Strål
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Swedish Radiation Safety Authority

2016:09

SSM's external experts' reviews of SKB's safety assessment SR-PSU – radionuclide transport, dose assessment, and safety analysis methodology

Initial review phase

Report number: 2016:09 ISSN: 2000-0456
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SSM perspective

Background

The Swedish Radiation Safety Authority (SSM) received an application for the expansion of SKB's final repository for low and intermediate level waste at Forsmark (SFR) on the 19 December 2014. SSM is tasked with the review of the application and will issue a statement to the government who will decide on the matter. An important part of the application is SKB's assessment of the long-term safety of the repository, which is documented in the safety analysis named SR-PSU.

Present report compiles results from SSM's external experts' reviews of SR-PSU. The general objective of these reviews has been to give support to SSM's assessment of the license application. More specifically, the instructions to the external experts have been to make a broad assessment of the quality of the application within the different disciplines and to suggest needs for complementary information. The results may also be helpful in guiding SSM to detailed review issues that should be addressed in the assessment of the application.

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Project information

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Contact persons and registration numbers for the different expert review contributions are given in the report.

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Review of radionuclide transport methodology in SR-PSU

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Registration number:SSM2015-1019
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Abstract

SKB has submitted an application to SSM for expansion of the final repository for low and intermediate level waste at Forsmark (SFR). SSM has contracted a number of organisations to support its review of SKB's safety analysis (SR-PSU), with each organisation contributing to the review of a different technical area. SSM has divided its review activities into an initial review phase and a main review phase. This report describes the findings of Quintessa Limited's initial review of the analysis of radionuclide transport in SR-PSU.

There are a number of objectives for the initial review phase. The first objective is to achieve a broad understanding of SKB's application. The second objective is to assess if SKB's documentation is understandable and complete with regard to the information needed to make an assessment of the application. SSM will ask SKB for any additional information that is needed prior to starting the main review. The final objective is to identify key review topics for the main review phase. These are topics that will have a significant impact on the assessment if the application fulfils relevant requirements.

The overall finding of this initial review is that SKB have undertaken a systematic and comprehensive safety assessment for SFR. The safety assessment has been comprehensively documented, and the documentation is largely clear. Based on this initial review the documentation appears to be complete. However, the flow of information through the documentation is not always in one direction, which reduces clarity, and can sometimes make it difficult to fully understand treatment of specific topics. Consequently some clearer statements regarding the treatment of uncertainties in the conceptual and numerical models are required.

The calculated doses for SKB's main scenario (global warming variant) are within a factor of three of the dose criterion (5.6 µSv compared with 14 µSv). SKB have included many cautious assumptions in their assessment, which builds confidence that the dose criterion will not be exceeded. However, the assessment results are particularly sensitive to uncertainties in the inventory and the performance of the near-field barriers, including their construction quality (initial state) and degradation over time. It will be important for SSM to have confidence that these and other uncertainties are not likely to lead to significantly higher doses than calculated by SKB.

The treatment and presentation of uncertainty could have been improved through greater use of deterministic calculations; complemented by probabilistic sensitivity analysis to explore the impacts of uncertainties. In addition to making the results simpler to analyse and understand, this would also make it easier to undertake independent calculations for checking / comparison. This approach would be consistent with regulatory guidance.

The key issues identified for further assessment in the main review comprise better understanding the treatment of certain processes and process couplings; the flow of information through the assessment, integration and coupling / consistency between different technical areas; and treatment of uncertainty.

Contents

1. Introduction

SKB has submitted an application to SSM for expansion of the final repository for low and intermediate level waste at Forsmark (SFR). SSM has contracted a number of organisations to support its review of SKB's safety analysis (SR-PSU), with each organisation contributing to the review of a different technical area. SSM has divided its review activities into an initial review phase and a main review phase. This report describes the findings of Quintessa Limited's initial review of the analysis of radionuclide transport in SR-PSU.

1.1. Objectives of the Initial Review

There are a number of objectives for the initial review phase. The first objective is to achieve a broad understanding of SKB's application. In the context of this report, this means obtaining a broad understanding of SR-PSU, focusing on the analysis of radionuclide transport.

The second objective is to assess if SKB's documentation is understandable and complete with regard to the information needed to make an assessment of the application. Areas where complementary information may be needed should be identified, and SSM will ask SKB for this information prior to starting the main review.

The final objective is to identify key review topics for the main review phase. These are topics that will have a significant impact on the assessment if the application fulfils relevant requirements. Furthermore these will be topics that tend to be difficult to make judgements on. Detailed analysis of specific issues will be undertaken during the main review phase, with the detailed review tasks being defined at the beginning of that phase.

The initial review work is being undertaken independently by the individual reviewers. A structured collaboration between external reviewers and SSM staff will be needed during the main review phase so that multi-disciplinary issues can be handled in a more comprehensive manner than is required for the initial review. In the main review phase, SSM will also determine if SKB can be expected to fulfil all necessary regulatory criteria.

1.2. Scope of the Initial Review

The scope of the initial radionuclide transport review is to consider:

1. If SKB's methodology applied in SR-PSU for radionuclide transport is appropriate and adequate for its purpose.
2. If SKB's abstraction of FEPs (features, events, processes) into the radionuclide transport models is appropriate and adequate for its purpose.
3. If site information and other data used in assessments for radionuclide transport are appropriate and sufficient for its purpose.
4. If SKB's technical arguments are sound, appropriate and adequate to support the results and conclusions.

The structure of this report reflects this scope:

- Section 2 presents the findings of the initial review of SKB's methodology.
- Section 3 presents the findings of the initial review of SKB's abstraction of FEPs.
- Section 4 presents the findings of the initial review of site information and other data used in the assessments. This section additionally considers the assessment codes used by SKB and the numerical implementation of the conceptual model, in anticipation of more detailed review of these aspects in the main review phase.
- Section 5 presents the findings of the initial review of SKB's technical arguments.

Having fulfilled the scope of the initial review, Section 6 identifies areas where complementary information would be desirable for the main review, and proposes key review topics for the main review phase. Finally, Section 7 presents the overall findings of the initial radionuclide transport review.

The documents consulted as part of this initial radionuclide transport review are described in Appendix 1. Appendix 2 lists suggested questions to be addressed by SKB and Appendix 3 lists suggested topics for the main review phase.

Throughout this document the main SKB reports are referred to as:

- The Main Report: TR-14-01
- The FEP Report: TR-14-07
- The Radionuclide Transport Report: TR-14-09
- The (Safety Assessment) SA Data Report: TR-14-10
- The Model Summary Report: TR-14-11
- The Input Data Report: TR-14-12

While the objectives of this initial review are associated with taking a high level overview across SR-PSU to obtain a broad understanding and identify topics for the main review, we have examined some aspects of SR-PSU in more detail, The purpose of this is to investigate questions and topics of interest and determine whether it is possible to reach a conclusion at this stage, or whether further work is required as part of the main review. Commensurate with this being an initial review, it has not been possible to investigate all questions and topics of interest in detail at this stage. Therefore the depth of analysis underpinning the different aspects of this initial review varies, but we consider this to be a reasonable approach that is appropriate to an initial review phase.

2. Methodology

2.1. Regulatory Requirements

There are two documents issued by SSM relevant to the regulatory requirements for SFR: SSM (2008a,b). Both documents contain regulations and general advice. In addition, SSM, in accepting the SAR-08 safety assessment, placed some injunctions on SKB and provided a review of that assessment with the expectation that subsequent assessments would take this into account (Appendices C of the Main Report).

SKB have summarised their approach to handling the applicable regulations. The Main Report has two relevant appendices: Appendix A covers SSM (2008a) and Appendix B covers SSM (2008b). Particular sections of the Main Report also reflect the regulations and guidance and explain how these have been implemented.

Appendix C of the Main Report describes how SKB responded to SSM's injunctions at the time of the approval of SAR-08. These responses were made prior to the publication of SR-PSU but are relevant to some aspects of the approach that has been adopted.

Appendix D of the Main Report provides a commentary on how SR-PSU responds to SSM's review comments on SAR-08.

This approach is to be commended and provides a useful check list for linking the SR-PSU assessment to the regulations that govern it. It also means that SR-PSU builds on SAR-08 and that experience is recorded.

The responses given by SKB are discussed further in Section 2.3.

2.2. Summary of Approach

The approach taken to radionuclide transport modelling is presented in Chapter 2 of the Radionuclide Transport Report. This reflects the more general methodology discussion in Chapter 2 of the Main Report.

The full methodology is described in 10 steps:

1. Handling of FEPs;
2. Description of the Initial State;
3. Description of External Conditions;
4. Description of Internal Processes;
5. Definition of Safety Functions;
6. Compilation of Input Data;
7. Analysis of Reference Scenario;
8. Selection of (other) Scenarios;
9. Analysis of Selected Scenarios; and
10. Conclusions.

The radionuclide transport aspects of this relate to the two analysis steps (7 and 9 above) with the other steps providing the background to determine which calculation cases are to be considered.

Although not discussed as a separate step, the treatment of uncertainty throughout the assessment is crucial. The Radionuclide Transport Report reflects the five types of uncertainty discussed in SSM (2008b):

- Scenario Uncertainty;
- System Uncertainty;

- Model Uncertainty;
- Parameter Uncertainty; and
- Spatial Variation.

Scenario uncertainty is handled by defining a set of scenarios, on the basis of the FEP analysis, that cover the possible range of behaviours.

System uncertainty relates to issues of completeness and correctness of the FEPs, while model uncertainty relates to how the models simplify the full set of processes that occur. SKB comment on these together and claim that they are handled through cautious (conservative) assumptions (or by considering multiple alternatives if the conservatism case is unclear). In fact, SKB's approach to handling system uncertainty appears to be to eliminate it as far as possible by undertaking FEP audits to ensure completeness (although this is not explicitly stated in the summary in the Radionuclide Transport Report, it is clearer in the Main Report, Section 2.6). Eliminating system uncertainty as far as possible is a sensible approach, but this is an example of where SKB's approach to handling uncertainty could be better described.

Parameter uncertainty is handled by assigning probability distributions to various input parameters. SKB also state that this handles the effects of (spatial) variations. Mixing of the subjective parameter uncertainty with the objective description of spatial variability may not provide a clear picture of the true uncertainty in outcomes (it may be over-estimated) since averaging will occur naturally over the spatial variability while averaging for the uncertainty is purely a device for determining a central forecast for use in the risk analysis. In some cases, input of time-dependent parameters is taken directly from the output of (stochastic) hydrogeological modelling.

It is not clear from the description of the methodology how uncertainties in the hydrogeological modelling have been passed through to the radionuclide transport modelling. This topic is further explored later in this document as we develop the initial review, and identify topics for the main review.

The results for each calculation case considered are presented as the arithmetic mean of the annual effective dose versus time. Calculations are presented up to 100 000 years. Breakdowns of the dose against radionuclide and/or waste vault are generally presented. A typical result presentation is shown in Figure 2-1.

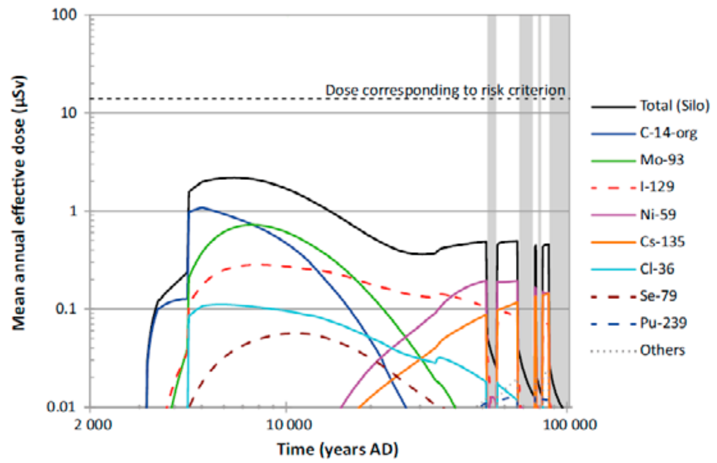

Figure 5-6. *Arithmetic mean of the annual effective dose to the most exposed group for releases from the* ***Silo*** *in the* ***global warming calculation case*** *(CCM_GW). The white area corresponds to temperate climatic conditions in the radionuclide transport modelling and the grey shaded area to periglacial conditions with continuous permafrost.*

Figure 2-1. Arithmetic mean of the annual effective dose to the most exposed group for releases from the Silo in the global warming calculation case (CCM_GW). (Figure 5-6 of the Radionuclide Transport Report).

Deterministic calculations are rarely presented (Figure 5-11 in the Radionuclide Transport Report is a singular exception for the main scenarios) and seem only to be used when the probabilistic approach is infeasible. In a small number of cases, the 5th and 95th percentiles of the calculated doses are presented (again Figure 5-11 of the Radionuclide Transport Report is an example).

Tables of peak values and timings are also reported, by radionuclide and by waste vault. The exposed group in the biosphere is also reported.

2.3. Comparison with Requirements

Given the comprehensive nature of SKB's responses to the regulatory requirements, guidance and review comments that are given in Appendices A to D of the Main Report, we can address the question of how the approach meets the requirements by considering SKB's responses and determining if they are sufficient and accurately reflect the assessment that is presented.

The radionuclide transport aspect of the assessment is, of course, the main vehicle for assessing the consequences of the potential release of radionuclides from the repository. Thus, it has a role to play in many of the regulatory aspects. The main exception to this is in the area of the design of the facility – so we do not consider those aspects. Also, aspects that are clearly in the realm of biosphere models and radiological consequence analysis are also excluded from our consideration.

In general, SKB have addressed the regulations and guidance appropriately. There are a small number of points where this is less clear.

The first point where we believe further discussion is merited is in the handling of uncertainties. This appears at the bottom of p398 (Section A1.3) of the Main Report. It is not clear to us that the approach used to handle spatial variation is adequately explained and justified. Neither is it clear that the chaining of uncertainties from the hydrogeological modelling to radionuclide transport models is adequately described.

At the top of p399 (Section A1.3) of the Main Report the guidance stating that, "*both deterministic and probabilistic methods should be used so that they complement each other and, consequently, provide as comprehensive a picture of the risks as possible*" is reproduced. SKB state that mainly probabilistic calculations are used and that for some cases deterministic calculations are performed. This seems to miss the point of the guidance – by showing both deterministic and probabilistic calculations a more comprehensive picture can be gained. It is much easier for the reader to understand a deterministic calculation and then to see the impact of uncertainty. It is also substantially more straightforward to verify deterministic calculations, particularly when the probabilistic calculations rely on probabilistic outputs from other codes. Figure 10-1 of the Radionuclide Transport Report provides a useful comparison of peak doses from deterministic calculations with the range from probabilistic calculations, but this does not fully achieve the objectives of presenting both deterministic and probabilistic calculations.

Page 410 (Section B1.3) of the Main Report returns to the issue of uncertainties. The guidance states that "*the different categories of uncertainties specified there* [in SSM's regulations] *should be evaluated and reported on in a systematic way and evaluated on the basis of their importance for the result of the risk analysis*." It is not clear that this is done – generally all of the uncertainties that can be represented by varying model parameters have been lumped together.

On p411 an assessment time period of 1,000,000 years is mentioned. It is thought that this is erroneous and that 100,000 years is used throughout.

2.4. Comparison with Other Assessments

The IAEA publishes a series of Safety Standards related to the disposal of radioactive waste. The most relevant of these is SSG-23 (IAEA, 2012). This includes a chapter on the radiological impact assessment for the period after closure, which is directly relevant here. It states that the key components are:

- Specification of the context for the assessment;
- Description of the waste disposal system;
- Development and justification of scenarios;
- Formulation and implementation of models;
- Performance of simulations and analysis of results, including sensitivity and uncertainty analysis;
- Comparison with safety criteria; and
- Review and modification of the assessment, if necessary.

It is clear that the approach used by SKB in SR-PSU, and the context provided by the SSM regulations, closely follows the approach suggested by the IAEA. The overall approach can therefore be said to follow international best practice.

3. FEPs and the Conceptual Model

3.1. Inventory of Key Radionuclides

There is no formal system of waste classification in Sweden, although SKB uses definitions of Low-, Intermediate- and High-level waste that reflects IAEA guidance (e.g. IAEA, 2009). SKB also distinguish between wastes that are 'long-lived' and 'short-lived' in terms of the content of radionuclides greater than or less than 31 years in half-life, but the criteria relating to content are qualitative; short-lived wastes should contain 'limited amounts' of long-lived radionuclides. It is thus the responsibility of SKB to demonstrate that the wastes disposed, or planned to be consigned, to a repository are consistent with safety and environmental criteria.

Historically, SFR has received low- and intermediate wastes from the operation of nuclear power plants and nuclear facilities. SKB describes the origin of these wastes and the main types of materials. These have comprised contaminated operational wastes, ion-exchange resins, and redundant equipment as well as small amounts of wastes from non-nuclear applications. The largest portion of operational wastes are combustible materials, most of which are incinerated by Studsvik.

Future wastes, proposed to be disposed of in the SFR extension, will differ in that much will arise from the decommissioning and dismantling of closed nuclear facilities. There will be a greater proportion of activated materials, as well as contaminated materials. The wastes will also include large items (e.g. entire reactor pressure vessels), with the materials likely to be dominated by steel and concrete.

SKB's estimate is that the volumes of decommissioning wastes (approximately 107,000 m^3) will exceed the operational waste (60,000 m^3). Around 80% of future wastes allocated to SFR3 are decommissioning wastes, with 10% being operational and 10% secondary decommissioning waste. SKB do not describe the assumptions underlying the inventory volume projections in the Main Report; this information is potentially available in a supporting inventory report (SKB, 2013, in Swedish).

SKB's inventory information includes estimated masses of key materials (aluminium/zinc, concrete, bitumen, cellulose, cement, filters, resins, iron/steel, sludge and other inorganic or organic material) as well as surface areas of metals (for corrosion calculations) and voidage estimates. Data are presented for each component of the SFR separately, but there is no estimate of uncertainties in the volumes, presumably on the basis that the vaults will be filled to capacity. Although SKB give data on the materials present, there is no detail of the specific waste types present (except where it can be inferred, e.g. resins) or the numbers of each waste container type.

In its introductory text, SKB do not present radionuclide inventory information in terms of Bq, but in terms of total volume. More detailed information (Bq) is included in the repository description (Section 4.2.4 of the Main Report). The derivation of the radioactivity values is not described in the Main Report, but presumably involves the application of radionuclide "fingerprints" and correlations. Such information may be available in the supporting inventory report. Although the basis for the inventory estimates is also not discussed in the Main Report, SKB do present radionuclide amounts and also uncertainty estimates (the 95^{th} percentile inventory estimates). SKB state that the uncertainties are derived from measurement uncertainties and other uncertainties in the methods used to calculate the radionuclide concentrations. The uncertainties do not include uncertainties in waste volumes, however. Furthermore, for some decommissioning wastes, no inventory has been assumed due to lack of information.

Inventory data are presented for each of 51 radionuclides (with C-14 being categorised as organic, inorganic and induced activity) for each of the main components of SFR. SKB does not discuss the selection of the radionuclides used in the inventory. SKB reports that more details are presented in the supporting inventory report, which also examines key assumptions such as the estimated burn-up of wastes.

There is an indication of the relative significance of particular radionuclides, in terms of total activity and in terms of radiotoxicity, but the values are normalised. In terms of the inventory, SKB reports the dominant radionuclides to be:

- in terms of activity content, nickel isotopes, Cs-137 (before 100 y) and C-14;
- in terms of radiotoxicity, Am-241, Cs-137 (100 y or so), and plutonium isotopes (beyond 5,000 y).

The derivation of radiotoxicity-weighted content is not explained in detail, but as the results presented are normalised it is suspected that the approach is to multiply the radioactivity amount by the relevant ingestion dose coefficient. This is not unreasonable, and has been used before, but might underplay the importance of radionuclides that are strong gamma-emitters in circumstances where such a pathway is important (e.g. human intrusion situations).

The normalised inventory information also shows the decline in the radionuclide inventory with time. It is not stated whether this curve includes the effects of radionuclide migration as well as radioactive decay. It is notable that the decline in activity is initially faster than the decline in radiotoxicity, but on timescales of more than 5,000 y the radiotoxicity declines more rapidly to a value of 0.1% that at closure.

Some of the future decommissioning wastes are proposed to be emplaced in the SFR directly (e.g. reactor pressure vessels). Other wastes will be emplaced in the same type of containers already used in the facility. These include ISO containers, other carbon-steel containers, concrete tanks, steel drums, and concrete or steel moulds. Wastes will be encapsulated in either cement or bitumen. Wastes will be pre-treated as appropriate e.g. incineration, compaction, segmentation or even melting of the wastes. It is stated by SKB that all waste disposed of in SFR must conform to approved waste acceptance criteria (SKBdoc 1368638 is cited in the Main Report). These criteria are not expanded upon, but may be significant in understanding repository performance, e.g. the allowable content of organic materials or complexants. There are no details of the basis for selecting particular waste packages and encapsulants in terms of post-closure performance of the SFR.

3.2. Summary of SKB's Conceptual Model

This section briefly describes the site and repository. Then the implications of the site's characteristics for its potential performance for disposal of low- and intermediate-level waste (L/ILW) are considered, and compared with SKB's safety principles. SKB's safety principles are designed to achieve post-closure safety for the SFR, so an appropriate first review step is to check that SKB's safety principles are consistent with the site characteristics.

Having considered the site's characteristics, and their consistency with SKB's safety principles, the next step is to summarise the conceptual model for the main scenario. The objective of this is both for familiarisation purposes, and to provide introduction / context to the subsequent initial review of the abstraction of key FEPs:

- Safety Functions and assessment scenarios derived from them.
- Key Thermo-Hydraulic-Mechanical-Chemical (THMC) processes.
- Systems External Features, Events and Processes (EFEPs) and environmental evolution.

Summary Description of SFR and the Site

SFR is a repository for short-lived low- and intermediate-level radioactive wastes that has been in operation since 1988. The repository is located below the Baltic Sea (Figure 3-2). The existing facility, SFR1, consists of four waste vaults plus a 70 metre high concrete silo, covered by about 60 metres of granitoid rock. Operational waste from nuclear power plants and from other nuclear facilities is disposed of in SFR1. A proposed extension, SFR3, is planned to be built adjacent to SFR1, but with a rock cover of about 120 m, i.e. at about the same level as the bottom of the silo. The underground part of SFR3 will consist of six new waste vaults. Additional operational waste and the waste from decommissioning of the Swedish nuclear power plants and other nuclear facilities will be disposed of in SFR3. There will also be room for disposal of nine reactor pressure vessels from boiling water reactors.

