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Interim data report for the safety assessment SR-Can

Svensk Kärnbränslehantering AB

August 2004

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Preface

This report describes, with example applications, the methodology for the handling of input data uncertainties in the safety assessment SR-Can. The report is authored by Fredrik Vahlund, SKB and Johan Andersson, JA Streamflow AB.

The presented methodology, which builds on that used in SKB's most recent safety assessment, SR 97, was developed mainly by Johan Andersson, in collaboration with Fredrik Vahlund and the undersigned.

Several other experts and generalists have been involved in specific parts of the work, as is further described in the report.

Stockholm, August 2004

Allan Hedin

Project leader, SR-Can

Summary

This document is the interim data report in the project SR-Can. The purpose of the data report is to present input data, with uncertainty estimates, for the SR-Can assessment calculations. Besides input data, the report also describes the standardised procedures used when deriving the input data and the corresponding uncertainty estimates.

However, in the present interim version of the report (written in the initial stage of the project when site characterisation has yet not been completed) the standardised procedures have not been possible to apply for most of the data and, in order to present a compilation of the data used in the assessment, much of the input data is presented without following the standardised procedures. This will however be changed for the final version of the SR-Can data report, in order to show the methodology that will be used in the final version one example of how input data will be presented is included (section 5.2, migration data for buffer) . The recommended input data for the assessment calculations are, for the interim version, mainly based on SR 97 Beberg data, these are merely presented without any background or uncertainty discussion (this is presented in the SR 97 data report).

Contents

1 Introduction

This report provides input data, with uncertainty estimates, to the SR-Can assessment calculations for a wide selection of conditions. The data are assessed through standardized procedures and input provided by experts is distinguished from judgements made by the SR-Can team. However, in this interim version of the data report, this only applies to some of the data – in order to demonstrate these procedures. Other data, needed for the illustrative calculations presented in the SR-Can interim main report, are provided with a more relaxed procedure.

1.1 Background

SKB, the Swedish Nuclear Fuel and Waste Management Co, is currently preparing license applications to locate, build and operate i) the deep repository for spent nuclear fuel and ii) an encapsulation plant in which the spent fuel will be emplaced in canisters to be deposited in the deep repository. Several investigations are conducted in support of these license applications.

1.1.1 Planned safety assessments

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.

Two safety reports will be produced within the next five years; one for the application to build an encapsulation plant, SR-Can, and one for the application to build the repository, SR-Site. SR-Can will be based on site data from the initial site investigation phase and SR-Site on data from the complete site investigation. After an initial phase of the SR-Can project, an SR-Can Interim report will be produced, with the main purpose of demonstrating the adopted methodology, so that this can be reviewed before it is used for the applications. Also, preliminary safety evaluations /SKB, 2002/, of each site will be made as sub-tasks within the SR-Can project.

1.1.2 Assessing input data – need for traceable expert decisions

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 data uncertainty is therefore required.

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

Among other things, the reviewers required *quantification of uncertainties* into a form suitable for probabilistic assessment and *traceable records on the expert input* to data selection and uncertainty assessment. A new procedure, based on the one used in SR 97 and taking into account review comments is therefore established for SR-Can.

1.2 Objectives and scope

The objective of this report is to compile input data, with uncertainty estimates, to the SR-Can assessment calculations and for a wide selection of conditions. In contrast to SR 97, data are provided not only for the radionuclide migration calculations, but also for some important aspects of the quantification of repository evolution. Furthermore, data are assessed through standardized procedures, adapted to the importance of the data, aiming at identifying the origin of uncertainty and where the input provided by experts are distinguished from judgements made by the SR-Can team.

There are also several aspects related to data not covered in this report. Evaluation of processes and selection of models fit for the assessment processes is made in the SR–Can process report /SKB, 2004c/. Selection of scenarios and calculation cases, which in turn define the conditions for which data need to be supplied, is made in the main SR-Can report /SKB, 2004a/. The initial state of the fuel and the engineered components according to the reference design is given in /SKB, 2004d/. Descriptions of the sites are given in the respective site descriptive reports, i.e. /SKB, 2004b/ (for the Forsmark area which serves as a representative site for the modelling in the SR-Can interim reports), for this interim version of SR-Can. The data report will accept the judgements made in these reports and will not repeat information given there, unless it is needed for the further assessment of the information.

The current report is an interim version of the SR-Can data report. It supplies data to the assessment calculations presented in the SR-Can interim version, but most of its content is preliminary. In particular:

- the inventory of parameters for which it should supply data is incomplete since there is still some development of the models to be used for assessing system evolution and some decisions to be made with respect to what aspects of the evolution should be covered by the fully qualified data processes,
- the standardised procedure for data assessment is only demonstrated in full on the buffer migration data, whereas more relaxed procedures are applied on other data.

In the final SR-Can version of the data report, the standardised procedures will be applied to all data.

1.3 Experts and the SR-Can team

As further explained in section 2.2, all factual information in this report is based on expert input provided in supporting documents. The experts are generally identified in these documents – see also the list of references. More specifically:

- M. Ochs and C. Talerico (BMG Engineering Ltd) have provided the primary expert input to the buffer migration data (section 5.2).
- L. Hartley, I. Cox, D. Holton, F. Hunter and S. Joyce (Serco Assurance) together with B. Gylling and M. Lindgren (Kemakta Konsult AB) have provided the primary expert input to the flow related migration data (section 6.5).

In addition, the teams behind the preliminary site description of the Forsmark area (version 1.1) /SKB, 2004b/ have provide d the expert input to this site description. This information is primarily used in chapter 6. Furthermore, the input has been evaluated, including final judgement made of selection of data and distribution for the SR-Can calculations, by a subset of the SR-Can project consisting of:

- Fredrik Vahlund (SKB) and Johan Andersson (JA Streamflow AB) – compilation of this report and overall judgements.
- Patrik Sellin (SKB), sections 3.2, 3.4, Chapter 5.
- Lars Werme (SKB), Chapter 4, and section 3.3.
- Rolf Christiansson (SKB), sections 6.2.
- Jan-Olof Selroos (SKB), sections 6.5.
- Ulrik Kautsky (SKB), Chapter 7.
- Allan Hedin (SKB) SR-Can project management and overview.

1.4 Organisation of the report

This report is organised as follows. Chapter 2 outlines the means of data and uncertainty assessment by listing the inventory of parameters to which data are to be supplied and describing the procedures for obtaining expert input and judgements made by the SR-Can team. Subsequent chapters assess the data according to this procedure. Each subsection covers one or a few parameters for which data are to be supplied. These subsections follow a standardized outline covering:

- modelling in SR-Can,
- sensitivity to assessment results,
- source of information,
- conditions for which data are supplied,
- conceptual uncertainties,
- data uncertainty,
- spatial and temporal variation,
- correlations,
- quantification of the data with uncertainty.

2 Means of data and uncertainty assessment

This chapter outlines the means of data and uncertainty assessment by listing the inventory of parameters to which data are to be supplied and describing the procedures for obtaining expert input and judgements made by the SR-Can team.

2.1 Input data and information flow

In SR-Can, data are needed for quantifying the evolution of the safety functions of the repository and for radionuclide migration calculations leading to dose and risk estimates. As further explained in the SR-Can main report, these calculations are made with a series of partially coupled models. 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 the interim version of the SR-Can main report, regarding both general evolution and radionuclide dose/risk. Those, 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 section 2.1.3 below.

It should also be pointed out that the initial state of the fuel and the engineered components according to the reference design is given in the Initial State Report /SKB, 2004d/ and the descriptions of the sites are given in the respective site descriptive reports, i.e. /SKB, 2004b/, for this interim version of SR-Can. The data report will not repeat information given there, unless it is needed for the further assessment of the information.

2.1.1 Example of models for assessing repository evolution

Some important aspects of the general evolution of the repository near field are assessed by a newly developed integrated near-field evolution model /Hedin, 2004/, complemented by more elaborate analyses of specific issues. The integrated model consists of a number of sub-models, see Figure 2-1, that each mimics a process model that was used in the SR 97 assessment. The integrated model uses the same input data as the process models, meaning that the qualified data can be used for both modelling levels.

Evolution of the far-field is assessed using the general groundwater flow codes, i.e. CONNECTFLOW (NAMMU+NAPSAC) /Marsic et al, 2001, 2002/ and DarcyTools /Svensson, 2002a,b/ and by codes for the analysis of rock mechanics and chemical evolution. The input data to these analyses are basically obtained from the site descriptive models and are, with a few exceptions, not discussed in this report

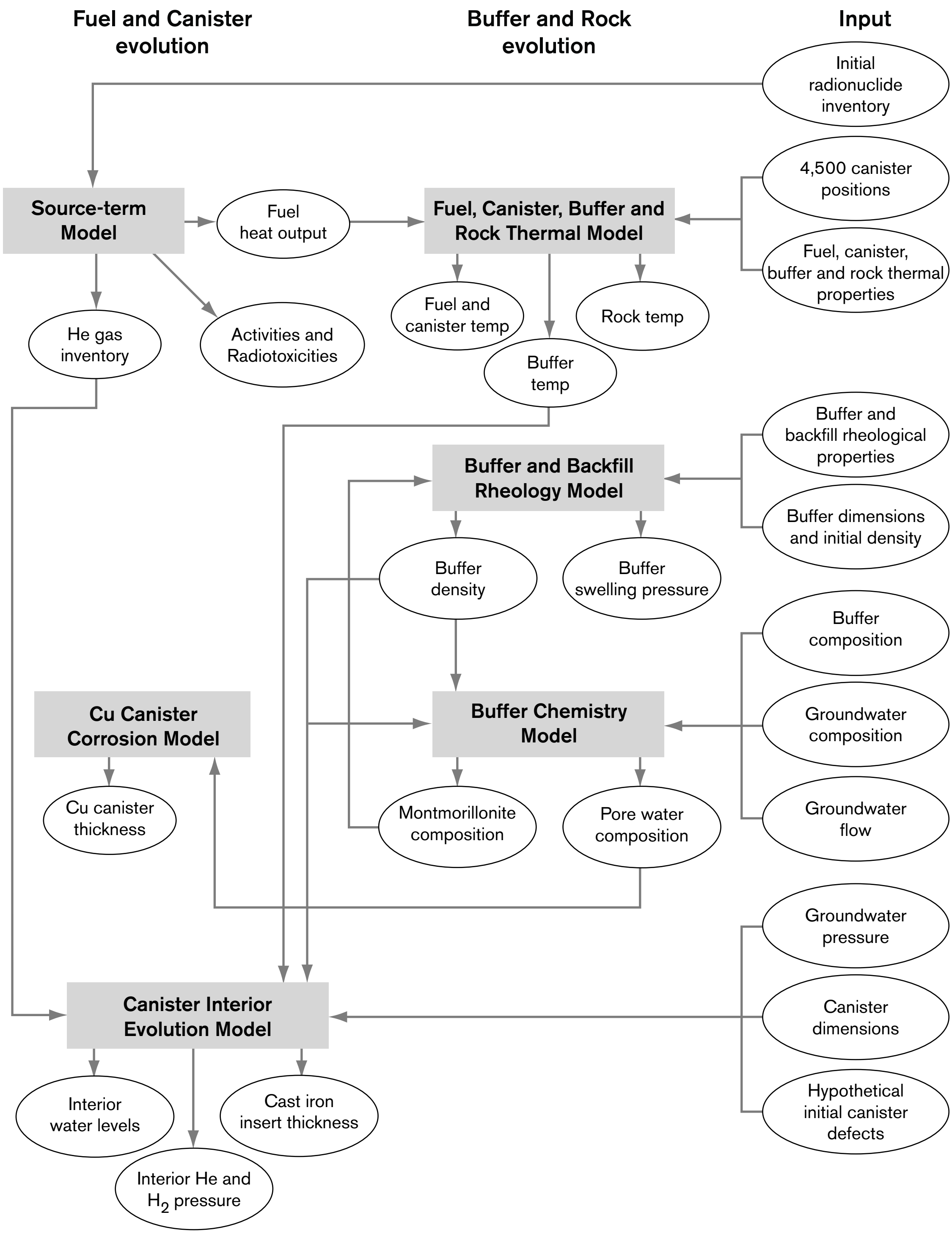

Figure 2-1. *The near field evolution model with sub-models represented as rectangles; input data and time dependent calculation results as ellipses.*

Also input to codes and analyses used for modelling the external environment (mainly the climate evolution) are not covered by the data report. Input to the analyses not covered in this report is assessed in the modelling reports themselves.

2.1.2 Chain of models for radionuclide migration calculation

Radionuclide migration is studied using a chain of models, which handles radionuclide transport in the near field, the far field and the biosphere. These migration models require input from analyses of the state of the barriers and the rock, i.e. the results of the system evolution analyses. The input data used by the different models (the data inventory) and the flow of information between the models are shown in Figure 2-2. Although the models are used in sequence, and radionuclide flow is only passed downstream in the chain of models, different input data may be shared by the different models or derived using the same tools. Figure 2-2 also shows supporting documentation, either as a reference to an SKB report or to the corresponding section in the present report. The data presented in this report has in turn other supporting documents referred to in each section, these are however not shown in the figure.

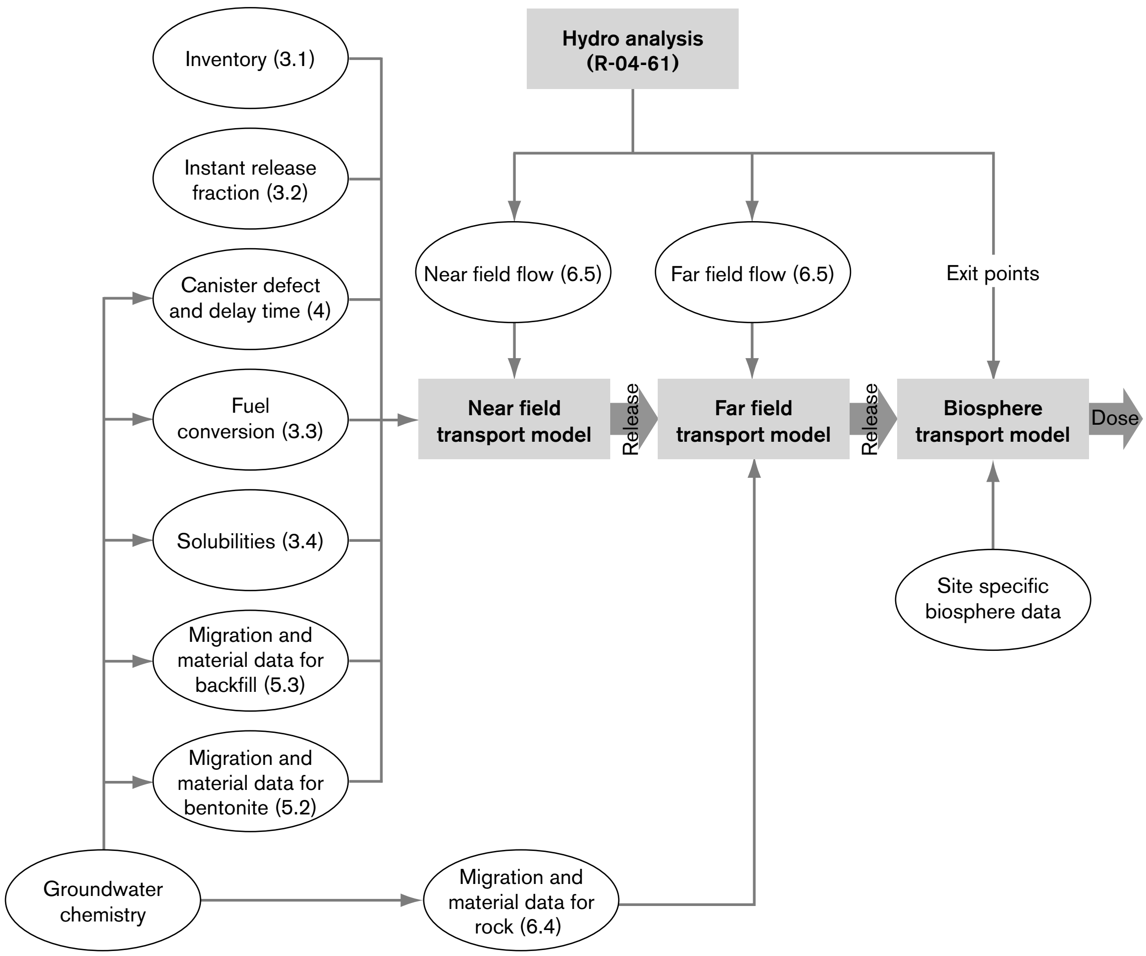

Figure 2-2. *The different radionuclide migration models used in the safety assessment, the input data and the source of the input data.*

The near field model used in SR-Can is based on the COMP23 model /Romero et al, 1999; Cliffe, 2004/. In this model, fuel dissolution and radionuclide transport in the near field is simulated for a canister having a defect, which allows water to enter. The canister may not necessarily have this defect initially and its geometry may evolve over time. The near field model requires input data on e.g. groundwater composition, radionuclide inventory, fuel conversion data (the fraction of the inventory that is instantly released and fuel dissolution rate), solubility limits, geometry and the physical properties of the canister, the buffer and the backfill is needed. Although many of these input data correspond to engineered properties of the barrier system, the dependence on groundwater chemistry (like salinity or pH) will result in site-specific data for most of the near field parameters. Radionuclide release from the near field, as calculated by COMP23, is then passed to the geosphere.

