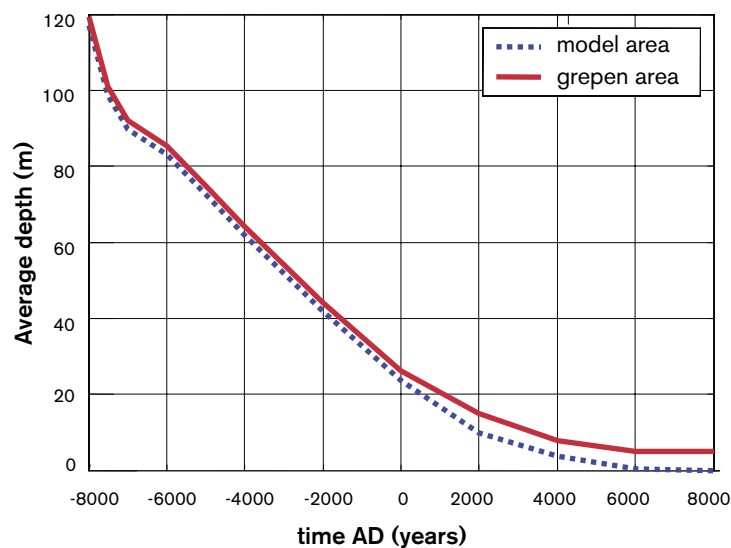

Figure C-7. *Average depth as a function of time based on shore-line displacement. Model area and grepen area (Öregrundsgrepen) are defined in /Brydsten, 1999b/.*
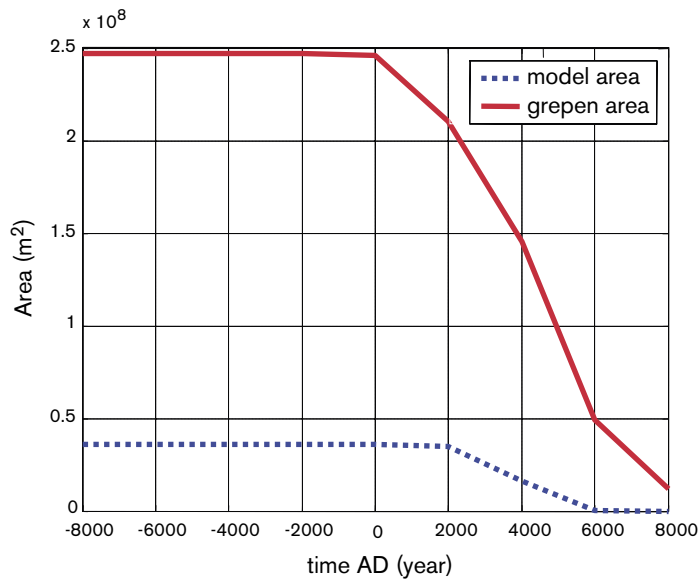
Figure C-8. *Extents of model area and grepen area (Öregrundsgrepen) that are under water as a function of time, based on shore-line displacement.*
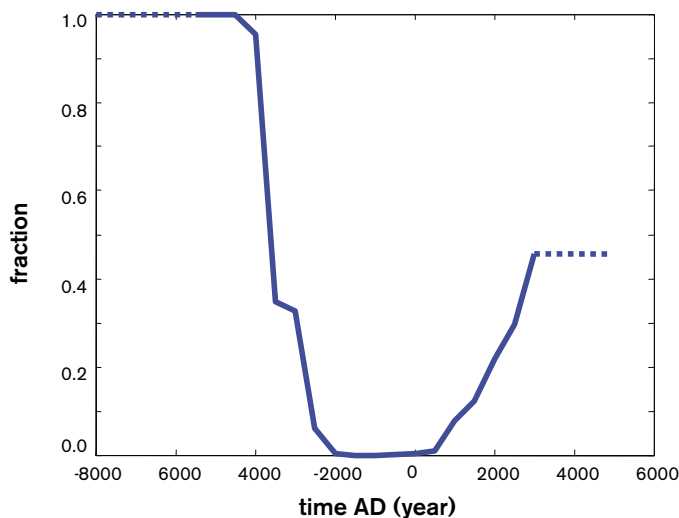

Figure C-9. *Fraction of accumulation bottoms in model area, from /Brydsten, 1999b/, but extrapolated to a longer time period.*

A unit release of radionuclides (1 Bq/y) was simulated from different start dates between –8,000 AD and 4,900 AD. The plots showed a decreasing curve, as expected with a plateau in the curves around year 0 AD. (Figure C-10).

The immediate dose from human activities during the marine period is shown in Figure C-11. The doses increase towards the end of the period mainly due to smaller water volumes and lower water exchange rates, however they are, in these preliminary simulations, several orders of magnitude less than the accumulated dose due to subsequent agricultural use of the sediments.
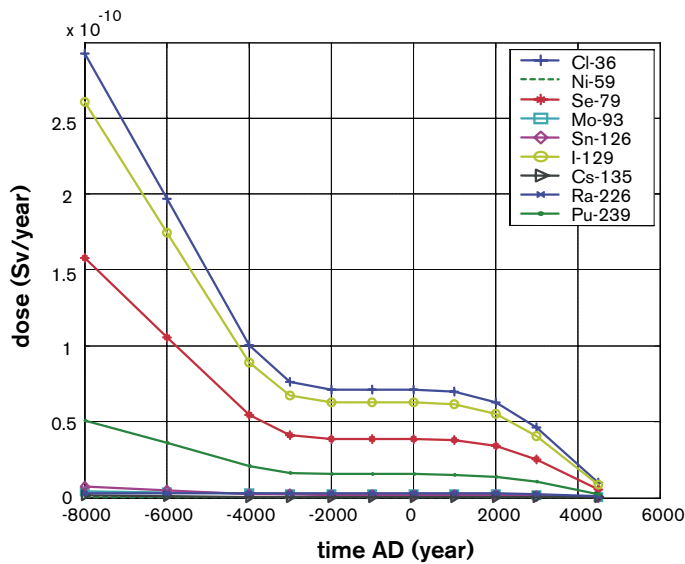
Figure C-10. *Probabilistic results of dose to humans from coastal model plotted against various starting times of release of 1 Bq/y from –8,000 to 4,500 AD. Simulation stop time is always 4,900 AD. Doses are calculated for cultivated land immediately after the transition to land at year 4,900 AD.*
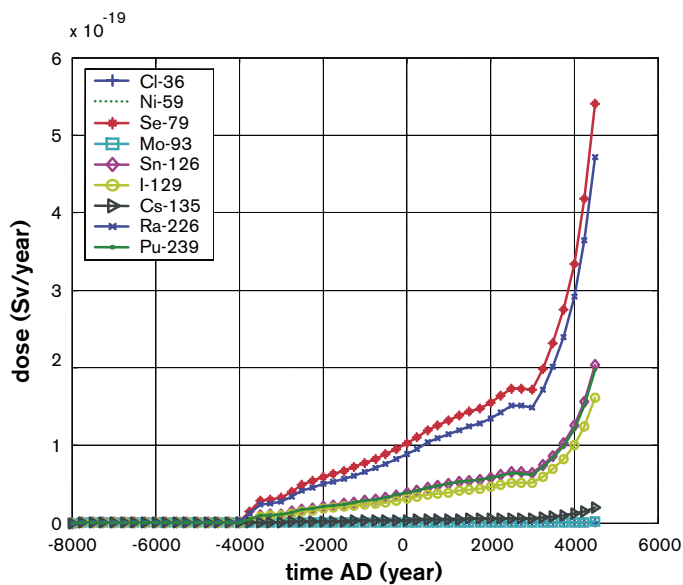
Figure C-11. *The dose from ingestion of aquatic food for nine radionuclides during the marine period (–8,000 AD to 4,900 AD) for a continuous release of 1 Bq/yr.*

This example shows that the time scale for accumulation of radionuclides is limited in a coastal area due to shore-line displacement. The dose is dependent on the time for accumulation. Moreover, it shows that the knowledge about the transition between states will be important in assessing the dose due to subsequent use of contaminated agricultural land, e.g. sediment transport offshore due to erosion.

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C.3   Discharge locations

The positions of discharge locations of radionuclides into the biosphere are essential input to the modelling of radionuclide transport in the biosphere. The positions for such discharges are determined by the transport in the geosphere, the geosphere-biosphere interface zone, the transport in Quaternary deposits and the surface hydrology. 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 has also to be considered.