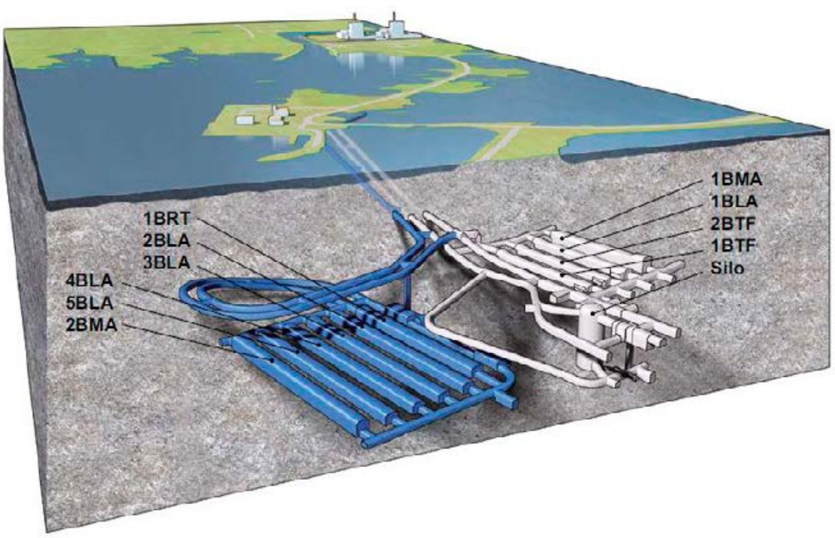

Figure 3-2. SFR. The existing repository (SFR1) is shown in white, while the proposed extension (SFR3) is shown in blue (Figure 1-2 of the Main Report)

The types of wastes disposed in the different vaults and silos are:

- BLA - LLW
- BTF – lower activity ILW
- BMA – higher activity ILW
- Silo – higher activity ILW
- BRT – BWR pressure vessels

The granitoid rock is fractured, and groundwater flow can take place in connected open fractures. SKB describe how the bulk permeability of the rock is generally low at the scale of the facility, but the transmissivity of individual fractures may be significant, giving the potential for high flow velocities. However, the site is located in an area of low topographic relief, such that the driving forces for groundwater flow are low, and the offshore location of SFR further reduces the potential for groundwater flow through the facility to the sea bed.

During the current operational phase SFR is being dewatered, such that the natural groundwater flows and gradients are disturbed, and flow is into the facility. Once SFR is closed, it will resaturate and the natural groundwater gradients and flows will re-establish, except with some localised disturbance due to the presence of the repository. SKB anticipate this to result in weak groundwater flows through the facility to the sea bed, which in turn may lead to transport of radionuclides from the facility to the marine environment. Low fluxes of radionuclides to the marine environment would be rapidly diluted and dispersed, which reduces the potential environmental impacts compared with discharge to a terrestrial environment.

The Forsmark region is still isostatically rebounding following the end of the last ice age. Even accounting for eustatic sea level rise in response to anthropogenic global warming, SKB calculate the ground surface above SFR will transition from the marine environment to the terrestrial environment after approximately 1,000 years. At this time, and as uplift continues, groundwater flow rates through SFR may increase, and groundwater flow paths may develop from SFR to newly emergent land.

The evolution conceptualised by SKB is supported by the results of groundwater flow models (Figure 3-3), which show the reduction in groundwater travel time from the facility to the biosphere in response to isostatic and eustatic processes and the resultant movement of the shoreline. Figure 3-4 shows the modelled discharge locations of a large number of particles (1,000,000) released from the facility and transported to the biosphere. Over time, the groundwater discharge location moves slightly further away from the site, but the majority of particles are still discharged close to the site. It should be noted that while these model results support and add detail to the conceptual model, the detailed results are sensitive to a number of assumptions and uncertainties, and these may need to be explored as part of this review.

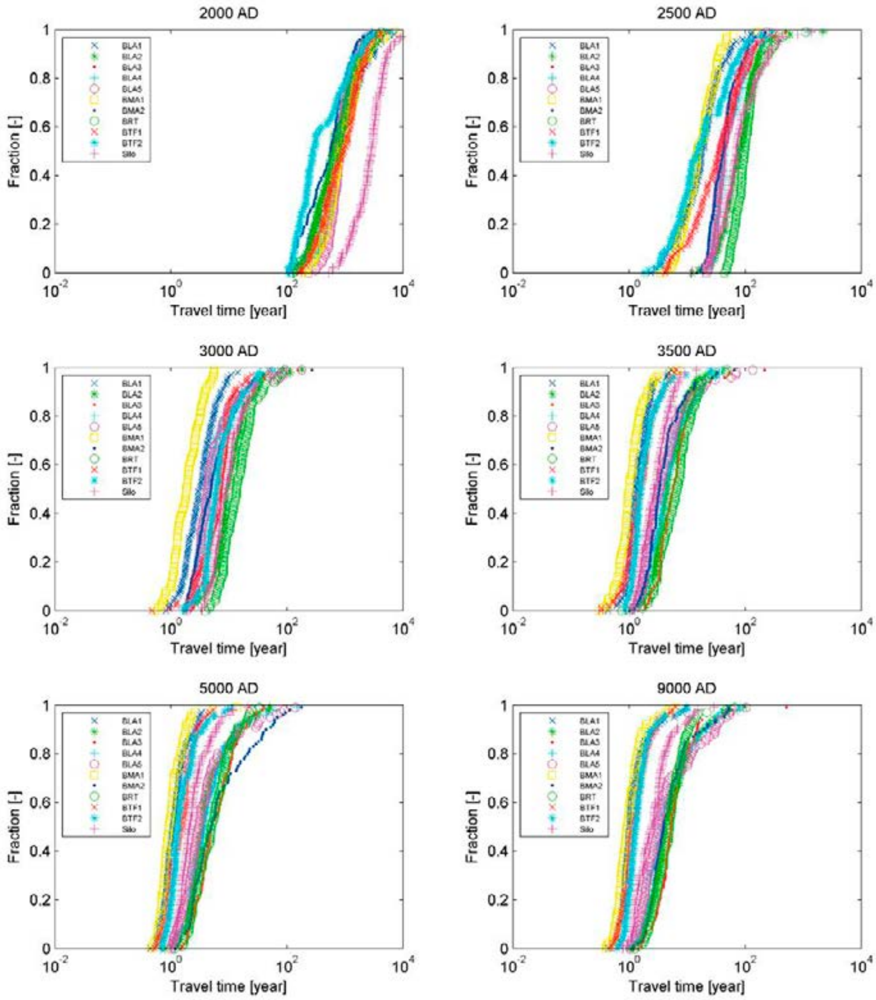

Figure 3-3. Groundwater travel times from different areas of SFR to the biosphere for the global warming variant of the main scenario (Figure A-2 of the Radionuclide Transport Report)

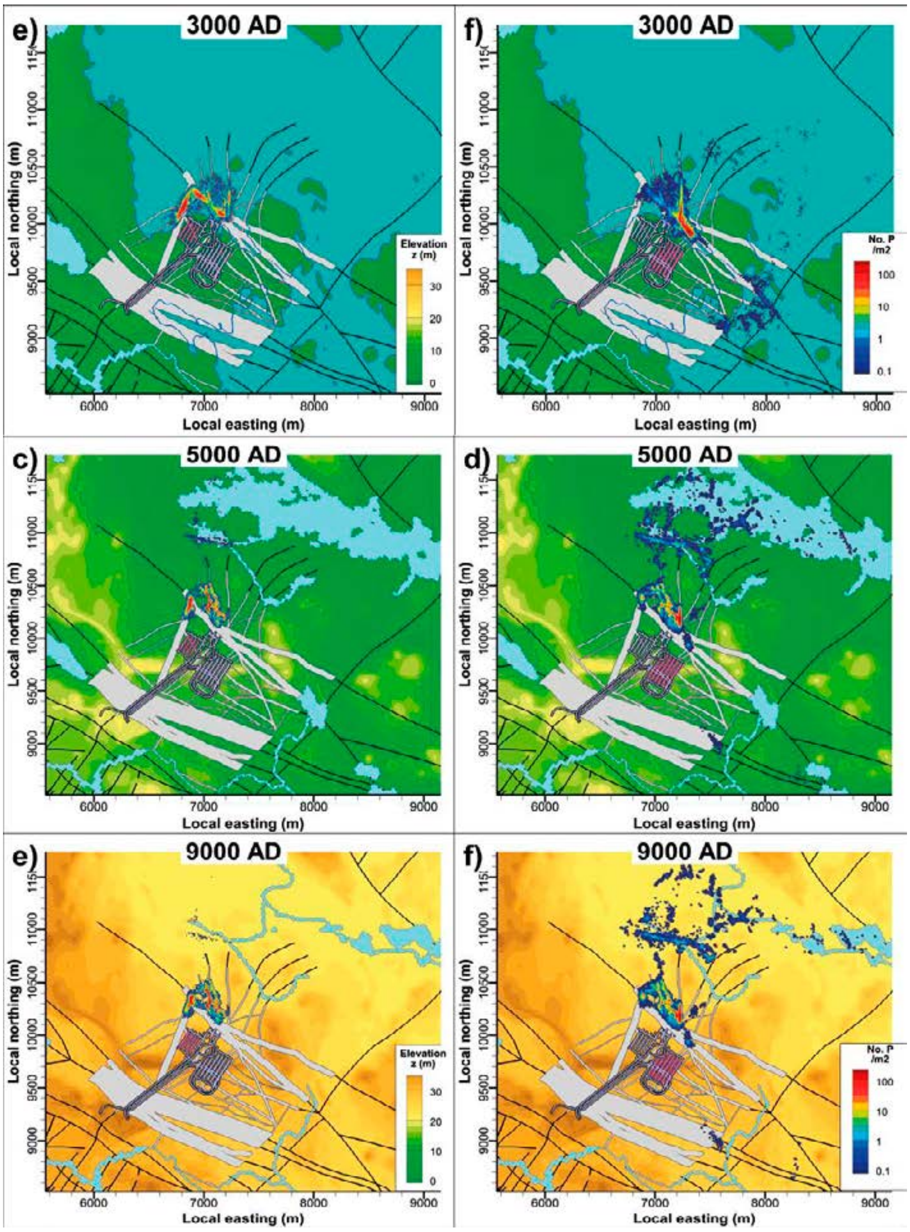

Figure 3-4. Discharge locations from SFR 1 (pink shade; left) and from SFR 3 (pink shade; right) illustrated by particle density at the surface, based on 1,000,000 particles released at repository depth. The black lines represent deformation zones. The white areas also represent deformation zones, but zones closer to the SFR repository where the width of a white area indicates the zone thickness at ground surface. (Figure 7-3 of the Main Report).

Implications of the Site's Characteristics for Radioactive Waste Disposal

The geosphere could limit groundwater flow rates through the facility and hence the rate of radionuclide release. However, the short groundwater travel times from the repository, through fractures in the rock, to the biosphere (Figure 3-3) mean that we do not expect the geosphere to be a significant barrier to radionuclide migration. In addition, since flow is within fractures, there will be limited opportunity for sorption of radionuclides. These expectations are supported by the different scenarios explored by SKB, and are illustrated by the results of the residual scenario, loss of barrier function scenario – no sorption in the repository; in comparison to the results of the residual scenario, loss of barrier function – no sorption in the bedrock. This comparison shows that the near-field is a much more significant barrier to radionuclide migration than the geosphere (Section 9.4 of the Main Report). Therefore the near-field is the main barrier to radionuclide migration, and as such SKB's assessment of radionuclide release and transport in the near-field is a key focus of this review. However, the understanding of the geosphere is important because it controls the mechanical stability of the repository; groundwater flow rates through the repository, and evolution of groundwater geochemistry with time in response to landscape change; and the location(s) of groundwater discharge to the biosphere, and hence the nature of the Geosphere-Biosphere Interface Zone (GBIZ).

Granitoid bedrock typically has high strength and therefore is suitable for the construction of stable excavations. However, the presence of fractures can lead to instability, including the potential for rockfall or movement of large blocks of rock. Mechanical stability is one of the potential aspects considered by SKB in the long-term safety analysis (Table 5-2 of the Main Report), and this has been taken into account in the waste packaging and SFR vault /silo design. Not only is bedrock stability considered, but also development of stresses associated with expansive degradation reactions. These expansive stresses could result in cracking of low permeability concrete barriers. Hydration and swelling of dried evaporator concentrates and ion-exchange resins are the main processes considered, although anaerobic corrosion reactions are also identified and included in the programme of further R&D (Section 11.5.3 of the Main Report). These mechanical and coupled chemical-mechanical processes might significantly affect the performance of the near-field barriers, and therefore will be an important focus of this review.

The current groundwater composition reflects a mixture of inputs including deep brackish non-marine waters, glacial melt water, Littorina sea water, and Baltic sea water. The distribution of groundwater types has been affected by dewatering of SFR, notably including enhanced intrusion of Baltic sea water towards the repository. Table 6-1 of the Main Report describes the groundwater composition assumed for the first 1,000 years of the assessment, while SFR is below the sea. Notable features of the composition include the elevated salinity and sulphate content, which may be particularly important in the context of corrosion and cement degradation.

As the landscape transitions from a marine environment to a terrestrial environment, SKB anticipate the groundwater geochemistry will change towards a less saline terrestrial composition, in response to groundwater recharge from rainfall. The compositions assumed and the fluxes of solutes through the repository are important because they will affect the key processes for barrier degradation, the rates of degradation and radionuclide mobility. Therefore, both the groundwater flow rates through the facility, the chemical degradation of near-field barriers and the influence of chemical conditions on radionuclide mobility will all be important considerations for this review.

Note that, as described above, these hydrochemical processes are coupled to mechanical processes, and the identification and treatment of such couplings also needs to be considered in this review.

The nature of the GBIZ is important because it will affect dilution and dispersion of radionuclides in the biosphere. It will also affect the non-human biota that may be exposed, migration of radionuclides through the foodchain, and doses to humans due to occupancy of contaminated areas and consumption of contaminated foodstuffs, including the potential for use of groundwater (well water) for drinking, irrigation, etc.

The location and nature of the GBIZ is affected by SKB's landscape evolution model, but it is also noted that landscape evolution might be influenced by the properties of the geosphere. For example, zones of highly fractured bedrock might be more readily eroded than relatively unfractured bedrock, forming topographic lows where groundwater discharges to streams or other surface water features. Given the low topographic relief of the region, it might be anticipated that over the assessment timescales of 100,000 years, geomorphological processes could affect the topography and hence the location and nature of the GBIZ. In addition to evolution of the local topography, the impacts of geomorphological processes on the thickness and nature of the regolith may also be important. For example, Section 9.2 of the Site Description Report (TR-11-04) notes that, "*the stratification and hydraulic parameterisation of the regolith affects the inflow to the existing SFR facility and hence the calibration of the groundwater flow model*". Detailed assessment of the landscape and groundwater models is beyond the scope of the initial radionuclide transport review, but may be an important multi-disciplinary topic for the main review.

The transition from a marine environment to a terrestrial environment is very important because it significantly increases the potential impacts of radionuclide releases to the biosphere. The timing of this transition is also very important, particularly in the context of cautious assumptions in the assessment. In long-term safety assessments, uncertainties are often treated by making cautious assumptions that lead to earlier radionuclide releases, reduced containment, faster radionuclide migration, less decay[1], etc. The objective of these cautious assumptions is that radionuclide releases and impacts will be overestimated, i.e. cautious.

In the context of SFR, such assumptions might lead to radionuclide releases to a marine environment rather than a terrestrial one, which is not cautious, because impacts might be underestimated. SKB have recognised this issue, and in the main global warning calculation case (CCM_GW) they assume there is no radionuclide transport during the first 1,000 years (Section 8.3.1 of the Main Report). An alternative calculation case (CCM_TR), assesses the impact of radionuclide transport beginning immediately following closure. This is considered to be a good treatment of this issue, and SKB's approach needs to be taken into consideration when evaluating cautious assumptions during this review.

Safety Principles

SKB have identified two post-closure safety principles in order to achieve post-closure safety for SFR (Section 2.1.2 of the Main Report):

[1] It is noted that less decay may not be cautious in situations where ingrowth of daughter radionuclides is important. However, this should not be important for SFR where the inventory of long-lived actinides is low.

- "*Limitation of the activity of long-lived radionuclides is a prerequisite for the post-closure safety of the repository. This is achieved by only accepting certain kinds of waste for disposal. The design of engineered barriers is a consequence of the total activity disposed in each waste vault.*
- *Retention of radionuclides is achieved by the performance of the engineered barriers and the repository environs. The properties of the wastes, together with the properties of the waste containers and of the engineered barriers in the waste vaults, contribute to safety by providing low water flow and a suitable chemical environment to reduce the mobility of the radionuclides. The host rock provides stable chemical and physical conditions and favourable low groundwater flow conditions*".

These safety principles are consistent with the implications of the site characteristics for radioactive waste disposal described above. The safety functions, and in turn the assessment scenarios, 'flow-down' from these principles, so this provides confidence in SKB's assessment approach at a high level; although the safety functions and assessment scenarios will still need to be considered in more detail as part of this review. It is also apparent that these safety principles have influenced the engineering design, e.g.:

- Providing low water flow - The intermediate-level waste in 1BMA and 2BMA is emplaced in concrete caissons where the walls, floor and lids of the structures limit flows through the waste (Section 6.3.5 of the Main Report).
- Stable physical conditions - The top part of the silo cupola will be backfilled mainly with macadam to protect against rock fallout (Section S2.2 of the Main Report).

SKB recognise the reliance on the near-field barriers to provide containment due to the limited containment provided by the geosphere, and that these near-field barriers will degrade over time (i.e. their containment performance will decrease). Therefore, SKB recognise that appropriate limits on the activity of long-lived radionuclides disposed "*will be essential to ensuring safety*" (Section 2.1.2 of the Main Report). Indeed, SFR is not intended for disposal of significant quantities of long-lived radionuclides.

Summary of SKB's Conceptual Model

This section provides a more detailed summary of SKB's conceptual model. The objective of this is both for familiarisation purposes, and to provide introduction / context to the subsequent initial review of SKB's abstraction of FEPs into the radionuclide transport models. Although the focus of this section is on the conceptual model, aspects of the implementation of the conceptual model in the assessment models are noted where they are considered to be of particular interest or potentially significant, and may influence the main review. However, in general, implementation of the conceptual model in the assessment models is beyond the scope of this initial review and will be a key focus for the main review[2].

[2] We define a conceptual model as describing the disposal system, including the relative importance of different FEPs, and which FEPs are important for safety. The assessment models include the FEPs and couplings that are important for safety and these are assessed quantitatively.

Figure 3-5 shows our summary of SKB's conceptual model for the global warming variant of the main scenario. Together with the early periglacial variant of the main scenario, these two variants describe SKB's best estimate[3] evolution of the repository. Figure 3-5 shows a 'generic' vault that enables some of the key FEPs to be described. In reality the vaults and silo contain different wastes and waste packages, and have different engineering that performs different detailed functions. SKB's conceptual model describes the individual vaults and the silo. However, in all cases the general functions of the engineering are to:

- Promote mechanical stability.
- Minimise flow of water through the waste.
- Allow gas to escape and prevent pressurisation.
- Promote geochemical conditions under which the mobility of radionuclides is low.

This is achieved by the use of low permeability materials, such as concrete for the waste encapsulant, packages and engineered barrier components. In some vaults, the low permeability barriers are surrounded by permeable materials such as macadam, which creates a hydraulic conductivity contrast and diverts flow away from the wastes (Section 7.4.3 of the Main Report), for example vault 2BMA (Figure 3-5).

In relation to 1BMA, it is noted in Section 4.3.1 of the Main Report that "*An extensive programme for investigation of the concrete structure has been carried out and has revealed that extensive repair and reinforcement measures need to be adopted to achieve the desired hydraulic and mechanical properties at closure. The Closure plan for SFR (SKBdoc 1358612) describes the planned measures for closure of 1BMA*". Construction Quality Assurance (CQA) is beyond the scope of this review. However, a relevant consideration is whether the desired hydraulic and mechanical properties can be achieved, especially where repair and reinforcement works are required. It is relevant to consider whether these potential construction issues are captured by the FEPs, and fed into the scenarios and calculation cases. With respect to 1BMA in particular, an important question is whether the repair and reinforcement can achieve the desired hydraulic and mechanical properties, or whether inaccessible parts of the engineering will underperform?

[3] These are the scenarios SKB assign the highest probability (probability of one: Section 10.3 of the Main Report) and are equivalent to what other assessments might term the expected or normal evolution scenario.