The migration in the geosphere is modelled using the FARF31 code /Norman and Kjellbert, 1990/. The conceptualisation assumes that the radionuclides migrate with the groundwater through advection and dispersion in the fractured rock, the radionuclides may also diffuse into and sorb on the surfaces of the rock matrix adjacent to the fracture in which the groundwater flows. The flow properties of the ground water are calculated by a separate code and the results are passed to the far field code as input files. The FARF31 model is based on site specific data either measured and/or modelled (based on site specific models).

For the biosphere analysis, radionuclide release points given by the hydro analyses are used together with site specific data describing the biotope at the modelled site. This is further described in the SR-Can interim main report /SKB, 2004a/.

The model chain runs either as Fortran 77 programs in the Proper package (PROPER 1996) or as Matlab applications in the Tensit package /Jones at al, 2004/. Both codes are based on the same conceptual models for the near field and the far field, hence results from the two are very similar. For the biosphere, the Tensit implementation is however more advanced. While the biosphere model in Proper, the BIO42 uses on equivalent dose factors calculated in a separate code, Tensit may be used to determine these as well as being a part of the computational chain where releases are linked to certain biotopes.

In order to make probabilistic risk assessments these models are run for a large number of realisations using probabilistic data sets. To do this, the probabilistic input data set may either be generated using the Proper probabilistic engine or using a third part application like @Risk which is the primary probabilistic engine for Tensit.

2.1.3 Preliminary inventory of data needs

Table 2-1 is a preliminary list of the main parameters needing data for the SR-Can assessment calculations (with the exceptions discussed above).

Table 2-1. Preliminary data inventory for SR-Can interim.

Chapter	Section	Example of data	Treatment in SR-Can interim
Spent fuel data	Inventory	Inventories used in the near field simulation	Inventory from SR 97
	Instant release fraction (IRF)	IRF used in the near field simulation	IRF from SR 97
	Fuel conversion	Fuel dissolution rate used in the near field simulation	New values for SR-Can interim, no discussion.
	Solubilities	Solubilities used in the near field simulation	Solubilities for Beberg in SR 97
Canister data	Copper physical data	Emissivities etc	Not handled in SR-Can interim
	Initial minimum copper coverage	Remaining copper ligament used for determining the time for a continuous water pathway.	Discussion in the main report.
	Cast iron physical data	Emissivities etc	Not handled in SR-Can interim
	Delay time	Time between an established water path and a large canister defect.	Discussion in the main report
	Corrosion parameters		Not handled in SR-Can interim
Buffer and backfill data	Material data	Data like Thermal and rheological properties	Not handled in SR-Can interim
	Buffer chemistry data	Chemical data for the buffer	Not handled in SR-Can interim, redox conditions assigned.
	Migration data for bentonite	Diffusivities, porosities and sorption data	This is the detailed example of how data uncertainties will be treated in SR-Can
	Migration and material data for backfill	Diffusivities, porosities and sorption data	Data for Beberg in SR 97
Rock mass data	Thermal properties	Conductivity, heat capacity and temperature	Data based on the present site description
	Hydraulic properties and the EDZ		Extended discussion for SR-Can interim
	Rock mechanics		Not handled in SR-Can interim
	Migration properties of the rock (non flow related)	Diffusivities, porosities and sorption data used in far field migration simulations	Data from Beberg, SR 97
	Flow related migration parameters	Advective travel times Peclet numbers and other flow related data used in the near and far field simulations	Extended discussion for SR-Can interim
Biosphere	EDF-factors	Ecosystem specific dose conversion factors.	New data, the methods to derive these will be improved for the final SR-Can report

2.2 Expert input and judgements made by the SR-Can team

All factual information in this report is based on expert input provided in supporting documents. However, all data are not equally important and it would be an unnecessary effort to require the same precision and detail in procedure for all data. Various sensitivity analyses are used for determining the ambition level needed in the data assessment. Furthermore, for this interim version of the data report, most data needed for the illustrative calculations are provided with a more relaxed procedure.

2.2.1 Instructions to experts

In subject areas where data may have a large impact on assessment results, specific subject area data assessments have been conducted and documented in reports following a preset outline[1]. These special reports:

- are produced by identifiable experts,
- follow a fixed outline with instructions to the author on how to address uncertainty, and
- clearly differentiates between input provided by identified experts and input provided by the SKB SR-Can team.

Section 2.3 provides the main parts of these instructions, but for details the reader is referred to the individual subject reports.

2.2.2 Expert input and judgements by SR-Can team in this report

The report also aims at separating between expert input 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".

The SR-Can Team will make all the final judgements on which values and ranges to use in the assessment calculations. These judgements will then be reviewed by the concerned experts.

2.2.3 Identification of experts

The individuals behind the expert input are identified in the supporting document as well as in the SR-Can Expert Database[2]. The individuals making the judgements for this interim data report are identified in the preface to this report.

[1] For this interim report this only applies to the Buffer Migration Data report by /Ochs and Talerico, 2004/.

[2] The expert data base is not available for this interim report. See the SR-Can interim main report for a description of this procedure.

2.3 Assessing input data for different subject areas

The data and uncertainty estimation is made for the various subject areas. The evaluation of uncertainties and the final selection of input data for various conditions are presented in a fixed outline. Each subsection summaries input from expert, usually from a subject specific data report, and shows the judgements made by the SR-Can team. The outline, as well as the main part of the instructions to the experts, is provided below.

2.3.1 Modelling in SR-Can

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

The text is usually provided by the SR-Can team and does not involve additional expert input.

2.3.2 Conditions for which data are supplied

In this section of the protocol for data uncertainty discussion, various "conditions" are listed 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.

2.3.3 Sensitivity to assessment results

As appropriate, this section 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.

Instructions to experts

In case sensitivity analyses have been performed the expert should discuss the following in the supporting document:

- At what ranges of the parameter is the impact on safety assessment significant and are there ranges where the impact is negligible? (For example, an element solubility larger than say 0.1 mole/litre is unlikely to imply any solubility limitation. Consequently, we need not be very precise in estimating such solubilities as long as it is established that the solubility is “high enough”).
- Is the impact monotonous, i.e. higher/lower values will always provide “worse” performance – is there an “optimal” value – or is the impact complicatedly dependent upon the values of other input parameters?
- What precision is needed to have an impact on safety assessment results (this answer may be different for different parameter ranges)?
- Do the answers apply to all applicable conditions – or only to some?
- In answering the above, do consider if the cited sensitivity analyses are sufficiently general to provide definitive answers.

The findings are summarised in the data report.

Judgements by the SR-Can team

In the data report the SR-Can team judges whether the expert input can be supported. When needed additional judgements are made.

2.3.4 Conceptual uncertainties

The next section explores conceptual uncertainty.

Instructions to experts

The expert should discuss means of handling conceptual uncertainty in the supporting document by addressing the following set of 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 as a parameter uncertainty in the given model?

The findings are summarised in the data report.

Judgements by the SR-Can team

In the data report the SR-Can team judges whether the expert input can be supported. However, this assessment will essentially be based on the discussion in the SR-Can process report, which focuses on conceptual uncertainty. When needed additional judgements are made.

2.3.5 Data Uncertainty, spatial and temporal variation

The next section concerns spatial and temporal variation and data uncertainties.

Instructions to experts

In the supporting document the experts should address the following type questions:

- What is known about the spatial variation (scales, variography, discrete feature statistics etc) of the parameter? Is there any information about the uncertainty in the spatial variability? How is this considered in the parameter and uncertainty estimates?
- What is known about the temporal variability of the parameter? How is this considered in the parameter and uncertainty estimates?
- If the parameter value and uncertainty estimates are drawn from a database, is this site specific or generic? In the latter case, how would the lack of site specific data influence the uncertainty?
- Are parameter 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?

The findings are summarised in the data report.

Judgements by the SR-Can team

In the data report the SR-Can team judges whether the expert input can be supported. When needed additional judgements are made.

2.3.6 Correlations

The extensive work with the FEP database 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 correlation may exist.

Instructions to experts

In the supporting document experts should address the following questions:

- 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?

The findings are summarised in this report.

Judgements by the SR-Can team

In the data report the SR-Can team judges whether the expert input can be supported. When needed additional judgements are made.

2.3.7 Quantification of uncertainty

Finally, the various sources of information are combined into quantified data and uncertainty estimates.

Instructions to experts

Based on their previous assessment, i.e. also considering conceptual uncertainty etc, the experts are asked to provide justified uncertainty estimates of the applicable data. 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? Preferably, the expert should provide two ranges i) the range where it is extremely unlikely that the parameter would lie outside this range and ii) a range where it is likely that the parameter would lie within.

Furthermore, 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. This is thus allowed as long as the expert clearly documents this together with the motivation.

The uncertainty estimates should also provide information on correlations. The expert is asked to list other parameters to which the parameter in question may be correlated, and where this correlation is not already taken care of by functional relations in the safety assessment models. An important example to consider is correlation between different elements (e.g. K_d values, solubilities) or between different nuclides (e.g. inventory, IRF, EDF:s).

The findings are summarised in the data report.

Judgements by the SR-Can team

In the data report, 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.

2.4 Input data for the base case of SR-Can interim report

As already discussed it is for this interim report essentially only the buffer migration data where the data selection follows the envisaged data selection procedure described in the previous section. At this interim stage, most other data are based on the SR 97 data report /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 per cent and the pessimistic values a probability of 10 per cent for many data types /SKB, 1999a,b/. 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 per cent 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.

3 Spent fuel data

3.1 Inventory

For the base case in the SR-Can interim calculations, the radionuclide inventory is the same as that used in SR 97, i.e. for BWR (Svea) fuel for a burn-up of 38 MWd, presented in Appendix A.1. A discussion about the uncertainties in these are presented in the SR 97 data report /Andersson, 1999/.

3.2 Instant release fraction (IRF)

For the base case in the SR-Can interim calculations, the instant release fractions are the same as those used in SR 97. A discussion about the uncertainties in these are presented in the SR 97 data report /Andersson, 1999/. Based on these, lognormal distributions are constructed as discussed in section 2.4. The data are presented in Appendix A.2.

3.3 Fuel conversion

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.

3.4 Solubilities

For the base case in the SR-Can interim calculations, the solubilities are the same as those used in SR 97. A discussion about the uncertainties in these are presented in the SR 97 data report /Andersson, 1999/. For SR-Can interim base case a log-normal distribution is assumed with the mean corresponding to the reasonable value and a standard deviation chosen so that 5% of the probability distribution is less favourable than the pessimistic. Data are presented in Appendix A.3.

4 Canister data

For the base case of SR-Can Interim Report, the canister data are provided in the SR-Can interim main report /SKB, 2004a/. The main report provides the rationale for the number of defective canisters as a function of time as well as data related to the internal evolution of the canister. The final SR-Can report will certainly update these input data, using the most recent findings from the canister R&D work. In support of these evaluations, the final SR-Can data report will tentatively provide data on:

- Copper physical data.
- Initial minimum copper coverage.
- Cast iron physical data.
- Delay time.
- Corrosion parameters.

However, at the time of completion of this interim data report, the exact division on what information will be provided in the final data report and what will be provided elsewhere had not been decided.

5 Buffer and backfill data

5.1 Buffer chemistry data

For the base case in the SR-Can interim calculations only reducing conditions in the groundwater and in the buffer are studied. The groundwater compositions and oxidation states of the different radionuclides included in the analysis are presented in Appendix A.4, see also discussion in the next section. Reducing conditions would most certainly prevail for the groundwater compositions studied. In the final SR-Can report, a much more elaborate evaluation of the expected, and site specific, groundwater composition will be provided.

5.2 Migration data for bentonite

This section concerns migration data for bentonite, or more specifically sorption coefficients, diffusivities and porosities. The data evaluation is based on a designated expert report /Ochs and Talerico, 2004/ which follows the pre-set outline prescribed in SR-Can (described in section 2 in the present report). Apart from actually providing the data for the SR-Can interim migration calculations, this section could also be seen as an example of how some of the more important data will be assessed in the final SR-Can data report. However, since groundwater speciations and other site specific data are not available for this interim version, the numerical values of the migration parameters given will most likely be updated for the final version of this report.

5.2.1 Modelling in SR-Can

Radionuclide migration

As shown in the SR-Can interim process report /SKB, 2004c/, radionuclide migration through the compacted bentonite buffer is predominantly a diffusional transport which may be modelled using Fick's law. In the buffer, radionuclides are (to different degrees) also assumed to sorb to the buffer material, which will influence the migration. Sorption of radionuclides in the near field may be modelled using a linear relation (justified by a low radionuclide concentration) between sorbed and solute concentrations with the sorption coefficient, K_d, as the proportionality coefficient /SKB, 2004c/.

Both diffusion and sorption properties of the buffer depend on the composition and physical properties of the buffer material and the speciation of the pore water, which depends on the groundwater composition etc. Many of the parameters controlling radionuclide transport through the buffer will hence be site specific and conversion procedures of experimental data derived at other conditions may be necessary. At present (at the interim stage of SR-Can) the groundwater composition at the site is unknown and groundwater speciations from SR 97 (the Beberg site) are used, presented in Appendix A.5.

Radionuclide migration though the bentonite buffer is in the near field transport simulation code COMP23 /Romero et al, 1999; Cliffe, 2004/ modelled as a diffusive transport through the porous network in the buffer in combination with sorption of radionuclides to the buffer material. The modelling parameters used to describe these processes are the effective diffusivity, D_e, the sorption distribution coefficient, K_d, and physical properties of the buffer like density and porosity, ρ and ε respectively. From these, an apparent diffusivity, D_a, may be derived /Ochs and Talerico, 2004/.

The porosity used in the calculations is for most nuclides equal to the porosity of the buffer material. However, for anions a lower porosity than that of the bentonite is used due to interactions with the negatively charged pore walls /SKB, 2004c/.

Migration of other chemical elements

Migration parameters are also used in assessments of buffer evolution. These analyses primarily concern other elements, but consistency with RN-migration parameters is still needed. Since no reliable data is available for the diffusion of sulphide in bentonite the selected value for effective diffusivity of HTO from Ochs and Talerico will be used in the interim version of SR-Can. This is probably conservative since sulphide most likely will be present in an anionic form.