In the calculations in this Interim report it is assumed that the horizontal transport in the regolith is negligible so that the discharge points from the geosphere (cf section 9.3) represent the points of entry to the surface ecosystems (cf section C.1). Horizontal transport at the surface occurs in lakes, river runoff and oceans. For SR-Can the potential for horizontal transport in the regolith will be analysed further (cf section 9.3.3).

C.3.1 Surface hydrology

Only the surface hydrology including oceanography and the interface between the geosphere and ecosystems are considered here. Other aspects of hydrology are described in Chapter 9. For the safety assessment, the water flow is a fundamental parameter, which usually is driven by the effective precipitation (P-E) in the drainage area (i.e. runoff), and water level fluctuations (mainly in the sea). Both of these variables are sensitive to the climate. The runoff, together with the water volumes in lakes and other reservoirs, determines the water turnover times, which are important parameters in biosphere models. Up to now there is a limited amount of information available from the sites on water turnover times. As a consequence, regional data, mainly from /Larsson-McCann et al, 2002/, are used instead of site-specific data.

The hydrological and oceanographical variables must be put in context of the biosphere development (e.g. shore-line displacement and climate change). Today, both regional and site-specific data are available, but these data need to be integrated into characterisations of the catchment areas. This will be done in SR-Can. However, inclusion of newly collected data and enhanced understanding will not be possible until SR-Site, due to the fact that the major part of the surface hydrological description of the site will not be available until after site descriptive model version 1.2.

The hydrological processes in the regolith (soils and Quaternary deposits) are important in order to estimate the mixing of groundwater with deep groundwater. The groundwater fluxes in the Quaternary deposits are also of importance for sub-horizontal radionuclide transport at depths where the radionuclides are inaccessible to biota. Finally, since the discharge points to surface ecosystems seems to be sea- and lake floors, the upward transport in the Quaternary deposits towards these ecosystems as well as to areas with high abundance of roots, is important to estimate. The importance of these processes will be evaluated for SR-Can. Some examples are shown in sections C.4 and C.5.

In this SR-Can Interim report, the evapotranspiration is assumed to be uniformly distributed over the landscape and the runoff is calculated as the total area upstream multiplied by the specific runoff measured for the region (Figure C-12). Thus, the runoff and water turnover time for a lake or mire is calculated for the catchment area above the outlets (Figure C-12). For the coastal waters and sea, calculations by /Engqvist and Andrejev, 1999, 2000/ are used for the estimates of water turnover time.

There is no clear stratification in the sea due to short water turnover time, or in any of the lakes due to their limited depth.

Figure C-12. *The area upstream (red) the discharge point (black dot) is multiplied with area spe-cific runoff to obtain the waterflow at the discharge point.*

In SR-Can, the oceanographic model will be updated and more data and models are expec-ted to be available to distribute the evapotranspiration over the different landscape elements (e.g. forest, lake etc). The redistribution of evapotranspiration will be modelled with the CoupModel (cf section C.5.5) and other hydrological models, e.g. MIKE-SHE.

C.3.2 Wells

Wells constitute an important exposure pathway for humans. The extent to which wells can be used is dependent on climate conditions and surface hydrology, as well as on water quality, i.e. its chemical composition.

For SR-Can it will be necessary to analyse the existing well archive for the studied area to evaluate its data quality and extract useful information. There is also a need to assemble information on the spatial distribution of wells in the region. The history of drilled wells may help to estimate the future development and utilisation of wells, i.e. amount and types of wells that will be drilled in relation to e.g. the population, as in the SAFE study /Kautsky, 2001/. Furthermore, the establishment of a model that describes the dilution of radio-nuclides discharged in wells is also needed. The hydrological part of the well model will be developed in the hydrological programme.

In this Interim report, the well is modelled as in SR 97 /Bergström et al, 1999/ with only one property, the well capacity. Here, the well capacity has been assigned a probabilistic distribution adjusted to data available from the well archive.

In SR-Can, the probability that a well will exist will be discussed, since during long time-periods wells cannot be drilled (cf section C.2). This is e.g. during glaciation, permafrost and when the area is submerged under the sea, a mire or a lake. Moreover, the limiting capacity of a well has implications. The size of a population that can use a particular well as their main water resource is restricted. Thus, the size of a population that may be exposed to contaminated water from a specific well is also restricted, which is important when the size of the exposed group is defined.

Dose model for the well

To provide some values to compare SR-Can interim results with previous assessments, the ecosystem specific dose conversion factors (EDF) were calculated for a well and a mire (see section C.5.2) for a 10,000 year release of 1 Bq/yr of various key nuclides.

The well model together with an irrigation submodel for garden plots from SR 97 /Bergström et al, 1999/ has been used. The non-radionuclide specific parameters used were derived from the SAFE study /Karlsson et al, 2001/ and are shown in Table C-3 and Table C-4. Nuclide specific parameters were used from /Karlsson and Bergström, 2002/.

The well module has been simulated probabilistically with 1,000 realisations. The EDF distributions show the same typical log-normal distribution as the EDF from the mire model (cf section C.5.2). Results are presented in the data report /SKB, 2004c/.

Table C-3. Data specific to the well model. Values for mean and standard deviation are geometric with the base of 10. Min and max are truncation limits.

Parameter	units	dist	mean	std. deviation	min–max	type
Capacity[1]	m³/year	LN	6.92·10³	3.4	300–∞	site-specific

[1] Distribution fitted from the SAFE study /Kautsky, 2001/ Distribution truncated at min = 300

Table C-4. Data used in the irrigation sub module with the well model. The sources are from /Karlsson et al, 2001/ except for runoff. Min and max are truncations of normal (N) distribution and minimum and maximum values for triangular (T) or log-triangular (LT) distributions.

Parameter	Units	dist	best est.	std.	min–max	type
Depth of top soil	M	T	0.25		0.2–0.3	site-specific
Porosity of top soil	-	T	0.5		0.4–0.6	site-specific
Total soil depth	M	Const.	1		-	site-specific
Porosity deep soil	-	T	0.5		0.4–0.6	site-specific
Irrigation volume	m³/m²	LT	0.03		0.014–0.067	site-specific
Bioturbation	kg/(m²·y)	T	2		1–3	site-specific
Weeding	kg/(m²·y)	-	-		-	site-specific
Density of soil particles	kg/m³	T	2,650		2,600–2,700	site-specific
Irrigation area	m²	T	200		150–250	site-specific
Runoff[1]	m³/(m²·y)	N	0.232	0.078	0.071–0.451	site-specific

[1] Effective precipitations from /Larsson-McCann et al, 2002/

The difference in resulting EDFs between SR 97 and SR-Can is relatively small. For most nuclides the ratio between the two results was close to one. For about a quarter of the simulated nuclides the ratio was larger than 1, but was always within a factor 4.

The largest change in parameter values is the well capacity. Compared to SR97 the mean value for this parameter in the probabilistic simulations has increased by about a factor 7 which leads to higher dilution and decreased EDF. At the same time the dose conversion factors for inhalation have been raised about a factor 3 /Karlsson and Bergström, 2002/, which increases the EDFs. A number of small changes in parameters have occurred due to the use of universal data from SAFE instead of SR 97, which affects EDFs to some extent. Moreover, unclear documentation in the SR97 report, as identified in /Jones et al, 2004/ also introduces some variations. In total, however, the deviations from SR97 are relatively small.

C.4   Aquatic ecosystems

There are tree types of aquatic ecosystems in the area; the sea, lakes and running waters. The major abiotic features describing these systems are geometry (depth, volume, elevation, and area), water turnover and chemistry which in turn affect the mix of species present and their relative abundance. The approach estimating water turnover is described above. The geometry is described using the digital elevation model (DEM) of the site. The long-term changes of water bodies are affected mainly by the shore-line displacement and by sedimentation and infilling of organic matter. A description of the ecology of the present aquatic ecosystems is based on information from the site investigations. More details are given below.

Radionuclides can enter water bodies either from the surrounding land, mires or other water bodies, or alternatively through the groundwater. Then they become rapidly mixed and are subsequently lost by water turnover.

There are three extreme cases for the fate of radionuclides entering a water body.

1. Direct inflow through the bottom or shore with no significant accumulation, with subsequent dilution and transport to other water bodies. This type of discharge would result in a rapid dilution but also an immediate dose. In principle, the aquatic models in SR97 /Bergström et al, 1999/ and SAFE /Karlsson et al, 2001/ are for discharges of this nature.