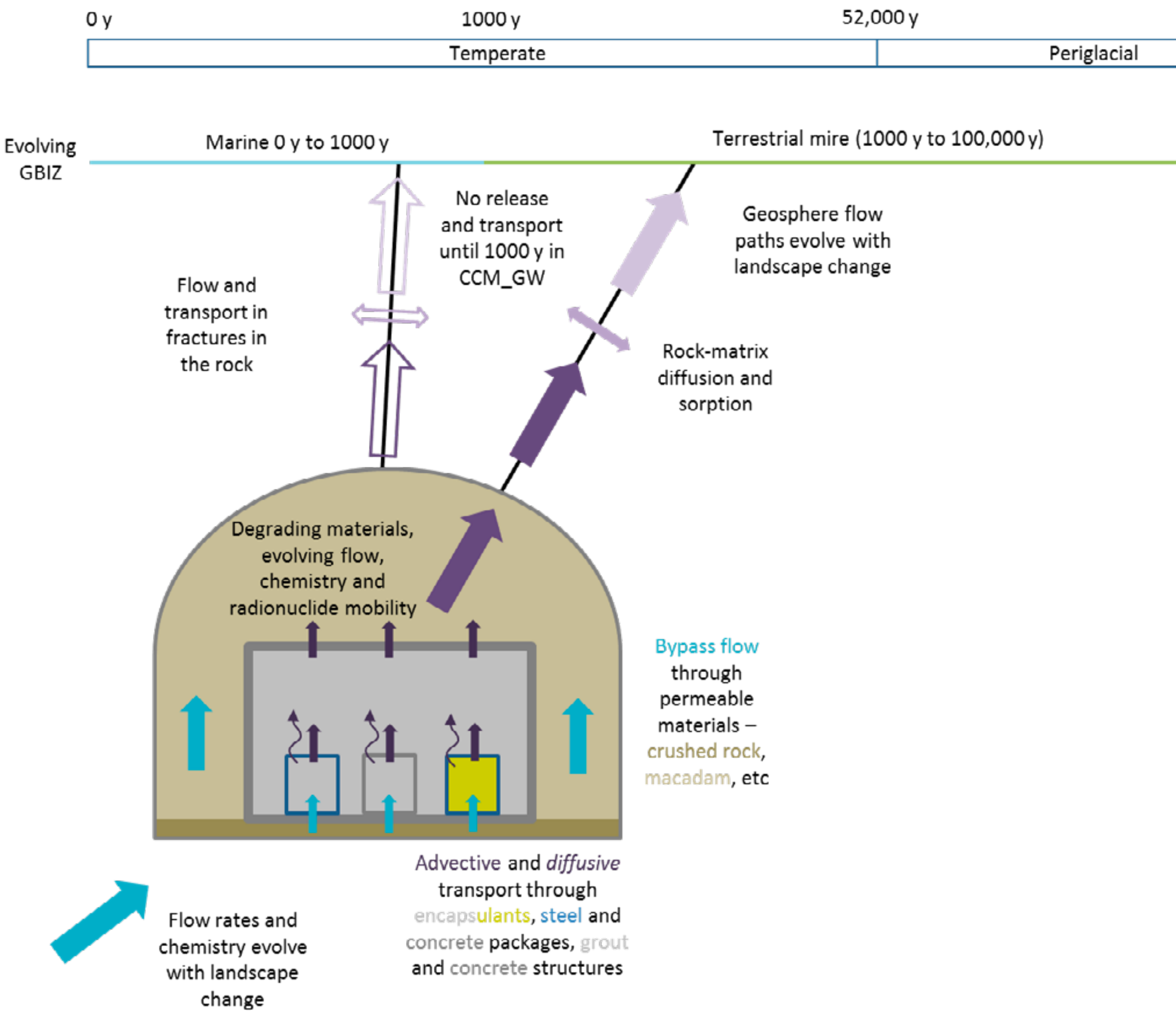

Figure 3-5. Our summary of the conceptual model for the global warming variant of the main scenario

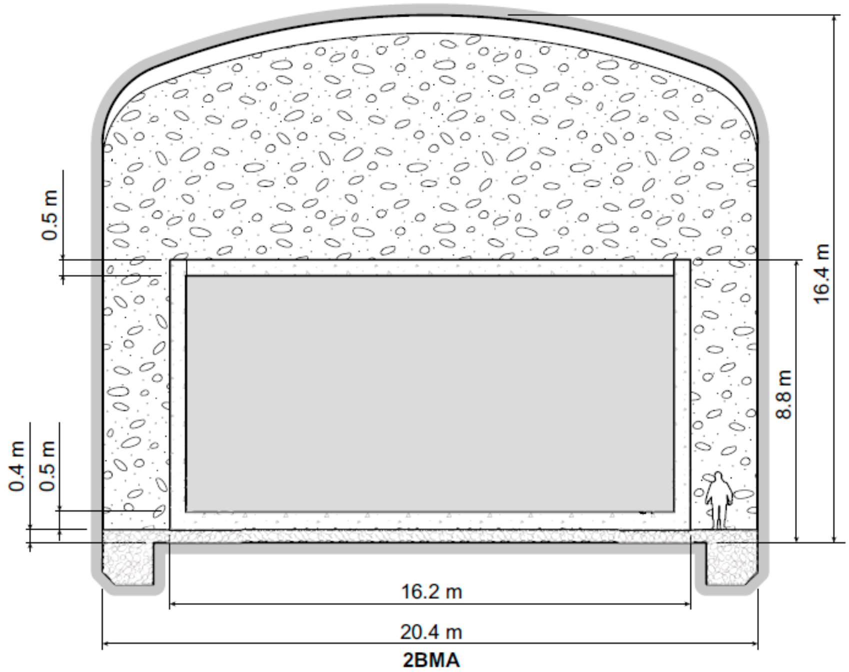

Figure 3-6. Schematic cross-section of vault 2BMA, for higher active ILW, after closure. The waste packages are grouted into concrete caissons, which sit on a bed of crushed rock levelled with gravel, and are surrounded by macadam. (Figure 4-9 of the Main Report).

Further investigation is required to understand SKB's assumptions regarding the availability of radionuclides in the waste, but based on the initial review work our understanding is that SKB assume radionuclides are immediately available for transport upon contact with water (e.g. Section 4.1.1 of the Radionuclide Transport Report). SKB do identify one exception to this: activation products present as matrix contamination in the metal reactor pressure vessels (BRT vault) are assumed to be released congruently with corrosion (Section 7.4.3 of the Main Report). Contaminants are released from waste packages by advection and diffusion (Section 7.4.3 of the Main Report), but no account is taken of the containment provided by steel containers, which are assumed to fail quickly (Section 2.4.1 of the Radionuclide Transport Report). This assumption may result in earlier release of radionuclides from steel waste packages than if the packages were assumed to be intact and gradually degrade, because radionuclides can be transported out of the package by both advection and diffusion once the steel has corroded. While the steel package is intact release may only be possible by diffusion, for example out of any gas vents in the lids of the steel packages.

As previously noted, assumptions regarding the timing of radionuclide release with respect to the landscape change from a marine environment to a terrestrial environment may be important for calculated impacts. However, since in the main global warning calculation case (CCM_GW) SKB assume there is no radionuclide transport during the first 1,000 years while the repository is under the sea (Section 8.3.1 of the Main Report), the assumption that steel packages have failed immediately is likely to be cautious, i.e. it will result in radionuclide fluxes immediately following the transition to a terrestrial environment being overestimated.

Radionuclides are subsequently transported through the engineered barrier systems by advection and diffusion, subject to retardation by sorption. Radionuclides are considered to be sorbed onto cementitious materials, bentonite and crushed rock / macadam (Data Report). No references have been found for sorption onto bitumen, so presumably SKB assume that sorption onto bitumen is insignificant. Sorption onto corrosion products is not considered (Section 7.4.3 of the Main Report). There is assumed to be no sorption in the BLA vaults, which contain LLW, and are not backfilled. In the assessment models none of the radionuclides are considered to be solubility limited (Section 2.4.1 of the Radionuclide Transport Report). Ignoring solubility limitation and sorption onto certain substrates will be cautious, unless, for example, it results in calculations underestimating radionuclide fluxes in the longer-term to a more 'sensitive' receptor.

Radionuclides migrate out of the near-field and then through fractures in the bedrock. Radionuclides may be retarded by sorption onto the fracture surfaces and by diffusing into the walls of the fractures where they may also be sorbed (Section 7.4.2 of the Main Report). In the global warming variant of the main scenario, radionuclides discharge to the regolith in a terrestrial mire environment (Figure 8-22 of the Main Report).

As the landscape evolves from a marine environment to a terrestrial environment, groundwater flow rates through the repository may increase, and groundwater pathways to newly emergent land may develop. The groundwater chemistry will change from an initially brackish / saline composition, becoming increasingly dilute in response to recharge from rainwater (Section 7.4.2 of the Main Report). This will affect the chemistry of water flowing into the repository. In turn, this will affect the near-field geochemistry, degradation reactions and radionuclide mobility (sorption) (Section 7.4.3 of the Main Report), bentonite swelling pressure, and radionuclide mobility (sorption) in the geosphere (Section 7.4.2 of the Main Report).

SKB anticipate the waste packages and engineered barriers will degrade over time, principally due to chemical and coupled chemical-mechanical processes. The processes considered include (Section 6.3.7 of the Main Report):

- Generation of degradation products including Isosaccharinic acid (ISA), which can affect radionuclide mobility (reduced sorption).
- Chemical alteration of cements leading to fracturing, changes in hydraulic properties, porewater chemistry and radionuclide sorption.
- Corrosion of rebar, resulting in swelling and cracking of associated concretes.
- Hydration and swelling of bitumen encapsulated wastes, and associated potential cracking of containers and concrete structures.
- Alteration of bentonite by reaction with alkaline cement porewaters.
- Corrosion of steel containers.

As concretes degrade their hydraulic conductivity is considered to increase (Figure 7-8 of the Main Report) and their diffusivities, porosities, densities and sorption coefficients also evolve (Figure 7-9 of the Main Report), such that radionuclides diffuse through them more quickly and are more weakly retarded. SKB conceptualise physical and chemical degradation as proceeding at different rates, and the degradation rates are different for the different vaults / silo. Section 7.4.3 of the Main Report states that, "*for the 1–2BMA waste vaults, the possible future occurrence of larger fractures is modelled explicitly by an advective transfer* *directly through the barriers, without taking into account the sorption in the barriers*". However, it is not immediately clear under what circumstances such fractures are considered to develop, for example, later in the same section it is stated that "*The flow rates through all concrete barriers are sufficiently low for effective sorption as long as the flow barriers do not degrade completely resulting in the flow becoming localised to a few major fractures*". Given the importance of concrete barriers for containment of radionuclides, the timing and rate of degradation and the conditions under which larger fractures are considered to form, are identified as topics, for both this initial review and ultimately also the main review.

Bentonite will react with high pH waters forming calcium-silicate minerals, zeolites and new clays. These minerals have different properties from the original montmorillonite, including poorer swelling properties and a higher molar volume. In general, the zeolites formed strongly sorb cations, therefore SKB argue they should be as good or better sorbants than the original minerals (Section 6.6.2 of the Main Report). By 17,500 years, SKB expect that more than one third of the total quantity of montmorillonite in the bentonite may be transformed to other minerals (Section 6.6.2 of the Main Report), and all the montmorillonite is expected to be altered after 100,000 years (Section 6.6.4 of the Main Report).

Ion-exchange resins, to some extent mixed with evaporated salts, are solidified in bitumen before being placed in waste packaging. The bituminised waste is allocated to the silo, 1BMA and BLA. When ion-exchange resins and evaporated concentrates absorb water, they expand in volume. The consequent expansive stresses can result in cracking of concrete packages and engineered barriers. Different strategies are applied by SKB to prevent adverse effects of swelling bitumen waste forms (Section 6.3.7 of the Main Report):

- "*In 1BMA, grouting must be done in such a way that there is enough free volume available to accommodate the increased volume.*
- *In 2BMA, no bituminised waste form will be deposited.*
- *In the silo, engineered expansion cassettes are placed between the drums of bituminised waste from the Barsebäck nuclear power plant. Bituminised waste from the Forsmark nuclear power plant has between 5 and 10% free void inside the moulds to accommodate the swelling. However, there is probably not enough free volume to accommodate all volume expansion. According to von Schenck and Bultmark (2014), the internal structure of the silo will probably be affected in the future as a consequence of swelling bituminised waste forms. In their findings the outer silo walls were not affected by this process.*"

It is interesting to note that swelling of bitumenised wastes is expected to affect the internal structure of the silo but not the outer walls. This may be an important conclusion that could be further examined within the main phase of this review, although it may fall outside of the scope of the radionuclide transport area.

Ion-exchange resins may also be solidified in cement rather than bitumen, and in the BTF vault they are stored unconditioned, but dewatered, in concrete tanks (Section 6.3.7 of the Main Report). The Main Report does not state whether these wastes will also swell significantly, and whether this might lead to damage to the waste packages and engineered barriers.

Section 6.3.7 of the Main Report also notes that bitumen conditioned ion-exchange resins in the BMA vaults may contain evaporator concentrates, which may contain a significant amount of highly soluble salts, such as sodium sulphate. SKB note that sulphate released from these waste packages may affect the integrity of adjacent concrete waste packages and engineered barriers. Cement used to solidify ion exchange resins and associated evaporator concentrates may be directly attacked.

Groundwater flows through the near-field evolve as the waste packages and barriers degrade. Hydraulic conductivity contrasts between the waste packages / low permeability barriers and coarse grained backfill such as macadam are considered by SKB to decrease with time as the materials degrade, so a greater proportion of flow through the near-field interacts with the wastes (Section 6.4.5 of the Main Report).

A number of processes lead to the generation of gas. These include anaerobic corrosion of metals, microbial degradation of organic wastes and radiolysis (Section 6.3.7 of the Main Report). There may be relatively rapid generation of gas from aluminium wastes during the first few years (Section 6.6.1 of the Main Report). Gas should be able to readily migrate through the fractured bedrock. However, if gas is trapped in the near-field by low permeability engineered barriers, the pressure could potentially increase until the barriers are physically disrupted and the gas is able to escape. A build-up of trapped gas could also result in pressure driven flow of water, and associated dissolved radionuclides, out of the repository. This has been taken into consideration in the design, for example the silo incudes materials and features specifically designed to allow gas to escape (Section 4.3.4 of the Main Report), while in other vaults, features such as small concrete shrinkage cracks are considered to be adequate to allow gas to escape without the need for an engineered gas pathway, e.g. 2BMA (Section 4.3.2 of the Main Report).

Gaseous radionuclides can also be released from the repository. These gaseous radionuclides can be transported to the biosphere by bulk gases such as H_2 generated through anaerobic corrosion of steel, etc. The key gases we consider to be of concern are $^{14}CO_2$ and $^{14}CH_4$, since H-3 will decay to insignificant levels before the transition to a terrestrial environment and Rn-222 will likely decay within the repository. Bulk CO_2 and CH_4 can be generated through microbial degradation of organic wastes, with trace quantities of $^{14}CO_2$ and $^{14}CH_4$ being generated at the same time. Although SKB do not discuss $^{14}CO_2$, under high pH repository conditions, the partial pressure of CO_2 will be low, and the majority of CO_2 would likely react with cement minerals forming carbonates. The rest of the CO_2 will be in solution. SKB consider that methane formation through methanogenesis is unlikely to occur under hyperalkaline conditions (Section 6.3.7 of the Main Report). None of the calculation cases assessed consider the impacts of C-14 labelled gases (Main Report, Radionuclide Transport Report), therefore presumably SKB consider the potential fluxes of C-14 labelled gases are negligible. This is in contrast to assessments undertaken for other L/ILW repositories (e.g. Sumerling, 2013), therefore a useful initial review activity will be to try and understand the reasons for the differences.

SKB argue that thermal processes are not significant due to the low heat output from radioactive decay and degradation reactions. It is stated that the temperature of the repository will be almost entirely determined by the exchange of heat with the surrounding rock and groundwater (Section 6.3.2 of the Main Report). This is reasonable although it would be useful if SKB could cite supporting evidence, including calculations performed by other waste management organisations.

The geosphere flow paths, flow rates and hence travel time, are considered to gradually evolve as the landscape changes, until the sea has regressed sufficiently far from the repository that it no longer has any influence (Section 7.4.2 and 7.4.3 of the Main Report). Geosphere travel times and flow-related transport resistances have been derived by SKB from detailed modelling, for a number of times in the future, and fed into the assessment models (Section 8.2.4 of the Main Report).

The global warming variant of the main scenario assumes the onset of permafrost at 52,000 years, with a number of periods of permafrost occurring before the end of the assessment timeframe at 100,000 years. During periods of permafrost there is assumed to be no groundwater flow or radionuclide transport (Section 8.3.1 of the Main Report).

The early periglacial variant of the main scenario assumes periglacial conditions develop during a period of minimum insolation between 17,500 years and 20,500 years. Thereafter, climate and landscape evolution is identical to the global warming variant. Conditions during this early periglacial period are considered to be less cold than during later periglacial periods, such that permafrost is discontinuous rather than continuous. Therefore, groundwater flow does not completely stop, but is significantly reduced and discharge of groundwater is restricted to taliks. The entire modelled land area and regolith layers are considered to be frozen, so discharge is considered be to a wetland area or deep lake (Section 8.3.2 of the Main Report).

The formation of permafrost at 52,000 years is considered to result in freezing of the repository. Temperatures are considered to be sufficiently low that the concrete freezes, resulting in the formation of penetrating micro-cracks. SKB consider this causes such a serious structural deterioration of the concrete that it cannot be relied on to remain intact after freezing and thawing. Therefore, when the permafrost subsequently melts, the concrete is no longer considered to limit advective flow, although it continues to act as a sorption barrier (Section 6.6.3 of the Main Report). In the early periglacial climate case the temperature at repository depth is not expected to be low enough during the early periglacial period for concrete to freeze (–3°C) and therefore it is not damaged by cracking (Section 6.6.2 of the Main Report).

If permafrost reaches the repository, an ice lens may form in the silo bentonite. SKB consider this could happen during the early periglacial period, or during a later, colder, periglacial period (Section 6.6.2 of the Main Report). Bentonite will gradually be displaced as the lens grows. After thawing, when the ice lens melts and the bentonite swells, the sealing properties of the bentonite are expected to be locally degraded. SKB cite simulations that show an order of magnitude increase in water flow in the degraded volume, but assume the silo structure will limit the amount of water that can penetrate to the waste, since the concrete barriers are not expected to be degraded during the early period of permafrost. SKB note that another possible process in the bentonite during the period of permafrost is freezing of trapped water which may cause a considerable pressure increase.

SFR3 is deeper than SFR1, so it is possible that SFR1 may be frozen during periods of permafrost while SFR3 is not. For example, Figure 7-1 of the Main Report shows that, during some periods, permafrost may penetrate to the depth of SFR1 but not to the depth of SFR3. SKB do not appear to have differentiated their treatment of SFR1 and SFR3 in the assessment calculations (Section 8.3 of the Main Report), but this is likely to be cautious given the degradation of barriers that is considered to be caused by freezing and subsequent thawing.

A very low probability 'residual scenario' considers the possibility of glaciation and subsequent deglaciation before the end of the assessment timeframe (Section 7.7.8 of the Main Report).

Findings from the Summary of the Conceptual Model

Although the objective of summarising the conceptual model was for familiarisation purposes, and to provide introduction / context to the subsequent initial review of SKB's abstraction of FEPs into the radionuclide transport models, a number of important topics have already been identified for consideration in the subsequent steps of this initial review and potentially for further investigation during the main review phase. These are:

- CQA and deviations in the properties of waste packages and engineered barriers from the design specifications / assessment assumptions.
- Changes in groundwater flow and geochemistry in response to isostatic rebound, and the transition to a terrestrial biosphere.
- Rates of waste package and engineered barrier degradation, the impact(s) of these processes on flows and radionuclide mobility, and their representation in assessment models.
    - Conditions under which larger fractures form in concretes.
- Coupled mechanical processes, including prevention of rockfall, the potential impacts of voids, and the impacts of expansive reactions and associated swelling stresses on barrier integrity.
- Generation and release of C-14 gas.
- Geomorphological evolution, influenced by the features of the geosphere, and the nature of the GBIZ.

3.3. Abstraction of Key FEPs

3.3.1. Review of SKB's FEP Analysis

Summary of SKB's Methodology

SKB have developed a FEP database that covers the spent fuel repository and SFR. The database contains a FEP catalogue for SR-PSU. The FEP catalogue for SR-PSU was initially developed from the FEP catalogue for the spent fuel repository (SR-Site) and earlier FEP work for SFR (Section 3.2.2 of the Main Report). The catalogue was then audited against NEA's FEP database and the FEPs from two other projects for disposal of low- and intermediate-level waste (Olkiluoto L/ILW and Rokkasho 3). We have not conducted our own audit of the SR-PSU FEP catalogue, however the approach used by SKB builds confidence that the catalogue is likely to be comprehensive.

SKB have used the SR-PSU FEP catalogue to systematically develop conceptual and assessment models[4] from the 'bottom up'. It is important to understand and review this process to assess if SKB's abstraction of FEPs into the radionuclide

[4] We define a conceptual model as describing the disposal system, including the relative importance of different FEPs, and which FEPs are important for safety. The assessment models include the FEPs and couplings that are important for safety and these are assessed quantitatively.

transport models is appropriate and adequate for its purpose. SKB's methodology is summarised below and is then discussed.

The FEPs in the SR-PSU FEP catalogue have been categorised into initial state FEPs, internal processes in the system components (i.e. waste form, waste packaging, etc), variables for the system components (e.g. geometry, temperature, hydrological variables, etc), biosphere FEPs, external FEPs and methodology related issues.

The categorised FEPs have then been fed into a number of reports: initial state report; biosphere reports; climate report; Future Human Actions (FHA) report; and process reports for waste, barriers and geosphere (Figure 3-3 of the Main Report). The process reports are of particular interest in relation to understanding the abstraction of FEPs into the radionuclide transport models. Section 2.4.4 of the Main Report summarises the treatment of FEPs within the process reports: "*Each process is documented in the process reports according to a template with a number of set headings. At the end of the process documentation, it is established how the process is to be handled in the safety assessment, a central result from the process reports. The process reports thus provide a "recipe" for handling the different processes in the assessment. The handling of all processes in the process reports is summarised in tables that describe whether a process can be neglected, whether a qualitative assessment is made, or whether it is handled by quantitative modelling*".

Within the process reports, influence tables have been used to explore process couplings for the individual system components. For a given system component, an influence table has been developed for each process that may act on the component. The influence table describes the interactions between the process and one or more variables that describe the state of the component (an example is provided in Table 3-2 of the Main Report). Process diagrams are generated on the basis of the influence tables. A diagram is generated for each system component and shows the influences between processes and variables (an example is provided in Figure 3-1 of the Main Report). Interaction matrices are used as an alternative to process diagrams to illustrate couplings between variables and processes for each system component (an example is provided in Figure 3-2 of the Main Report).

The focus of the influence tables, process diagrams and interaction matrices is to describe the couplings between processes and variables for individual system components. Couplings between the system components have been described as 'boundary conditions' (Section 3.4.1 of the Main Report). Boundary conditions describe the transport of materials or energy across the interfaces between system components in response to different processes (an example is provided in Figure 3-1 of the Main Report).

Development of the FEP catalogue for SR-PSU, the FEP audit, and the methodology used to categorise and record FEPs is further described in the FEP Report. In general this report expands the summary description provided in the Main Report. Nevertheless there are a couple of additional points that are worth noting as part of this initial review. The engineered barrier systems associated with each vault and the silo are treated as individual system components, e.g. BMA barriers, Silo barriers (Section 4.1of the FEP Report). This means that processes, variables and associated couplings are considered for each vault and the silo, taking into account the differences in the engineering, design and materials. We consider this to be a good and thorough approach given that SKB have used the FEPs to develop the conceptual and assessment models from the 'bottom up'.

Appendix 2 of the FEP Report describes the variable FEPs associated with each system component. We have reviewed the variable FEPs for some of the system components to check them for completeness, and to better understand SKB's approach to treating couplings. For the system components reviewed, we considered that all the relevant variables had been identified.

The FEP Report provides an extensive audit of the SR-PSU FEP catalogue, including comprehensive appendices that map NEA FEPs to the SR-PSU FEPs. Explicitly recording this mapping builds good confidence that all relevant FEPs have been identified and there are no omissions in the SR-PSU FEP catalogue. The appendices also describe which aspects of each FEP are addressed in SR-PSU and which aspects are not addressed and why. This provides an excellent audit to confirm that all the relevant FEPs are treated in the assessment, although it cannot confirm that they are treated appropriately.

In Section 3.2 we noted SKB have identified that repair and reinforcement measures are required for 1BMA to achieve the desired hydraulic and mechanical properties at closure. More widely we noted that a relevant issue for this review is whether these potential construction issues are captured by the FEPs, and fed into the scenarios and calculation cases. Figure 3-3 of the Main Report shows that initial state deviations are identified from the initial state FEPs, and fed into the scenarios. Table 5-1 of the FEP Report describes the initial state FEPs in the SR-PSU catalogue. These include "*Design deviations – mishaps*" (Table 3-1).