5.2.2 Sensitivity to assessment results

Based on analyses in SR 97 /SKB, 1999a,b; Lindgren and Lindström, 1999/, and subsequent sensitivity analyses, the buffer migration data generally affect calculated dose or risk in the following way:

- The release of nuclides from the near-field depends on half-life and canister containment time. However, for some nuclides, (like I-129 and other long lived anions) the near field release is proportional to D_e. The impact of K_d is inversely proportional for some nuclides (with $K_d\rho >> \varepsilon$ and long half-life) while other may be totally unaffected by uncertainties (within the ranges considered) in K_d. Impact on porosity is less pronounce (but porosity affects other buffer conditions as well).
- In general, the impact of K_d and D_e is monotonic, i.e. low K_d and high D_e values tend to increase risk.

In conclusion, this means that the values of buffer migration data may (for some elements and associated nuclides) affect calculated risk linearly. This should be considered when assessing the precision in the uncertainty estimates. Further results of sensitivity analysis are provided in the interim version of the SR-Can interim main report /SKB, 2004a/.

5.2.3 Source of information

A dedicated buffer migration data report /Ochs and Talerico, 2004/ has been prepared. Details about sources of information and how they were used are found there.

Generally, Ochs and Talerico focus on element-specific batch K_d data. D_e values for most elements are selected based on data for HTO, which are not sensitive to the specific chemical conditions and therefore more representative than element-specific data obtained under different conditions. For anions and Cs the selection procedure was however somewhat different where the electrostatic potential in bentonite pores was taken into account when in selecting the D_e values. The main data sources used are:

- A Nagra report on selected K_d values for MX-80; /Bradbury and Baeyens, 2003/, and original data sources cited therein.
- SKB reports on K_d, D_e and groundwater /Yu and Neretnieks, 1997; Laaksoharju et al, 1998/, and original data sources cited therein.

- JNC reports on diffusion in bentonite as a function of dry density (mainly by Sato and co-workers).

5.2.4 Conditions for which data are supplied

Ochs and Talerico consider the buffer material to be MX-80 at the reference dry density of 1590 kg/m^3 and a porosity of 0.41 corresponding to a bulk density for saturated bentonite of 2000 kg/m^3. No other density was evaluated in the supporting document but Ochs and Talerico state there is clear evidence that the porewater composition and, therefore, radionuclide sorption, is not significantly influenced by limited variations in buffer density. The following variations were considered for some cases:

- Bentonite converted completely to the Ca-form.
- Bentonite completely depleted of soluble impurities (NaCl, KCl, gypsum).

Based on a selection of groundwater compositions Ochs and Talerico calculate the following pore water compositions:

- a reference porewater (RPW), based on the saline reference Beberg groundwater and a pCO_2 imposed by the host formation according to /Laaksoharju et al, 1998/,
- a case where no exchange of CO_2 between the buffer and the host rock is assumed and the pH buffering capability is changed. For this case, the water defined as RPW above is used but the bentonite is treated as a closed system with respect to CO_2 (RPWC),
- a porewater based on highly saline groundwater (HSPW).

These porewaters are fully defined in Appendix C of /Ochs and Talerico, 2004/ and in short in Appendix A.5 in the present report.

Experimental sorption data derived at other conditions (different CEC of the clays used, different pH and different radionuclide speciation) than those above were converted to the application condition and used in the data selection process. For the effective diffusivity, D_e, of elements other than anions and Cs, no radionuclide specific experimental values were used. Experimental data for diffusion of HTO was the source for the data selection process.

5.2.5 Conceptual uncertainties

Input from experts

Ochs and Talerico identify a number of conceptual uncertainties both in the data derivation process and in the underlying databases and models. In short:

- Several related conceptual uncertainties exist regarding the interpretation of, and self-consistency among, batch K_d values and diffusivities of sorbing radionuclides on the one hand, and of diffusivities and diffusion available porosities of anions on the other.
- There are some open questions regarding the fundamental, underlying chemistry of radionuclides in aqueous solutions. For example, the importance of actinide(III)–silicate, mixed actinide(IV)–OH-CO_3 and Ni-CO_3 complexes is not established to date. There are also uncertainties regarding the solution speciation of many of the less well researched elements, such as Nb, Zr, etc. The different migration parameters may also be sensitive to the thermodynamic data used when deriving these.

- There are significant scientific shortcomings regarding the derivation of the pore water composition in compacted bentonite and its evolution over time under repository conditions. Since pore water composition of compacted bentonite cannot be determined experimentally with any certainty for the present purpose, it is calculated using thermodynamic surface chemical models. Several published models are available for this purpose, and while they are based on the same principles, they differ in a number of details regarding e.g. the treatment of specific surface chemical equilibrium. These differences are however small in comparison to other uncertainties /Ochs and Talerico, 2004/. Further questions regarding the effects of electrical double layers in the pore space on e.g. the amount of "free" water, water activity etc are clearly beyond the present scientific understanding.
- There are uncertainties in the interpretation of raw diffusion data (concentration profiles, fluxes etc).

/Ochs and Talerico, 2004/ address these when quantifying uncertainty ranges for various conditions.

Judgements made by SR-Can team

The judgements made by /Ochs and Talerico, 2004/ are accepted by SR-Can team.

5.2.6 Data Uncertainty, spatial and temporal variation

Input from experts

According to /Ochs and Talerico, 2004/ the following applies concerning spatial variability, temporal variation and data uncertainty:

- On the scale of a typical buffer, bentonite can be considered homogeneous. Therefore, spatial variation and its related uncertainty is not considered relevant for the bentonite buffer.
- Temporal variation becomes important for the evolution of the buffer/pore water (extensions of the uncertainty in the groundwater chemistry), which needs to be assessed through models. The sorption and diffusion data as well as the various models underlying the present data selection are generic and therefore not site-specific. However, the extracted buffer migration parameters will be site-sensitive to the extent that they were derived based on site-specific conditions (including the respective variability). Of particular importance are groundwater composition (including redox conditions) and pCO_2 imposed by the host rock formation.
- Experimental errors and other sources of data uncertainty are discussed at length by /Ochs and Talerico, 2004/.

Judgements made by SR-Can team

The judgements made by /Ochs and Talerico, 2004/ are accepted by SR-Can team.

5.2.7 Correlations

Input from experts

Ochs and Talerico also assess correlations within the buffer migration data. In short they conclude the following:

For most radionuclides (i.e. actinides, lanthanides, transition elements and heavy metals, U(VI) is however an exception to this) a lower pore water pH (within the range considered) will decrease the K_d in a similar way. Similarly, an increase in major cation concentration will lower K_d values for alkaline and alkaline earth elements.

Following their chemical characteristics, the radionuclides considered can be organised into groups of elements and oxidation states whose migration behaviour will generally show a similar response to variations in pore water composition caused by variations in groundwater composition, bentonite evolution, etc. Moreover, elements handled via chemical analogies correlate with the respective analogues. Overall, the following grouping is used, where analogies are also indicated (X/Y: both elements were treated identically in the data derivation; X(Y): X was derived based on analogy with Y)

1. Alkaline and alkaline earth elements: Cs, Ra/Sr.
2. Other di-valent elements (Pb, Ni).
3. Tri-valent elements: Am, Cm(Am), PuIII(Am), Sm/Ho/Ce(Eu).
4. Tetra-valent elements and Zr: Th, UIV(Th), PuIV(Th), NpIV(Th), TcIV(Th), Zr(Th), Sn(Th).
5. Penta-valent elements: NpV, PuV(NpV).
6. Hexa-valent elements: UVI, PuVI(UVI).
7. Non-sorbing anions: Cl^-/I^-/TcO_4^-/SeO_4^{2-}/HSe^-/simple organic anions/carbonate.
8. Some elements are not known well enough to assess correlations (Pa, Nb, Pd, Ag).
9. Very weakly sorbing anions: SeO_3^{2-}, carbonate (to be handled via isotope exchange).
10. Gases: Rn, CH_4.

The redox-sensitive radionuclides will take on higher oxidation states if oxidising conditions are considered, generally leading to lower K_d values. An exception is Se(–II→IV).

A lower density of the buffer will lead to higher D_e and D_a values.

Judgements by the SR-Can team

The correlations stated by /Ochs and Talerico, 2004/ need to be considered in the probabilistic analyses made within SR-Can. The overall impact of changing conditions should be handled by considering varying buffer pore water compositions – and then select migration parameters consistent with each condition. Furthermore, the correlation between various elements suggests that a reasonable, but yet pessimistic assumption would be to consider full correlation between the elements for a given condition (i.e. consistently select high or low K_d-values for all elements in a realisation).

5.2.8 Quantification

Input from experts

The data selection procedure applied by /Ochs and Talerico, 2004/ rely strongly on sorption data obtained in batch experiments. No element-specific D_e values were derived for reactive elements. Instead, the selected D_e value for HTO was relied upon. D_e values for anions and

Cs were selected to take into account the electrostatic potential in bentonite pores. Data derivation and assessment of uncertainties was carried out in four steps.

- *Step 1*: Definition of all conditions to be considered, and calculation of the bentonite porewater composition, see section 5.2.4, corresponding to the reference density.
- *Step 2:* Derivation of K_d values for each element through a) selection of source data and quantification of their uncertainty and b) conversion of source data to reference and alternative conditions (different CEC of the clays used, different pH and different radionuclide speciation) and quantification of the uncertainties introduced in this process.
- *Step 3:* Derivation of D_e values and diffusion-available porosity, ε, for the specified reference density through a) Selection of D_e value for HTO, to be used together with the entire physical porosity for all elements except non-sorbing anions and Cs and for all conditions, b) selection of D_e value for all non-sorbing anions (Cl^-, I^-, TcO_4^-, SeO_4^{2-}, HSe^-, simple organic anions) to be used for all conditions together with the selected anion diffusion-available porosity and c) selection of D_e value for Cs, to be used together with the physical porosity.
- *Step 4:* Calculation of apparent diffusivity, D_a, values for the specified reference density based on the results for points 2 and 3 above, and comparison with experimental data. Final assessment of overall consistency and uncertainty.

Uncertainty is derived by considering the uncertainty contribution from the following levels:

- Uncertainty at the source condition: In the case of K_d values, this corresponds to the experimental error. In the case of diffusion coefficients, this corresponds to the experimental error as well as any uncertainty introduced in the required modelling for raw data reduction. Additional conceptual uncertainties are introduced in the interpretation of the diffusivity and diffusion-available porosity of anions (as well as of certain mobile cations, in particular Cs).
- Uncertainty at well defined application conditions relevant for the safety assessment. Almost invariably, the conditions relevant for the safety assessment will not be covered exactly by matching experimental data. This necessitates the conversion of the source data to the application conditions through models or estimation procedures. The overall uncertainty at the application condition will then include any uncertainties introduced by the applied conversion procedures in addition to the uncertainties already listed under the first point.
- If there are significant uncertainties associated with the application conditions themselves, the conversion procedures need to be extended to cover the expected variability. Because of the interplay of the various geochemical factors (pH, carbonate concentration etc) in affecting radionuclide behaviour, it is difficult to address this variability by considering a range of values for an individual chemical parameter (e.g. pH). Instead, self-consistent sets of input data for different conditions, defined in /Ochs and Talerico, 2004/ were applied to assess the influence of conditions on buffer migration parameters.

In providing migration data and uncertainty estimates for the various conditions, /Ochs and Talerico, 2004/ provide a median value and a lower and upper limit in logarithmic scale. The likelihood for any data to fall within the recommended ranges is expressed verbally, i.e. based on expert judgment by the authors. This is supported by consistency checks using independent data and a traceable and extensive documentation of data derivation in appendices.

The uncertainties are evaluated in a way that makes it generally very likely that the indicated limits encompass all possible values. Where data are more uncertain, this is discussed specifically. For each element, this is supported with illustrations and consistency checks using diffusion data to facilitate an independent interpretation by the user of the report, where required. /Ochs and Talerico, 2004/ describe in detail which factors were considered in this uncertainty estimation.

Resulting estimates for D_e, ε and K_d-values for the various explored conditions are provided in Appendix A.5.

Judgements made by the SR-Can team

The judgements made by /Ochs and Talerico, 2004/ are generally accepted by SR-Can team. For the selection of data to the assessment calculations the following additional considerations are made by the SR-Can team:

- According to the discussion by /Ochs and Talerico, 2004/ and /SKB, 2004c/, the external impact on the buffer migration parameters is essentially through groundwater composition (including assumptions of the redox conditions) and assumptions of CO_2 interactions with the host rock. It is for the SR-Can interim base case calculations suggested to use Beberg data for reference groundwater together with the assumptions of redox conditions given in Appendix A.4. This will together with the assumption that the system is open for CO_2 result in the diffusivities, porosities and sorption coefficients given in Tables A-7–A-8 (according to the pore water speciation given in A-6).
- The ranges (lower to upper) provided for the given conditions are evaluated in a way that makes it generally very likely that the indicated limits encompass all possible values. In order to convert these values to probability distributions, a triangular distribution (lower, mode, upper) is suggested. In SR-Can interim, values outside these ranges are considered as “hypothetical” or “what-if”.
- The correlations stated by /Ochs and Talerico, 2004/ need to be considered in the probabilistic analyses. The overall impact of changing conditions should be handled by considering varying buffer pore water composition – and then select migration parameters consistent with each condition. Furthermore, the correlation between various elements suggests that a reasonable, but yet pessimistic assumption would be to consider full correlation between the elements for a given condition (i.e. consistently select high or low K_d-values for all elements in a realisation).

For SR-Can interim there is no new pore water for the explored site. However, for the final SR-Can report, site specific pore water compositions will be determined. Hence some of the values given in this report might be revised for the final SR-Can report.

5.3 Migration and material data for backfill

For the base case in the SR-Can interim calculations, the migration data for the backfill are the same as those used in SR 97, presented in Appendix A.6. A discussion about the uncertainties in these are presented in the SR 97 data report /Andersson, 1999/. 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 outlined in section 2.4.

6 Rock mass data

6.1 Thermal properties

Thermal properties, i.e. rock thermal conductivity and rock heat capacity as well as the temperature at repository depth are needed for evaluating repository evolution. These quantities are assessed in the site descriptive model, i.e. /SKB, 2004b/ for the SR-Can interim version. The thermal properties are judged important input to the safety assessment, but will not be assessed rigorously in this interim version of this report. The confidence in the input data is limited in version 1.1 and a more rigorous assessment is expected in version 1.2 of the site descriptive modelling, to be used in SR-Can.

6.1.1 Modelling in SR-Can

The following thermal properties and thermal conditions are used as input data in SR-Can:

- Spatial distribution of thermal conductivity [W/(mK)].
- Temperature in the regional scale at about 500 m depth.
- Regional heat flow [mW/m^2].
- Temperature gradient [˚C/km].

These data are used for calculating the temperature evolution in repository and host rock.

6.1.2 Sensitivity to assessment results

Not ready for the interim report

6.1.3 Source of information

Site specific thermal properties of the bedrock are provided from the applicable site descriptive models as described in the corresponding model reports. For the SR-Can interim analyses, data are obtained from the version 1.1 site descriptive model of the Forsmark site /SKB, 2004b/. The thermal properties are assessed in section 5.3 and summarised in section 7.2.3 of that report.

6.1.4 Conditions for which data are supplied

Data for the thermal properties of the bedrock provided in the version 1.1 site descriptive model of the Forsmark site /SKB, 2004b/ concern the situation as it appears today.

6.1.5 Conceptual uncertainties

The site descriptive model report only discusses uncertainties connected to the actual data. Conceptual uncertainties are judged to be small.

Judgement by the SR-Can team

For the purpose of this interim report the description of conceptual uncertainty as provided in the report cited above is judged adequate. Furthermore, there is likely to be few conceptual uncertainties related to determining site thermal properties.