2. Accumulation in bottom sediments through diffusion, with subsequent sorption, precipitation and/or biological uptake. This may cause accumulation of radionuclides that can give high doses at a later transition of the ecosystem, but in the interim no/slow release to the water body with no/low dose.

3. Accumulation due to precipitation in an oxidising environment, sorption and biological uptake at the shore. This case can give high immediate doses due to concentration in vegetation and low dilution by surface water. However, the long-term accumulation is expected to be less than when accumulation in sediments occurs.

A simplified model handling the aspects of case 2 is exemplified with the coastal waters model shown below. In SR-Can, further support for applications of a simplified approach to the various environments of interest will be developed.

C.4.1 Marine ecosystems

There are two types of marine models available for the SR-Can assessment. One is a bioconcentration-factor-based model similar to the model used in SAFE, and one is an ecosystem model which describes the transfer of radionuclides dependent on food and energy transfers in the marine ecosystem. The long-term changes in marine ecosystems are dependent on external changes, i.e. shore-line displacement and climate. Humans are assumed to be exposed from food harvested from the marine ecosystems and from future use of land that formerly lay beneath the sea.

Bioconcentration factor model

The bioconcentration factor model is based on the coastal waters model used in SAFE /Karlsson et al, 2001/ but the model is modified with an input pathway through the sediment. For this Interim report, the partitioning between dissolved and particulate phases was based on a K_d-driven exchange between the interstitial water and the top sediment (Figure C-13).

The process of shore-line displacement was included in the model as a change in the sub-merged area and water depth of Öregrundsgrepen and the "model area" (defined in SAFE).

The exposure to humans has been considered for two pathways. First there is the original approach calculating dose from consumed food that has been exposed to contaminated sea water. Secondly, an approach has been implemented which calculates dose from farming on former sea sediments containing accumulated radionuclides.
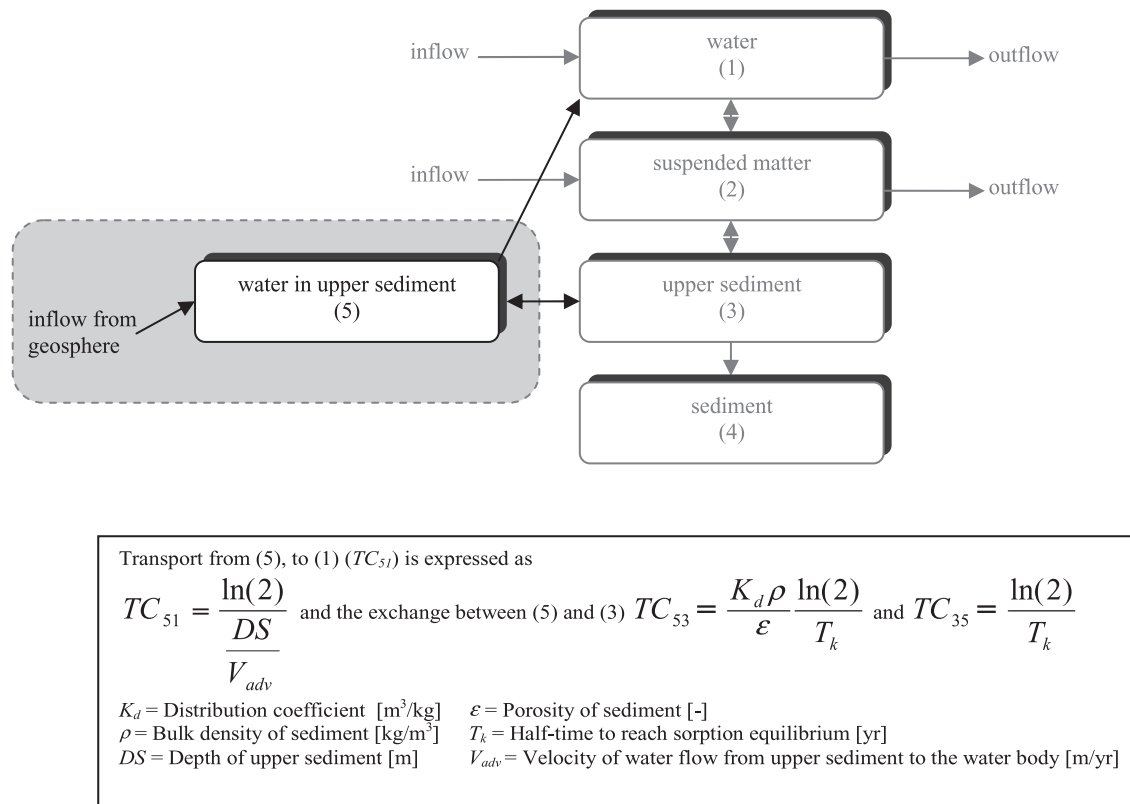

Transport from (5), to (1) (TC_{51}) is expressed as

$$TC_{51} = \frac{\ln(2)}{\dfrac{DS}{V_{adv}}} \quad \text{and the exchange between (5) and (3)} \quad TC_{53} = \frac{K_d \rho}{\varepsilon} \frac{\ln(2)}{T_k} \quad \text{and} \quad TC_{35} = \frac{\ln(2)}{T_k}$$

K_d = Distribution coefficient [m³/kg] ε = Porosity of sediment [-]
ρ = Bulk density of sediment [kg/m³] T_k = Half-time to reach sorption equilibrium [yr]
DS = Depth of upper sediment [m] V_{adv} = Velocity of water flow from upper sediment to the water body [m/yr]

Figure C-13. *Structure of the improved section of the coastal and lake module. The parts that have been added to the model are highlighted in the grey box. In the panel the additional equations describing the transfer are listed. The remaining parts are described in /Karlsson et al, 2001/.*

The updated coastal model was used as a part of the integrated landscape model (cf section C.1) and for the example of a time-dependent model of the coast (cf section C.2.1).

For SR-Can, this model will be reviewed, especially the input pathway through the sediments. More site-specific data will are expected be available for the safety analysis group to describe the geometry of the area and the properties of the sediments.

The estimated doses resulting from agricultural activities involving former sediments after 10,000 years of unit release are seem to be higher than doses obtained from aquatic sources in this preliminary analysis. This holds for most radionuclides in this assessment. This is mainly due to accumulation in the sediments.

The processes in the sediment, as well as the discharge through the sediments need to be evaluated further before SR-Can. Especially the long accumulation of discharges in the sediments for 10,000 year because of the shore-line displacement. This illustrates the importance of a time dependent coastal ecosystem, which is shown in section C.2.1.

Marine ecosystem model

The ecosystem model for the marine environment in Öregrundsgrepen developed by /Kumblad et al, 2003; Kumblad et al, in manus/, will be used to calculate concentrations in compartments that are not represented in the model above or in site-specific BCF for the bioconcentration factor based models. The model was originally developed for the assessment of C-14 in the SAFE study, but was recently extended to be able to handle other radionuclides as well /Kumblad et al, in manus/. The extent to which this model can be used in the safety assessment is dependent on the availability of site-specific data. The data needed to run the model is summarised in Figure C-14 and subdivided in categories of radionuclide specific data, universal and site specific data.

C.4.2 Lakes

The transfer of radionuclides in lake ecosystems is influenced by different processes over various time scales. Over the shorter time perspectives, processes of main importance for the fate of radionuclides are the rate of water turnover and transfers in the food web. Over the long time perspectives, processes influencing the development of the lake, i.e. the birth of the lake and its transformation into mire by the infilling process, are of main importance. Lake development is ultimately dependent on the shore-line displacement. Lake ecosystems are also affected by human habits, e.g. draining and the building of dams.

In SR-Can, the long term perspective of lake ontogeny will be handled by identifying when lakes in the area will appear and how long they will persist. The geometry and water turnover times for the lakes will then be estimated for specific periods in the future, for which maps will be developed. In the Forsmark region several studies have described the infilling of lakes and their ontogeny during an interglacial period /Brunberg and Blomqvist, 1999, 2003; Brydsten, 2004/. In general, it takes less than 2,000 years for lakes shallower than 2 meters to be transformed into wetlands in this area. This information will be used in the assessment.