Table 3-1. Extract from Table 5-1 of the FEP Report, Initial state FEPs in the SR-PSU catalogue

FEP ID	FEP Name	Description
ISGen05	Design deviations - mishaps	Design deviations due to undetected mishaps during manufacturing, transportation, deposition and repository operations affecting the initial state. This includes e.g. incorrect structural design, deviating material properties, incompletely backfilled or sealed vaults, boreholes and shafts; undesirable or unexpected material left in the vaults.

Therefore, design issues and deviations have been identified in the assessment, and fed into the scenarios, but we have not reviewed their assessment in detail at this stage.

Finally, we note that the SR-PSU FEP catalogue includes site specific FEPs (Section 5.7 of the FEP Report). Even though only two site specific FEPs have been identified, we consider site specific FEPs to be a potentially important consideration, and it further indicates the comprehensive identification and assessment of FEPs that has been undertaken.

Discussion of SKB's Methodology

SKB have undertaken a systematic and comprehensive process to identify, assess, record and audit FEPs and their treatment in the assessment. Although we have not undertaken a comprehensive audit of the SR-PSU FEP catalogue or the process reports, the methodology used is logical and suitable to achieve the desired outcomes. 'Spot checking' of variables has not revealed any obvious omissions, and additional considerations such as site specific FEPs have been identified and captured.

SKB have used the SR-PSU FEP catalogue to systematically develop conceptual and assessment models from the 'bottom up'. While there is good confidence in the comprehensiveness of the SR-PSU FEP catalogue, further analysis is required within this review to understand if SKB's abstraction of FEPs into the radionuclide transport models is appropriate and adequate for its purpose.

Based on our experience of undertaking assessments using 'bottom up' approaches, one of the most challenging aspects is determining the relative importance of different FEPs and couplings, and how they should be treated in the assessment; i.e. whether they can be treated qualitatively or whether they need to be assessed quantitatively using assessment models, including relevant uncertainty / sensitivity analysis.

Ideally the most-important FEPs and couplings will be identified and then appropriate code(s) selected to allow the most important FEPs and couplings to be assessed quantitatively, rather than choosing the code(s) first, and this dictating the treatment. Of course there are limitations in terms of the available codes, practical run times, etc. Nevertheless, it will be useful to better understand the approach that has been used. To help achieve this, it is proposed that the underpinning process reports for waste, barriers and the geosphere should be reviewed as part of the main review phase.

Although the process reports describe and assess the coupled processes for each system component, they may not describe couplings between system components. Coupled transfers of mass and energy between system components are recorded in SKB's FEPs database, but it is difficult to understand how these are used in the assessment and abstracted into the conceptual models.

Relevant questions for SKB are:

- Are there any additional reports that describe the decision making processes used to determine how FEPs and couplings should be treated in the assessment?
- Are there any additional reports that describe how couplings between system components are treated in the assessment?

An additional approach that can be used to assess whether the key FEPs and couplings have been identified and treated appropriately in the assessment is to take a 'top down' view of the conceptual and assessment models. This is undertaken as part of the subsequent steps of this initial review, but first we review SKB's identification and use of safety functions.

3.3.2. Key Safety Functions

SKB use safety functions to help formulate the assessment scenarios. Selection and description of the safety functions have been made based on the long-term safety principles, with safety functions being identified for each of the system components. The different vaults / silo have different safety functions reflecting their different wastes, engineering design, engineered barriers and backfill. In order to evaluate how a safety function influences the long-term safety of the repository, each function is associated by SKB with one or more safety function indicators, which describe measurable or calculable quantities. The safety functions and safety function indicators, mapped to the different system components, are summarised in Table 3-2. SKB note that in the process reports, the processes "*that are of significance for determining the importance of repository components for the* *long-term functioning of the repository and that help in the formulation of scenarios are singled out*" (Section 5.2.1 of the Main Report). However, just because a process is important for safety, a safety function does not have to be defined for it. For example, SKB note that some FEPs such as radioactive decay are also important for safety, but they are not significantly uncertain so corresponding safety functions are not defined, and they do not require assessing via different scenarios. We agree with this approach, but note that it is important that all the processes that are important to safety, that are potentially uncertain (e.g. evolution of barrier hydraulic conductivity with time), and that can be 'controlled' (by site selection, waste packaging, engineered barrier system design, etc.) need to be mapped to the safety functions.

Table 3-2. Safety functions and safety function indicators (Table 5-3 of the Main Report)

Safety function	Safety function indicator	Component
Safety principle: Limitation of the activity of long-lived radionuclides		
Limited quantity of activity	Activity of each radionuclide in each waste vault	Waste in 1BMA, 2BMA, 1BTF, 2BTF, silo, 1BLA, 2–5BLA and BRT
Safety principle: Retention of radionuclides		
Low flow in waste vaults	Hydraulic contrast	1–2BMA, 1–2BTF
	Hydraulic conductivity	Bentonite in silo and plugs
	Gas pressure	Silo
Low flow in bedrock	Hydraulic gradient	Geosphere
	Hydraulic conductivity	Geosphere
Good retention	pH	Cementitious materials in waste packages Concrete barriers in 1–2BMA, 1–2BTF, silo and BRT
	Redox potential	Cementitious materials in waste packages Concrete barriers in 1–2BMA, 1–2BTF, silo and BRT Geosphere
	Concentration of complexing agents	Cementitious materials in waste packages Concrete barriers in 1–2BMA, 1–2BTF, silo and BRT
	Available sorption surface area	Cementitious materials in waste packages Concrete barriers in 1–2BMA, 1–2BTF, silo and BRT
	Corrosion rate	Reactor pressure vessels BRT
Avoid wells in the direct vicinity of the repository	Intrusion wells	Surface
	Wells downstream of the repository	Surface

During this initial review phase we have not consulted the process reports. However, the safety functions and safety functions indicators capture what we consider to be the key FEPs in SKB's conceptual model (summarised in Section 3.2 of this report).

Identification of near-field safety functions and safety function criteria is significantly informed by SKB's SR-PSU Initial State Report. The initial state report describes the different components in the repository and their 'functions'. These 'functions' are listed in Table 5-2 of the Main Report, under the heading 'Aspects'. Section 5.4.1 of the Main Report describes each aspect in turn, leading to identification of the safety functions and safety function indicators.

We consider this process to be appropriate and logical, and the resultant safety functions and safety function indicators are sensible. A potential issue for further examination in the main review phase is the treatment of mechanical aspects, although it may fall outside the scope of the radionuclide transport review. Table 5-2 of the Main Report identifies mechanical stability as being important for the waste form, waste packaging, grouting surrounding the waste package, concrete structures, bentonite and sand/bentonite, and backfill in waste vaults. SKB's discussion of mechanical aspects is summarised in Table 3-3.

Table 3-3. Discussion of mechanical aspects in Section 5.4.1 of the Main Report

Component	Mechanical stability
Waste and packaging	The mechanical stability of the waste packages is taken into account in the waste acceptance criteria and waste type descriptions and is further described in the Initial state report (TR-14-02).
Engineered barriers in vaults	The mechanical stability of the repository is taken into account in the design of the repository and is presented in the Initial state report (TR-14-02). Lack of mechanical stability generally results in fractures being formed, changing the hydraulic conductivity in consequence. No specific safety function for long-term safety is linked directly to mechanical stability.
Plugs and other closure components	Not discussed.

SKB consider that safety functions and safety functional criteria do not have to be defined for mechanical aspects because they are controlled by waste acceptance criteria (WAC) and the engineering design. Therefore, SR-PSU does not include any scenarios in relation to mechanical evolution / behaviour. This is a reasonable approach so long as the assumptions and specifications within the waste package WAC and engineering designs will ensure post-closure mechanical stability, including over long timescales (i.e. up to the assessment timeframe of 100,000 years), taking into consideration the relevant degradation processes and resultant changes in materials properties, including density, volume, strength, etc. Therefore, the activities to be undertaken during the main review phase could potentially include reviewing the assumptions and specifications within the waste package WAC and engineering designs. The priority of this potential task will be further informed by our review of the key Thermo-Hydro-Mechanical-Chemical (THMC) processes presented in the next section of this report.

SKB identify avoiding wells in the direct vicinity of the repository as a safety function (Table 3-2). Section 5.4.5 of the Main Report notes that, "*wells intended for drinking water or agricultural purposes radically affect the radionuclide transport model for the biosphere. The use and location of wells therefore influence the risk contribution…*". Wells are not relevant while the repository is under the sea, but as the landscape changes, there is potential for development of a well that intersects the repository (although this is less likely for SFR3 than SFR1 because SFR3 is deeper: Section 7.6.8 of the Main Report), or wells down-gradient of the repository that intersect radionuclides in the geosphere. As previously discussed in the context of the wider biosphere, assumptions that affect the timing of radionuclide release will affect the potential impacts due to use of well water.

We have previously noted that SKB's safety principles are consistent with the implications of the site characteristics for radioactive waste disposal. Therefore the safety functions are also consistent with the site characteristics. We have reviewed the process SKB have used to feed the safety functions into the scenarios (Section 7 of the Main Report) and this is clear and logical, with clear relationships between the safety functions and scenarios. Therefore, so long as all the relevant safety functions have been identified, the list of scenarios should be similarly comprehensive.

We compared SKB's list of safety functions (Table 3-2) with RWM's list of generic safety functions (NDA RWMD, 2010a). Two potentially relevant safety functions identified in RWM's list of generic safety functions in relation to the backfill around the waste container, that have not been identified by SKB are:

- *"Suppress microbial activity in the vicinity of the waste.*
- *Control or prevent the movement of radionuclide-containing colloids from the wasteform into the rock".*

Section 6.3.7 of the Main Report describes chemical evolution of the waste domain, including microbial activity. It notes that high pH conditions are expected to significantly limit microbial activity, although microbial activity could be significantly higher in microbial niches, for example where the activity of acidogenic microbes locally reduces the pH. SKB note that an important mechanism is the likely formation of microbial biofilms on the waste surfaces and on the surfaces inside the packaging. Microbial activity is likely to be particularly high in the BLA vaults due to the large amount of organic (cellulosic) waste, and because the waste packages are not cement conditioned and the vaults are not backfilled, so the pH will be less alkaline than in the other vaults / silo. In other vaults and the silo, bitumen may be a substrate for microbes, although it is expected to only be degraded slowly under anaerobic conditions. Similarly plastics may be slowly degraded.

One of the potential microbial processes of interest is methanogenesis, in particular since it can result in generation of $^{14}CH_4$ gas. As previously noted in Section 3.2 of this report, SKB argue that methane formation through methanogenesis is unlikely to occur under hyperalkaline conditions and they do not assess the potential impacts of release of $^{14}CH_4$ gas. However, they also note there is some contradictory evidence which indicates methanogenesis might be possible under hyperalkaline conditions. Presumably methanogenesis is much more likely to occur in the BLA vaults where the pH is expected to be lower, and might also be possible in microbial niches in the other vaults and the silo.

In comparison Small et al. (2011) developed a biogeochemical model for the cementitious vaults at the Low Level Waste Repository (LLWR), UK. The model results indicate that significant methane could be generated in the vaults at pH 11. Therefore, even if methanogensis is not possible under hyperalkaline conditions, the results of Small et al. indicate methanogenesis may be significant once the pH has decreased a little.

SKB have calculated cement degradation and pH evolution for the different vaults and the silo (Figure 3-7). The cements will degrade heterogeneously depending on whether they are interacting with inflowing groundwater, or with solutes from the wastes. Therefore Figure 3-7 only describes the bulk conditions. The results suggest that high pH conditions under which methanogenesis is less likely to occur could be maintained for at least 10 half-lives of ^{14}C in the vaults containing ILW and the silo. This builds some confidence that significant quantities of $^{14}CH_4$ are unlikely to be generated, but uncertainties remain. Further examination of this issue is a potential topic for the main review, and depending on the contents of SKB's process and other reports, it may be necessary to request further information from SKB.

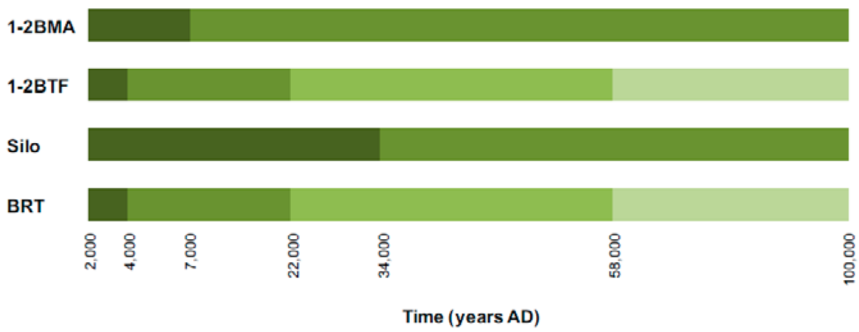

Figure 3-7. Illustration of succession of the four chemical concrete degradation states for each waste vault in the main scenario. Initially all cementitious materials are in the chemical degradation state I (dissolution of sodium and potassium hydroxides and the pH is higher than 12.5). Thereafter follows degradation state II (dissolution of portlandite pH ≈ 12.5), degradation state IIIa (incongruent dissolution of CSH phases, presence of Ca-aluminates pH ≈ 12) and degradation state IIIb (incongruent dissolution of CSH phases, absence of Ca-aluminates pH ≈ 10.5). Only 1–2BTF and BRT exhibit the full succession during the assessment period of 100,000 years. (Figure 7-9 of the Main Report).

Section 6.3.7 of the Main Report also considers colloids. SKB note that, "*the concrete barriers and the concrete packaging will supply calcium ions, suppressing colloid formation. Furthermore, the calcium content of the intruding groundwater is relatively high, which should also prevent extensive colloid formation in the BLA vaults, where no concrete barriers are present*." SKB also consider formation of bitumen colloids. While there is evidence that these are likely to occur, SKB expect the extent of radionuclide complexation by bituminous colloids to be low, so they will not have a significant impact on radionuclide transport.

Section 6.3.8 of the Main Report considers bentonite colloid formation and the mobility of colloids in general. Bentonite colloid formation from the silo is only likely to occur where the bentonite intersects flowing fractures, and then only once the landscape has transitioned to a terrestrial environment and the groundwater salinity has decreased from its present values. Considering the mobility of colloids in general, SKB identify a number of mechanisms that retard colloids in pores and fractures, and note that bentonite and bentonite sand will filter colloids generated within the silo.

Overall it seems the potential for radionuclide transport by colloids is low, so it reasonable that SKB have not identified a safety function in relation to preventing colloid generation / migration.

3.3.3. Key THMC Processes

We have used a number of 'top down' approaches to assess whether the key FEPs and couplings have been identified and appropriately abstracted into the radionuclide transport models:

- Further consideration of the findings from our summary of SKB's conceptual model and review of the safety functions.
- Initial review of SKB's calculation case results to identify the key sensitivities.

- Compare the key processes identified by SKB with safety assessments for other L/ILW facilities.

These top down approaches complement the ‘bottom up’ approach used by SKB.

Findings from our Summary of SKB’s Conceptual Model and Review of the Safety Functions

From our summary of SKB’s conceptual model and review of the safety functions, we have identified a number of important topics for further consideration:

- Coupled mechanical processes, including prevention of rockfall, the potential impacts of voids, and the impacts of expansive reactions and associated swelling stresses on barrier integrity.
- Rates of waste package and engineered barrier degradation, the impact(s) of these processes on flows and radionuclide mobility, and their representation in assessment models.
  - Conditions under which larger fractures form in concretes, which may permit radionuclide transport with little sorption (or no sorption as assumed by SKB).
- Deviations in the properties of waste packages and engineered barriers from the design specifications / assessment assumptions.
- Coupling between components and co-location issues, i.e. between vaults, and between vaults and the silo.
- Generation and release of ^{14}C labelled gas.
- Changes in groundwater flow and geochemistry in response to isostatic rebound, and the transition to a terrestrial biosphere.
- Geomorphological evolution, influenced by the features of the geosphere, and the nature of the GBIZ.

Each of these topics is further explored below, in particular considering whether the key FEPs and couplings have been identified and appropriately abstracted into the radionuclide transport models. The findings of our initial review of SKB’s calculation case results to identify the key sensitivities, and comparison of the key processes identified by SKB with safety assessments for other L/ILW facilities are presented subsequently.

Coupled mechanical processes, including prevention of rockfall, the potential impacts of voids, and the impacts of expansive reactions and associated swelling stresses on barrier integrity

As previously described, SKB have identified the importance of mechanical stability and this is controlled through WAC and engineering design. We have not reviewed the WAC and engineering design documents, but the key mechanical FEPs considered in the safety assessment are rockfall and expansive stresses arising from the hydration and swelling of ion-exchange resins and evaporated salts solidified in bitumen. Expansive stresses associated with metal corrosion reactions have also been identified as an area for further research by SKB.

There is probably not enough open voidage (free volume) within the silo to accommodate all the volume expansion, and SKB expect that the internal structure of the silo will be affected as a consequence of swelling of bitumenised waste forms.

However, SKB consider that the outer silo walls will not be affected by this process (Schenck and Bultmark (2014), cited in Section 6.6.4 of the Main Report). We have not reviewed Schenck and Bultmark (2014), but note that it is slightly surprising that the expansive stresses will affect the internal structure of the silo, but not the outer walls, given that the stresses on the outer walls are likely to be similar to those on the internal structures. This may be because the outer walls are more robust than the internal structures, the stresses on the outer walls are more uniform than on the internal structures, and movement of the silo concrete walls is resisted by the external bentonite and rock.

SKB assess an earthquake calculation case (CCL_EQ), in which an earthquake is assumed to damage the silo structure, leading to increased water flow through the silo (Section 8.4.5 of the Main Report). This, according to SKB, can increase doses by up to a factor of three (Section 9.3.5 of the Main Report). The increase in dose is small because the increase in flow through the silo is small: although the earthquake damages the silo concrete structure, the bentonite outside the concrete structure still significantly limits flow through the silo (Section 7.6.5 of the Main Report). The impacts of the earthquake on the geosphere are hard to predict, so calculation case CCL_EQ also assumes no delay of radionuclides in the geosphere, which partly contributes to the increases doses. In the loss of barrier function scenario – no sorption in the bedrock, the peak dose increases by ~50%, i.e. a factor of ~1.5 (Section 9.4.2 of the Main Report), so increased flow through the silo is the more significant contributor in the CCL-EQ case. The peak dose increases by a factor of about two due to damage to the silo.

Assuming damage to the silo concrete structure from expansive stresses would be similar to or less than that associated with an earthquake, the impacts on doses would be similar to or less than those associated with the earthquake calculation case. A factor of two increase in doses for the global warming variant of the main scenario would result in the peak dose approaching that corresponding to the risk criterion (~11 μSv compared with ~14 μSv). Therefore the potential impacts of swelling stresses on the outer silo walls are likely to be an issue of interest to SSM, and therefore SSM may wish to examine this in more detail during the main review phase.

A related important issue is how SKB treat the impacts of swelling stresses on the waste packages in the assessment models. Section 9.3.10 of the Radionuclide Transport Report states that steel moulds and drums are not accounted for in the assessment models, including for cement- and bitumen-solidified wastes, and transport limiting effects are not considered for release from bitumenised wastes. These simplifying assumptions mean that the assessment models do not have to account for damage to steel moulds and drums due to swelling. Concrete moulds are accounted for the assessment models, but the Radionuclide Transport Report does not state whether they can be damaged by swelling, and whether this is accounted for in the assessment models. This is a question for clarification from SKB.

We have identified additional FEPs that could potentially affect the mechanical evolution of the silo, with consequences for barrier performance that are not captured in the scenarios and calculation cases. It would be useful to ask SKB whether they are captured in the FEP catalogue and the arguments for their treatment in the assessment:

- Creep of metal containers under the load from over-stacked packages.

- Compaction of waste packages as they age and weaken due to the load from over-stacked packages.
- Creep / flow of bitumen out of damaged / ruptured waste containers, and into the wider silo, in response to expansive stresses and the load from over-stacked packages. (Note that once waste containers have been ruptured by swelling bitumenised wastes, their ability to withstand the load of over-stacked packages may be significantly reduced).

Some of the above processes may also be relevant in the vaults, but they will be less significant due to the much lower height of the waste stacks compared with the silo, and therefore the lower loads on the waste packages. For the silo, stack settlement combined with damage to the internal concrete walls due to swelling stresses, might also affect the integrity of the concrete slab (lid), because these processes could lead to reduced support against the loads on the slab from overlying materials (bentonite-sand), friction material and cement-stabilised sand, and any rock loads. Therefore, stack settlement could increase the risk of fracturing the concrete slab (lid) and disrupting the overlying barriers. Damage to the lid is not of concern for release of aqueous radionuclides because it already contains vent holes (for release of gas), but damage to the overlying barriers is.

The potential for stack settlement in the silo (and to a lesser extent in the vaults) depends on a number of factors including the initial open voidage, and the relative rates of processes that lead to:

- volume increases (expansive reactions);
- voidage generation (dissolution);
- weakening of the waste packages; and
- creep / flow of bitumen from ruptured waste packages.

Rates of waste package and engineered barrier degradation, the impact(s) of these processes on flows and radionuclide mobility, and their representation in assessment models

Concrete and Cement

SKB have identified the key FEPs associated with degradation of cementitious barriers, including coupled physico-chemical processes that affect the physical (flow) and chemical barrier properties. These include leaching, mineral alteration, fracturing, and fracture surface alteration, which lead to changes in density, porosity, hydraulic conductivity and pH. However, as discussed previously, some mechanical and coupled mechanical-chemical FEPs, such as loads from over-stacked containers, do not appear to have been considered.

Section 6.3.7 of the Main Report notes that there is not expected to be any significant degradation of concrete packaging and cement matrices during the first 1,000 y, and Section 6.4.7 of the Main Report states that concrete packaging and cement matrices may not be significantly altered for more than 12,000 y, and 100,000 y in the case of the silo. However, it is not clear how much local degradation is expected due to solutes originating from the wastes, and whether any degradation is represented in the assessment models. In addition, we previously noted that it is not clear whether the effects of swelling stresses are significant for concrete packages and whether they have been taken into account.

The different degradation behaviours of the vaults and the silo have been considered, as have the different degradation behaviours of the individual barriers, taking into account their geometry and exposure to inflowing groundwater and solutes originating from the wastes, for example Figure 6-27 of the Main Report. Detailed underpinning models have been used to describe evolution of the physico-chemical properties of the cementitious barriers with time, with the results being fed into the assessment scenarios (Section 7.4.3 of the Main Report), and reflected in the parameterisation of the assessment models (Section 7.4.3 of the Main Report, and Section 4.1.1 of the Radionuclide Transport Report). SKB have therefore identified the key FEPs and couplings with regards to degradation of concrete barriers, and have fed them into the radionuclide transport models.