6.1.6 Data uncertainty, spatial and temporal variation

Input from the Site descriptive model report

Several uncertainties connected to the actual data are discussed in the Forsmark version 1.1 report /SKB, 2004b, section 5.3.6/, including:

- *Uncertainties in measurement techniques*: The technique used to determine thermal conductivity perpendicular and parallel to the rock foliation has large uncertainties and was not developed for that purpose. It is possible to evaluate both principal directions with the TPS-method but a special measurement and evaluation technique is necessary. These uncertainties may also influence the determined mean values for the samples.
- *Small number of samples*: The small number of measurements for each rock unit gives uncertainties in measured values and low accuracy in the comparison with calculated values.
- Lack of data concerning thermal properties at *elevated temperature*.
- *Modelling from mineral content*: Uncertainties in the chemical composition of primarily plagioclase in the investigation area. Uncertainties in the representativeness of calculated thermal conductivities for different rock units and domains.
- *Assigning thermal properties to the rock mass*: Small-scale variation in thermal properties for rock units makes the up-scaling to a larger volume uncertain.
- Small volumes of *anomalous rock variants* within a lithological unit may bias the estimate of thermal conductivity based on modal analysis, because data are used without any possibility to weight with respect to the amount of occurrence. Future descriptions on the lithological distributions within the rock units would help to increase a general understanding of the lithological variations within the domains.

However, neither of these uncertainties are actually quantified in the version 1.1 site descriptive model.

Judgement made by the SR-Can team

For the purpose of the interim report the uncertainty treatment is not a major issue. However, a better understanding of the especially the up-scaling of the small scale samples into the more appropriate canister scale would be needed. Potentially, much of the variability measured in core samples would be averaged out and resulting in much less variance in the more appropriate canister scale.

6.1.7 Correlations

Input from the Site descriptive model report

The most important aspect of correlation of thermal properties is related to the spatial correlation as this would affect the up-scaling of thermal properties measured at core samples. However, such correlations are not quantitatively assessed in version 1.1 but may potentially be assessed in version 1.2.

Chapter 6 of the site descriptive model report also assesses the consistency between disciplines. It concludes that the thermal property assignment is consistent with the geological description.

Judgement by the SR-Can team

When there is a spatial correlation provided by the site descriptive modelling this should be used to up-scale thermal properties based on core sample measurements. However, for the interim report the spatial correlation is not quantified, which means that the resulting variance in canister scale thermal properties would be overestimated. The noted consistency between the thermal model and the geological description enhances confidence, but has no direct impact on selection of input data for the safety assessment.

6.1.8 Quantification

Input from Site Model report

Section 7.3.3 of the Forsmark version 1.1 report /SKB, 2004b/ summaries the modelled thermal properties and conditions of the site.

In-situ temperature

Temperature loggings from KFM01A indicate that the in situ temperature increases from about 7°C at a depth of 100 m to about 13°C at 600 m and about 18°C at the depth 1000 m. The temperature gradient increases with depth, from about 11°C/km at the depth 400 m to about 14°C/km at 900 m. The temperature gradient curve has a relatively constant slope but there is a tendency for the gradient to be lower at larger depths (weak convex shape of the temperature gradient curve).

Thermal transport properties

Thermal conductivity has been calculated from mineral composition of a total of 71 rock samples. Results are categorized for the rock domains. Rock domains with only 1–2 rock samples are excluded from the following presentation.

Rock domains 29 and 17 dominate the candidate area and the mean values of the thermal conductivity are 3.41 W/(m·K) and 2.73 W/(m·K), respectively. The corresponding standard deviations are 0.206 W/(m·K) and 0.216 W/(m·K), respectively. However, in section 5.3.2 it is noted that "… distributions only are valid at the SCA scale, i.e. at the mm-cm scale. If the distributions are to be applied at a different scale, a transformation to the appropriate scale must first be performed".

Measurements of anisotropy of thermal conductivity, parallel and perpendicular to the foliation in the rock, did not give unambiguous results.

Judgement made by the SR-Can team

For the interim assessment it is judged appropriate to use the mean values and standard deviations provided in version 1.1 report and cited above. Table 6-1 lists the values recommended for SR-Can interim.

Table 6-1. Thermal properties to be used in SR-Can interim.

Rock thermal conductivity	2.73 3.41	W/(m·K)
Temperature at repository depth	12	°C

6.2 Hydraulic properties and the EDZ

Groundwater flow modelling provides some key entities for the subsequent radionuclide transport calculations in the SKB safety assessment model chain. The primary input to the flow modelling are the hydraulic properties of the bedrock. These are assessed in the site descriptive model, i.e. SKB 2004b for the SR-Can interim stage. Furthermore, the impact on these properties from the tunnel and its construction, i.e. the potential for development of an excavation damaged zone need also be considered.

While the hydraulic properties are judged essential input to the safety assessment, they will nevertheless not be assessed rigorously in the interim report. The confidence in the input data is too poor and the actual values are also likely to be quite changed in version 1.2 of the site descriptive model. A more rigorous assessment is expected in SR-Can itself.

6.2.1 Modelling in SR-Can

The groundwater flow modelling in the SR-Can interim concerns:

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

The modelling will use two codes for the analysis, CONNECTFLOW (NAMMU +NAPSAC) /Marsic et al, 2001, 2002/ and DarcyTools /Svensson, 2002a,b/. It should also be noted that in SR-Can, migration in the rock and tunnel will be handled together (in the FARF31 code, see section 6.5).

The required property input for this modelling is the geometry and transmissivity of the deformation zones and the fractures of the bedrock. Depending on scale, the geometry and properties of these features are provided "deterministically" or "statistically" as a Discrete Fracture Network (DFN), see /SKB, 2004b/. With the adopted modelling approach also the effect of the Excavation Damaged Zone (EDZ) needs to be included in this description as a (potential) change in the DFN-properties close to the tunnel and not as a specific input to COMP23 – as was the case in SR 97 /SKB, 1999a,b/.

The EDZ is defined as the *remaining impact*, i.e. after resaturation, on the hydraulic properties (see above) from the tunnelling. The EDZ basically originates from:

- excavation damages (i.e. from the blasting or TBM if this is used) and
- the changes of the stress field resulting from the changed stress boundary conditions compared to the undisturbed situation.

The hydraulic modelling will also require initial and boundary conditions. These are, however, not discussed in the data report, but in the assessment and modelling reports.

6.2.2 Sensitivity to assessment results

Groundwater flow directly affects near-field release and far-field retention. The latter is essentially proportional to the transport resistance and the advective travel time. SR 97 /SKB, 1999a,b/ as well as subsequent sensitivity studies /e.g. Hedin, 2002/ demonstrate that transport resistance in particular has a large impact on retention and thus on resulting risk and dose – in case there is a release. See also discussion in chapter 7.

The importance of the EDZ, being limited to a portion of rock around the tunnel is less pronounced. It would only have an impact if it results in a flowing pathway allowing for more effective migration from the deposition hole to highly flowing fractures. Minor changes of transmissivity of individual fractures are not likely to have any impact at all.

6.2.3 Source of information

Initial geometry and transmissivity of deformation zones and fractures

Data for the geometry and transmissivity of the deformation zones and the fractures of the bedrock are provided from the applicable site descriptive models as described in the corresponding model reports. For the SR-Can interim analyses data are obtained from the version 1.1 Site descriptive model of the Forsmark site /SKB, 2004b/. The hydraulics properties are assessed in section 5.4 of that report.

Impact from the EDZ

A special assessment of the hydraulic significance of the EDZ is planned for SR-Can. The development and extent of an Excavation Damaged 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.

Since the coming analyses are likely to suggest that the EDZ is likely to be limited and its extent can be controlled by the tunnel design and excavation technique, the impact of the EDZ may be probably be very insignificant for the interim study. Nevertheless, some data are provided here on its possible properties, based on personal communication with the SKB experts (see section 1.3) involved in assessing the EDZ.

6.2.4 Conditions for which data are supplied

Data for the geometry and transmissivity of the deformation zones and the fractures of the bedrock provided in the version 1.1 Site descriptive model of the Forsmark site /SKB, 2004b/ concern the situation as it appears today. Changes in rock mechanics or chemistry may alter these properties but the impacts are generally small apart from possibly the following conditions:

- impacts from repository opening and construction and operation (the EDZ),
- impacts from the thermal load,
- impacts from major future mechanical loads such as earthquakes and glaciations.

However, only the impact of the EDZ is assessed here. The other impacts are part of the SR-Can scenario analysis and are to be analysed in the SR-Can main report. Limited or no assessment of these impacts is expected in the SR-Can interim main report.

6.2.5 Conceptual uncertainties

Input from the Site descriptive model report(s)

Section 5.14 and section 6.3 of the Forsmark Site descriptive model report /SKB, 2004b/ discusses the main uncertainties of the hydrogeological model. It is generally concluded that model version 1.1 is the first step towards a realistic site description of the in situ conditions at Forsmark. Some of the uncertainties are due to lack of data and will be resolved in due time, whereas others will always be, more or less, a part of any site description, regardless of the extent of the investigations. The latter condition is obvious for two reasons:

- large areas are far from the target area and will never be investigated, and
- the number of boreholes in the target area must be limited due to, among other things, physical reasons.

It is within this framework that numerical hydrogeological modelling comes into play as a tool for analysing the impact of both parameter heterogeneity and various conceptual uncertainties. The following uncertainties and issues are particularly emphasised in the Site descriptive model report:

- The uncertainties of the structural geological model of the target area; in particular, the occurrence and extensions of sub-horizontal deformation zones.
- Due to lack of data, the hydraulic properties, signature and potential differences between deformation zones of varying geological confidence are essentially only provided based on assumed similarity with deformation zones where there is data.
- The geological fracture network description; in particular, surface variability, the coupling between surface and depth data, and the geological classification of conductive fractures.
- The assumed fracture transmissivity correlation to fracture size and the assumption that the intensity of features of different sizes in different directions varies as power law distributions, with a unique slope for each fracture, set is more a hypotheses than a well-established fact.
- The database for the deduction of fracture transmissivity; in particular, the motives, e.g. rock mechanics ones, for assigning set-specific differences (geometric anisotropy) and depth variation is very small. Current assumptions on anisotropy and depth variation are thus uncertain.
- For version 1.1 the distribution groundwater salinity is poorly known at depth. This limits the possibilities of checking whether the hydrogeological model is reasonable with respect to the hydrogeochemical one.
- The state of stress is known to a limited extent, based on old data – and some re-evaluation of this information.

These conceptual uncertainties form the basis for hypotheses of alternative hydrogeological models as outlined in section 6.3 of the model report. However, in version 1.1 the hypotheses are not developed into alternative descriptions.

Input from assessing the EDZ impact

Conceptual uncertainty related to the EDZ will be discussed in the coming special report for SR-Can. The issue is not further discussed in this interim report apart from the following (based on input from SKB expert, section 1.3):

- The excavation technique (Drilling and Blasting, D&B, or Tunnel Boring Machines, TBM) may damage the rock wall. However, experiences from blasting the APSE tunnel /Staub et al, 2004/ suggest that blasting damages can be controlled and can certainly be limited to in the order of decimetres.
- Review of earlier results /Bäckblom et al, 2004/, primarily the ZEDEX experiment, show weak evidences for a significant increase in hydraulic conductivity in the EDZ.
- Another issue is effects of stress. The removal of the rock implies introduction of a "zero" stress boundary in an environment where in-situ stresses may be high. This could result in spalling, but with proper design this problem could be mitigated, once the state of stress is known with a reasonable confidence.
- Furthermore, both direct excavation damages and the stress "redistribution" may mobilise existing fractures both in shear and normal mode. This can occur at much lower stress levels than needed for spalling and has also been observed e.g. at the ongoing pillar stability experiment at Äspö /Staub et al, 2004/. Visual observations suggest that the fracture opening is restricted to a few decimetres close to the tunnel and only applies to the existing fractures.). More information on the fracturing will be obtained later when the pillars at APSE experiment will be excavated. Conclusions may be reached by the end of 2004. Various works has demonstrated a reasonable good predictive capability of these phenomena, which means that they can be taken into account in the design.
- The potential development of an EDZ largely depends on the actual excavation practices. The APSE experiment demonstrates that the EDZ may indeed be very limited – also in the tunnel floor. Furthermore, it is also possible to actively enhance construction quality by inspection followed by adjustment of the excavation technique. This means that the possibility for development of an EDZ to a large extent is a management and QA issue. The TBM method is a continuous excavation method, but causes a relatively small EDZ, as long as stresses are at a moderate magnitude. The D&B method may cause deeper damage, but the method is discontinuous. The evidences for a continuous hydraulic flowpass in the EDZ of a D&B tunnel is so far weak. Local depth of damage zone using the same sawing technique as in the ZEDEX tunnel is planned for the APSE tunnel. Possibilities for setting up experiments to study the hydraulic connectivity of the EDZ are discussed in the SKB RD&D Programme 2004. Results are not likely in the near future. At least before data from such experiments are obtained – it is probably necessary to conservatively assume that the fractures opened in the EDZ also will be significant hydraulically.
- Even if fractures are formed or opened the question remains whether this could result in continuous water paths. Possibilities for setting up experiments to study this are discussed in the SKB RD&D Programme 2004. Results are not likely in the near future. At least before data from such experiments are obtained – it is probably necessary to conservatively assume that the fractures opened in the EDZ also will be significant hydraulically.

In conclusion it is reasonable to assume that the EDZ, if it all develops, is limited to a narrow zone (a few tenth of cm) close to the tunnel and that it essentially only affects already existing fractures. Possibilities for more extensive fracturing would only be connected to poor engineering and QA practices, i.e. they lie outside the expected range of repository conditions.

Judgement by the SR-Can team

For the purpose of this interim report the description of conceptual uncertainty as provided in the reports cited above is judged adequate. For SR-Can, a more elaborate and quantified description of the uncertainties are expected.

6.2.6 Data uncertainty, spatial and temporal variation

Input from the Site descriptive model report(s)

The site descriptive model, (see section 5.4 of /SKB, 2004b/) captures the strong spatial variability of the hydraulic properties in the form of a statistical discrete fracture network model. This means that the uncertainty in exactly where the conducting fractures occur in the rock is expressed by the different realisations of this model. Furthermore, there are quantified estimates of the uncertainty in orientation of the "deterministic" deformation zones in the model. However, the lack of data makes these estimates quite speculative.

The various conceptual uncertainties discussed in the previous section may also lead to the formulation of alternative setups of hydraulic properties, but this is not the case for version 1.1.

Input from the EDZ assessment

As the EDZ essentially is confined to existing fractures the spatial variability of the EDZ will be related to the spatial variability provided by the discrete fracture network. The depth dependence will depend on the stress situation. In SR-Can data uncertainty and variability of the EDZ will be assessed in the special EDZ report. No specific assessment of spatial variability and data uncertainty is made here for the interim report.

Judgement by the SR-Can team

For the purpose of this interim report the description of data uncertainty and variability as provided in the reports cited above is judged adequate.

6.2.7 Correlations

Input from the Site descriptive model report(s)

The statistical discrete fracture network, with its connection to the "deterministic deformation zones", is intended to capture the spatial correlation of the hydraulic properties. Alternative models, with other spatial correlation structure, are only briefly discussed in version 1.1, but may potentially be assessed in version 1.2.

Chapter 6 of the SDM report also assesses the consistency between disciplines:

- The hydrogeological description is directly correlated to the geological description. Foremost, the geometry of deformation zones and fractures (deterministic and stochastic DFN) is directly transferred to the hydrogeological model. Indirectly, also the rock domain description is used as it motivates the spatial distribution of the DFN-model.
- Possibilities of e.g. anisotropy consistent with stress are discussed – but not quantified in 1.1.
- Simulation of past salinity evolution makes is possible to compare the hydrogeological model predictions with the predictions made in hydrogeochemistry and thus enhance

understanding of the hydrogeochemical evolutionary processes. Conversely, the hydrogeochemical description of the current salinity distribution provides a "calibration target" for simulation (but the salinity distribution in rock matrix would also be "needed"). However, limited data in version 1.1 did not allow for any far reaching conclusions.

Input from the EDZ assessment

The significance of the EDZ is likely to be much related to the actual discrete fracture network, to the stress situation and to the local rock mechanics properties. The EDZ will manifest itself mainly as a transmissivity increase due to depth of failure in spalling studies and because of existing (i.e. modelled) fractures in the vicinity of the tunnels. These correlations will be further elaborated on in the EDZ report planned for SR-Can.