The life span of the lakes will provide guidance on how the short time models should be applied, i.e. the transfer of the radionuclides within the lakes. There is a substantial dataset from Forsmark concerning the ecology of the lakes, their geometry, sediment properties and chemical and biological composition. This information will be compiled by the site analysis group during next year and will be used for SR-Can as the work progresses.
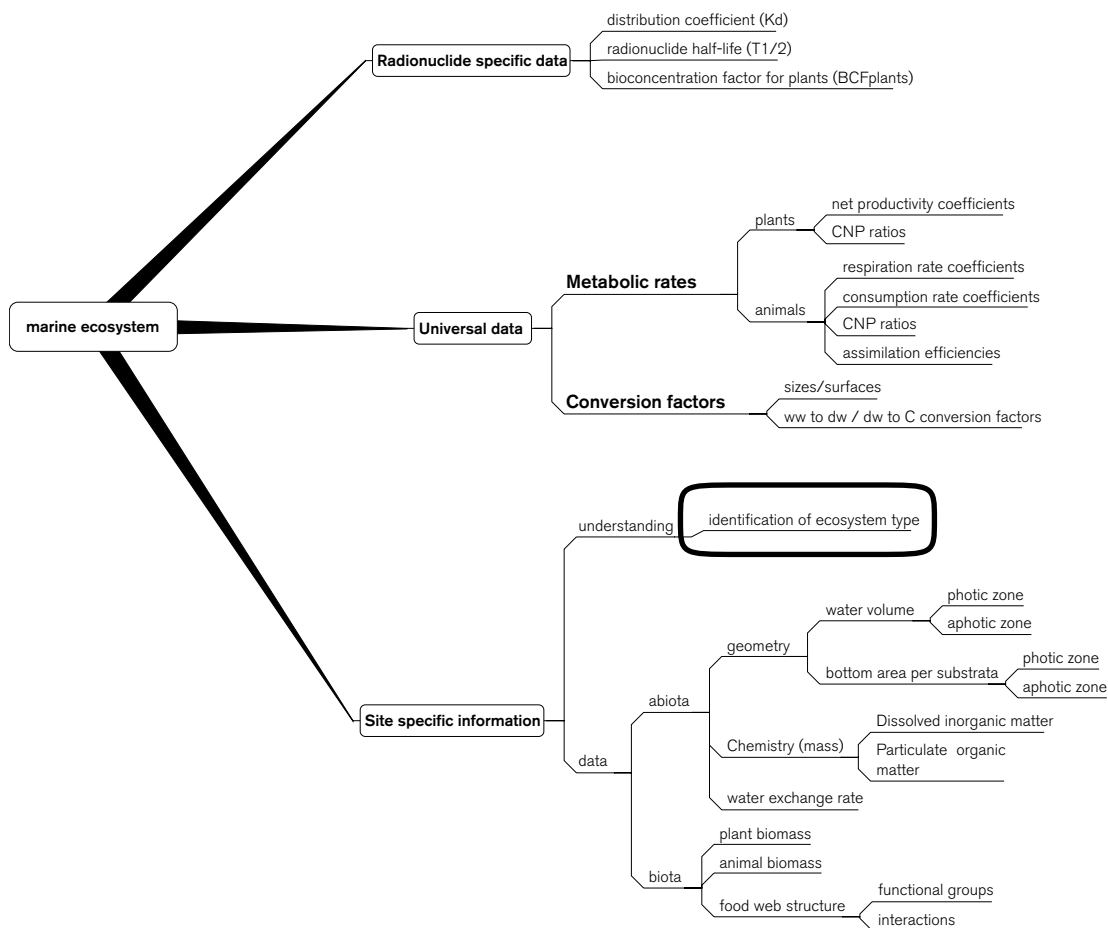
Figure C-14. *Information needed for the ecosystem model of the marine environment. The parameters are subdivided into radionuclide specific data, universal data and site-specific information. Note that identification of type of ecosystem is fundamental site information. Similar datasets will be needed for all ecosystems.*

One of the short-time models is a bioconcentration factor based model, developed for lakes. This model is a modified version the model applied in SAFE /Karlsson et al, 2001/. To the SAFE model a second input pathway for radionuclides to the system through the sediment was added in a similar manner as for the marine model (cf section C.4.1 and Figure C-13). In the landscape model (section C.1), site-specific data are used for the different lakes where the releases are identified to occur (Table C-1).

There is also an ecosystem model for lakes under development. This model is scheduled to be available at the end of 2004. The lake ecosystem model is developed according to the same principles as the coastal model by Kumblad (cf section C.4.1). It is based on the initial work from the Marholmen workshop /Lindborg and Kautsky, 2004 in manus/ and the PhD work by /Andersson, 2003/. Depending on the progress with the development work and available data the model will be utilised in SR-Can to obtain radionuclide concentrations in biota and site-specific bioaccumulation factors that can be used in the other type of models (cf section C.4.1).

C.4.3   Running water

Running water, i.e. rivers, streams, creeks and ditches are essential objects connecting the different ecosystem types in the landscape. Especially in a future perspective when the sites are far from the shore-line, running water can be an important component in the transfer and potential accumulation of radionuclides. The occurrence of running waters is dependent on external factors such as shore-line displacement (long-term) and climate (short- and long-term) and internal factors such as meandering (intermediate to long-term). Humans may affect running waters substantially by draining and building of artificial shore-lines and watersheds.

A new model framework for radionuclide transport in streams is under development /Jonsson and Elert, in prep/. The aim of the new model is to include retention processes that occur along the stream to be able to investigate the effect of the retention on radionuclide transport and on doses to humans. The focus in the first phase of this model development to describe the transport mechanisms and retention processes, a conceptual illustration shown in Figure C-15. In the next phase of the model development the uptake in biota will be developed by utilising the concepts from the forest and lake models.
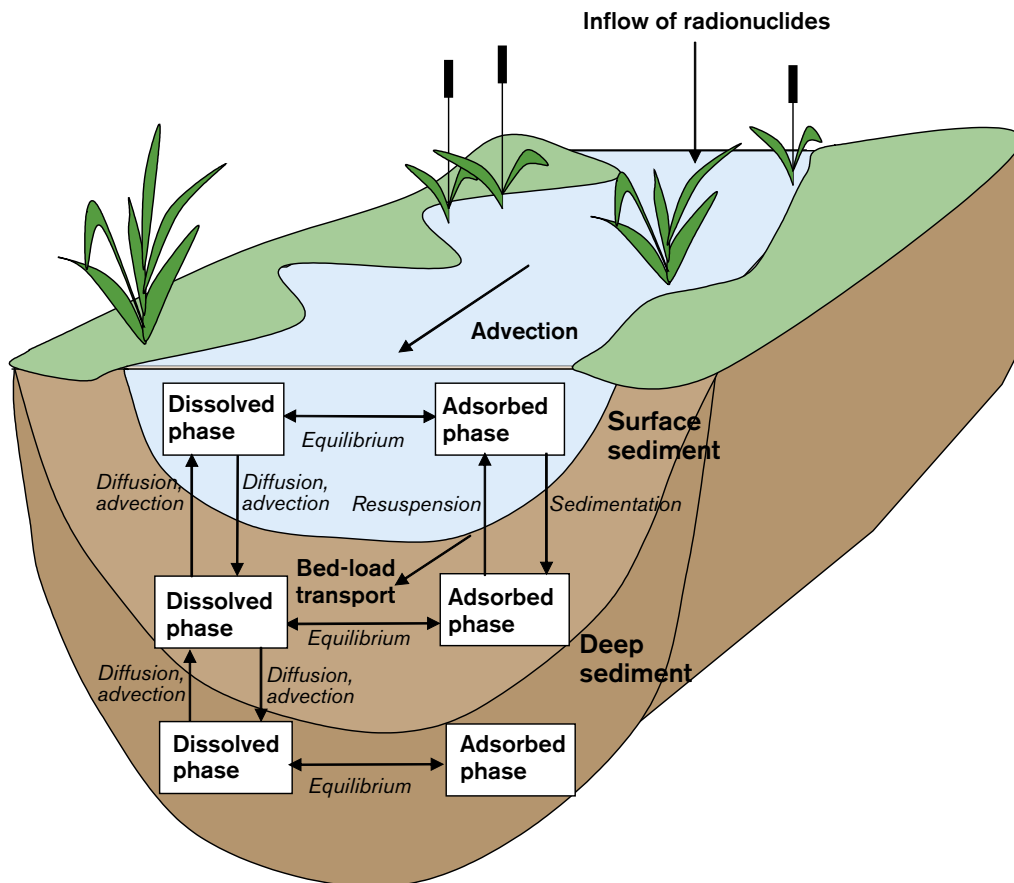

Figure C-15. *Preliminary conceptual illustration of the phases and processes considered in the model for radionuclide transport in streams. Boxes represent mass conservation relationships and arrows mass transfer relationships. The biological processes will be added in the next version*

The proposed model includes the transport for both adsorbed and dissolved phases of the radionuclides. Transfers between the sediment and the stream water are described as advective and diffusive for the dissolved phase of the radionuclide, whereas the exchange of the adsorbed phases is due to sedimentation and resuspension. The transport of radionuclides along the stream is due to advection with the water and due to bed-load transport. The hydraulic calculations performed to determine the advection velocity and area of the interface available for uptake of radionuclide in the sediment will be based on information on specific run-off and application of Manning´s equation.