Some more detailed questions of interest to the radionuclide transport review are:

- Do the parameter values and mathematical models used in the assessment models reflect the conceptualised degradation behaviour?
- How are physical and chemical degradation processes coupled in the underpinning detailed models that are used to calculate degradation with time?
- Are assumptions in the underpinning detailed models appropriate?

The first question above is further explored in the following subsection, in the context of the conditions under which larger fractures may form in concretes.

The second and third questions need to be further investigated during the main review phase, through review of the relevant detailed modelling reports. From Section 7.4.3 of the Main Report, it seems that flow rates through cementitious barriers have been calculated for different combinations of concrete degradation state and associated hydraulic conductivity, and shoreline positions (Abarca et al., 2013, 2014 are cited). Next, the pH evolution with time is calculated (Table 6-5 of the Main Report citing Cronstrand, 2014; and Figure 7-9 of the Main Report) and this is used to describe the times when the degradation states, and hence flows, change (Figure 7-8 of the Radionuclide Transport Report). On initial review the degradation behaviour appears to be described based on calculations that are not fully coupled, and the implications of this should be considered further in the main review. In addition, it is not clear how the chemical degradation, described by the pH change, is mapped to the physical degradation state and associated physical properties. The Main Report cites Höglund (2014) as synthesising the results of modelling the different degradation processes, so this will be an important reference for further review.

Examining the model results, Figure 9-5 of the Main Report for example, shows a significant increase in the fluxes of Cl-36 and I-129 from the 1BMA vaults at 22,000 years. A relevant question for the main review is to consider whether this apparent step change in properties and releases is realistic, or if degradation would be more gradual, leading to higher fluxes at earlier times.

Some potentially important assumptions underpinning the detailed models that require further consideration in the main review are:

- Mapping of the physical degradation states to the chemical degradation states.

- The hydraulic conductivities chosen for the different physical degradation states, and whether these are appropriate for the corresponding chemical degradation states.
- The simplistic assumption underpinning the calculated pH and hence chemical barrier evolution that the entire cement mineral inventory is available to react with water flowing through the barrier (Section 6.4.7 of the Main Report). This may not be sufficiently consistent with the conceptualised cracking behaviour of concretes (Figure 6-15 of the Main Report). It may overestimate the available cement inventory and therefore may underestimate the rate of degradation.
- Whether the individual concrete barriers and their stepwise degradation is adequately represented in the assessment models, including the concrete waste packages.

Bentonite

SKB have identified the key FEPs associated with resaturation and long-term chemical alteration of the bentonite around the silo. The barrier function of the bentonite is not expected to significantly degrade over the assessment timescales, although most of the montmorillonite is expected to be altered after 100,000 y. Alteration products such as zeolite are expected to be as good sorbants as the original montmorillonite, therefore the assessment models assume there is no change in the barrier properties. This is an appropriate approach, however we have not reviewed the underpinning detailed calculations of the bentonite alteration rate. It may be appropriate to further examine the detailed underpinning calculations as part of the main review phase, to confirm the calculated alteration rate.

SKB note the possible reduction in protection of the concrete silo walls from mechanical forces due to bentonite alteration and loss of swelling pressure. This is another example where coupled mechanical-hydraulic-chemical processes may be important and might require further consideration in the future.

Conditions under which larger fractures form in concretes, which may permit radionuclide transport with limited sorption (or no sorption as assumed by SKB)

The approach to modelling radionuclide transport through fractured concrete is described in Appendix D of the Radionuclide Transport Report. Two radionuclide transport models are used (standard model and fracture model), with the choice of model depending on the concrete degradation state. The standard model describes radionuclide transport through a homogeneous porous medium. The fracture model assumes radionuclides are transported through larger fractures in concrete without significant sorption, i.e. no sorption.

The decision whether to use the standard model or the fracture model is based on the results of a reference model, which SKB considers to give more correct results for radionuclide transport through fractured concrete than either the standard model or the fracture model. The reference model is used, "*to find a range of water flow (governed mainly by the fracturing) where the standard model can expected to give a more pessimistic result than the reference model. In this range the standard model is later used in the assessment. If this condition does not apply, the more pessimistic approach with the fracture model will be used*".

Appendix D then goes on to describe the choice of model for the different concrete degradation states in the BMA vaults. The choices are sensible, with the standard model being used for moderately degraded concrete and the fracture model being used for severely and completely degraded concrete. However, we note that the calculated flow rate for moderately degraded concrete is approaching the point where SKB change to using the fracture model. It is possible that the standard model might not always be cautious given the uncertainty in the flow rate through the vaults under moderately degraded conditions, for example due to uncertainty in the number and connectivity of fractures in the concrete, the nature of the geosphere fracture network and the total flows through the vaults, etc.

Overall, we consider that the FEP of the potential for large fractures to form in concrete structures, with the consequence that radionuclides are poorly sorbed, has been appropriately abstracted into the radionuclide transport models. However, we note that the reference model describes transport through fractures with a rock-matrix diffusion approach. Given that a similar approach is used by SKB to model radionuclide transport through fractures in the geosphere, it may have been possible just to use the reference model directly. This would have been a more realistic approach and would have removed any uncertainty surrounding decisions when to use standard model or the fracture model. In parameterising the reference model there would be uncertainties about the extent and nature of fracturing associated with a given degradation state, however the same uncertainties underpin the decision whether to use the standard model or the fracture model.

Deviations in the properties of waste packages and engineered barriers from the design specifications / assessment assumptions

In Section 3.3.1 we identified that initial state deviations have been identified from the initial state FEPs (e.g. Design deviations – mishaps), and fed into the scenarios. Table 3-1 of the Main Report states that this FEP is handled in the assessment by the chosen data uncertainty ranges. Also taking into consideration the simplifying assumptions made with regard to representation of waste packages in the assessment models, e.g. no account is taken of steel moulds and drums (see above), we consider that expected manufacturing variations and mishaps are adequately considered in the assessment, and do not require further consideration, so long as appropriate parameter values are chosen and the parameter variations are appropriately propagated from the near-field flow models into the radionuclide transport models.

The treatment of more extreme defects, e.g. resulting from operational accidents, is also described in Table 3-1 of the Main Report. We consider the treatment to be appropriate from the perspective of the radionuclide transport review.

Coupling between components and co-location issues, i.e. between vaults and vault / silo

Depending on the nature of the rock fracture network and the background flow field, potentially there could be interactions between adjacent vaults and between the silo and the vaults, as water flows from one excavation into another. The potential for this to occur depends on the detailed groundwater flow field through the rock fracture network, and how this interacts with the repository.

While this will not be significant in terms of radionuclide transport (indeed it is more likely to be beneficial in terms of radionuclide retardation), it could potentially be significant in terms of transport of solutes originating from the wastes, and their interaction with barriers in the adjacent vaults / silo. For example, an alkaline plume could lead to alteration of the silo bentonite from the outside inwards, in addition to from the inside out due to contact with the silo concrete walls. From the documentation reviewed so far, it is not clear if such interactions are possible, if they are expected to have any significant effect, and if they have been taken into account in the estimate of barrier lifetimes.

In addition there could potentially be mechanical interactions, although these should have been accounted for in design of the repository layout, and the spacing between excavations. Post-closure, backfill will also act to mechanically stabilise the excavations and reduce the likelihood of mechanical interaction.

These FEPs are not discussed in the Main Report, but they may be considered in the FEP catalogue. It would be useful to ask SKB if such FEPs are included in the FEP catalogue, and if so, how they are treated.

Generation and release of ^{14}C gas

We have already identified this as a topic for further consideration as part of the main review phase. Therefore SKB's treatment will not be further considered as part of this initial review, but the treatment of generation and release by ^{14}C gas by other waste management organisations will be considered.

Changes in groundwater flow and geochemistry in response to isostatic rebound, and the transition to a terrestrial biosphere

During the early post-closure phase, once the repository has resaturated, regression of the shoreline is likely to be the dominant control on evolution of groundwater flows. The groundwater chemistry is also expected to evolve with the transition from a marine environment to a terrestrial environment. The issues of interest include coupling between the nature of the fracture network, e.g. the degree of compartmentalisation and how this is affected by the repository, and the rate of geochemical evolution; the way in which groundwater chemistry might evolve noting that current composition reflects waters from a number of sources with different ages; and the effects on radionuclide mobility with time. This topic is too large for consideration as part of this initial review, and therefore is proposed as a topic for the main review.

Geomorphological evolution, influenced by the features of the geosphere, and the nature of the GBIZ

The issues of interest include how geosphere features such as fracture zones and biosphere features such as the regolith affect geomorphological evolution, the nature of the GBIZ, and groundwater flow. This includes treatment of these coupled processes in the models and the timings of key changes in different parts of the system. Of particular interest is the longer term behaviour once the sea has regressed sufficiently that movement of the shoreline is no longer the dominant control on the system evolution. Again, this topic is too large for consideration as part of this initial review, and therefore is proposed as a topic for the main review.

Initial Review of SKB's Calculation Case Results

Tables 9-20 and 9-21of the Main Report provide a useful summary of the peak doses from all the calculation cases. It is useful to cross-compare the calculation case results and 'sense check' the impacts of conceptual model and parameter changes on doses. Where doses increase significantly, or are unexpectedly little changed, it useful to consider whether all the key FEPs and couplings have been identified and abstracted into the radionuclide transport models, or if something has not been considered.

The first calculation cases of interest are those for the high flow in the bedrock scenario and the accelerated concrete degradation scenario. The former considers the maximum flow through each vault from different realisations of the near-field groundwater flow models, while the latter considers physical degradation of concrete in the repository leading to earlier or greater increases in the water flow though the vaults, and diffusivities and porosities in the concrete barriers (Section 7.6.3 of the Main Report). The accelerated concrete degradation scenario does not consider enhanced chemical degradation of the concrete, and hence decreased chemical barrier performance: "*No accelerated chemical degradation of the concrete barriers is assumed in this scenario as it is judged to be sufficiently cautiously treated in the main scenario and hence there are no changes of the partitioning coefficients for sorption*" (Section 7.6.3 of the Main Report). These two cases lead to similar increases in doses compared with the calculation case for the global warming variant of the main scenario. Scenario combination 1 considers the combined effects of these two scenarios.

In the accelerated concrete degradation scenario, the majority of the dose increase is due to increased flow through the 1BMA and 2BMA vaults. Flow through the silo is not increased due to the surrounding bentonite. Therefore doses due to the silo do not change.

The earthquake scenario assumes that the concrete barriers in the silo are disrupted, but the bentonite still acts as a flow barrier (Section 7.6.5 of the Main Report). The conditions in the geosphere following the earthquake are uncertain, so SKB assume the geosphere does not provide any barrier function. The doses for the earthquake calculation case are greater than for the accelerated concrete degradation case (16.9 μSv in the earthquake scenario compared with 8.0 μSv in the accelerated concrete degradation scenario), and therefore the earthquake scenario leads to a bigger increase in doses than the accelerated concrete degradation scenario when compared with the global warming variant of the main scenario.

The results for the loss of barrier function scenario – no sorption in the bedrock case show that the majority of the dose increases for the earthquake scenario is due to degradation in the performance of the silo, because ignoring the geosphere barrier only results in a small increase in doses. It is not clear why the earthquake scenario leads to a greater reduction in the near-field performance than the accelerated concrete degradation scenario, but at least part of the reason is that for the earthquake scenario, peak doses are associated with an earthquake occurring at early times (Section 6.5 of the Radionuclide Transport Report), while in the accelerated concrete degradation case, the reduction in near-field performance occurs more gradually. The use of deterministic parameter values in the earthquake case rather than stochastic parameter values may also affect the results, depending on the shapes of the parameter distributions.

The loss of barrier function scenario – no sorption in the repository leads to a significant increase in doses (to 41.3 μSv). This is a much greater increase than the increase associated with the accelerated concrete degradation scenario and suggests that the physical degradation, and the resultant increased flows, in the accelerated concrete degradation scenario are not sufficient for the fracture sorption model (which assumes no sorption), to be invoked in preference to the standard model. Therefore, none of the less probable scenarios involve any degradation in the chemical barrier performance compared with the main scenario. An important task for the main review phase will be to confirm that the assumptions within the main scenario, and the associated assessment model parameterisation, are sufficiently cautious for this to be a reasonable approach.

The loss of barrier function – high water flow in the repository scenario also results in a significant increase in doses (to 46.9 μSv). The calculation case assumes there are no hydraulic barriers, and ascribes unrealistically high hydraulic conductivities to all the materials in the repository. It is not clear if the dose increase is due to the increase in flow through the repository alone, or if it is also associated with a change from the standard sorption model to the fracture sorption model, and therefore whether there is no sorption in this case too.

The calculation case results for the wells downstream of the repository scenario are interesting because they just exceed the dose corresponding to the risk criterion. A key FEP is the assumed capture zone of the well, and therefore the fraction of the radionuclide flux from the repository that enters the well water. This is taken to be 10% (Section 7.6.7 of the Main Report). The probability of there being a well is 13% (Section 7.6.7 of the Main Report), therefore the risk associated with there being a well downstream of the repository is about one order of magnitude below the risk criterion. It is very unlikely that the capture fraction could be 100%, leading to exceedance of the risk criterion, but it could be higher than 10% (Section 6.4.5 in Werner et al., 2013). Given the uncertainties associated with the probability of there being a well, a useful task for the main review phase is to further review the basis for the 10% capture fraction. In addition it would be useful to review the basis for the probability of there being a well, since it could be argued that this might increase with time, in addition to the increasing probability with time that if there is a well it will intersect the groundwater pathways downstream of the repository (Section 10.6.3 of the Main Report).

The Future Human Actions (FHA) scenario considers not only the acute effects associated with drilling into the repository, but also the long-term chronic effects associated with contamination by excavated materials. The potential effects of an unsealed site investigation borehole are bounded by the intrusion wells scenario, which assumes drinking water is abstracted from an intruding borehole. A wider range of potential intrusion scenarios are discussed in Section 7.6.8 of the Main Report. Overall, all the key potential future human activities have been considered in the assessment.

Comparison with Safety Assessments for Other Facilities

RWM and its predecessors (NDA RWMD, Nirex) have developed a concept for disposal of L/ILW in a higher strength host rock, e.g. a granitoid rock, but at greater depths than are being considered by SKB. RWM's concept has a number of similarities and differences to SFR, the key similarities being disposal of cement encapsulated waste with cementitious backfill in vaults. Important differences are that the wastes packages do not include concrete containers or bitumenised wastes; the cementitious backfill is not intended to provide a hydraulic barrier, but is intended to be gas permeable; only cementitious backfill is used, different materials are not used to form bypass flows / a hydraulic cage; the waste packages are only sub-divided into contact handled (SILW) and remote handled (UILW) categories, and within each category waste packages containing different waste types are assumed to be well mixed in the vaults.

The key barriers included in RWM's generic Post-Closure Safety Assessment (NDA RWMD, 2010b) are the low permeability of the host rock and the chemical barrier provided by the cementitious encapsulant and backfill. In the assessment models, no account is taken of the barrier provided by the waste containers. Taking into consideration the differences in the concepts, RWM's and SKB's conceptual and assessment models capture the same FEPs, although the treatment in the assessment models may be different, for example RWM's cement degradation assumptions are based on the types of conditions that may be found at generic sites, while SKB have modelled degradation under site specific conditions. No additional FEPs have been identified that are not considered by SKB.

An additional radionuclide transport pathway considered by RWM, but not SKB, is generation of $^{14}CH_4$ gas. SKB's treatment of $^{14}CH_4$ formation via methanogenesis was discussed above. However, RWM consider an additional FEP which is also relevant to SKB's waste inventory: direct release of $^{14}CH_4$ gas from irradiated metals, congruent with corrosion. ^{14}C is present in metals in carbide form. As the metal corrodes and the carbide comes into contact with water, $^{14}CH_4$ is formed by hydrolysis of the carbide. The Environmental Safety Case (ESC) for the UK Low Level Waste Repository (LLWR) also considers this process, and release from metals is a key source of $^{14}CH_4$ gas (Sumerling, 2013). LLWR's congruent release models take into account the distribution of ^{14}C in metals, noting that the concentration of ^{14}C decreases with distance into the metal from the irradiated surface. Therefore the majority of the ^{14}C inventory will be released while the metal waste is only partially corroded.

These FEPs may be relevant to the reactor pressure vessels (RPVs) in the BRT vaults. However, the ^{14}C inventory in the RPVs is low, i.e. 1.0E10 Bq (Table 4-6 of the Main Report) compared with 6.0E12 Bq in LLWR (Table A-1 of Sumerling, 2013). Therefore the RPVs are unlikely to be a major source of $^{14}CH_4$ gas and are unlikely to lead to significant doses via this pathway. However, there needs to be good confidence in the C-14 inventory for this to be true.

3.3.4. EFEPs and Environmental Evolution

External FEPs (EFEPs) are identified as part of the FEP analysis process and included in the FEP database. The FEP report, following NEA, identifies four subgroups of EFEPs:

1. Climate-related issues;
2. Large-scale geological processes and effects;
3. Future human actions;
4. Other (specifically meteorite impact).

Climate-related issues are the most important external factors. These include the ongoing isostatic rebound from the previous glaciation as well as different potential future climates. The main scenario and other specific scenarios are designed to cover these aspects; all of the climate FEPs in SR-PSU are considered in at least one scenario.

Geological processes at a large scale that are relevant to SFR are considered to be the same as those considered in SR-Site for a deep repository. The Main Report (Section 3.5.2) claims that large-scale geological processes are indirectly inferred in the descriptions of intrinsic processes and interactions in the Geosphere Process Report (TR-14-05). This report is outside of the scope of the current review, but this statement appears rather weak and perhaps should be subjected to further scrutiny by appropriate experts as part of the main review phase.

Future human actions (FHAs) that can impact on the functioning of the repository system have also been considered. Some FHAs are included in the main scenario while others have specific scenarios allocated to them. Some FHAs have been excluded on the basis that their consequences are obviously insignificant.

In terms of radionuclide transport (other than in the biosphere), the impact of most of the EFEPs is indirect. External conditions impact on the driving forces for flow (and in the extreme case of permafrost halt flows) and potentially influence the geochemistry. More direct impact occurs only in the FHA-related scenario of drilling into the repository, which clearly has the potential for directly moving contaminated material and for opening new transport paths.

Figure 7-16 of the Main Report (also appearing as Figure 2-1 in the Radionuclide Transport Report) summarises the scenarios that are considered. This is reproduced in Figure 3-8.

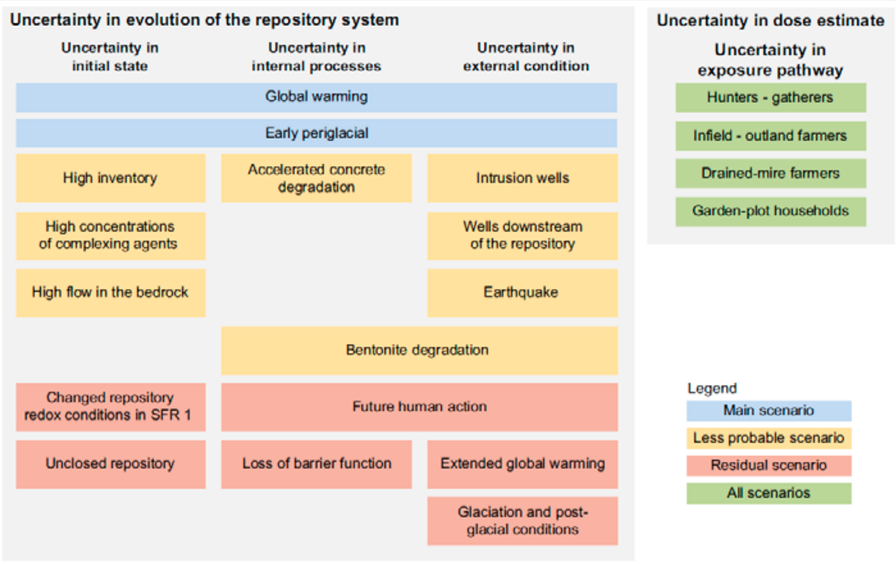

Figure 7-16. Illustration of how uncertainties are handled in the scenarios.

Figure 3-8. Summary of the scenarios that are considered (Figure 7-16 of the Main Report)

It is notable that the motivation for the selection of the earthquake scenario comes from consideration of the potential for the safety function "low flow in waste vaults" to be violated, rather than from consideration of the geological process FEP. This illustrates that the scenario selection process is used not only to cover expected and less probable external evolution of the environments, but also to explore potential violations of safety functions. This combination of motivations can make understanding the reasons behind the choice of scenarios hard to follow.

To the reviewer, "loss of barrier function" is not a scenario but simply a collection of calculations to illustrate some behaviour - the term "residual scenario" arises from the regulations and SKB simply follow the guidance given there.

4. Numerical Models and Data

This section focuses on how the conceptual model was implemented in the radionuclide transport models, whether site information and other data used in assessments for radionuclide transport are appropriate and sufficient for its purpose, and the treatment of uncertainty. It is anticipated that a more detailed review of the model implementation will be undertaken as part of the main review phase.

In the context of obtaining a broad understanding of SR-PSU, a particular focus of the initial review is understanding the outputs from the underpinning groundwater flow (DFN) and hydrological models, how the outputs from these models feed into the radionuclide transport and biosphere models respectively, and consistency and integration between the models. This also reflects the important role of the geosphere in providing an environment with low groundwater flow conditions.

4.1. Calculation Cases and Treatment of Uncertainty

The Radionuclide Transport Report (Section 2.3) describes a calculation case as providing "*a parameterised model chain for the quantitative assessment of a scenario*". For some scenarios (particularly the main scenario) several calculation cases are defined to examine uncertainties in the scenario and to address different end points (e.g. collective dose). In the residual scenarios, different illustrative calculations are grouped under a single scenario heading, e.g. the loss of different barrier functions are grouped together.

Section 4 of the Radionuclide Transport Report gives a description of each of the calculation cases. The CCM_GW (main global warming) calculation case is also the basis for many of the other cases and so is presented in most detail. The way that the calculation case is handled in various aspects of the calculation is described.

In the near-field, it is stated that, "*In the modelling, the repository is assumed to be immediately saturated post-closure*". No reference is given to justify this simplification. We presume that this is considered to be cautious, but a discussion as to whether there are degradation processes that are more rapid in a partially saturated repository would be useful. The resaturation of bentonite is a particular issue that ought to be discussed, and regulator guidance notes that resaturation should be described, "*in as much detail as possible*". This may be described in the Initial State Report (TR-14-02), but that is outside the scope of this initial review.

A delayed release is imposed in this case until the surface environment becomes terrestrial; a separate case allows immediate release. As previously discussed, this is a sensible approach to handling this uncertainty.