Judgement by the SR-Can team

The spatial correlation provided by the Site descriptive modelling should of course be maintained in the safety assessment calculations, e.g. by noting that individual realisations of the hydraulic DFN represents spatial variability, whereas uncertainty is captured by multiple realisations. The noted consistencies between disciplines enhances confidence in the models, but has no direct impact on selection of input data for the Safety Assessment.

In case an EDZ analysis is conducted already for the interim assessment the correlation to the discrete fracture network should be considered (see next section).

6.2.8 Quantification

Input from SDM report

Table 5-38 of /SKB, 2004b/ summarises the hydraulic properties of the deterministically modelled deformation zones of the Forsmark version 1.1 Site descriptive model. Section 5.4.6 defines the hydraulic properties of the statistical (DFN) description. The actual data are not repeated here.

Input from EDZ assessment

Provisionally, it is assumed reasonable to accept the APSE tunnel blasting damages and observed fracture openings as realistic. These observations suggest that the EDZ, if it all develops, is limited to a narrow zone (a few tens of cm) close to the tunnel, that it essentially only affects already existing fractures and that it may not be significantly continuous.

However, for the purpose of this interim report it is suggested to apply a 0.3 metre EDZ in the tunnel bottom. Within this zone any fracture as generated by the DFN-model and with a dip less than 30 degrees in relation to the tunnel floor could have its transmissivity increased by more than an order of magnitude. Evidently a more elaborate data analysis is expected for the EDZ assessment report to be produced in support of SR-Can.

Judgements made by the SR-Can team

The judgements made above are generally accepted by the SR-Can team. The selection of these available data for the actual flow simulations in support of the SR-Can interim analyses are provided in the interim main report.

6.3 Rock mechanics

In SR-Can, there will also be some assessment of the rock mechanics and coupled THM effects. However, at the time for this interim report, the premises for this modelling as well as the selection of input data to be used, has not been finally selected. This means that this section will not be further developed in the interim report.

6.4 Migration properties of the rock (non flow related)

Migration of solutes, including dissolved radionuclides depend on several parameters. Some of these parameters, like matrix diffusivity, porosity and distribution coefficients are related to the rock mass properties themselves, whereas other are closely related to the groundwater flow i.e. are "flow related". This section evaluates the rock mass related properties, whereas the flow related ones are discussed in the next section (section 6.5).

In this interim report, rock porosities, diffusivities and sorption coefficients are based on SR 97 Beberg data /Andersson, 1999/ and are presented in Appendix A.7. Based on the SR 97 data report, rock porosities of 0.005 and 0.0005 are assumed for cations and anions, respectively. For rock diffusivities and sorption coefficients a log-normal distribution is assumed with the mean corresponding to the reasonable value and a standard deviation chosen so that 5% of the probability distribution is less favourable than the pessimistic. In the final SR-Can report, these data will be re-evaluated and uncertainty estimates provided.

6.5 Flow related migration parameters

An important part of the parameters controlling the radionuclide migration are related to the amount and distribution of the groundwater flow. The values of these flow related migration parameters are essentially obtained by simulation, using the basic data and description as provided in the applicable site description.

6.5.1 Modelling in SR-Can

The radionuclide transport calculations in the near-field, COMP23 /Romero et al, 1999; Cliffe, 2004/, and the far-field, FARF31 /Norman and Kjellbert, 1990; Elert et al, 2004/, use the following flow related migration parameters:

- Transport resistance, the so-called F-factor [T/L].
- Advective travel time, t_w [T].
- Darcy velocity, or specific flow rate, at representative canister locations, q [L/T].
- Equivalent flow rates Q_{eq1} and Q_{eq2} [L^3/T].
- Peclet number, Pe [1].

The transport resistance, advective travel time and Peclet number are direct input parameters for FARF31. Internally, FARF31 uses the flow-wetted surface per volume of water, a_w, for each path line defined as $a_w=F/t_w$.

COMP23 is based on using the Darcy velocity; however, this parameter is modified in the internal COMP23 use. Two issues are brought up here. First, two separate Darcy velocities are considered, one for fractures intersecting a deposition hole (the Q1 path in SR 97), and one for the EDZ (the Q2 path in SR 97). Second, several fractures may intersect a deposition hole and here a summation of the water flux of all fractures is done yielding a conservative assumption.

For the fractures intersecting a deposition hole, the flux into all fractures that intersect the deposition hole and contribute to advective flow away from the canister are included in the calculation of the equivalent flow rate Q_{eq1} used by COMP23. That is, an effective flow rate is calculated for all fractures that cut the deposition hole and at least one other fracture. These effective flow rates are summed for the deposition hole to give the total Q_{eq1}. The equivalent groundwater flow rate can be written as:

$$Q_{eq1} = \sum_f \left(2Q_f \sqrt{\frac{4D_w t}{\pi}} \right), \quad t = \frac{L\,\alpha_t}{Q_f}$$

Correspondingly, the equivalent Darcy velocity for all fractures intersecting the canister is:

$$q = \frac{(\sum_f Q_f)}{W_c}$$

where:

- D_w is the diffusivity in water, $[L^2\ T^{-1}]$.
- t is the time the water is in contact with the source area, [T].
- L is the length of the advective pathway in contact with the source, [L].
- q is the average Darcy velocity in the fracture system around the canister (water flux) $[L^3\ L^{-2}\ T^{-1}]$.
- Q_f is the average flux per unit fracture length in the fracture adjacent to the deposition hole $[L^2\ T^{-1}]$.
- α_t is the transport aperture adjacent to the deposition hole [L].
- W_c is the canister height [L].

For the EDZ, the equivalent groundwater flow rate Q_{eq2} can be written as:

$$Q_{eq2} = 2Wq^{0.5} \cdot \sqrt{\frac{4D_w L\varepsilon}{\pi}}$$

where:

- q is the Darcy velocity for the advective pathway (water flux) $[L^3\ L^{-2}\ T^{-1}]$.
- W is the contact height for the advective pathway [L].
- D_w is the diffusivity in water, $[L^2\ T^{-1}]$.
- L is the length of the advective pathway in contact with the source, [L].
- ε is the porosity of the material surrounding the source area, [1].

The remainder of this section will only discuss F, t_w and q (Darcy velocity) at the canister scale.

6.5.2 Sensitivity to assessment results

Sensitivity analyses of the parameters discussed in this report were made in SR 97 /SKB, 1999a,b; Lindgren and Lindström, 1999/.

The flow related parameters which mostly affect radionuclide retention in the geosphere are q and F. For the Darcy velocity (flux) it was shown that low values may result in the boundary layer between the buffer and rock being the limiting factor for doses; conversely, for higher fluxes other resistances control the dose.

For the transport resistance, it was shown that a value larger than 10^4 years/m for most nuclides provides adequate retention. The impact is monotonous, but not linear, for both these parameters; a higher F and lower q always yield lower doses and associated risks.

The advective travel time is mainly of interest for non-sorbing nuclides. However, a long advective travel time is beneficial only for short-lived, non-sorbing nuclides. Thus, the maximum release rates of long-lived nuclides such as iodide are effectively un-affected by the advective travel time.

Varying the Peclet number within the range used in the SR 97 assessment does not influence the breakthrough of radionuclides in any significant manner. This is an important observation, since it is difficult to estimate this parameter from field or any other evidence.

6.5.3 Source of information

The transport resistance, advective travel time, and Darcy velocity are direct output entities from numerical groundwater flow models. /Hartley et al, 2004/, using the code CONNECTFLOW /Serco Assurance, 2004/, have analysed a base case and a number of cases addressing some uncertainties. The SR-Can team has then selected a subset of these results for further radionuclide transport calculations. Furthermore, the proposed values for the Peclet number are solely based on previous experience and expert judgement.

Databases

The modelling performed uses the Forsmark site descriptive model version 1.1 /SKB, 2004b/ as input, see also section 6.2 above. The site descriptive model provides e.g. information on regional model domain size, geometrical information and parameterisation of deterministic fracture zones, and a statistical description of the stochastic discrete fracture network (DFN). Also, the site descriptive model provides information on relevant initial conditions for the salinity distribution, and relevant boundary conditions for the flow simulations; e.g. a functional relationship for the expected future shore-line displacement is provided.

In the Formark version 1.1 model, two alternative DFN models are provided. Both have been used in the modelling described below.

It is noted that the Forsmark version 1.1 model is based on the first data-freeze; i.e. the model contains surface-based information and information from one deep borehole only. Thus, the model is to a great extent hypothetical and should not be considered to fully or even correctly reflect actual site conditions.

Simulations

A modelling methodology has been developed to produce the requested data. Generic work and early methodology development are described in /Gylling et al, 2004/, whereas the site-specific application serving as a basis for the data presented in this report is fully described by /Hartley et al, 2004/.

A regional continuum porous medium (CPM) model is used to describe the evolution of the pressure and salinity fields at the site. The CPM properties are obtained by up-scaling of the underlying DFN network properties on a 1000m block. The transient CPM model provides boundary and initial conditions for a regional nested CPM-DFN model where an explicit DFN description, encompassing the repository foot-print, is nested within the CPM. The regional DFN description includes fractures down to a length scale of 50 m for the Base Case DFN model of /Hartley et al, 2004/.

In the DFN model, density driven flow can not be included; instead, quasi-steady state flow is computed in the nested model using a salinity distribution interpolated from the fully transient CPM model at a number of discrete times. This involves computing the salinity distribution in the CPM region from a snapshot of the salinity at a set of appropriate times in the future (2,500 AD and 12,000 AD), and then using this to calculate the flow-field in the nested model based on the appropriate salinity and boundary conditions for that time. The density of water in the DFN part is taken as a constant. In the CPM part, the groundwater density is held fixed at the value calculated at that time in the pure CPM model. The salinity, and water density, are therefore fixed distributions in the CPM part, but pressure, and hence flow, are recalculated in the nested model. Pressure and mass flux are continuous at the interface. However, to ensure that the correct driving force for flow, or potential, are used in the DFN part, the continuity equation at the CPM/DFN interface is modified to account for variable density. The modification is to equate the residual pressure in the DFN model to the environmental pressure in the CPM model at the interface.

The nested CPM/DFN model provides exit locations for particle starting positions within the full repository; however, the transport/retention on finer scales closer to canisters are not resolved with this model.

A nested canister-scale DFN/CPM model of the fracture network around the repository, and the continuous engineered structures (tunnels and deposition holes) is constructed to resolve transport and retention at the finest scale. Here fractures down to a length scale of 3.5 meters are included. The canister-scale model provides a representation of the deposition holes and fractures intersecting the holes. Also, the tunnel and EDZ are explicitly modelled (however, in the present version, the tunnel and EDZ are not resolved separately). The information obtained from this model is Darcy velocity (groundwater flux) for the Q1 and Q2 pathways, where Q1 represents the fracture intersecting a deposition hole, and Q2 represents the EDZ pathway, and corresponding F-factor and t_w values for the two pathways. When particles reach the boundary of the nested canister-scale DFN/CPM model, the pathways continue in the regional scale nested CPM/DFN model. Thus, particles can be traced to the ground surface of the regional model domain.

More details of the modelling strategy can be found in /Hartley et al, 2004/, where all model cases analysed also are presented in detail.

6.5.4 Conditions for which data are supplied

The following conditions are considered by /Hartley et al, 2004/:

- A situation corresponding as closely as possible to today's conditions at the Forsmark site, as expressed through the Site-descriptive model for Forsmark, version 1.1 /SKB, 2004b/, but with a back-filled and water saturated repository.
- Future conditions extrapolated in time but otherwise based on current Forsmark conditions. The repository is also assumed back-filled and water saturated for these conditions. A time span up to 12,000 AD is considered.
- The present and future conditions are also evaluated for a case where the back-filled repository has poorer hydraulic properties; i.e. a lower hydraulic conductivity.
- Two alternative models of the discrete fracture network (DFN) describing the site are assessed.
- Conditions corresponding to an open repository in operation, and the resaturation phase after closure, should ideally also be considered. However, in the present report no such data are provided due to the lack of site-specific hydrogeological simulations dealing with these issues.
- Future climatic conditions such as permafrost and glacial regimes should ideally also be covered. However, in the present report no such data are provided due to the lack of site-specific hydrogeological simulations dealing with these issues.

6.5.5 Conceptual uncertainties

Judgement by SR-Can team

The main conceptual uncertainty is related to the DFN description (see also section 6.2), i.e. is the selected discrete fracture network representation the most valid model of the Forsmark site? Could it e.g. be argued that such a tight rock with a few water conducting features as found in Forsmark in fact is better modelled as a (more or less impermeable) continuum with a few deterministic water conducting features? Such a hypothesis can not be answered with the presently available knowledge; future model versions of the Forsmark site will shed light on this issue. At present, we can only acknowledge the uncertainty stemming from the limited knowledge.

In general, the present day simulations of the back-filled repository are believed to have the highest confidence of the cases presented. However, a differentiation is made concerning the base case DFN and variant DFN, where the variant DFN is believed to more accurately reflect actual site conditions. The reasons are given in /SKB, 2004a/, but can in short be summarised such that the variant DFN is based on a better classification of the fractures found at site. Specifically, the base case DFN has too many water conducting fractures, resulting in lower transmissivities of the fractures. Conversely, the variant DFN has fewer fractures with higher transmissivities. The latter model is believed to be a more accurate description of actual site conditions.

All simulations of future conditions have a higher uncertainty since the shore-level displacement constitutes an additional source of uncertainty. Moreover, additional changes expected to occur during the next 10,000 years are not incorporated in the model. This limitation also adds to the overall increased uncertainty. The issues concerning the variant DFN and variant back-fill options discussed above also applies to the future conditions.

6.5.6 Data uncertainty, spatial and temporal variation

Judgment by the SR-Can team

All flow related parameters are subject to spatial variation. In fact, the single-realisation distributions presented reflect the spatial variability found at the site (assuming the underlying statistics of governing parameters are known). The likely non-ergodic conditions prevailing are assessed by using multiple realisations. The difference in resulting distributions between realisations captures the uncertainty resulting from the spatial variability.

Temporal variability is accounted for by analysing to discrete points in time. However, here a possibly severe, and site-specific, limitation is that F-factors and travel times are calculated as snap shots in time (i.e. in a steady-state velocity field). If path lines for different discrete points in time are similar, the effect of this simplification is small; for larger discrepancies the effect of the simplification can most easily be addressed by supporting calculations as outlined in /SKB, 2003/.

A clear lack of knowledge is related to intra-fracture heterogeneity. In the models used, all fractures have homogeneous properties. This results in a misrepresentation of channelling within single fracture planes. Such channelling may result in a lowering of the fracture surface over which flow occurs, which in turn results in a lowering of the transport resistance (F-factor). To account for such channelling, a correction factor is proposed, see below.

The implication of the uncertainty due to channelling may not be as severe as one may first expect when the transport resistance is considered. This is due to the fact that when strong channelling prevails, diffusion of solutes from the mobile water phase to the immobile water phase in the fractures will take place. The solute will subsequently diffuse into the matrix from the stagnant water. Thus, effectively the surface for matrix diffusion has increased. This process is likely to be relevant on the time scales considered for performance assessment applications. A quantification of the process and implementation in present computational tools remain to be done.

6.5.7 Correlations

Judgement by SR-Can team

As discussed above, all parameters discussed here vary in space. The Darcy velocity values are point values, whereas the F-factor and advective travel time are Lagrangian quantities integrated along path lines. However, the values at the end of the path lines can be represented as point values with uni-variate distributions.

The auto-correlation is not an issue of interest, but rather the uni-variate distribution of each parameter, and the cross-correlation between the parameters. A clear cross-correlation is seen between travel time and F-factor (in fact, a functional relationship can be approximated as $F=a_w \times t_w$ where a_w is the flow-wetted surface per volume of water), whereas the correlation between Darcy velocity and F (or t_w) is weaker in a discrete fracture network.