In the SR-Can Interim report, running water is just a transport vector, whereas in the SR-Can Final report the intention is to use a version of the model described above extended with uptake in biota.

C.5   Terrestrial ecosystems

The terrestrial environment includes wetlands, forest and different types of open land (e.g. agriculture land). The main external factors affecting the terrestrial ecosystems are, as for the aquatic ecosystems, the shore-line displacement and the climate. The shore-line displacement process restricts the periods terrestrial ecosystems may exist to a relatively short period both in Forsmark and in Oskarshamn during a glacial cycle as outlined in the main scenario.

The mire development and succession of forest are the major internal factors which affect the distribution of the different types of terrestrial ecosystems. Human land-use is another important factor affecting the properties of the terrestrial ecosystems, although the land-use to a large extent is constrained by the available soil types (cf section C.6.1).

In the terrestrial models, the key factors determining the transfer of radionuclides are the groundwater flux and processes in the regolith, i.e. hydrology and sorption processes, root uptake and a further uptake and transfers in the food chain. In Figure C-16 the general outline of the work to generate an ecosystem model for the terrestrial environment at the site is illustrated. Several alternative models regarding the terrestrial environment are under development. The models highlight different aspects of the key factors. The mire and agricultural model uses radionuclide-specific root uptake factors and K_d values, whereas in the forest model and the "Marholmen" model radionuclide uptake processes are modelled in a more mechanistic way, e.g. by consideration of transpiration flux or nutrient uptake. The forest model (see below) will be the main terrestrial mechanistic model used in SR-Can, but results from the hydrological modelling and CoupModel will also be included as support. However, for SR-site the aim is to a have a single model for each type of terrestrial system, e.g. mire, agricultural land and forest. In the following the approaches are described for SR-Can.
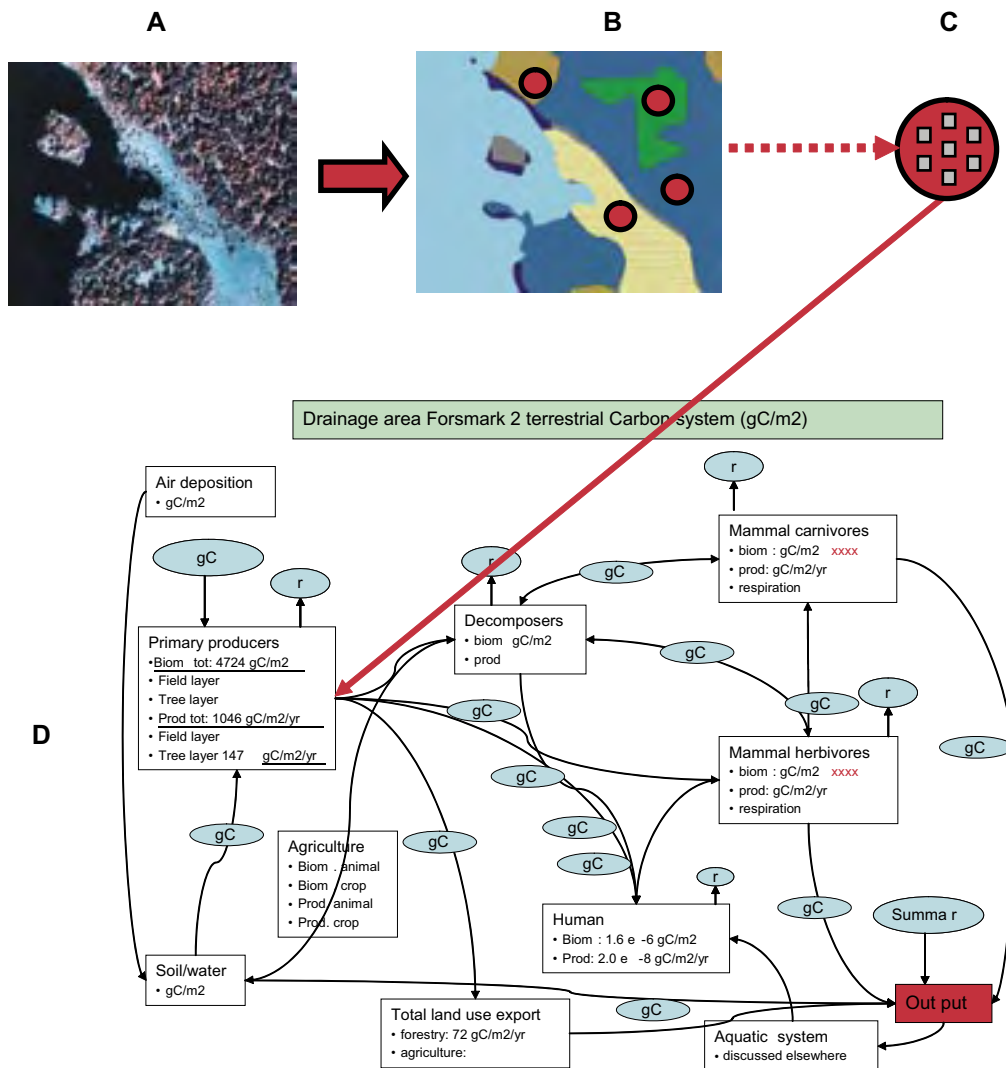
Figure C-16. *The site (A) is mapped by site investigations (B) for a outline of the different vegetation types. Then samples are taken (C) for biomass analysis and later flux estimates. This information is then compiled by the analysis group together with generic data to produce a system ecological model describing the major flows of matter and standing stocks (D). This flow model is either used directly in radionuclide transport models or important factors and processes are derived from this model /Lindborg and Kautsky, 2004 in manus/.*

C.5.1 Agricultural land

For this SR-Can Interim report, the same model as in SR97 and SAFE was used for irrigated plots or farming on land derived from mires or sea/lake beds. In SR-Can, site data on properties of the regolith will be used to delimit the areas suitable for farming.

C.5.2 The mire model

In many areas around the sites, mires are the common pre-stage before they are drained by ditching and used as agricultural land. The mire model is, in principle, the same as was used in SR97 and SAFE /Bergström et al, 1999; Karlsson et al, 2001/ except that the water turnover in this version is estimated from the total amount of water coming from the drainage area according to the equation:

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$$TC = \frac{R}{\varepsilon \cdot D} \frac{A_d}{A_m}$$

where

R = Effective precipitation

ε = Porosity

D = Depth

A_d = Drainage area

A_m = Mire area

In the previous model, only the area of the mire was receiving the effective precipitation. Moreover, the geometry of the mires and their location is also based on site-specific data (Table C-5), which for the EDF model is collected in statistics used for the probabilistic consequence calculations. In Table C-6 the mires receiving potential discharges from the repository are listed.

The site-specific data used for the model are shown in Table C-5. Radionuclide-specific data are based on /Karlsson and Bergström, 2002/.

The ecosystem specific dose conversion factors (EDF) were calculated using probabilistic simulations with the *Tensit* tool (cf section C.7) integrated over a 10,000 years period. An example of the EDF distributions for some radionuclides is shown in Figure C-17.

For most radionuclides the EDFs in SR-Can are one to two orders of magnitude lower than in SR97 for the mire model. This decrease is mainly because the drainage area is larger than the mire, which on average makes the water turnover coefficient a factor 50 higher. However, there are also other site-specific parameters contributing to the differences, i.e. the depth and surface area of the mire. Some of the differences are because assumed human consumption of vegetables has increased slightly (since the SR97 assessment) and root uptake factors are lower for some radionuclides (e.g. Ra-226). Some radionuclide-specific data, e.g. dose coefficients for inhalation have considerable increased since SR97 due to updated dose conversion factors /Karlsson and Bergström, 2002/.

Table C-5. Data used in the mire model. Min and max are truncations of normal (N) and log-normal (LN) distributions and minimum and maximum values for triangular (T) or log-triangular (LT) distributions.