Groundwater Flows

Groundwater flow through the repository is described in terms of which near-field hydrogeological cases have been used in various time periods. In particular the hydraulic conductivity of concreate barriers degrades with time. The implication of the way this information is presented is that larger step-wise changes in the hydraulic conductivity are imposed at particular times. However, Appendix A.2 of the Radionuclide Transport Report clarifies that linear interpolation is performed between the flow values to mimic continuous change. It is unclear from the information presented how the calculated flows link to the evolving surface conditions, although it is clear that both are treated deterministically.

Diffusivity, porosities and sorption properties are also linked to the degradation state. However, as noted in Section 3.3.3 of this review, the radionuclide transport calculation results suggest step-wise changes were applied to these parameters, consistent with changes in degradation state. It is not clear why these parameters should not be linearly interpolated consistent with the flows.

The linkage to the far-field model states that the intermediate flow case was used. It is stated that travel times and transport resistance pairs are used for a set of realisations/particle tracks and that these are available for a sequence from 2000 AD to 9000 AD. It is not clear what this implies – does the transport resistance change with time; do the pathways take the same route regardless of starting time?

The linkage to the biosphere is also not very clearly explained. It is stated that the biosphere calculation case BCC1 is used, which seems to use slightly different climate assumptions compared to the other aspects. Hydrological water fluxes are said to be modelled for future biospheres at three times: 3000 AD, 5000 AD and 11000 AD, but again it is unclear how these times relate to the other times used. Finally, it is not explicitly stated how fluxes from the geosphere as a function of time are passed to the biosphere. This is, however, clear in the Input Data Report; there it is stated that each vault has its own model, the fluxes from these are then passed through the geosphere model, and then they are passed through the biosphere model.

Uncertainty

Uncertainty within the calculation cases is handled probabilistically. Many of the input parameters have probability distributions assigned to them. The inputs from the hydrological models are travel times and transport resistance pairs in order to preserve the correlation structure. It is not clear to the reviewer whether these are particles from a single realisation of the hydrological model (representing variability) or whether multiple realisations have been included (representing uncertainty). This issue is further explored later in this initial review.

The handling of uncertainty in the water flows in the near-field is similarly unclear. The naming convention for the files described in the Input Data Report (Section 4.8.1) includes BASE_CASE1_DFN_R18, suggesting that a single realisation is used. R18 is described in Odén et al. (2014) as an optimistic realisation for the existing SFR 1, which sounds inconsistent with the "intermediate-flow case" that the radionuclide transport report refers to (Page 43 of the Radionuclide Transport Report). We note that the hydrological input for the biosphere is stated to be from BASE_CASE1_DFN_R85 which is said to be a pessimistic realisation for the existing SFR. There seems to be a lack of clarity and potential inconsistency in terms of which hydrological data were used.

The other calculation cases are simple variants on the main case for the most part and are clearly described. The reason for choosing to undertake calculations for earthquakes at every 100 year interval is not clear – a much coarser set of times would surely have been adequate.

The well cases assume 10% capture fraction. From the ranges given by Werner et al. (2014) this looks to be a reasonably cautious value, although it is not a maximum. We have already identified this as a topic for further investigation as part of the main review.

Correlations

Correlations between input parameters are generally ignored. The Main Report (Section 8.2.1) states: "*Apart from the pairing of parameters describing hydrogeological conditions, parameter correlations are not accounted for in the probabilistic assessments*." It goes on to claim that "*This approach rather overestimates uncertainty ranges and it is not assumed that it will tweak the assessment towards compliance.*" The Data Report is referenced for further discussion.

The Data Report has a section called "Correlations" in each chapter, but these appear to describe how the data are used in several places within the assessment rather than any concept of correlations in the uncertainty structure. For example the section on correlation in Metallic Corrosion (Section 5.9) reads, in full: "*This section supplies corrosion rates that will be used and included in gas formation calculations, oxygen consumption, and degree of corrosion of reinforcement bars i.e. the reducing capacity of the material within the waste and waste packaging as well as the transport of radionuclides from BWR*." This appears not to meet the requirements for correlations set out in Section 2.1.9 of the same report, which states that: "*An appropriate treatment of probabilistic input data requires that any correlations and functional dependencies between those data are identified and quantified. In the extensive work with the FEP database and the three process reports, many correlations and functional dependencies between parameters have been identified. Where appropriate, these correlations and functional dependencies should also be implemented in the safety assessment models. It should be an aim to aid those performing probabilistic modelling, by giving well defined and usable information on how to handle correlations between input data*."

Thus, it appears that the ambition to handle correlations between the input parameters has, at some stage, been dropped. This has been justified by assuming that it doesn't matter. This does not seem to be a good argument because there are clear reasons that correlations might be important. This occurs most obviously where a single cause of uncertainty affects several aspects of the model chain. For example, geochemical conditions are uncertain and could affect both near-field and far-field at once.

The treatment of sorption data is unclear. Section 7.8 of the Data Report suggests that radionuclides should be treated in groups: "*the radionuclides considered can be organised into correlating groups of elements and oxidation states whose migration behaviour will generally show a similar response to variations in chemical conditions*"; Section 7.10 accepts this. However, there does not appear to be any discussion of how this was handled in the Radionuclide Transport Report – indeed the word "correlations" does not appear in that report.

4.2. Codes and Flow of Information

The preceding section raised a number of questions about the propagation of information, particularly groundwater flow information, through the models. This section describes the codes that were used by SKB to undertake the assessment calculations in more detail, and further explores the flow of information through the assessment.

4.2.1. Codes Used

As discussed in Section 3.7 of the Model Summary Report, Ecolego 6.0 was used as the modelling vehicle for the near-field, far-field and biosphere modelling. Each model was implemented separately and results calculated and used as input to the next model in the chain.

Ecolego is a commercial software tool that can be used to create dynamic models and is particularly suited to radiological risk assessment. The development of Ecolego was co-funded by SSM (previously SSI). A code comparison undertaken by Maul et al. (2004) with an earlier version of Ecolego and a similar tool, AMBER 4.5, concluded that in general there was excellent agreement between the two codes. Agreement was slightly reduced (from at least 3 to 2 significant figures) for radionuclides that were subject to substantial losses due to radioactive decay, at times very much greater than the radionuclide half-life. No reasons for this effect were given. At the time of the inter-comparison study Ecolego was built on Simulink; since the release of Ecolego 4 in 2008, this dependency has been removed and Ecolego now uses its own set of solvers.

Section 3.7.2 of the Model Summary Report indicates that Ecolego has integrated radionuclide and parameter databases. It is not clear to the reviewer whether these are pre-populated and were used at all by the radionuclide transport models.

The Input Data Report makes it clear that, in general, input to the Ecolego models is in the form of Excel data files. Section 3.7.5 of the Model Summary Report indicates that Java code is used to pre-process at least some of the raw input data, and that this processed data is stored along with the model and the results in an "assessment file".

4.2.2. Flow of Information

The Assessment Model Flowchart (AMF; Appendix B of the Input Data Report) indicates how information flows from one model to another. A summary of the input data information from the Input Data Report for the near-field is given in Table 4-4. The corresponding information for the geosphere is given in Table 4-5.

Table 4-4. Input data for the near-field model

AMF Number	Data	Description	Comments
50	Near-field hydrology	Annual water flows across surfaces of control volumes, as described in Arbarca et al. (2013). This data is generated by Comsol Multiphysics.	The raw data is pre-processed into Excel files. The original data files will be required if calculations are to be replicated. See further discussion in main text.
75	Non-flow related RN transport properties	Sorption coefficients, effective diffusivity, porosities and densities.	All parameters except density are time-dependent. The density of materials will change over time as they degrade. Lower densities equate to larger capacities and could impact on the release of radionuclides. It is not clear why a consistent approach of making all transport properties time-dependent has not been taken.
85	Initial state concrete barriers	Dimensions (height and width) of concrete barriers in the silo, BMA, BRT and BTF vaults.	
86	Initial state waste	Inventory and number of packages.	Includes alternative data for the High Inventory Calculation case (CCL_IH)
95	Corrosion of reactor pressure vessels	Vessel thickness, corrosion rates and time of change in rate (due to change in pH).	Only saturated conditions are considered. The Input Data Report references Cronstrand (2014) but this report does not seem to include pH calculations for the BRT vault.
100	Initial state bentonite barriers	Dimensions of bentonite barriers in the silo.	

Table 4-5. Input data for the geosphere model

AMF Number	Data	Description	Comments
11	Hydrogeology	F-factors and travel times for paths to the surface, and Peclet number. The F-factors and travel times are generated from particle tracking simulations, as described in Odén et al. (2014). The data is produced by DarcyTools.	F-factor and travel time data is in text files. Includes data for high flow in bedrock case (CCL_FH). The original data files will be required if calculations are to be replicated. See further discussion in main text.
76	RN transport in water phase	Radionuclide release from near-field to geosphere. Output from Ecolego. Resolution of 50 y.	
87	Non-flow related migration properties	Sorption coefficients, effective diffusivities, rock matrix porosity.	K_d values are given for different redox conditions; diffusivities for cations and anions.
136	Well-related flow data	Dose to well, used to estimate radiological risk related to water usage of future inhabitants using wells.	
211	Peclet number	Ratio of rate of advection to rate of diffusion.	

The near-field hydrological data is calculated as steady-state values for three time points, defined by characteristic shoreline positions (submerged, shoreline-dominated and land-dominated), and several barrier degradation states (Section A.2 of the Radionuclide Transport Report, and Arbarca et al., 2013). Combinations of these steady-state flows are then used in the radionuclide transport calculations, with linear interpolation used to mimic continuous change. Some justification of this interpolation approach should be given: are the processes involved, particularly climate processes, continuous or are there step-changes or 'cliff edge' effects? What effect might a faster switch between these states have on the models – is the current assumption conservative?

As this is an advection-dominated system, the flow modelling is key to the radionuclide transport results. It is not clear how all of the uncertainties in parameter values in the near-field hydrological data are carried through to the radionuclide transport calculations. The accelerated concrete degradation scenario, which assumes the hydraulic properties of the concrete degrade more rapidly than in the main scenario (Table 4-1 and Table 4-7 of the Radionuclide Transport Report), likely captures the effects of the most significant uncertainties, but it is not clear how uncertainty in the properties of the other near-field materials is captured, and any variance between the design and built properties due to CQA issues.

The effects of plugs (taking into account degradation) are included in the hydrological input to the near-field (Section 9.3 of the Radionuclide Transport Report) and thus are not explicitly included by SKB in the near-field model.

For the geosphere hydrogeological data, 100,000 particle tracks were produced for each hydrogeological calculation (Section A.3 of the Radionuclide Transport Report). For deterministic calculations, the median value was used. For probabilistic calculations 100 tracks for each repository were used, selected randomly from the larger sets.

4.2.3. Probabilistic Cases

The flow of information between the three radionuclide transport models in probabilistic cases is described in the Radionuclide Transport Report (start of Section 5). Monte Carlo simulations with Latin-hypercube sampling is performed on the near- and far-field models with 100 iterations. The report does not discuss why 100 iterations was an appropriate number to use. Each realisation from the near- and far-field models is then matched with 10 realisations of input parameter sets for the biosphere model (it is not entirely clear but appears that the same 10 realisations are used in each case), giving a total of 1,000 realisations for the model chain.

4.3. Numerical Implementation of the Conceptual Model

4.3.1. Models, Realisations and Flow of Model Results

Although as summarised in the preceding section the AMF (Appendix G of the Main Report; Appendix B of the Input Data Report) summarises the overall flow of information and model results through the assessment, we have developed our own summary of the critical information flow which describes the key times considered by the different models and how uncertainties are assessed and carried forward at each stage through the use of probabilistic calculations. This is provided in the following bullet point list:

- The far-field hydrogeological model was developed using Darcy Tools. Models were developed for 17 realisations of the DFN, with flow being calculated at 5 times >=2500 AD for each DFN realisation (2500, 3000, 3500, 5000 and 9000 AD: Figure 7-4 to 7-6 of the Main Report). The flows at 9000 AD are little different to those at 5000 AD, and at 9000 AD the shoreline has regressed sufficiently far from the site that it no longer exerts any influence.
- For each DFN realisation and time, 100,000 particle tracks were calculated. 100 of the 100,000 particle tracks were selected at random (p226 of the

Radionuclide Transport Report) and were used to describe coupled travel time and transport resistance PDFs for used in the risk assessment (Ecolego) models. The PDFs for the different realisations were not combined, rather the PDF for a single realisation was carried forward to the calculations cases for the main scenario.

- Groundwater flow through the near-field was calculated using repository scale models in COMSOL. The far-field (Darcy Tools) models were used to provide the boundary conditions for the near-field (COMSOL) models. Flows were calculated for three shoreline positions relative to the repository (submerged, shoreline, land) (Section 6.1 of Abarca et al., 2013), corresponding to the far-field models for 2000 AD, 3000 AD and 5000 AD respectively (Section 8 of Abarca et al., 2013), and different concrete degradation states for each time.
- Flows through the near-field were extracted from the COMSOL model for use in the risk assessment (Ecolego) models. At each of these times the barrier degradation state is also considered to determine the flow field.
- Page 25 of the Radionuclide Transport Report states that water flow rates were linearly interpolated between stages of landscape development. Appendix A.2 of the Radionuclide Transport Report makes it clear that this includes flows in the near-field. However, the stepwise changes in the calculated radionuclide fluxes suggest that step-wise changes were applied to the other transport parameters, consistent with changes in degradation state.
- The near-field and far-field (Ecolego) models were run for 100 realisations. For each of the 100 realisations, 10 realisations of the biosphere model (also implemented in Ecolego) were run. The Radionuclide Transport Report is not entirely clear but it appears that the same 10 realisations were used in each case.
- Page 44 of the Radionuclide Transport Report states biosphere hydrological flows were calculated for 3000 AD, 5000 AD and 11,000 AD. At about 12,000 AD succession has turned all lakes that may receive radionuclides originating from the repository into terrestrial areas, and hydrological water flows have come to a steady state (Section 6.4.1 of the Main Report).

The times considered in the far-field hydrogeological models and the biosphere hydrological flows are slightly different, but presumably reflect the different evolution of the surface and groundwater systems. We have not examined underlying reports to see if this is further explained, but it may be important given that SKB have stated that flows through the repository (and hence also the geosphere) are sensitive to the thickness and properties of the regolith. It would have been useful if SKB has presented a summary similar to the above, with descriptions of key decisions regarding selection of the times chosen to describe evolution for the different parts of the system. We note that as reviewers we don’t have confidence that we have a complete understanding of this aspect of the assessment.

Where flow path information was carried forward from the far-field hydrogeological (DFN) model, it is not clear whether the 100 particle tracks selected at random were sufficient to fully capture the shape and extremes of the PDF for that realisation of the DFN, and therefore fully capture the heterogeneity described by the DFN. By selecting a single realisation of the DFN, parameter uncertainty has not been carried forward, although this has been explored by the high flow in the bedrock calculation case.

We have not yet found a description of why 100 realisations was considered to be sufficient for the near-field and far-field models. Since the calculations for each vault and the geosphere were preformed separately, we assume the PDFs were sampled first so a consistent set of parameters were used for each realisation of the model chain. A question for SKB is whether sampling the near-field and geosphere flows was correlated, including the geosphere flows at each future time? The same question about coverage applies to the decision to run 10 realisations of the biosphere model for each realisation of the near-field / geosphere models.

Figure 7-3 of the Main Report shows that at 5000 AD and 9000 AD some of the particle tracks discharge further from the repository, to streams and lakes, rather than to mires. This could lead to different impacts / risks, but we have not found any mention of different biosphere models being used for different pathlines or regions of the PDFs which described the DFN model results. In addition, Section 6.4.1 of the Main Report notes that, "*the modelled landscape should be seen as an example of a possible future"* and *"the main uncertainties in the future landscape configuration are associated with the locations of the thresholds that determine where future lakes are formed in the landscape"*. Comparison of the landscape modelling prediction for today with what is observed shows that some lakes that are present are not anticipated in the landscape modelling (Figure 5 of the Biosphere Synthesis Report, TR-14-06). It is not clear whether discharges to lakes rather than mires would lead to higher environmental impacts, and this is a relevant question for SKB. The uncertainty in the landscape model and the effect of this on doses should be a key topic in the discussion of the assessment results.

In addition, some of the fractures that radionuclides are being transported along will change with time as the shoreline retreats and the discharge location changes. However, a single set of compartments are used in the radionuclide transport models in which the transport parameters evolve to represent the evolving flows. Therefore the models do not capture any changes in the fractures through which radionuclides are migrating with time, and so they may underestimate dispersion of the radionuclide flux to the biosphere. Another question for SKB is how would more dispersed discharge to the biosphere objects influence doses, compared with the focused releases implied by particle tracks?

Overall, the interrelationships between the different models needs to be better described, beyond the basic description of flow of information provided by the AMF, and the further information that is spread throughout the assessment reports. In particular the way in which stochastic modelling has been used to explore uncertainties needs further description, including where the intention is to explore heterogeneity and / or parameter uncertainty and demonstrating that sufficient model realisations have been run, or results adequately sampled and carried forward to achieve this.

4.3.2. Radionuclide Transport Models

Detailed review of the configuration of the radionuclide transport models is beyond the scope of this initial review, and is a topic that should be further considered as part of the main review. This might involve developing assessment models to reproduce SKB's calculations, or developing independent models to build confidence in the results of SKB's assessment. Developing assessment models is a good way of reviewing and assessing SKB's work since it drives the reviewer to comprehensively consider all SKB's decisions during model implementation. An initial review has been undertaken at this stage for familiarisation purposes and to identify any requests for further information from SKB.

The configuration of the radionuclide transport models is described in Section 9 of the Radionuclide Transport Report. A number of control volumes have been defined to allow near-field flows to be imported directly from underpinning detailed groundwater flow models, which is a good approach because it enables more representative flows to be specified than is possible using simple flow calculations within the compartmental (Ecolego) model. The discretisation of the vaults / silo and the different waste package types are also described, as are the transfers between compartments which represent advective and diffusive transport.

Appendix B of the Radionuclide Transport Report provides the results of supporting sensitivity calculations to examine the impacts of discretisation on numerical dispersion, to support the chosen discretisation. From the results of the sensitivity calculations, Appendix B concludes that near-field (concrete) flow barriers should be discretised into 5 compartments, to provide an optimal balance between minimising numerical dispersion without excess computational overhead.

The introduction of numerical dispersion into a model can be cautious or non-cautious, depending on the radionuclide in question, how strongly it is sorbed and its half-life. Numerical dispersion reduces peak concentrations and fluxes, and hence may be non-cautious. However, numerical dispersion can be cautious because it can also allow a small contaminant flux to travel faster than expected in reality, such that it reaches a receptor, while actually it would be expected to decay to negligible levels within the pathway, or not reach a receptor within the timescales of interest. Due to the radionuclide specific impacts, ideally the numerical dispersion will be close to the amount of dispersion expected in reality.

The decision to use five compartments is reasonable, but not only for the reasons given in Appendix B of the Radionuclide Transport Report. Use of five compartments results in a Peclet number (the ratio of advective velocity to dispersive velocity) of 10, which is a generic value that is typically considered to be representative of transport through porous media. For example, see Appendix F in Quintessa (2011).

Page 218 of the Main Report notes that, "*The coarse spatial resolution of the compartmental structure introduces a dispersive effect with respect to radionuclide transport in the system. This numerical dispersion can be assumed to be larger than the real physical dispersion and hence this treatment is regarded as cautious…*". As noted above, introduction of numerical dispersion is not always cautious, and this statement seems to be slightly inconsistent with the effort that has gone into avoiding excess numerical dispersion in the model.

The configuration of the five compartments used to represent the flow barriers is unclear. It would be useful for this to be clarified: are the five compartments used to represent the near-field barriers configured and parameterised to represent radial transport through the barrier, or are five compartments used to represent linear transport in each direction (up, down, sideways), so the total number of compartments is much greater? (It is noted that dimensions of each compartment are not reported so they cannot be used to deduce the answer to this question).

Although the near-field barriers have been discretised into five compartments, crushed rock / macadam backfill and the waste packages (where taken account of) have been more coarsely discretised. This is probably for simplicity and to maintain practical model run times, with the focus being on accurately representing transport through what is expected to be the most resistive barrier. However it would be useful if these modelling decisions were further described.

Where diffusive transport dominates, it would also be useful to check that the configuration preserves the diffusion area / diffusive length ratios, and the model results have been checked to confirm there are no issues associated with diffusive 'short-cuts', back diffusion, or unrealistic build-up of contaminants due to diffusion from a large compartment into a small compartment(s).

The geosphere (far-field model) has been configured to represent transport within a fracture pathway, with perpendicular diffusion into the fracture walls. The configuration of the model is appropriate, with the depth of the wall compartments increasing away from the fracture walls. This is important since it will avoid excessive retardation due to numerical dispersion into the rock.

Again, the chosen discretisation could do with further discussion. For example, discretisation of the wall rock is based on Equation 9-25 in the Radionuclide Transport Report. A reference for this equation would be desirable, potentially also with further justification. In Appendix B of the Radionuclide Transport Report the results have been compared against the semi-analytical code FARF31, and are very similar to FARF31, which builds confidence that Ecolego model results are very similar to the analytical solution. It would be useful if the analytical solution was also presented, or if it was confirmed that the FARF31 results match the analytical solution.

We have noted two aspects of the model configuration, which are likely to result in radionuclide fluxes associated with the silo being overestimated, i.e. cautious. Firstly, diffusive resistance is neglected for bitumen-stabilised wastes (Section 6.3.7 of the Radionuclide Transport Report). Secondly, radionuclides diffusing through the bentonite surrounding the silo will have to diffuse into the small fractures in the rock where they intercept the bentonite. This limits the area of diffusion, and increases the effective diffusion length through the bentonite. These effects do not seem to have been accounted for in the models.

4.4. Availability of Data

The data used in SR-PSU is described in two reports. The SA Data Report describes selected data deemed to be important for safety, i.e. data connected to the safety functions. A proforma has been completed for each safety function, which records a 'conversation' between the safety assessment (SR-PSU) team (the customer), and technical experts (the supplier) which records: what data the customer needs and how it will be used (Stage A); the data the supplier has available, the conditions for which it is valid, conceptual uncertainty, data uncertainty, spatial and temporal variability, etc. (Stage B); and the judgement by the customer and data recommended for use in SR-PSU (Stage C).

The key data identified in the SA Data Report are generally available from radioactive waste disposal programmes in other countries, and from collations and reviews of data published in IAEA technical reports. Therefore, there should be no major data deficiencies, although of course the site specific values, for example pertaining to the specific composition of the concretes used, may not be available elsewhere.