Due to the correlations, triplets of values should be sampled (i.e. corresponding values of q, t_w and F for the same canister location) for further transport calculations. If the two separate pathways Q1 and Q2 are considered, two pairs of triplets for the same canister location should be sampled.

6.5.8 Quantification

The uncertainty stemming from the spatial variability is accounted for by using multiple realisations. The single realisation distributions and ensemble distribution resulting from multiple realisations imply that actual probability density functions are available for use in subsequent radionuclide transport simulations. Thus, there is no need to use subjective ranges or estimated percentiles. However, a choice needs to be made between the different variants analysed with respect to which case(s) to propagate for further analyses. In this choice, also the probability (likelihood) of the case should be evaluated. That is, for what conditions is the proposed case supposed to be relevant for, and what is the likelihood for those conditions to prevail.

Input from simulations

/Hartley et al, 2004/ have modelled a number of variants. The main case is the Base Case model (denoted 1), which is further divided into 1A and 1B for present day and future conditions, respectively. Furthermore, the notation 1A1 for the whole ensemble, and 1A2 for a single realisation, is used. In simulations 1A1 and 1A2, only 604 canisters in a subset of the repository layout are included. However, results are available for the Base Case model where all 5026 canisters are included, but here the canister scale DFN/CPM model is not included. Thus, starting positions are located in fractures with sizes given by the regional scale DFN model. This case is denoted 1A3. Results are also available for the pure CPM model with 604 starting positions; this case is denoted 1A4.

Cases corresponding to 1A2 and 1A3 but for time equal to 12,000 AD are denoted 1B2 and 1B3.

Simulations with the variant DFN are performed only in the regional nested CPM/DFN model for transport calculations, but including the repository scale also for estimation of Darcy velocity. These simulations are carried out for both present and future conditions and give rise to the cases 2A3 and 2B3 for F-factor and cases 2A2 and 2B2 for Darcy velocity.

The cases with poor backfill are analysed both for present and future conditions for both the Base Case (denoted by the first digit ‘3’) and variant DFN model (denoted by the first digit ‘4’). These simulations are performed for present conditions (strictly 2,500 AD) only and are denoted 3A2 and 4A3, respectively. The Base Case DFN is simulated including the repository model, whereas the variant DFN is simulated without the repository model when travel time and F-factors are considered.

The resulting statistics of F, for the different cases are given in Table 6-2 below and the resulting statistics for Darcy velocity at the canister positions are presented in Table 6-3 below. Values are provided for the two paths corresponding to paths Q1 and Q2 of the near-field transport model. Q1 is the path through a fracture intersecting the deposition hole, and Q2 is the path through the Engineered Damaged Zone (EDZ).

Table 6-2. Median value, 5th and 95th percentiles of the F-factor /from Hartley et al, 2004/.

Case	Median log(F) (path1, path2)	5% log(F) (path1, path2)	95% log(F) (path1, path2)
1A1: Base Case 2500 AD (5 realisations)	6.5 , 6.5	5.2 , 5.3	8.0 , 8.1
1A2: Base Case 2500 AD (1 realisation)	6.8 , 6.8	5.3 , 5.3	8.1 , 8.1
1A3: Base Case 2500 AD (no repository scale but all canisters)	6.8 , -	5.1 , -	8.5 , -
1A4: Continuum Base Case 2500 AD	6.9 , -	6.6 , -	7.7 , -
1B2: Base Case 12000 AD	6.6 , 6.4	5.3 , 5.4	7.5 , 7.4
1B3: Base Case 12000 AD (no repository scale but all canisters)	6.3 , -	4.9, -	7.3 , -
2A3: Variant DFN 2500 AD (no repository scale)	7.6 , 7.7	4.9 , 5.0	10.0 , 10.0
2B3: Variant DFN 12000 AD (no repository scale)	7.7 , 7.8	4.9 , 5.1	10.5 , 10.5
3A2: Base Case 2500 AD poor back-fill	6.8 , 6.6	5.3 , 5.2	8.1 , 8.1
4B3: Variant DFN 2500 AD poor back fill	6.1, 6.1	4.1 , 4.4	9.7 , 9.7
5: Base Case DFN 2500 AD modified F	5.8 , 5.8	4.3 , 4.3	7.1 , 7.1

Table 6-3. Median value, 5th and 95th percentiles of the Darcy velocity at the canister locations /from Hartley et al, 2004/.

Case	Median log(q) (path1, path2)	5% log(q) (path1, path2)	95% log(q) (path1, path2)
1A1: Base Case 2500 AD (5 realisations)	–4.5 , –6.3	–5.5 , –6.6	–3.1 , –6.0
1A2: Base Case 2500 AD (1 realisation)	–4.4 , –6.3	–5.5 , –6.6	–3.1 , –6.0
1A3: Base Case 2500 AD (no repository scale but all canisters)	–4.6 , -	–5.8 , -	–3.1 , -
1A4: Continuum Base Case 2500 AD	–4.1, -	–4.5 , -	–3.1 , -
1B2: Base Case 12000 AD	–4.4 , –6.4	–5.5 , –6.6	–3.2 , –6.1
1B3: Base Case 12000 AD (no repository scale but all canisters)	–4.6, -	–5.8, -	–3.1 ,
2A2: Variant DFN 2500 AD	–5.1 , –6.6	–6.5 , –9.8	–3.0 , –6.1
2B2: Variant DFN 12000 AD	–5.2 , –6.7	–6.6 , –9.7	–2.9 , –6.3
3A2: Base Case 2500 AD poor back-fill	–4.5 , –5.4	–5.5 , –5.8	–3.2 , –5.3
4B2: Variant DFN 2500 AD poor back fill	–5.0 , –5.6	–6.5 , –9.9	–3.0 , –5.2

Model parameters

Diffusivity

Following the procedure described in the SR 97 data report, a diffusivity in water, D_w, of 10^{-9} m^2/s is used for all radionuclides in the SR-Can interim base case calculations.

Geometry of near-field/far-field interface

Lacking a detailed evaluation of the near-field/far-field interface it is suggested to use the values in SR 97 for the SR-Can interim simulations. Table 6-4 lists the suggested values of W_i and L.

Table 6-4. Values of W_i and L_i to be used in COMP23 (defined in section 6.5.1).

Path	W_i (m)	L_i (m)	Porosity, ε
Q1	5	2.8	1.00E–04
Q2	Triangular distribution T(0, 0.3, 1)	2.8	Triangular distribution T(0.0001, 0.0003, 0.001)

Judgements made by SR-Can team

Looking at the different cases and comparing the statistics for two paths in Table 6-2, it is seen that the F-values are essentially equal for the two paths. However, if individual canister locations are studied, it can be seen (not shown in the table) that the match between F for the two paths is not as good as indicated by the provided percentiles. Thus, it is suggested for the use in SR-Can Interim to use the separate paths for radionuclide transport calculations in the far-field.

The difference between a single realisation and an ensemble (5 realisations) indicates that the median value is somewhat shifted between the two, but the spread is similar. The number of realisations required needs to be tested from case to case. In the present application, it is suggested that the ensemble of five realisations rather than the single realisation is used for assessing the present day conditions when radionuclide transport is considered.

Comparing the two snapshots in time, it is observed that the case 12,000 AD has slightly lower F-factors then the case 2,500 AD. This is particularly true for the high tail of the distribution. However, since the present day simulations are of particular interest, and also are subject to less uncertainty, it is suggested that the case 2,500 AD primarily should be analysed.

Comparing the Base case and variant DFN models, it is seen that the variant DFN has a larger spread in F values. Thus it would be interesting to propagate this case, but the analyses were not completed in time for SR-Can interim and further development work would be needed. Therefore it is suggested to primarily propagate the Base case for radionuclide transport calculations.

The case with poor back-fill does not affect the F distributions. However, for the case with poor backfill, the Darcy velocity for path Q2 is increased approximately by one order of magnitude (as shown below). This motivates to propagate the case with poor backfill for radionuclide transport calculations.

The case with 5026 canisters represents the complete repository whereas the Base case only has 604 canisters in the south east corner of the repository; however, the case with 5026 canisters does not include the canister scale DFN/CPM model. Comparing these two cases it is observed that the median values are very close, but the spread in F values is larger for the case where the full repository is included. Thus, it seems important to include the full repository for further analyses. However, in order to resolve transport in the canister scale, it is necessary to use the canister scale DFN model. For the present SR-Can interim analyses it is thus suggested to use the Base Case with only a subset of the repository included but where the canister scale DFN incorporated. For later analyses the goal is to include the repository scale for the full repository.

The pure continuum case shows a median value compatible with the Base Case; however, the spread is much smaller. This case merely illustrates how calculations were performed in earlier assessments, and is not intended to be propagated.

As discussed above, the lack of representation of internal fracture variability implies an additional uncertainty. At present, this uncertainty can only be accounted for by using an empirical factor for re-scaling the transport resistance (F-factor). It is suggested that the F-factor is reduced by a factor of 10 for all cases to be propagated to radionuclide transport calculations. This consideration for case 1A2 results in the listed case 5 in Table 6-2. A factor 10 is believed to be conservative based on the arguments of additional surfaces for matrix diffusion arising under channelised conditions.

The statistics for the Darcy velocity shows a similar pattern between variants as the F-factor does. The cases with a poor backfill show a markedly increased flow for the EDZ path. However, one should keep in mind that in the present model application, this may be an artefact of the unresolved discretisation of the backfill and EDZ. In a model where the EDZ is explicitly resolved, an increased conductivity of the backfill is not likely to produce increased flow in the EDZ. Depending on the actual properties of the EDZ, the flow values produced for the case with an increased backfill conductivity in the present simulations may be representative for actual EDZ conditions.

Advective travel time is used internally in FARF31 to calculate the proper flow-wetted surface per volume of water, a_w, as a_w=F/t_w for each flow path. Thus, values for t_w are needed. It is suggested that t_w values are used such that t_w distributions are chosen in accordance with the F and q distributions. Specifically, the two pairs of triplets should be selected such that corresponding (q,F,t_w) values are selected for the two pathways considered.

No new information on Pe-number has been derived in the present work. Thus, the suggestion is to use the same ranges of values as suggested in SR 97. The central value is 10 with a range between 2–50. The effect of the Pe-value on radionuclide transport is small.

Based on the reasoning above, it is suggested that the ensemble results of the Base Case DFN for present conditions is propagated for further radionuclide transport calculations. This should be done both for the good and poor back fill variants. Also, all F values should be reduced by a factor of 10 to account for channelling within fracture planes.

As a final remark it needs also be stated that the relevance of the provided data is deemed low for estimation of actual doses since the model for simulation of groundwater flow is associated with large uncertainties. The provided data should be considered as a provisional input data set for assessing the implications of the developed methodology for simulation of groundwater flow on subsequent analyses of radionuclide transport. The variability in transport resistance and Darcy velocity contained in the provisional data set are judged to have large impacts on calculated doses for certain nuclides. However, the actual doses calculated may be of limited relevance due to the provisional character of the flow-related transport parameters provided.

7 Biosphere

7.1 General

In the migration calculations in the SR-Can interim main report, modelling of migration through the biosphere and the dose to man is performed in a similar way as in SR 97 where ecosystem specific dose conversion factors (EDF) were used to convert the release from geosphere to dose to man. In those EDF calculations an annual unit release was used to determine concentration in the modelled parts of the ecosystem and the dose to man after 10 000 years. For many radionuclides, 10 000 years was a time long enough to reach a constant dose while the dose for some nuclides were still increasing linearly. Since the time for natural successions of the ecosystem at the studied sites was less than 10 000 years, this treatment of the EDFs gives results that can be regarded to be pessimistic. Modelling with EDF factors given in the present report is however only temporary, in the SR-Can application report, the intention is however to perform dynamic simulations for a combination of ecosystems using exit points from the hydrology model and releases from the far field transport simulations as described in the SR-Can interim main report /SKB, 2004a/.

While the SR 97 EDF simulations were performed for six different ecosystems, only two, those with the highest EDFs (mire and well), were used in the simulations for this interim report. Since these have been performed using data from the ongoing site investigations, it is likely that these should be more representative than the generic SR 97 data. For the SR-Can safety assessment, the biosphere migration models and the dose conversions will be improved as well as the site specific data, cf SR-Can interim main report /SKB, 2004a/.

7.2 EDF-factors

Equivalent dose factors used in the calculations were based on an annual unit releases to an ecosystem for a period of 10 000 years. For many radionuclides, the concentration in many parts of the ecosystem (and also the dose to man) reaches a steady state level during that period. For the cases where this steady state is not reached, the EDF values will be based on accumulation over a time period over 10 000 years, hence the calculated doses is likely to be pessimistic for the studied sites.

7.2.1 Modelling in SR-Can

Models of well and mire have been simulated probabilistically over a time period of 10 000 years and the equivalent dose factor for that time has been calculated (reported in detail in the SR-Can interim main report /SKB, 2004a/). The modelled ecosystems are described in /Bergström et al, 1999/ (in that report, the mire model is however called peat model). Moreover, the mire model has been modified to include the effect of inflow from a larger drainage area than just the mire itself.

7.2.2 Sensitivity to assessment results

When using EDFs, the calculated dose to man is (per definition) linearly dependent on the RN release from the geosphere. The EDFs are however not necessarily linearly dependant on the input data to the EDF model (like model parameters and consumption behaviour) itself.

7.2.3 Source of information

This section will be discussed in more detail in the SR-Can report when a description of the ecosystems at the site is available. For the SR-Can interim report, the parameters used in the models are described in the SR-Can interim main report /SKB, 2004a/.

7.2.4 Conditions for which data are supplied

Presently, many but not all supplied site data are given for the Forsmark area, reported in the preliminary site description (version 1.1), /SKB, 2004b/. All nuclide specific data is reported in the Nuclide documentation report /Karlsson and Bergström, 2002/.

7.2.5 Conceptual uncertainties

This will be discussed in more detail in the SR-Can report.

7.2.6 Data Uncertainty, spatial and temporal variation

This will be discussed in more detail in the SR-Can report.

7.2.7 Correlations

This will be discussed in more detail in the SR-Can report.

7.2.8 Quantification

The results from each realisation in the probabilistic simulations for the mire and the well ecosystems were used as input directly to the radionuclide migration calculations. The mean value and standard deviation of the data is presented in Appendix A.8.

8 Concluding remarks

This report provides input data, with uncertainty, to the SR-Can assessment calculations for a wide selection of conditions. The data are assessed through standardized procedures and where input provided by experts is distinguished from judgements made by the SR-Can team. However, in this interim version of the data report, this only applies to some of the data – in order to demonstrate these procedures. Other data, needed for the illustrative calculations of SR-Can interim, are provided with a more relaxed procedure. In the final SR-Can version of the data report the inventory of data will be updated and the standardised procedures will be applied to all data.

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Appendix A

Data used in the migration base case

A.1 Inventory

Table A-1. Inventory for BWR 38 MWd/kg U after 40 years (taken from Table 9 of /Håkansson, 1999/).