Parameter	units	dist	best est.	std	Min- max	type
Runoff[1]	m/year	N	0.23	0.078	0.071–0.451	site-specific
Density[2]	kg/m^3	T	100		80–120	site-specific
Porosity[2]	-	T	0.9		0.8–0.95	site-specific
Area[3]	m^2	LN	10,931	3.82	900–$1.1 \cdot 10^6$	site-specific
Depth[4]	m	T	0.33		0.2–2.1	site-specific
Drainagearea[3]	m^2	LN	550,935	2.61	$9 \cdot 10^3$–$1.7 \cdot 10^7$	site-specific
Tk[2]	year	LT	10^{-3}		10^{-5}–10^{-1}	universal

[1] Effective precipitation from /Larsson-McCann et al, 2002/

[2] /Karlsson et al, 2001/

[3] Wetlands statistic from SICADA database and areas from GIS

[4] Data from SICADA based on smallest cultivation depth, best estimate depth is from database while max depth is taken from /Karlsson et al, 2001/
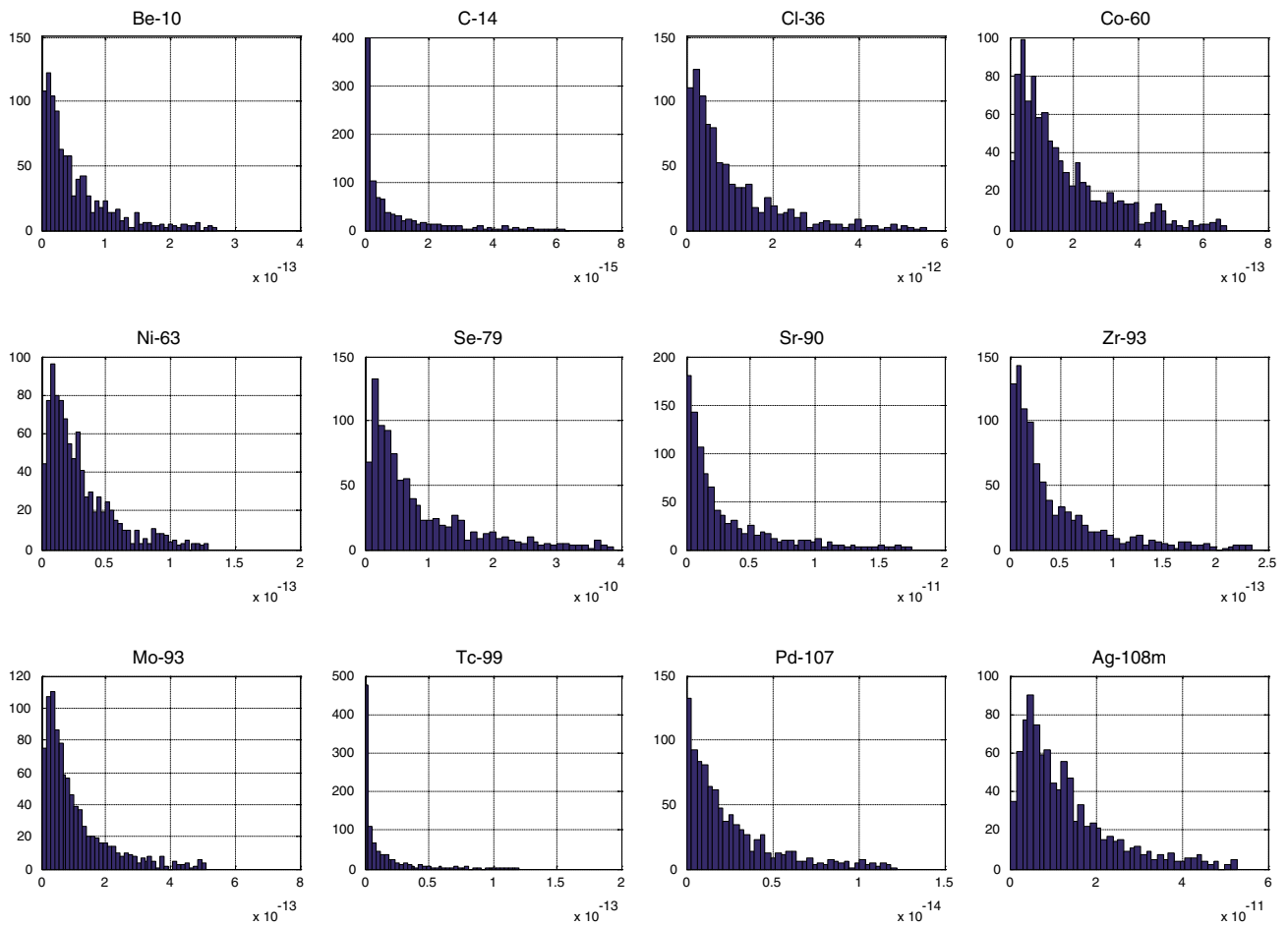
Figure C-17. *Examples of the distribution of EDF for 12 simulated nuclides out of 44. The figures are histograms with frequency on the vertical axis and EDF (Sv/Bq) on the horizontal axis.*

This relatively simple mire model shows that the use of site-specific information improves understanding for the actual site and thus the model formulation, which results in considerable changes in estimated doses. Still this type of EDF model is a very coarse estimate which is probably pessimistic. For example the accumulation time in a mire affects the dose considerable and thus the assumptions of how long time a mire can be used for agriculture before the transition from mire to agricultural land is important. Many mires can be utilised before 10,000 years of accumulation, which gives lower doses. The growth of the mire is omitted which gives higher concentrations in the peat etc. Most of these parameters can be obtained from the site data and a careful analysis of historical development of the site /Bergström, 2001; Brydsten, 2004/ and this will developed for the SR-Can final report.

C.5.1 Forest model

At the proposed sites a substantial area is covered by forests (Figure C-1). However, radionuclide migration in forest ecosystems could not be explicitly addressed in previous safety assessments, SR97, since a suitable radioecological model was not available. This shortcoming was pointed out in a review of SR97 made by SSI and SKI. In response to this, a project was initiated that aimed to develop a radioecological model for the type of forests existing in the region of interest /Avila, in prep/.

In a review of available radioecological forest models /Avila, in prep/, it was concluded that there is no model presently available in the literature which can handle groundwater contamination with several radionuclides for a changing biosphere. The existing models handle only a few radionuclides, mainly radioisotopes of caesium, by aerial deposition. The majority of the existing models rely on calibrated parameters, such as half-lifes in different compartments and transfer factors, which are difficult to extrapolate to other sites and radionuclides. Some of the models describe radionuclide transfer and redistribution as functions of ecological variables, such as biomass growth and evapotranspiration. The approaches used in these models, with some modification, could be used in a generic forest radioecological model.

On the basis of this review, it was decided that a workable strategy would be to model radionuclide behaviour in forests by incorporating radionuclide specific features in existing models for analogue nutrients or trace elements. A first version of this model has now been developed and is described below.

A conceptual diagram of the model is shown in Figure C-18. A single homogeneous soil layer is adopted, i.e. the effect of vertical distribution of the radionuclides in soil is not represented. The export of radionuclides from the soil via run-off is calculated as a function of the precipitation and evapotranspiration. The model includes two approaches describing the uptake of radionuclides by vegetation, which can be selected between depending on the availability of information. One approach uses biomass growth as the driving variable and requires analogue concentrations in the vegetation or alternatively the uptake rates of the analogues. In the other approach, transpiration by the vegetation is the driving variable and it is assumed that the uptake rate is proportional to the transpiration rate and the radionuclide concentration in the soil pore water. The recycling of radionuclides from the vegetation to the litter layer and the soil are also described as functions of ecological processes such as vegetation mortality and litter decomposition. The transfer from vegetation to animals is calculated with a food-web model using a kinetic-allometric approach.

The radionuclide independent parameters required by the model (biomass growth rates, element levels in vegetation, evapotranspiration and transpiration rates, vegetation mortality rates, decomposition rates, etc) are either site data or could be estimated with the help of the CoupModel or similar models (cf below). One particularity of the model is that it only requires a few radionuclidedependent parameters, such as the selectivity and permeability coefficients for root uptake and the bioavailability of the radionuclides in soil. The values of these parameters are bounded and usually expressed in relation to values for analogue elements. If the values are not available then it is easy to assign a heuristic or conservative values, without violating the mass balance in the system. This is especially useful for forest, where radionuclide specific data are lacking as stated earlier.