A keyword search of the document was undertaken to identify any limited, poor quality or badly constrained data identified by SKB. A number of data limitations have been identified, but these are generally typical of many waste disposal programmes, for example limited data on the real long-term evolution of cements (p79 of the SA Data Report), sorption data for some radionuclides and the effects of complexants.

One area of significant conceptual and data uncertainty is the swelling pressure exerted by bitumen encapsulated ion exchange resins and evaporator concentrates. This uncertainty might be important for the mechanical integrity of concrete barriers in the silo and 1BMA, because it may affect the success of controls put in place to manage swelling pressures, and the calculated impacts of swelling on integrity of concrete barriers.

Uncertainty in the inventory has the potential to significantly affect the assessment results, especially since calculated doses for the main scenario (5.6 μSv) are approaching the risk criterion (14 μSv) (Table 9-1 of the Main Report). Table 4-6 of the SA Data Report gives the best estimate and high inventories, which are both determined on a radionuclide specific basis. The high inventory is the 95th percentile of the distribution. The ratio between the best estimate and high inventory varies between 1.17 and 52.2, but typically is a factor of 2 to 3. The peak dose for the high inventory scenario is 23.4 μSv (Table 9-3 of the Main Report), but the risk is only 8.3E-8 y^{-1} (Table 10-2 of the Main Report). The risk is low because it has been multiplied by a scenario probability of 0.05.

It is noted that there is an inconsistency in the calculation of risk between the main scenario and the high inventory scenario. The main scenario considers the 50th percentile inventory and assumes a scenario probability of 1. The high inventory scenario considers the 95th percentile inventory and assumes a scenario probability of 0.05. The issue arises because uncertainty in a parameter value has been ascribed to a scenario probability, which is not appropriate.

The Input Data Report describes all the data used in the safety assessment, mapped to the AMF. The Input Data Report contains a proforma for each data input / flow in the AMF, which describes what the data are, where they are from, how they are used in SR-PSU and what the values are (either stated or referenced). This provides a very comprehensive audit trail for the data used in the assessment.

It is beyond the scope of this initial review to consider all this data. However, the scope does include considering whether site data used in the assessment for radionuclide transport are appropriate and sufficient. Since low flow in the bedrock is a key safety function we have focused on limitations in the site data that may affect the calculated flow rates in the bedrock.

Section 9.7.3 of the Site Description Report (TR-11-04) provides a number of lines of evidence that the fracture system is not vertically well connected, in particular that, despite being located in fractured rock below the Baltic Sea, there is not much inflow into SFR, and that the fracture network is significantly compartmentalised. Extension of SFR may reduce compartmentalisation and therefore increase flow through the facility. The significance of this effect is difficult to predict due to uncertainties in the fracture network.

Since low flow in the bedrock is a key safety function, SKB assess effects such as reducing compartmentalisation through a “high flow in the bedrock scenario”. The calculation case is based on a different realisation of the DFN model, which gives higher water flow into the vaults (Section 8.4.2 of the Main Report). A this stage we have not reviewed the groundwater flow modelling report (Odén et al., 2014) in detail, but it is clear that SFR is represented as an explicit feature in the models, which should allow loss of compartmentalisation to be explored.

We have previously noted that Section 9.2 of the Site Description Report (TR-11-04) states, “*the stratification and hydraulic parameterisation of the regolith affects the inflow to the existing SFR facility and hence the calibration of the groundwater flow model*”. A potentially relevant question to be explored as part of the main review, although not necessarily part of the radionuclide transport review, is the quantity and quality of information available regarding the regolith below the present sea floor, and whether any uncertainties in the distribution and properties of the regolith have been fully captured in the groundwater flow modelling? Depending on the findings, it might also be appropriate to consider the potential significance of differences between the groundwater flow model and hence the geosphere flow and transport calculations, and the hydrological modelling which feeds into the biosphere modelling, including differences in the step times modelled.

5. Assessment Results

5.1. Key Dose Radionuclides

5.1.1. Selection of Radionuclides for Assessment

While there is no information in the Main Report and Radionuclide Transport Report to describe the selection of inventory radionuclides, SKB do present information on the selection of key radionuclides for the radionuclide transport modelling in the Radionuclide Transport Report. SKB have screened the radionuclide inventory to select the key radionuclides for transport and dose calculations, and the approach is described in Section 3 of the Radionuclide Transport Report. The criterion for including a radionuclide is “*that it cannot be ruled out that it has a non-negligible radiological impact when taking uncertainties into account*”. Radionuclides were selected for inclusion where the half-life is greater than 10 y and the product of the total activity and ingestion dose coefficient is greater than 10 mSv at repository closure. The rationale for the half-life criterion is obvious and reasonable, but the dose-weighted criterion is unclear in its basis and rationale.

For the remaining radionuclides, short-lived progeny have been included with the parents where the radioactive daughter has a half-life of less than 100 days, which is reasonable. Progeny with a half-life greater than this were explicitly modelled.

The radionuclide transport report provides useful illustrations of the selection of key radionuclides and comparison with those included in previous safety assessments as well as the variation of inventory and relative radiotoxicity with time.

5.1.2. Key Radionuclides in Assessment Results

Turning to the results, SKB present results from the main scenario in terms of two calculation cases – global warming and early periglacial period. SKB then present results for a suite of less probable scenarios, including a higher inventory estimate, high flow in the bedrock, accelerated degradation of engineering, earthquakes, high concentrations of complexants, wells and intrusion. SKB also examines 'Residual Scenarios' which explores the safety functions of the disposal system but are not in themselves plausible scenarios.

For each calculation the same basic information is presented in the Main Report, with additional detail in the supporting Radionuclide Transport Report. The basic information includes results that give a clear indication of the dominant radionuclides. Doses are disaggregated according to time, radionuclide, vault/silo and exposure group.

No information is presented that provides an indication of the potential significance of the different waste packages and encapsulant, except what can be inferred from dose results for each vault and the anticipated contents of the vault. The results also do not indicate the relative significance of different types of wastes (e.g. resins). It is also not possible to explore the radiological effects on humans in any great detail as there is no breakdown of significance of the dose from key radionuclides with exposure pathway (e.g. ingestion, inhalation, external irradiation).

Finally, it is noted that fully understanding results may be difficult as the emphasis is on the arithmetic mean result from a probabilistic calculation. There is very limited reporting of deterministic calculations using specific parameter values rather than distributions. Furthermore, examination of parameter uncertainty does not appear to comment on what parameters the dose result is most sensitive to, only to focus on the range of results. This also misses an opportunity to explore the significance of uncertainties in the model.

Much of the discussion presented in the results focuses on a description of the curves shown in figures. The main report does not explore, with any consistency, the reasons why particular radionuclides are dominant, except in simple terms. For example, it is recognised that key radionuclides are typically highly mobile and effects such as reduction in sorption and increase in flow rate are thus significant. There is consequently a missed opportunity in terms of exploring and analysing the functions of the disposal system. This is exacerbated by the lack of "intermediate" results (e.g. radionuclide fluxes from the near-field) although these results are presented in the supporting Radionuclide Transport Report.

For the main scenario, the curves describing the estimated doses reflect the radionuclide releases from the wastes and near-field. For the main scenario (global warming variant) the peak doses are dominated by radionuclides that have a high mobility, including Mo-93, organic C-14, I-129 and Cl-36, which are responsible for more than 80% of the dose. U-235 and U-238 are responsible for more than 8%, while Ca-41 contributes between 3% and 4%. Around 40% of the dose is derived from the silo, 27% from 1BMA and 2BMA, 6% from BRT, 8% from 1BTF and 2BTF and 5-6% from 2–5BLA. C-14 dominates collective doses.

The inventory uncertainty scenario shows similar radionuclides to be important, although Se-79 is enhanced in significance. The calculation also provides results which exceed the dose that corresponds to the risk criterion. The treatment of inventory uncertainty as a separate calculation case is unusual and makes interpretation of the significance of this aspect of uncertainty difficult. A more transparent approach would be to assign distributions to inventory values directly, and include the uncertainty in a probabilistic calculation.

There is relatively limited discussion of the findings of the alternative calculation cases. Generally, the report concentrates on describing the results rather than what can be deduced from them. In some cases there are useful conclusions drawn, for example that the dose results are relatively insensitive to groundwater flow, particularly for vaults with engineered barriers. In other cases the conclusions are rather obvious (e.g. for the high complexants case, the conclusion is that radionuclides whose sorption is sensitive to complexants become more significant).

5.2. Audit Against Objectives and Regulatory Requirements

Our initial review indicates that SKB have acknowledged and followed the regulatory requirements. The only area for potential criticism is the very limited use of deterministic calculations. As discussed previously, p399 of the Main Report notes the guidance that "*both deterministic and probabilistic methods should be used so that they complement each other and, consequently, provide as comprehensive picture of the risks as possible*". However, with the exception of the deterministic results presented in Figure 10-1 of the Radionuclide Transport Report, and the earthquake calculation case where it was not possible to undertake probabilistic calculations, all the results presented are for probabilistic calculations.

This seems to miss the point of the guidance – by showing both deterministic and probabilistic calculations a more comprehensive picture can be gained. It is much easier for the reader to understand a deterministic calculation and then to see the impact of uncertainty. It is also substantially more straightforward to verify deterministic calculations, particularly when the probabilistic calculations rely on probabilistic outputs from other codes.

6. Approach to Main Review

6.1. Requests for Information and Clarification

During the process of undertaking this initial review we have identified a number of areas where further information or clarification would be desirable. These are not repeated here, but are summarised in Appendix 2.

6.2. Key Topics for Main Review

During the process of undertaking this initial review we have identified a number of topics for further consideration during the main review phase. Some of these topics directly relate to the radionuclide transport calculations, while some may be more applicable to other areas of the review. Many of the proposed topics are associated with system evolution (EFEPs) and coupled processes, and therefore would be best addressed via a structured collaboration between external reviewers and SSM staff. These topics are not repeated here, but are summarised in Appendix 3.

7. Overall Findings of Initial Review

The overall finding of this initial review is that SKB have undertaken a systematic and comprehensive safety assessment for SFR. The safety assessment has been comprehensively documented, and the documentation is largely clear. Based on this initial review the documentation appears to be complete. However, the flow of information through the documentation is not always in one direction, which reduces clarity, and sometimes can make it difficult to fully understand treatment of specific topics. Consequently some clearer statements regarding the treatment of uncertainties in the conceptual and numerical models are required.

The calculated doses for the global warming variant of the main scenario are within a factor of three of the dose criterion (5.6 μSv compared with 14 μSv). SKB have included many cautious assumptions in their assessment, which builds confidence that the dose criterion will not be exceeded. However, the assessment results are particularly sensitive to uncertainties in the inventory and the performance of the near-field barriers, including their construction quality (initial state) and degradation over time. Uncertainty in the inventory and engineered barrier performance could lead to the dose criterion being approached or even exceeded. In addition a number of other conceptual, process and parameter uncertainties might combine to give higher than calculated doses. Although outside the scope of this radionuclide transport review, we anticipate that the assessment results will also be particularly sensitive to assumptions and uncertainties in the biosphere model.

A potentially important uncertainty that is not explored by any of the scenarios or calculation cases is accelerated degradation of the near-field chemical barrier. SKB state that their base assumptions are sufficiently cautious that this is not required. The results of SKB's residual scenarios (loss of barrier function – no sorption in the repository calculation case) show this is a particularly important argument, and therefore this is one of the key topics for the main review.

The treatment and presentation of uncertainty could have been improved through greater use of deterministic calculations for the main scenario; complemented by probabilistic sensitivity analysis to explore the impacts of uncertainties. In addition to making the results simpler to analyse and understand, this would also make it easier to undertake independent calculations for checking / comparison. This approach would be consistent with regulatory guidance.

The interrelationships between the different models needs to be better described, beyond the basic description of flow of information provided by the AMF, and the further information that is spread throughout the assessment reports. In particular the way in which stochastic modelling has been used to explore uncertainties needs further description, including where the intention is to explore heterogeneity and / or parameter uncertainty and demonstrating that sufficient model realisations have been run, or results adequately sampled and carried forward to achieve this.

The key issues identified for further assessment in the main review comprise better understanding the treatment of certain processes and process couplings; the flow of information through the assessment, integration and coupling / consistency between different technical areas; and treatment of uncertainty.

8. References

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APPENDIX 1

Coverage of SKB reports

The following reports have been covered in the initial review.

Table A1

Reviewed report	Reviewed sections	Comments
TR-14-01	All	
TR-14-10	All	Scope and approach, not data values
TR-14-07	Main report sections	
TR-14-09	All	Selected review to complement information in TR-14-01
TR-14-12	All	Scope and approach, not data values
TR-14-11	All	Codes relevant to radionuclide transport modelling only

APPENDIX 2

Suggested needs for complementary information from SKB

1. Can SKB confirm that, except for the Reactor Pressure Vessels, radionuclides are present as surface contamination, and therefore are immediately available for transport upon contact with water (Section 4.1.1 of the Radionuclide Transport Report)?
2. Are ion-exchange resins and evaporator salts solidified in cement fully hydrated, or might they swell upon contact with water once the repository has been closed and it has resaturated? Can the concrete moulds be damaged by the swelling pressures? Is this accounted for in the assessment models? (See Section 3.3.3 of this report).
3. Is a description of the decision making process that was used to decide the treatment of FEPs and couplings available? (See Section 3.3.1 of this report).
4. Do the process reports, or any other reports, describe how couplings between system components are treated in the assessment? (Note review of the process reports was outside the scope of this initial review). (See Section 3.3.1 of this report).
5. Do the assessment models capture degradation of concrete containers due to contact with sulphate and other solutes originating from the wastes? Do the concrete packages degrade at different rates for different waste types? (Sections 6.3.7 and 6.4.7 of the Main Report).
6. Are the following FEPs included in the FEP catalogue and how are they treated in the assessment? (See Section 3.3.3 of this report).
    a. Interactions between adjacent vaults and vaults / the silo.
    b. Waste stack settlement, e.g. due to creep of metal containers and degradation of waste packages.
    c. Creep / flow of bitumen out of damaged / ruptured waste containers, and into the wider silo, in response to expansive stresses and the load from over-stacked packages.
7. Please clarify the configuration of the five compartments used to represent the near-field flow barriers in the Ecolego models, e.g. radial or five compartments in each direction (up, down, sideways). (Section 9 of the Radionuclide Transport Report).
8. Have SKB undertaken calculations to confirm that post-closure resaturation of the vaults / silo will be rapid? Could any degradation processes be enhanced while conditions are unsaturated?
9. Can SKB clarify the linkages between the hydrological and hydrogeological models including providing any relevant comments on our

compilation of information in Section 4.3.1 of this report. Also please clarify if the model realisations used are considered to be cautious, representative, etc. and from what perspectives?

10. Is sampling of the near-field flow PDFs correlated with sampling of the geosphere flow PDFs, including at each future time; and is sampling of the geosphere flow PDFs for different future times also correlated? (See Section 4.3.1 of this report).
11. Please clarify why the types of correlations described in the Safety Assessment data report seem to be different to the requirements set out in the same report. (Sections 2.1.9 and 5.9 of the SA Data Report).
12. Please clarify the correlation of sorption coefficients for different radionuclides in the radionuclide transport models, i.e. are sorption coefficients correlated by element and oxidation state? (Sections 7.8 and 7.10 of the SA Data Report).
13. Regarding the treatment of inventory uncertainty, do SKB consider that there is a probability of 0.05 that the inventory is larger than the high-inventory values? Should the 95^{th} percentile values for the inventory be treated as a group or separately? (See Section 4.4. of this report).
14. Is it likely that the repair and reinforcement measures required for 1BMA can achieve the desired hydraulic and mechanical properties, or is there significant risk that inaccessible parts of the engineering will underperform?
15. How would more dispersed discharges of radionuclides to the biosphere objects affect calculated doses compared with the more focussed releases implied by particle tracks? (See Section 4.3.1 of this report).
16. Would doses be higher if discharges were to lakes / other surface waters rather than to mires? (See Section 4.3.1 of this report).
17. Near-field flows calculated for different shoreline positions and near-field degradation states have been linearly interpolated, while other transport parameters for different near-field degradation states appear to change in a step-wise manner. Please provide further information on the reason(s) for this different treatment.
18. In order to allow calculations to be replicated, please provide deterministic calculation case results for the Global Warming Variant of the Main Scenario; specifically time-series radionuclide fluxes, for the Silo and 1/2BMA vaults, from the near-field to the geosphere and from the geosphere to the biosphere, and time series doses for individual radionuclides. If calculation case data are read into ECOLEGO from a data input file, e.g. Excel, please provide these data input files. Also please provide the time series flow data for the near-field models. Finally it would also be useful to have a copy of the ECOLEGO model files if they are available.

APPENDIX 3

Suggested review topics for SSM

1. Uncertainties and assumptions underpinning the DFN groundwater flow models, and the flow rates and flow path information fed into the assessment models. Do the groundwater models developed for SR-PSU consider the remaining uncertainties and groundwater modelling cases proposed in TR-11-04?
2. Interaction between the geological and landscape models including geomorphological processes, location and nature of the GBIZ, and groundwater flows including through the repository. Has the groundwater flow modelling fully captured the effects of geological uncertainty, associated with both the fracture network and the regolith (particularly offshore), and the potential nature of the GBIZ, including geomorphological evolution? What is the potential significance of differences between the groundwater models underpinning the near-field and geosphere radionuclide transport calculations, and the hydrological models underpinning the biosphere calculations, including differences in the future times modelled?
3. Assessment of the expected mechanical damage to the silo as a result of swelling of bitumenised wastes, if Schenck and Bultmark (2014) and any other key references can be translated into English.
4. Review underpinning initial state report and the process reports for waste, barriers and the geosphere, to further understand SKB's treatment of FEP couplings. Review of the geosphere processes report should include consideration of SKB's treatment of large scale geosphere processes.
5. Review WAC and design information relevant to structural stability and controlling long-term mechanical evolution.
6. Changes in geochemistry in response to isostatic rebound and evolution of the groundwater flow system.
7. Influence of the geochemical conditions with time on the cement and bentonite degradation rates, including local variations, the underpinning degradation rate calculations, and selection of Kds for the radionuclide transport models. Complementary calculations may be beneficial to help understand the potential degradation rates and behaviour, e.g. coupled reactive transport calculations, which could be undertaken as part of the near-field review.
8. Detailed assessment of coupled physical and chemical concrete degradation processes, and the relationship to barrier performance, including review of Höglund (2014). (Also see the wider ranges of related issues in Section 3.3.3 of this report). Does the approach justify SKB's argument that the main scenario is sufficiently cautious that enhanced cement degradation does not need to be explored as a less probable scenario? Complementary calculations, for example using coupled reactive transport models, may be particularly beneficial to help understand the coupled evolution of the concrete barriers and test the overall behaviour considered by SKB, not

least since the information we have reviewed so far indicates that fully coupled models were not available to Höglund (2014). Such coupled calculations could be undertaken as part of the near-field review. Also review parameter values used to capture the effects of design deviations, e.g. in 1BMA.

9. Review the potential for methanogenesis in the individual vaults considering the vault inventory and location conditions; and the concurrent formation of $^{14}CH_4$ gas considering the local C-14 inventory and the potential for C-14 transport from adjacent vaults / silo.
10. Resaturation of the vaults / silo and the significance of unsaturated conditions for degradation processes, depending on SKB's response to our question on this topic. (Appendix 2, item 8)
11. Treatment of correlations, depending on SKB's response to our question on this topic (Appendix 2, item 11).
12. The number model realisations explored and the relationship between probabilistic calculations for the geosphere and biosphere undertaken in separate models.
13. Review of the detailed configuration of the assessment models. Relevant activities include checking that where diffusion dominates, the configuration preserves the diffusion area / diffusive length ratios, and the model results have been checked to confirm there are no issues associated with diffusive 'short-cuts', back diffusion, or unrealistic build-up of contaminants due to diffusion from a large compartment into a small compartment(s).
14. Review the assumed downstream well capture fraction and arguments for the probability of there being a well, since it could be argued that this might increase with time.

Items 12 and 13 would be best addressed by independently re-implementing some of SKB's assessment models. More widely, this would provide a detailed understanding of SKB's models, their configuration and parameterisation. Reproducing the results of SBK's calculations would build confidence in the results themselves and in our understanding of the models. The models could then be used to explore the effects of alterative assumptions, model configuration or parameter sensitivity, to further build our understanding and confidence.

It is proposed that independent assessment models should be built to reproduce SKB's calculated fluxes and doses for the Global Warming Variant of the Main Scenario. The calculations should be deterministic and focus on the silo and 1 BMA or 2BMA vaults and the associated key radionuclides. This task should be undertaken in collaboration with the biosphere review, in particular working together to explore issues associated with the Geosphere Biosphere Interface Zone (GBIZ). Ideally the near-field, geosphere and biosphere would be implemented in a single model, so there would be no model interfaces. Since the geosphere is only a weak barrier, and the focus will be on the key risk radionuclides, the treatment of the geosphere can be simple, with deterministic calculations considering a single, best estimate, geosphere pathway. Sensitivity to pathlength and discharge location can then be explored deterministically. Probabilistic calculations to explore the distribution of geosphere flow paths are not envisaged.

These calculations will require the information detailed in Appendix 2, item 18.

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SR-PSU Review of dose assessment landscape models

Activity number: 3030014-1006
Registration number: SSM2015-1020
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Abstract

SKB has submitted an application to extend the SFR repository for low- and intermediate-level radioactive waste at Forsmark. This report presents the outcome of a preliminary review of the material relating to the dose assessment modelling carried out by SKB in the context of the release and distribution of radionuclides in the future landscape around the Forsmark site. The aim of the review has been to i) gain a broad understanding of SKB's license application, ii) to assess how complete and understandable is the documentation of the safety case, and iii) to identify key topics for deeper review in the main phase. The review is necessarily at a high level. In addition to addressing the three areas specified a set of requests for complementary information have also been identified.

Detailed dose assessment modelling has been carried out over a period of 100 kyear, whereas previous similar assessments have only been carried out to 10 kyear in the future. Future evolution of the site therefore embodies significant change, not only in terms of landscape development but also with the need to address the impact of climate change. Up to 10 kyear temperate conditions are likely to persist, up to 100 kyear the potential for cooler conditions at the site must be taken into account. For the first time detailed landscape modelling has included a representation of a periglacial period, though details are not clear at this stage of the review.

During the first 10 kyear the landscape around the site changes markedly from coastal to inland conditions as a consequence of isostatic uplift following the of removal of ice cover at the end of the previous glaciation. Changes to hydrology in the overburden are therefore key to understanding the radionuclide distribution in the future landscape. Compared to earlier assessments the treatment of hydrology is more sophisticated in that individual basins are now treated independently with their own individual hydrological characterisation. Of interest therefore is how details from the supporting models are translated into the data for the dose assessment model. This is to be reviewed in the main phase, in particular the hydrology of the basin in the future landscape where the highest doses are calculated to arise. There is a need to better understand the circumstances leading to discharge of radionuclides from bedrock fractures upslope in the basin, rather than at the lowest point of the topography in the basin as is the case elsewhere in the landscape model.