Nuclide	Activity (Bq/t U) Fission products	Nuclide	Activity (Bq/t U) Actinides	Nuclide	Activity (Bq/t U) Light elements
H-3	$2.1 \cdot 10^{12}$	Ra-226	$1.4 \cdot 10^{5}$	H-3	$1.1 \cdot 10^{12}$
Se-79	$2.8 \cdot 10^{9}$	Th-229	$1.0 \cdot 10^{4}$	C-14	$5.0 \cdot 10^{10}$
Kr-85	$2.7 \cdot 10^{13}$	Th-230	$1.6 \cdot 10^{7}$	Cl-36	$5.5 \cdot 10^{8}$
Sr-90	$1.2 \cdot 10^{15}$	Th-234	$1.2 \cdot 10^{10}$	Fe-55	$9.3 \cdot 10^{9}$
Y-90	$1.2 \cdot 10^{15}$	Pa-231	$1.8 \cdot 10^{6}$	Co-60	$8.9 \cdot 10^{11}$
Zr-93	$5.0 \cdot 10^{10}$	Pa-233	$1.5 \cdot 10^{10}$	Ni-59	$8.8 \cdot 10^{10}$
Nb-93m	$4.2 \cdot 10^{10}$	Pa-234m	$1.2 \cdot 10^{10}$	Ni-63	$9.3 \cdot 10^{12}$
Tc-99	$5.7 \cdot 10^{11}$	U-233	$3.1 \cdot 10^{6}$	Sr-90	$2.6 \cdot 10^{7}$
Ru-106	$2.7 \cdot 10^{4}$	U-234	$4.6 \cdot 10^{10}$	Y-90	$2.6 \cdot 10^{7}$
Pd-107	$4.9 \cdot 10^{9}$	U-235	$4.5 \cdot 10^{8}$	Zr-93	$5.6 \cdot 10^{9}$
Cd-113m	$1.7 \cdot 10^{11}$	U-236	$1.0 \cdot 10^{10}$	Nb-93m	$2.3 \cdot 10^{10}$
Sn-121	$4.4 \cdot 10^{10}$	U-237	$1.9 \cdot 10^{10}$	Nb-94	$2.9 \cdot 10^{9}$
Sn-121m	$5.7 \cdot 10^{10}$	U-238	$1.2 \cdot 10^{10}$	Mo-93	$4.4 \cdot 10^{7}$
Sb-125	$1.1 \cdot 10^{10}$	Np-237	$1.5 \cdot 10^{10}$	Ag-108	$4.3 \cdot 10^{7}$
Te-125m	$2.7 \cdot 10^{9}$	Np-239	$1.2 \cdot 10^{12}$	Ag-108m	$5.0 \cdot 10^{8}$
Sn-126	$2.3 \cdot 10^{10}$	Pu-238	$9.5 \cdot 10^{13}$	Cd-113m	$3.4 \cdot 10^{10}$
Sb-126m	$2.3 \cdot 10^{10}$	Pu-239	$9.5 \cdot 10^{12}$	Sn-121	$1.4 \cdot 10^{10}$
I-129	$1.3 \cdot 10^{9}$	Pu-240	$1.2 \cdot 10^{13}$	Sn-121m	$1.7 \cdot 10^{10}$
Cs-134	$9.1 \cdot 10^{9}$	Pu-241	$7.7 \cdot 10^{14}$	Sb-125	$1.2 \cdot 10^{9}$
Cs-135	$2.1 \cdot 10^{10}$	Pu-242	$1.0 \cdot 10^{11}$	Te-125m	$3.0 \cdot 10^{8}$
Cs-137	$1.8 \cdot 10^{15}$	Am-241	$1.5 \cdot 10^{14}$	Eu-154	$3.2 \cdot 10^{11}$
Ba-137m	$1.7 \cdot 10^{15}$	Am-242m	$4.5 \cdot 10^{11}$	Eu-155	$1.3 \cdot 10^{10}$
Pm-146	$9.8 \cdot 10^{8}$	Am-242	$4.5 \cdot 10^{11}$	Ho-166m	$7.5 \cdot 10^{7}$
Pm-147	$1.5 \cdot 10^{11}$	Am-243	$1.2 \cdot 10^{12}$	Total	$1.2 \cdot 10^{13}$
Sm-151	$9.4 \cdot 10^{12}$	Cm-242	$3.7 \cdot 10^{11}$		
Eu1-52	$3.3 \cdot 10^{10}$	Cm-243	$4.4 \cdot 10^{11}$		
Eu-154	$1.8 \cdot 10^{13}$	Cm-244	$2.8 \cdot 10^{13}$		
Eu-155	$7.6 \cdot 10^{11}$	Cm245	$9.4 \cdot 10^{9}$		
Total	$6.0 \cdot 10^{15}$	Cm-246	$2.9 \cdot 10^{9}$		
		Total	$1.1 \cdot 10^{15}$		

A.2 Instant release fraction (IRF)

Table A-2. Reasonable and pessimistic estimates of the IRF based on SR 97 Beberg data /Andersson, 1999/. For SR-Can interim base case a log-normal distribution is assumed with the mean corresponding to the reasonable value and a standard deviation chosen so that 5% of the probability distribution is less favourable than the pessimistic.

Nuclide	IRF(%) reasonable estimate	IRF(%) pessimistic estimate
C-14	15	55
Cl-36	6	12
Co-60	-	-
Ni-59	100	100
Ni-63	100	100
Se-79	3	6
Kr-85	2	4
Sr-90	0.25	1
Zr-93	-	-
Nb-94	100	100
Tc-99	0.2	1
Pd-107	0.2	1
Ag-108m	100	100
Cd-113m	3	6
Sn-126	2	4
I-129	3	6
Cs-135	3	6
Cs-137	3	6
Sm-151	-	-
Eu-154	-	-
Ho-166m	-	-
actinides	-	-

A.3 Solubilities

Table A-3, Solubilities based on SR 97 Beberg data /Andersson, 1999/. For SR-Can interim base case a log-normal distribution is assumed with the mean corresponding to the reasonable value and a standard deviation chosen so that 5% of the probability distribution is less favourable than the pessimistic.

Nuclide	Realistic (mole/m^3)	Pessimistic in SR 97 (mole/m^3)
Ag	$9.39 \cdot 10^{-4}$	$3 \cdot 10^{-2}$
Am	$9.36 \cdot 10^{-5}$	$7 \cdot 10^{-3}$
C	high	high
Cl	high	high
Cm	$2.02 \cdot 10^{-6}$	$2 \cdot 10^{-3}$
Cs	high	high
Ho	$5.58 \cdot 10^{-3}$	$6 \cdot 10^{-2}$
I	high	high
Nb	1.37	40
Ni	high	high
Np	$1.05 \cdot 10^{-4}$	$2 \cdot 10^{-4}$
Pa	$3.16 \cdot 10^{-4}$	$4 \cdot 10^{-4}$
Pd	$4.17 \cdot 10^{-6}$	$8 \cdot 10^{-6}$
Pu	$5.35 \cdot 10^{-7}$	$3 \cdot 10^{-3}$
Ra	$5.02 \cdot 10^{-4}$	$2 \cdot 10^{-1}$
Se	$2.59 \cdot 10^{-6}$	high/4·1
Sm	$8.03 \cdot 10^{-4}$	$2 \cdot 10^{-2}$
Sn	$4.49 \cdot 10^{-6}$	$1 \cdot 10^{-2}$
Sr	3.09	40
Tc	$7.92 \cdot 10^{-6}$	$5 \cdot 10^{-5}$
Th	$1.22 \cdot 10^{-6}$	$2 \cdot 10^{-6}$
U	$1.29 \cdot 10^{-4}$	$2 \cdot 10^{-4}$
Zr	$2.51 \cdot 10^{-6}$	$3 \cdot 10^{-6}$

A.4 Buffer chemistry data

Table A-4. Ground waters used when determining the pore water composition, from /Ochs and Talerico, 2004/.

	Saline GW	Highly saline GW
Na^+ (mol/l)	$7.39 \cdot 10^{-2}$	$5.739 \cdot 10^{-1}$
K^+ (mol/l)	$3.32 \cdot 10^{-4}$	$3.32 \cdot 10^{-4}$
Ca^{+2} (mol/l)	$4.121 \cdot 10^{-2}$	$4.116 \cdot 10^{-2}$
Mg^{+2} (mol/l)	$4.53 \cdot 10^{-3}$	$4.53 \cdot 10^{-3}$
CO_3^{-2} (mol/l)	$7.7 \cdot 10^{-4}$	$7.248 \cdot 10^{-4}$
H^+ (mol/l)	$8.589 \cdot 10^{-4}$	$7.7 \cdot 10^{-4}$
Cl^- (mol/l)	$1.557 \cdot 10^{-1}$	$6.55 \cdot 10^{-1}$
SO_4^{-2} (mol/l)	$3.85 \cdot 10^{-3}$	$3.85 \cdot 10^{-3}$
pH	7	7.175
pCO_2	–2.558	–2.792
Change balance (%)	0.995	0.336
Precipitated solids	-	calcite
Ionic strength (mol/l)	0.2075	0.7062

Table A-5. The redox states used in the SR-Can interim base case.

Ag(I)
Am(III)
C
Cl(–I)
Cm(III)
Cs(I)
Ho(III)
I(–I)
Nb(V)
Ni(II)
Np(IV)
Pa(IV)
Pd(II)
Pu(IV)
Ra(II)
Se(IV)
Sm(III)
Sn(IV)
Sr(II)
Tc(IV)
Th(IV)
U(IV)
Zr(IV)

A.5 Migration and material data for bentonite

Table A-6. Pore water compositions in bentonite for different ground waters difined in Table A-4, from /Ochs and Talerico, 2004/.

	Saline GW (RPWC)	Saline GW (RPW)	High saline GW (HSPW)
Na^+ (mol/m^3)	$2.4725 \cdot 10^2$	$2.5667 \cdot 10^2$	$6.1173 \cdot 10^2$
K^+ (mol/m^3)	$5.2934 \cdot 10^{-1}$	$5.5048 \cdot 10^{-1}$	1.1504
Ca^{+2} (mol/m^3)	$1.5339 \cdot 10^1$	$1.4423 \cdot 10^1$	$5.0364 \cdot 10^1$
Mg^{+2} (mol/m^3)	3.9366	4.0783	$1.3048 \cdot 10^1$
CO_3^{-2} (mol/m^3)	$1.2514 \cdot 10^1$	1.4778	$8.9140 \cdot 10^{-1}$
H^+ (mol/m^3)	–2.6478	$-4.5512 \cdot 10^1$	$-4.1198 \cdot 10^1$
Cl^- (mol/m^3)	$1.6035 \cdot 10^2$	$1.6035 \cdot 10^2$	$6.5965 \cdot 10^2$
SO_4^{-2} (mol/m^3)	$4.7764 \cdot 10^1$	$4.3614 \cdot 10^1$	$1.7321 \cdot 10^1$
$H_2SiO_4^{-2}$ (mol/m^3)	$1.0524 \cdot 10^{-1}$	$1.0805 \cdot 10^{-1}$	$1.0826 \cdot 10^{-1}$
SOH (mol/m^3)	$8.5704 \cdot 10^1$	$8.5704 \cdot 10^1$	$8.5704 \cdot 10^1$
LAX (mol/m^3)	$3.3087 \cdot 10^3$	$3.3087 \cdot 10^3$	$3.3087 \cdot 10^3$
pH	6.593	7.377	7.046
pCO_2	–0.098	–2.6	–2.6
Solids	closed	open	open
	quartz	quartz	quartz
	calcite	calcite	calcite
	gypsum	gypsum	gypsum
Ionic Strength	0.29311	0.29046	0.75992

Table A-7. Summary of D_e and ε values, from /Ochs and Talerico, 2004/.

Radionuclide (Redox State)	De (m²/s)	Upper De limit (m²/s)	Lower De limit (m²/s)	ε (–)	Upper ε limit (–)	Lower ε limit (–)
Ag(I)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Am(III)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
C, carbonate species	$1.0 \cdot 10^{-11}$	$3.0 \cdot 10^{-11}$	$3.0 \cdot 10^{-12}$	0.17	0.12	0.24
C, methane	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.17	0.12	0.24
C, organic acids	$1.0 \cdot 10^{-11}$	$3.0 \cdot 10^{-11}$	$3.0 \cdot 10^{-12}$	0.17	0.12	0.24
Ce(III)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Cl(–I)	$1.0 \cdot 10^{-11}$	$3.0 \cdot 10^{-11}$	$3.0 \cdot 10^{-12}$	0.17	0.12	0.24
Cm(III)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Cs(I)	$3.0 \cdot 10^{-10}$	$3.0 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Eu(III)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Ho(III)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
I(–I)	$1.0 \cdot 10^{-11}$	$3.0 \cdot 10^{-11}$	$3.0 \cdot 10^{-12}$	0.17	0.12	0.24
Nb(V)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Ni(II)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Np(IV)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Np(V)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Pa(IV)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Pa(V)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Pb(II)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Pd(II)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Pu(III)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Pu(IV)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Pu(V)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Pu(VI)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Ra(II)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Rn(–)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Se(–II)	$1.0 \cdot 10^{-11}$	$3.0 \cdot 10^{-11}$	$3.0 \cdot 10^{-12}$	0.17	0.12	0.24
Se(IV)	$1.0 \cdot 10^{-11}$	$3.0 \cdot 10^{-11}$	$3.0 \cdot 10^{-12}$	0.17	0.12	0.24
Se(VI)	$1.0 \cdot 10^{-11}$	$3.0 \cdot 10^{-11}$	$3.0 \cdot 10^{-12}$	0.17	0.12	0.24
Sm(III)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Sn(IV)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Sr(II)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Tc(IV)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Tc(VII)	$1.0 \cdot 10^{-11}$	$3.0 \cdot 10^{-11}$	$3.0 \cdot 10^{-12}$	0.17	0.12	0.24
Th(IV)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
U(IV)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
U(VI)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-
Zr(IV)	$1.2 \cdot 10^{-10}$	$1.91 \cdot 10^{-10}$	$4.94 \cdot 10^{-11}$	0.43	-	-

Table A-8. K_d values for reference pore water (RPW) from /Ochs and Talerico, 2004/.

Radionuclide (Redox State)	Kd (m^3/kg)	Upper Kd limit (m^3/kg)	Lower Kd limit (m^3/kg)
Ag(I)	-	15	0
Am(III)	61	378	10
C, carbonate species C, methane C, organic acids	isotope exchange 0 0	- - -	- - -
Ce(III)	8	93	0.8
Cl(–I)	0	-	-
Cm(III)	61	378	10
Cs(I)	0.11	0.6	0.018
Eu(III)	8	93	0.8
Ho(III)	8	93	0.8
I(–I)	0	-	-
Nb(V)	3	45	0.2
Ni(II)	0.30	3.3	0.03
Np(IV)	63	1113	4
Np(V)	0.02	0.2	0.004
Pa(IV)	3	45	0.2
Pa(V)	3	45	0.2
Pb(II)	74	457	12
Pd(II)	5	75	0.3
Pu(III)	100	984	10
Pu(IV)	63	1111	4
Pu(V)	0.02	0.2	0.002
Pu(VI)	3	28	0.3
Ra(II)	0.005	0.03	0.001
Rn(–)	0	-	-
Se(–II)	0	-	-
Se(IV)	0.04	0.4	0.003
Se(VI)	0	-	-
Sm(III)	8	93	0.8
Sn(IV)	63	1764	2.3
Sr(II)	0.005	0.031	0.0009
Tc(IV)	63	1764	2.3
Tc(VII)	0	-	-
Th(IV)	63	700	6
U(IV)	63	1113	3.6
U(VI)	3	18	0.5
Zr(IV)	4	103	0.1

Table A-9. K_d-values for reference pore water closed CO_2 (RPWC) from /Ochs and Talerico, 2004/.

Radionuclide (Redox State)	Kd (m^3/kg)	Upper Kd limit (m^3/kg)	Lower Kd limit (m^3/kg)
Ag(I)	-	15	0
Am(III)	11	68	2
C, carbonate species	isotope exchange	-	-
C, methane	0	-	-
C, organic acids	0	-	-
Ce(III)	1	14	0.1
Cl(–I)	0	-	-
Cm(III)	11	68	2
Cs(I)	0.10	0.6	0.017
Eu(III)	1	14	0.1
Ho(III)	1	14	0.1
I(–I)	0	-	-
Nb(V)	3	45	0.2
Ni(II)	0.06	0.7	0.01
Np(IV)	40	703	2
Np(V)	0.01	0.1	0.002
Pa(IV)	3	45	0.2
Pa(V)	3	45	0.2
Pb(II)	35	219	6
Pd(II)	5	75	0.3
Pu(III)	30	300	3
Pu(IV)	40	703	2
Pu(V)	0.01	0.1	0.001
Pu(VI)	14	139	1.4
Ra(II)	0.005	0.03	0.001
Rn(–)	0	-	-
Se(–II)	0	-	-
Se(IV)	0.09	1.0	0.008
Se(VI)	0	-	-
Sm(III)	1	14	0.1
Sn(IV)	40	1113	1.4
Sr(II)	0.005	0.03	0.0009
Tc(IV)	40	1113	1.4
Tc(VII)	0	-	-
Th(IV)	40	442	4
U(IV)	40	703	2.3
U(VI)	14	88	2
Zr(IV)	11	305	0.4

Table A-10. K_d-values for high saline pore water (HSPW) from /Ochs and Talerico, 2004/.