The strategy for further development of the model will be developed when sensitivity and uncertainty analyses using the first version of the model have been carried out.

C.5.2 Mechanistic terrestrial radionuclide model

A model for dilution of radionuclide contaminated groundwater and uptake of radionuclide in vegetation was developed using ArcGis software and primary production data /Lindborg and Kautsky, 2004 in manus/. These are assembled from site-specific data (Figure C-19).
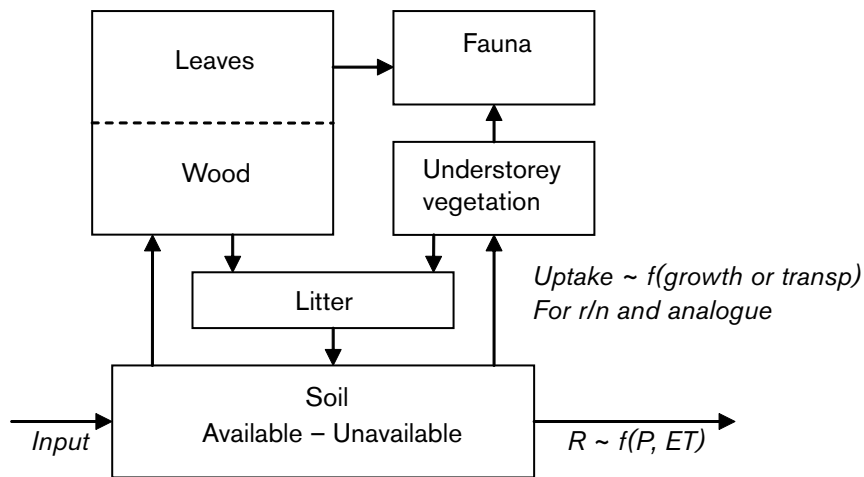
Figure C-18. *Simplified schematic representation of the conceptual model of the forest (R-runoff, P-precipitation, ET-evapotranspiration).*
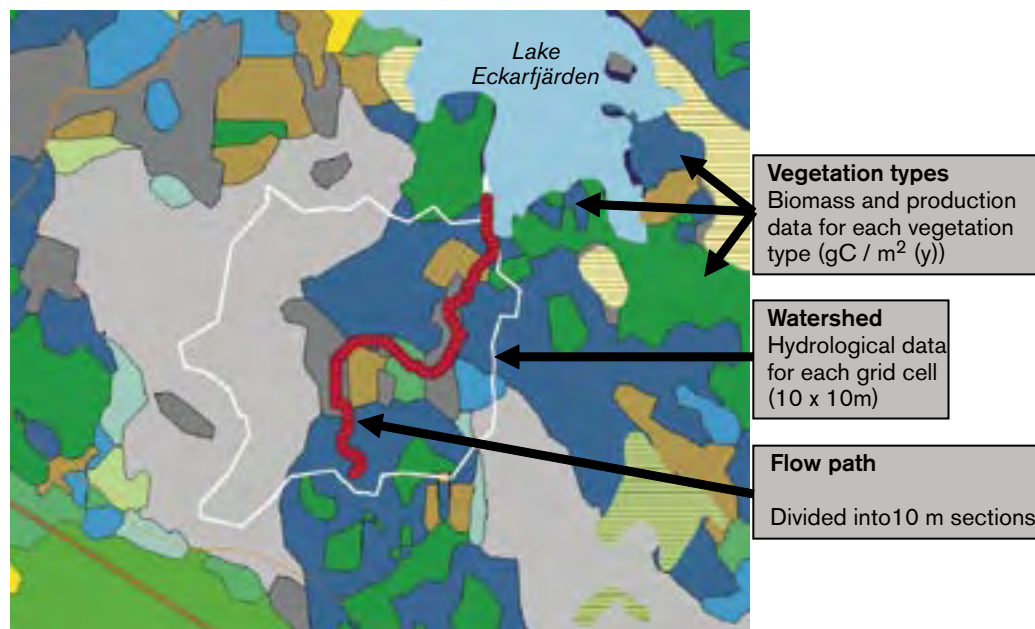

Figure C-19. *Site-specific data for hydrology and vegetation and predicted flow paths from a hypothetical release point. /Lindborg and Kautsky, 2004 in manus/.*

The model starts at a groundwater discharge point and ends up in the nearest downstream lake. The route for the contaminated ground water from the discharge point to the lake is calculated with the ArcGis Hydrological modelling extension /Lindborg and Kautsky, 2004 in manus/, see Figure C-19.

The example show that the spatial distribution of radionuclides in the landscape limits the areas with the highest contaminations, it also shows that uptake in plants can be modelled by means other than radionuclide specific root uptake factors. It will be further explored for SR-Can and in combination with the CoupModel described below.

C.5.3 CoupModel

One of the alternative terrestrial models is the CoupModel /Jansson and Karlberg, 2004/, which has the possibility to handle water transport, the root uptake and to estimate evapotranspiration, primary production and properties of soil compartments. SKB has also participated in development of a trace element application of the model. During the Marholmen workshop the extended CoupModel was tested with site-specific data /Lindborg and Kautsky, 2004 in manus/.

As the CoupModel is a general model, it can include water and heat processes in any soil in a soil-plant-atmosphere system, for any type of plant cover. The strength of the model is both that it has been developed to account for interactions between the climate, tree stand and soil temperature and that the model has mainly been applied for Nordic conditions.

The model consists of two main parts, the water and heat part and the nitrogen and carbon part. A complete budget and description of all major fluxes and storages of water, heat, nitrogen and carbon is therefore made. A detailed description of the model is given by /Jansson and Karlberg, 2004/.

The organic material in the soil is represented in different ways depending on the purpose of the simulation. Soil organisms, such as microorganisms, decompose the organic matter, and their activity, therefore, accounts for fluxes between different organic pools in the soil. To account for differences in substrate, the model has a minimum representation of two organic pools independent of soil horizon. One of these is *Litter* and has a high turnover rate. The other one is *Humus* and represents a low turnover rate.

The simulations of soil temperature, soil moisture conditions and soil water flows are based on physical equations. The most important interaction between carbon turnover and the physical conditions is governed by the leaf area index and the ratio between actual and potential transpiration. Both in turn influence the input of carbon to the system and both are strongly related to temperature and the moisture.

To handle radionuclide flow in the CoupModel, a trace element application was introduced and is used to model accumulation of a trace element in the soil and plant (Figure C-20).

Some processes are specific for the trace element application, such as plant uptake of trace elements, the allocation of trace elements in the plant and the flows of trace elements both to the soil and in the soil. The plant uptake can be passive or active. The passive uptake is calculated for the leaf, stem and roots separately, and is a function of plant water uptake. Alternatively, an active plant uptake of trace elements can optionally be chosen in the model. Allocation of trace elements to the grain pool from roots, leaves and stem is proportionate to the carbon allocation to these pools, multiplied by the trace element/carbon ratio of the source pool. Trace element content in litter fall from leaves, stem, grain and roots are calculated in the same manner. Trace elements in above-ground litter fall accumulate in the surface litter. From the surface litter, there is a constant flux of trace elements into the litter pool in the uppermost soil compartment. Litter fall from roots (i.e. dead roots) go directly the corresponding litter compartment (i.e. organic matter pool) in each soil layer. Decomposition of litter results in one flux of trace elements to humus and a second to the dissolved trace element pool, i.e. some form of mineralization. Both fluxes are a function of the total turnover.

For SR-Can, the model will be further explored and results from the modelling will be incorporated in the development of a terrestrial model (cf section C.5.3) or used as an alternative model. The results will also be used for the site description of primary production and surface hydrology.
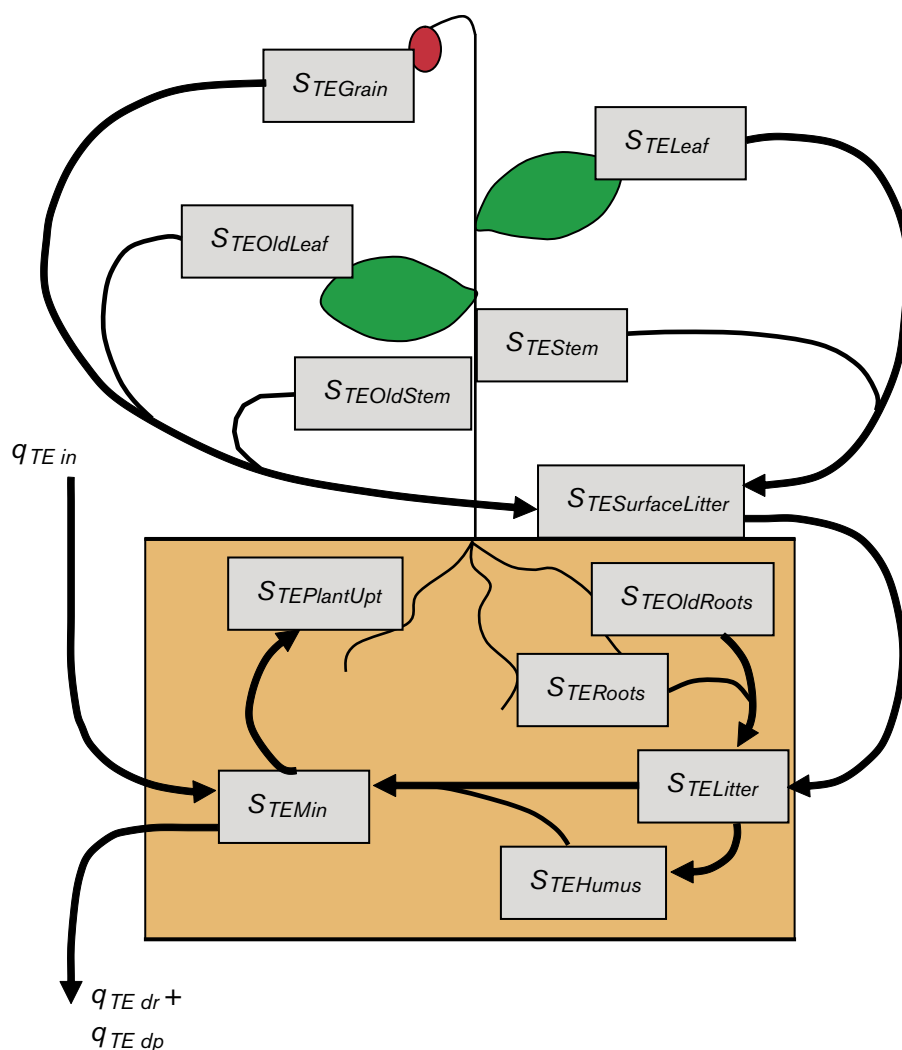
Figure C-20. Distribution of trace elements (S) in a terrestrial ecosystem as represented in the CoupModel, as well as the fluxes of tracers (q) between different components /Jansson and Karlberg, 2004/.

C.6   Human activities

To be able to estimate the influence of human activities and behaviour on the potential dose to humans, many of the activities such as daily intake of food need to be generalised although human habits are known to vary. However, the maximum exploitation base for humans can be estimated by the constraints of the actual size and conditions of the site in terms of e.g. fish production and available water. In previous assessments, only the effects of the dose maximising of individuals were reported. The new regulations from SSI propose that more realistic exposure of the human populations should be considered. There is an option to use the most exposed individual in a group of humans, but that requires that SKB can justify the size of this group. It is quite straightforward to calculate the size of a sustainable population in an area, since there are data on the situation today and some data on the past, and also a theoretical maximum to the amount of people that can live sustainable in the region. We do not expect that humans will change much in their dietary requirements in future, thought the mix of the items that comprise their diet may change substantially.

A potential release of radionuclides will be distributed in both time and space and it is very unlikely that the same human individuals will be exposed to all sources simultaneously.

C.6.1 Constraints on a sustainable population

Human land use is an important factor not only since it may affect the dispersal and accumulation processes in the landscape, but also because it will affect the degree if human exposure to the various contaminated media. For instance, forestry may radically affect the run-off and the chemical composition of the run-off water. However, forestry is likely to be much less a direct source of exposure of radionuclides to humans than e.g. agriculture and hunting.

In the workshop at Marholmen /Lindborg and Kautsky, 2004 in manus/ ecosystem data were compiled which are used in the following example.

There are no inhabitants within Bolundsfjärden today. If the population density of 0.2 inhabitants/km^2 in the main drainage area of Forsmark is applied, it gives a population of 1.7 within Bolundsfjärden. The area that is classified as grassland or arable land in the Bolundsfjärden drainage area is in total 130 550 m^2. However, no agricultural activities currently exist in this area. If this land were utilised as arable land and the remaining parts of the drainage area were used for other types of food production (e.g. grazing), the production would amount to about 1,200 kg C per year, which is sufficient for about 10 individuals (Table C-6). This value is based on the best estimates of site-specific data or data from the region that we have today.

The theoretical production based on site-specific data was estimated during the workshop /Lindborg and Kautsky, 2004 in manus/ and assumed that everything from the total production today was fully utilised, e.g. all production of mushrooms and berries. This gives an estimate of food production that was 4 times higher, i.e. about 40 persons could be sustained. Thus, only a limited population can live within the drainage area, and if for example releases occurred only to lake Bolundsfjärden (cf Section C.1), then the total harvestable fish production from that lake would be less than sufficient for one person. That means that other food sources, which in this example are uncontaminated food, needs to be utilised. Therefore, the potential dose to humans needs to be compensated for the insufficient supply of contaminated food.

These types of calculations show that the exposed group will be very small and thus the higher risk limits should be applied.

Table C-6. Annual utilised food production in the Bolundsfjärden drainage area based on preliminary calculations during the Marholmen workshop /Lindborg and Kautsky, 2004 in manus/.

	Food item	Kg C/year
Animals	Slaughtered calves	16
	Milk production	619
	Game production	73
	Fish	80
Plants	Barley yield	327
	Wild berries	68
	Mushrooms	2
Total		1,186

In SR-Can, similar types of estimates of food production in the area will be utilised. For SR-Can, also the theoretical limits and future land use needs to be explored. Site-specific data and generalisations from regional data will be very valuable.

C.6.2 Irrigation

An important pathway for nuclides from groundwater or surface water to soil is via irrigation with contaminated water. Irrigation may cause contamination of crops directly by e.g. interception and indirectly via root uptake from contaminated soil. In /Bergström and Barkefors, 2004/ an extensive analysis of the role of irrigation for possible future doses to people living in the area surrounding a repository is presented. Current irrigation practices in Sweden were summarised, showing that vegetables and potatoes were the most common crops subject to irrigation. In general, irrigation is not very common in Sweden due to the climate.

A sensitivity analysis of the irrigation model used in the latest assessments was performed, which showed that interception of irrigation water and retention on vegetation surfaces were important parameters. Moreover, a comparison was made with other irrigation models e.g. that used in BIOMASS, TAME and BIOTRAC.

For future assessments /Bergström and Barkefors, 2004/ suggest that the leaf area index (LAI) and a specific storage capacity needs to be taken into account in evaluating the radiological significance of irrigation. In addition, differentiation of retention on vegetation surfaces for various elements depending whether if they are cations or anions is proposed.

In this interim report, irrigation has been treated as described in SR97, although site specific data were used for e.g. precipitation. In SR-Can the new results from this model will be used together with improvements arising from the BIOPROTA project (cf section C.8.1).

C.7 Model tools

A new simulation tool for dose assessment was developed, called *Tensit* (Technical Nuclide SImulation Tool, /Jones et al, 2004/). The tool can handle transport and decay of radionuclides and is capable of both deterministic and probabilistic simulations. A great benefit with *Tensit* is that it provides a standard for how simulations are setup and provide a way to easily connect different ecosystems with each other through its graphical user interface. This makes the models easier to overview and is also more reliable, than if each model were to use its own standard.

Tensit utilises and connects two separate commercial software packages. The equation-solving capability and model building is derived from the Matlab/Simulink software environment to which *Tensit* adds a library of inter-connectable building blocks. Probabilistic simulations are currently provided through use of probabilistic software (@Risk) that communicates with Matlab/Simulink. An extension and improvement of the *Tensit* concept is currently being developed in conjunction with POSIVA.

Several examples of the capabilities of the tool are presented in the earlier sections.

C.8   Universal and radionuclide-specific 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 such as ICRP and SSI, or from generalised data derived from the sites.

C.8.1 Radionuclide data

K_d-values should 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 conversion factors for human ingestion, inhalation and external radiation needs to be updated according to ICRP recommendations. This is ongoing work in BIOPROTA and a draft will be available for the initial phase of SR-Can. Furthermore, this will be updated regularly and revised data will be available for SR-Site. The FASSET and ERICA projects will hopefully also give some guidance on dose conversion factors for biota other than humans.