Radionuclide (Redox State)	Kd (m^3/kg)	Upper Kd limit (m^3/kg)	Lower Kd limit (m^3/kg)
Ag(I)	-	15	0
Am(III)	24	152	4
C, carbonate species C, methane C, organic acids	isotope exchange 0 0	- - -	- - -
Ce(III)	5	57	0.5
Cl(–I)	0		
Cm(III)	24	152	4
Cs(I)	0.03	0.2	0.006
Eu(III)	5	57	0.5
Ho(III)	5	57	0.5
I(–I)	0	-	-
Nb(V)	3	45	0.2
Ni(II)	0.07	0.8	0.01
Np(IV)	40	702	2
Np(V)	0.02	0.1	0.004
Pa(IV)	3	45	0.2
Pa(V)	3	45	0.2
Pb(II)	46	287	7
Pd(II)	5	75	0.3
Pu(III)	43	421	4
Pu(IV)	40	700	2
Pu(V)	0.02	0.2	0.002
Pu(VI)	3	28	0.3
Ra(II)	0.001	0.01	0.0002
Rn(–)	0	-	-
Se(–II)	0	-	-
Se(IV)	0.05	0.6	0.005
Se(VI)	0	-	-
Sm(III)	5	57	0.5
Sn(IV)	40	1113	1.4
Sr(II)	0.001	0.008	0.0002
Tc(IV)	40	1113	1.4
Tc(VII)	0	-	-
Th(IV)	40	442	4
U(IV)	40	703	2.3
U(VI)	3	18	0.5
Zr(IV)	5	134	0.2

A.6 Migration and material data for backfill

Table A-11. Backfill porosity and diffusivity parameters based on SR 97 Beberg data /Andersson, 1999/. For SR-Can interim base case a log-normal distribution is assumed with the mean corresponding to the reasonable value and a standard deviation chosen so that 5% of the probability distribution is less favourable than the pessimistic.

Case	Realistic in SR 97	Pessimistic in SR 97
Reasonable estimate	De 10^{-10} m^2/s, fresh	De 10^{-10} m^2/s
	ε = 0.30	ε = 0.30

Table A-12. Backfill sorption parameters based on SR 97 Beberg data /Andersson, 1999/. For SR-Can interim base case a log-normal distribution is assumed with the mean corresponding to the reasonable value and a standard deviation chosen so that 5% of the probability distribution is less favourable than the pessimistic.

Element	Realistic (m^3/kg)	Pessimistic, (based on saline ground water) (m^3/kg)
Ag	0.5	0.009
Am	3	1
C*	0.0009	0.0004
Cl*	0	0
Cm	3	1
Cs	0.5	0.009
Ho	2	0.9
I*	0	0
Nb	0.9	0.4
Ni	0.1	0.01
Np	5	0.9
Pa	1	0.4
Pd	0.09	0.0009
Pu	5	1
Ra	0.2	0.009
Se	0.001	0.0004
Sm	2	0.9
Sn	0.5	0.002
Sr	0.08	0.0002
Tc*	0.9	0.3
Th	5	0.9
U	4	0.9
Zr	1	0.5

A.7 Migration properties of the rock (non flow related)

Table A-13. Suggested quantification of uncertainties in matrix porosity and rock matrix diffusivities (De).

Case	Cations	Anions
Matrix porosity	$5 \cdot 10^{-3}$	$5 \cdot 10^{-4}$

Table A-14. Rock diffusivity values, based on SR 97 Beberg data /Andersson, 1999/. For SR-Can interim base case a log-normal distribution is assumed with the mean corresponding to the reasonable value and a standard deviation chosen so that 5% of the probability distribution is less favourable than the pessimistic.

Element	Realistic (m^2/yr)	Pessimistic (m^2/yr)
Ag	$2.24 \cdot 10^{-6}$	$2.24 \cdot 10^{-7}$
Am	$1.26 \cdot 10^{-6}$	$1.26 \cdot 10^{-7}$
C	$1.58 \cdot 10^{-7}$	$1.58 \cdot 10^{-8}$
Cl	$2.52 \cdot 10^{-7}$	$2.52 \cdot 10^{-8}$
Cm	$1.26 \cdot 10^{-6}$	$1.26 \cdot 10^{-7}$
Cs	$2.84 \cdot 10^{-5}$	$2.84 \cdot 10^{-7}$
Ho	$1.26 \cdot 10^{-6}$	$1.26 \cdot 10^{-7}$
I	$2.52 \cdot 10^{-7}$	$2.52 \cdot 10^{-8}$
Nb	$1.26 \cdot 10^{-6}$	$1.26 \cdot 10^{-7}$
Ni	$8.84 \cdot 10^{-7}$	$8.84 \cdot 10^{-8}$
Np	$1.26 \cdot 10^{-6}$	$1.26 \cdot 10^{-7}$
Pa	$1.26 \cdot 10^{-6}$	$1.26 \cdot 10^{-7}$
Pd	$1.26 \cdot 10^{-6}$	$1.26 \cdot 10^{-7}$
Pu	$1.26 \cdot 10^{-6}$	$1.26 \cdot 10^{-7}$
Ra	$1.17 \cdot 10^{-6}$	$1.17 \cdot 10^{-7}$
Se	$1.26 \cdot 10^{-6}$	$1.26 \cdot 10^{-7}$
Sm	$1.26 \cdot 10^{-6}$	$1.26 \cdot 10^{-7}$
Sn	$1.26 \cdot 10^{-6}$	$1.26 \cdot 10^{-7}$
Sr	$9.47 \cdot 10^{-6}$	$9.47 \cdot 10^{-8}$
Tc	$1.26 \cdot 10^{-6}$	$1.26 \cdot 10^{-7}$
Th	$1.99 \cdot 10^{-7}$	$1.99 \cdot 10^{-8}$
U	$1.26 \cdot 10^{-6}$	$1.26 \cdot 10^{-7}$
Zr	$1.26 \cdot 10^{-6}$	$1.26 \cdot 10^{-7}$

Table A-15. Rock sorption values K_d, based on SR 97 Beberg data /Andersson, 1999/. For SR-Can interim base case a log-normal distribution is assumed with the mean corresponding to the reasonable value and a standard deviation chosen so that 5% of the probability distribution is less favourable than the pessimistic.

Element	Realistic (m^3/kg)	Pessimistic (m^3/kg)
Ag	0.5	0.01
Am	3	1
C	0.001	0.0005
Cl	0	0
Cm	3	1
Cs	0.5	0.01
Ho	2	1
I	0	0
Nb	1	0.5
Ni	0.1	0.01
Np	5	1
Pa	1	0.5
Pd	0.1	0.001
Pu	5	1
Ra	0.1	0.01
Se	0.001	0.0005
Sm	2	1
Sn	0.001	0
Sr	0.01	0.0001
Tc	1	0.3
Th	5	1
U	5	1
Zr	1	0.5

A.8 Statistics of EDF data

Table A-16. Statistics of EDF from mire (Sv/Bq).

Nuclide	Mean value	Standard deviation
H-3	0	0
Be-10	$7.7\cdot10^{-14}$	$1.5\cdot10^{-13}$
C-14	$1.6\cdot10^{-15}$	$3.1\cdot10^{-15}$
Cl-36	$1.5\cdot10^{-12}$	$2.2\cdot10^{-12}$
Co-60	$2.1\cdot10^{-13}$	$3.0\cdot10^{-13}$
Ni-59	$2.3\cdot10^{-14}$	$3.7\cdot10^{-14}$
Ni-63	$3.9\cdot10^{-14}$	$5.4\cdot10^{-14}$
Se-79	$1.1\cdot10^{-10}$	$1.9\cdot10^{-10}$
Sr-90	$4.4\cdot10^{-12}$	$7.8\cdot10^{-12}$
Zr-93	$6.2\cdot10^{-14}$	$1.2\cdot10^{-13}$
Nb-94	$1.1\cdot10^{-13}$	$1.8\cdot10^{-13}$
Mo-93	$1.5\cdot10^{-13}$	$2.4\cdot10^{-13}$
Tc-99	$3.3\cdot10^{-14}$	$1.7\cdot10^{-13}$
Pd-107	$4.0\cdot10^{-15}$	$7.9\cdot10^{-15}$
Ag-108m	$1.7\cdot10^{-11}$	$2.1\cdot10^{-11}$
Sn-126	$5.1\cdot10^{-12}$	$8.8\cdot10^{-12}$
I-129	$2.4\cdot10^{-12}$	$4.3\cdot10^{-12}$
Cs-135	$2.2\cdot10^{-13}$	$3.2\cdot10^{-13}$
Cs-137	$1.1\cdot10^{-12}$	$2.0\cdot10^{-12}$
Sm-151	$3.3\cdot10^{-15}$	$4.9\cdot10^{-15}$
Ho-166m	$2.3\cdot10^{-13}$	$4.6\cdot10^{-13}$
Pb-210	$3.1\cdot10^{-11}$	$4.4\cdot10^{-11}$
Ra-226	$1.6\cdot10^{-11}$	$3.0\cdot10^{-11}$
Ac-227	$1.9\cdot10^{-10}$	$2.9\cdot10^{-10}$
Th-229	$4.4\cdot10^{-9}$	$6.8\cdot10^{-9}$
Th-230	$2.1\cdot10^{-9}$	$3.7\cdot10^{-9}$
Th-232	$2.5\cdot10^{-9}$	$4.5\cdot10^{-9}$
Pa-231	$2.9\cdot10^{-10}$	$5.3\cdot10^{-10}$
U-233	$8.7\cdot10^{-13}$	$2.2\cdot10^{-12}$
U-234	$7.8\cdot10^{-13}$	$1.6\cdot10^{-12}$
U-235	$7.5\cdot10^{-13}$	$1.7\cdot10^{-12}$
U-236	$8.8\cdot10^{-13}$	$3.8\cdot10^{-12}$
U-238	$7.3\cdot10^{-13}$	$1.7\cdot10^{-12}$
Np-237	$1.4\cdot10^{-11}$	$2.3\cdot10^{-11}$
Pu-238	$3.6\cdot10^{-11}$	$6.5\cdot10^{-11}$
Pu-239	$6.8\cdot10^{-11}$	$1.4\cdot10^{-10}$
Pu-240	$7.0\cdot10^{-11}$	$1.5\cdot10^{-10}$
Pu-242	$6.3\cdot10^{-11}$	$1.3\cdot10^{-10}$
Am-241	$6.0\cdot10^{-10}$	$9.0\cdot10^{-10}$
Am-242m	$3.1\cdot10^{-10}$	$4.8\cdot10^{-10}$
Am-243	$1.8\cdot10^{-9}$	$3.5\cdot10^{-9}$
Cm-244	$2.2\cdot10^{-11}$	$3.1\cdot10^{-11}$
Cm-245	$2.5\cdot10^{-10}$	$4.5\cdot10^{-10}$
Cm-246	$2.5\cdot10^{-10}$	$4.2\cdot10^{-10}$

Table A-17. Statistics of EDF from well (Sv/Bq).

	Mean value	Standard deviation
H-3	$1.2 \cdot 10^{-14}$	$1.8 \cdot 10^{-14}$
Be-10	$6.4 \cdot 10^{-13}$	$1.0 \cdot 10^{-12}$
C-14	$2.4 \cdot 10^{-13}$	$3.8 \cdot 10^{-13}$
Cl-36	$1.0 \cdot 10^{-12}$	$1.7 \cdot 10^{-12}$
Co-60	$1.1 \cdot 10^{-12}$	$1.5 \cdot 10^{-12}$
Ni-59	$8.7 \cdot 10^{-14}$	$1.5 \cdot 10^{-13}$
Ni-63	$6.7 \cdot 10^{-14}$	$9.8 \cdot 10^{-14}$
Se-79	$4.5 \cdot 10^{-12}$	$1.2 \cdot 10^{-11}$
Sr-90	$1.5 \cdot 10^{-11}$	$2.2 \cdot 10^{-11}$
Zr-93	$5.1 \cdot 10^{-13}$	$8.2 \cdot 10^{-13}$
Nb-94	$5.3 \cdot 10^{-12}$	$9.8 \cdot 10^{-12}$
Mo-93	$4.3 \cdot 10^{-12}$	$9.2 \cdot 10^{-12}$
Tc-99	$8.8 \cdot 10^{-13}$	$3.0 \cdot 10^{-12}$
Pd-107	$3.1 \cdot 10^{-14}$	$5.3 \cdot 10^{-14}$
Ag-108m	$2.5 \cdot 10^{-12}$	$4.0 \cdot 10^{-12}$
Sn-126	$5.8 \cdot 10^{-12}$	$1.2 \cdot 10^{-11}$
I-129	$1.3 \cdot 10^{-10}$	$2.6 \cdot 10^{-10}$
Cs-135	$3.1 \cdot 10^{-12}$	$5.9 \cdot 10^{-12}$
Cs-137	$5.8 \cdot 10^{-12}$	$7.8 \cdot 10^{-12}$
Sm-151	$3.1 \cdot 10^{-14}$	$4.3 \cdot 10^{-14}$
Ho-166m	$3.1 \cdot 10^{-12}$	$4.7 \cdot 10^{-12}$
Pb-210	$1.6 \cdot 10^{-10}$	$2.2 \cdot 10^{-10}$
Ra-226	$1.1 \cdot 10^{-10}$	$1.6 \cdot 10^{-10}$
Ac-227	$3.6 \cdot 10^{-10}$	$5.0 \cdot 10^{-10}$
Th-229	$1.6 \cdot 10^{-9}$	$2.7 \cdot 10^{-9}$
Th-230	$9.5 \cdot 10^{-10}$	$1.6 \cdot 10^{-9}$
Th-232	$1.1 \cdot 10^{-9}$	$1.8 \cdot 10^{-9}$
Pa-231	$1.4 \cdot 10^{-9}$	$2.3 \cdot 10^{-9}$
U-233	$2.6 \cdot 10^{-11}$	$4.4 \cdot 10^{-11}$
U-234	$2.6 \cdot 10^{-11}$	$4.5 \cdot 10^{-11}$
U-235	$2.4 \cdot 10^{-11}$	$3.9 \cdot 10^{-11}$
U-236	$2.4 \cdot 10^{-11}$	$3.8 \cdot 10^{-11}$
U-238	$2.3 \cdot 10^{-11}$	$4.3 \cdot 10^{-11}$
Np-237	$8.5 \cdot 10^{-11}$	$1.8 \cdot 10^{-10}$
Pu-238	$8.4 \cdot 10^{-11}$	$1.2 \cdot 10^{-10}$
Pu-239	$7.2 \cdot 10^{-10}$	$1.3 \cdot 10^{-9}$
Pu-240	$5.8 \cdot 10^{-10}$	$1.0 \cdot 10^{-9}$
Pu-242	$7.3 \cdot 10^{-10}$	$1.3 \cdot 10^{-9}$
Am-241	$1.3 \cdot 10^{-10}$	$1.9 \cdot 10^{-10}$
Am-242m	$7.9 \cdot 10^{-11}$	$1.1 \cdot 10^{-10}$
Am-243	$5.1 \cdot 10^{-10}$	$8.8 \cdot 10^{-10}$
Cm-244	$3.1 \cdot 10^{-11}$	$4.2 \cdot 10^{-11}$
Cm-245	$6.9 \cdot 10^{-10}$	$1.1 \cdot 10^{-9}$
Cm-246	$5.5 \cdot 10^{-10}$	$9.2 \cdot 10^{-10}$