The supporting radionuclide-specific database for the SR-PSU is now wholly site specific with numerical data being more closely linked to local conditions than in earlier assessments. This is a welcome development but there are concerns in respect of the quality of data and, particularly, the sample sizes from which data have been derived. Other matters of interpretation are to be investigated in the main phase review, for example, the hydrogeochemical evolution of the newly emergent soils around the Forsmark site. As a result of deposition of material during the previous glaciation there is a relatively high $CaCO_3$ content in the overburden and this is expected to decrease over the 100 kyear period of the assessment. How this is modelling in the assessment will be addressed.

The representation of exposed populations in the future landscape has also been developed since the earlier assessments. The treatment of non-human biota is similarly improved. The overall standard of documentation the SR-PSU assessment is good being both clear and informative. In addition to the timescale of the assessment for which the detailed landscape model is used being longer than in earlier assessments it is also noticeable that there is more detail included in this project , requiring detailed review of the implementation of key features, events and processes in the dose assessment models.

Contents

1. SR-PSU Review - Overview

1.1. Scope of the initial-phase review

The Swedish Nuclear Fuel and Waste Management Co., SKB, submitted an application for an extension to the Forsmark low and intermediate waste disposal facility (the SR-PSU Assessment) to the Swedish Radiation Safety Authority (SSM) at the end of 2014. The application is in the form of a detailed assessment of the potential radiological impact on future populations of the landscape around the disposal site. As well as the consequences for future human populations, effects on non-human biota (NHB) are also considered.

This report sets out a review carried out on behalf of SSM by Dr Richard Kłos (Aleksandria Sciences Ltd, UK), Professor Anders Wörman (KTH Stockholm, Sweden) and Professor George Shaw (University of Nottingham, UK) in respect of the biosphere dose assessment in SR-PSU. Emphasis is on the understanding and implementation of landscape evolution processes and hydrology in the dose assessment but attention is also given to implementation of other aspects of the dose assessment model.

The requirements of the review, as expressed by SSM, are:

1. a broad understanding of the SKB's license application,
2. an assessment of how understandable and complete is SKB's documentation,
3. identification of key topics for deeper review in the main phase.

Within this remit, this initial phase of the SR-PSU is at a relatively high level with suggestions for detailed investigations of specific topics intended for the main review phase. A number of requests for complementary information have also emerged from this initial phase of the review.

As set out by SSM the review reported here covers the following SKB documents:

- SKB TR-14-01, Safety analysis for SFR. Long-term safety. Main report for the safety assessment SR-PSU (SKB, 2014a).
- SKB TR-14-06, Biosphere synthesis report for the safety assessment SR-PSU (SKB, 2014b).
- SKB TR-14-07, FEP report for the safety assessment SR-PSU (SKB, 2014c).
- SKB TR-14-09, Radionuclide transport and dose calculations for the safety assessment SR-PSU (SKB, 2014d).
- SKB TR-14-10, Data report for the safety assessment SR-PSU (SKB, 2014e).
- SKB TR-14-12, Input data report for the safety assessment SR-PSU (SKB, 2014f).
- SKB R-13-46, The biosphere model for radionuclide transport and dose assessment in SR-PSU (Saetre *et al*., 2013).
- SKB R-13-19, Hydrology and near-surface hydrogeology at Forsmark - synthesis for the SR-PSU project. SR-PSU Biosphere (Werner *et al*., 2014).

In addition to these, a number of additional documents have also been included as they provide important details relating to the main set of documents:

- R-12-03, Digital elevation model of Forsmark. Site-descriptive modelling. SR-PSU biosphere (Strömgren & Brydsten, 2013)
- R-13-22, Depth and stratigraphy of regolith FRS (Sohlenius *et al*., 2013)
- R-13-01, K_d and CR used for transport calculations in the biosphere in SR-PSU (Tröjbom *et al*., 2013)
- R-13-25, SR-PSU Bedrock hydrogeology. Groundwater flow modelling methodology, setup and results (Odén *et al*., 2014).
- R-13-43, Components, features, processes and interactions in the biosphere. (SKB, 2013).

The structure of the SR-PSU documentation is such that the TR-level reports are at the highest level of documentation, with little by way of the detailed description of the implementation of the FEPs necessary for an appropriate model (or set of models). The TR-reports set the scene and provide an overview. Detailed descriptions are found in the R-level reports. This initial review stage has allowed a broad understanding of the essential elements of the SR-PSU assessment, allowing the reviewers to determine specific areas within the R-level reports that will form the main review phase.

1.2. Initial impressions

1.2.1. Overall dose modelling assessment

A main aim of the SR-PSU license application is to demonstrate the radiological safety of the current SFR1 and planned SFR3 repositories for low and intermediate level radioactive waste. Naturally this requires the combination of many different disciplines. Above all this review focuses on the synthesis of these various strands of information into a coherent and appropriate model for the assessment of radiation safety.

Initial impressions suggest that the SR-PSU Assessment is considerably more complex than recent assessments carried out by SKB. In particular, compared to the most recent assessment – the SR-Site license application for the construction of a repository for spent fuel at Forsmark (SKB, 2011) – the dose assessment model comprises a significant increase in detail both in terms of the analysis of relevant features, events and processes (FEPs) relating to the transport and accumulation of radionuclides in those parts of the local geology that are accessible to humans and NHB, as well as a more detailed description of many of the exposure pathways.

Overall the quality of the documentation shows improvement over previous assessments. The reports are more accessible and detailed. In particular the biosphere synthesis report (SKB, 2014b) is helpful in that it brings together the many strands of biosphere related material into a coherent summary. Because of the mass of material collected in respect of the dose assessment modelling, this is essential. Nevertheless, the extensive biosphere documentation remains somewhat fragmented and, at this stage of the review, it is not clear that all elements of the biosphere model used in the dose assessment modelling are covered in appropriate detail. As with the SR-Site license application, it is not clear that all uncertainties are fully reported and explored, despite the clear improvements in documentation since the publication of SR-Site.

SR-PSU assesses potential releases from the existing SFR1 LILW repository as well as those from the proposed extension (SFR3). Treatment of the potential impact of ^{14}C has greatly improved since the previous SFR1 assessment (SKB, 2008) and other radionuclides are now anticipated to present higher potential radiological impacts. In SR-PSU ^{14}C is no longer the radionuclide that gives rise to the highest potential radiological impact, as it was in the previous SAR-08 assessment of SFR1 (SKB, 2008).

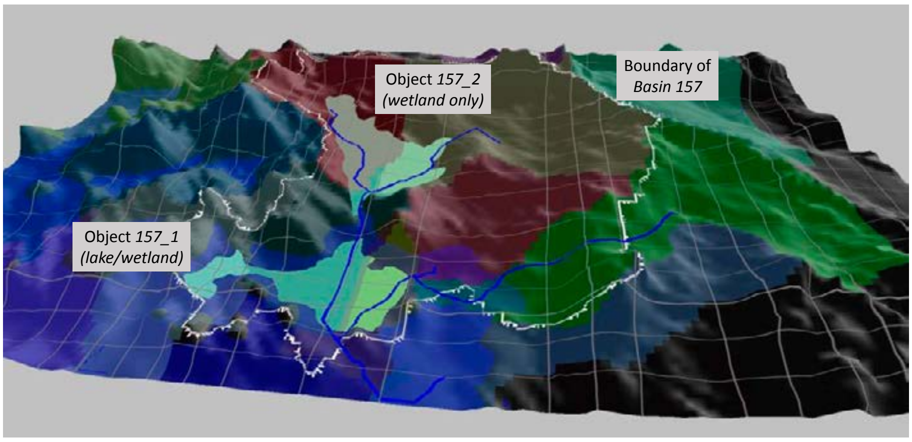
A major development in the assessment is that now, for the first time, dose calculations in the biosphere are directly linked to releases from the repository. Landscape dose conversion factors (LDFs) are no longer used to scale releases from the geosphere. LDFs are still used but as part of the assessment of sensitivity in the biosphere system. Overall the linking of all domains of the assessment modelling system (near-field, geosphere and biosphere) is welcome but the effect is to make sensitivity and uncertainty analyses of the system less straightforward, use of LDFs notwithstanding.

Essentially, SR-PSU, like SR-Site before it, is a radiological assessment of the potential impact of the disposal of radioactive waste. Its purpose is to demonstrate compliance with the Swedish regulatory framework (SSM, 2008). In moving from SR-Site to SR-PSU a great deal of new material has been added to an already complex dose assessment modelling framework. There is therefore a great deal of new science included in the SR-PSU dose assessment model (DAM). Not all of this new material has a major influence on the dose assessment results, insofar as they affect matters of regulatory compliance. Nevertheless the ‘new science’ is important in promoting the overall scientific credibility of the assessment. At this stage of the review it is not clear that all the new additions have been thoroughly documented *and* their workings properly discussed. As the aim of SR-PSU is to demonstrate compliance with regulations, this review aims to identify those elements of the application that relate directly to compliance, ie, those aspects of the assessment for which the radiological outcomes are most sensitive, applying a form of *de minimis* principle. How to account for the intricate details in the SR-PSU DAM remains an open question at this time as, at this stage of the review, the full identification and justification of the modelled FEPs does not appear to have been published.

1.2.2. Near-surface hydrology

Starting with SR-Site, SKB have begun to exploit their detailed site descriptive modelling database in order to characterise models for long-timescale dose assessments. Radionuclide transport in solution in groundwater is the most likely process that will lead to releases to the biosphere. The MIKE-SHE groundwater modelling tool is extensively used to define the flow system in the biosphere for individual “biosphere objects” (defined by SKB to be the regions of the surface system into which radionuclide migration takes place). This is a significant advance on the approach taken in SR-Site wherein an “average object” was defined by combining the hydrology of several disparate basins in the Forsmark landscape. Each release object therefore has its own set of groundwater flow vectors and the differences between different hydrologic basins in the landscape will be more representative than previously. However, the *evolving* flow system in each basin is not represented directly. Fluxes are characterised at three times for each of the basins in the landscape and

Figure 1: Illustration of the two biosphere objects identified by SKB within Basin 157. The outline of Basin 157 and of the two objects has been copied from maps in SKB (2014b). These have been superimposed on the digital elevation model (DEM) from SR-Site in order to illustrate the nature of the biosphere objects in SR-PSU. Object 157_1 is at the lowest part of the basin and will develop as a lake and then wetland. Upslope is Object 157_2, that will form as a wetland area only. The map is drawn using the Global Mapper 12 software. The coloured areas denote subcatchment areas determined by Global Mapper and the blue lines are drainage systems based on the sub-catchments. Note that the vertical scale is exaggerated for emphasis.



flow system "evolution" in the DAM is performed by interpolating between these fixed points. Implicitly then, after the final time the flow system remains constant. Hydrology of agricultural land is treated differently, and indeed, more simply.

These enhancements to the modelling capabilities are welcome. However, it is necessary to determine that the application and interpretation of results from MIKE-SHE are used optimally.

1.2.3. Releases from the geosphere

The coupling of the geosphere and biosphere models in SR-PSU is important in that it focusses attention on those radionuclides in the release from the repository that reach the biosphere *and* give rise to the highest doses associated with the release. Whereas in previous assessments the estimates of release location (from geosphere modelling) were sufficient to draw attention to potential biosphere objects into which releases could occur, there is now a greater emphasis on the density of points in the release map. The physical interpretation of the density of the points, in terms of Bq m^{-2} $year^{-1}$ in an implicit release plume remains obscure at this stage and may have implications for the definition of the most contaminated area with each hydrologic basin in the future landscape.

One thing that is clear is that discharges to local topographic minima (depressions) in the basin are not the only geosphere-biosphere interface of concern. The biosphere object with the highest density of release points is designated Object 157_2 by SKB and is found at a higher elevation in the basin (see Figure 1).

The detailed hydrology of the evolving basin is therefore of concern but equally there is a need to understand the nature of the bedrock flow system that results in discharge at relatively high elevations within the basins. In short, the issue is who, in the modelling chain, takes care of the geosphere-biosphere interface? It is necessary to clearly understand the nature of releases to distinct areas within the modelled basins.

1.2.4. Landscape and climate development, ecosystems

Compared to earlier assessments there is a greatly increased description of the evolution of the system with, consequently, less reliance on the nature of the system in the present day.

As well as land rise, which must now be considered as an evolving variable since the timescale of the assessment is 100 kyear (ten times longer than has been modelled in earlier assessments) the way in which the ecosystems develop is also modelled with increased complexity. In mires, for example, the thickness of the peat layer is described by a differential equation in the radionuclide transport modelling. The growth and compaction of peat layers (including burial of gyttja layers formed during lake stages) has an effect on the local topography. The implications of this level of complexity on the DAM are not yet apparent and it is not clear that all of the additional detail has been, or can be, justified in the context of the dose assessment.

The landform evolution processes are therefore intimately linked to the biotic component of the system. Many of the parameters in the new DAM relate to the interaction between vegetation, hydrology and topography.

The current climate evolution projection is taken to be the "global warming variant" with an additional "Extended global warming" case. Because of the long timescale of the assessment, it is also necessary to include, for the first time within the remit of the biosphere dose assessment, a period of periglacial conditions. Within this period, the hydrology, ecosystems and exposure scenarios are radically different compared to temperate conditions relevant to the global warming scenarios. While the effects of taliks are included in the assessment it is not clear that the important features of talik formation *and dissipation at the end of periglacial conditions* are adequately addressed. It is the times of transition that can potentially lead to higher exposures, as in that case of the dose-transients in transition from wetland to agricultural land in the SR-Site review modelling (Kłos, 2015).

Models for natural ecosystems and agricultural ecosystems are once more treated as being distinct. At least in SR-PSU, the agricultural ecosystems appear to be modelled with greater detail than in earlier assessments. They remain somewhat simpler than the models for natural ecosystems (mire, lake, marine), albeit with an improved representation of hydrology based on MIKE-SHE modelling. The implications of this divergence of modelling approaches need to be considered in some detail in the main phase.

1.2.5. "Special" radionuclides

Most radionuclides fit into the "standard" model described by SKB. There are some special radionuclides for which alternative transport, accumulation and exposure models are needed to a greater or lesser degree.

^{14}C is an important constituent of the SFR inventory at disposal. There is a new model in SR-PSU and this is reviewed in detail elsewhere. However, in the spirit of the integrated assessment modelling carried out by SKB, the ^{14}C model is explicitly included as a set of nuclide-specific FEPs in the main model. Additionally carbon pools and fluxes appear to be used to define transfers of radionuclides in the biosphere, perhaps finally fulfilling the promise of the ecological modelling that has been reported in site descriptive modelling over the past decade. The implications for the modelling of radionuclide transport will need to be considered; either a major change to ecosystem-based transport modelling or a slight modification of current practice.

Uptake by vegetation in natural ecosystems is, as with SR-Site, treated as a dynamic process and it is noted that some of the radionuclides considered have particularly high uptake factors and so simplifying assumptions are made. Special considerations are also given to the uptake of ^{36}Cl. Some attention is then paid to disposition of the radionuclide inventories between abiotic and biotic components of the model. The implications for dose modelling need to be addressed within the framework of the integrated DAM. Transport of carbon in the pore-space gases of soils is also to be considered, though this relates to $^{14}CO_2$ and not $^{14}CH_4$.

1.2.6. Radionuclide bio- hydro- and geochemistry

The principal transport-and-accumulation-related parameters are solid-liquid distribution coefficients (K_ds) and concentration ratios (CRs) of one type or another (primary importance is for soil-plant interactions). These are all now significantly more site-specific than in earlier assessments. In the words of SKB (2014b):

> *This dataset is probably one of the most detailed collections of synchronised surface data ever produced in Sweden.*

The site-specific data sets from Forsmark and Laxemar are certainly unique when viewed in the context of other environmental radiation protection exercises around the world, and it is unlikely that there has ever been a comparable data set amassed for the purposes of understanding the impacts of contaminants of any type in environmental systems. Given this large investment by SKB it is encouraging to see that full use is now being made of this rich resource. There is still a role for literature data, but this is principally directed towards “plausibility control” of the data values selected in the assessment.

The radionuclide transport model is enhanced with respect to the SR-Site model structure in that there is increased vertical discretisation compared with the previous assessment, so requiring that the hydrogeochemical properties of the different radionuclides in the multiple regolith layers be appropriately determined. There appears to be a requirement to allow radionuclides to be partitioned between solute, mineral solid and organic solid (in most but not all compartments). The implications of this feature of the modelling need to be better understood.

It also appears that the vertical structure of the regolith now distinguishes between saturated and unsaturated layers. The transport model is therefore capable of dealing with redox effects in a more coherent way than before. This should be based on distinguishing K_d values for high and low redox states.

A notable feature in the discussions, particularly in the biosphere synthesis report (SKB, 2012b), is the relatively high concentration of $CaCO_3$ in the newly emerged soils, recently (in geological terms) arisen from below the Baltic. It is severally noted that this concentration will decrease over time as the relatively low pH conditions of naturally developing soils (mainly peats) react with calcium carbonate left over from the previous glaciation. SKB anticipates that the chemical characteristics of the young soils will eventually approach those of more mature soils. In this way the composition of Forsmark soils will, over time, become to be more like that of soils at Laxemar.

The implications of these changes may not be suitably represented in the DAM. Variation of chemical characteristics over time is handled by a probability distribution function that is sampled in the probabilistic framework in which the model is run. It is not clear that this is an appropriate treatment. As well as a need for deeper review, there is the possibility of alternate modelling to assess the possible impact of this approach.

Because the SR-PSU assessment is fundamentally a *probabilistic* assessment the definition of probability density functions for the relevant radionuclide parameters is of primary concern. Despite the dataset being *one of the most detailed collections of synchronised surface data ever produced in Sweden* there are concerns that the number of discrete samples used to derive the pdfs can be rather low – $N = 3$ is classed as "relatively good" and $N = 10$ is taken to provide "high confidence". Perhaps because of these relatively sparse datasets for individual parameters SKB have developed a series of statistical techniques to allow the interpretation of geometric standard deviations (GSDs). This initial review suggests that a deeper review is needed to ensure that the processes is reliable. There are similar concerns relating to the way in which the number of K_d pdf values are obtained from paired measurements of solid and solute concentrations.

1.2.7. Exposure pathways, exposed groups and NHB

One criticism of the dose assessment methodology in SR-Site was that the approach did not take adequate care in matching the distribution of radionuclides in the landscape to the activities that human populations have traditionally practised in the Swedish landscape. This has now been rectified and considerable effort has gone into identifying appropriate patterns of behaviour. There are now four potentially exposed groups, each with a different lifestyle.

Further review will be required to determine that the lifestyles expressed in the modelling are appropriate. As noted above, there are concerns that the transition periods following the return to temperate conditions following a periglacial episode might not be comprehensive.

Treatment of the radiological impact on non-human biota is now fully integrated into the landscape modelling. The methodology has been upgraded to take site-specific considerations into account. As with the exposure pathway calculations for the human population the new developments are to be welcomed.

There remain some concerns, however, that radionuclide concentrations within the habitat of representative species may not be well represented by the spatial domains relevant to the estimation of dose to the human population. In short, there may be concentration gradients around the discharge points from the geosphere. Some investigation is therefore necessary, tied into the better understanding of the significance of the release points mentioned above.

Calculated dose rates to NHB in SR-PSU are, however, low compared to the action levels set out in the ERICA methodology. Nevertheless, because this is a new inclusion in the main dose assessment model, it is recommended that a review be carried out.

1.2.8. SSM's independent modelling

For SR-Site SSM commissioned a new alternative model (Kłos, 2015) to investigate the uncertainty associated with the SR-Site DAM. There are implications for this alternate model should SSM wish to pursue independent assessment modelling.

The spatial structure and the evolution of the vertical compartments in the model are amenable to a more site-specific representation using the details discussed by Saetre *et al*. (2013).The enhanced flow-system description in the regolith should also be included; in particular the elevated release scenario (see Figure 1) needs to be incorporated. In practice this may require an improved model of the Basin 157 evolving hydrology.

1.3. Report structure

The previous section has identified and discussed some themes in the review of the SR-PSU DAM. The following sections address each of them in turn:

Chapter 2	The dose assessment model in SR-PSU
Chapter 3	Hydrology
Chapter 4	Releases from the geosphere
Chapter 5	Development of landscape, climate and ecosystems
Chapter 6	Element and radionuclide specific data
Chapter 7	Special radionuclides
Chapter 8	Exposure pathways and exposed groups
Chapter 9	Treatment of non-human biota

Chapter 10 deals with remaining issues and the final chapter provides conclusions. The three appendices address, in turn, the SR-PSU reports reviewed, the complementary information sought from SKB and details of the recommendations to SSM in terms of further and deeper review topics. A further appendix summarises options for developing SSM's independent modelling capability in respect of alternate numerical assessments of SR-PSU.

As an aid to identifying themes to be carried forwards, colour-coding of elements of the text has been used below:

green - deeper review
red - potential RFI (Request for Further Information)
purple - potential SSM independent modelling.

2. The dose assessment model in SR-PSU

The dose assessment model is central to the assessment. In this section of the review report we consider overreaching concerns in the dose assessment modelling. The biosphere synthesis document (SKB, 2014b – TR-14-06) is the source for much of the discussion, with additional material in the biosphere model description (Saetre *et al*. 2013 – R-13-46). In the overall structure of the documentation the synthesis sets the scene (at the higher TR-report level) with the actual *details* of the model reported in the lower R-report level. This disjunction between description and detail makes the documentation less than transparent. The problem is compounded by the two further biosphere FEP reports (SKB, 2014g, R-14-02-43 and SKB, 2013 – R-13-43) which also need to be taken into account in order to make sense of all the new inclusions in the model. In fact, R-14-02, does not yet appear to be available but will be required for the main phase..

"We have aimed to make the transport model of natural ecosystems as realistic as possible, with respect to model structure, primary transport pathways, landscape development and the associated parameters." This statement (Biosphere synthesis, p33) serves notice that the model is more complex and detailed than any hitherto employed by SKB.

The new material is extensive and a structured approach should be undertaken to ensure the main phase review is as efficient as possible. Because the four biosphere model reports are not well connected it is difficult to define the content of the review at this stage. Part of the problem is the separation of the synthesis document and model description. With all the new detail in the dose assessment model (DAM) it is not readily apparent how important is each new embellishment to the previous iteration's models (SR-SITE, SAR-08). There has been no attempt to systematically document the justification and effect of the newly modelled FEPs. This is an important omission and forms a request for further information. Details are to be determined on completion of this report, it is likely that some filtering procedure will be needed. Ideally this material would include radionuclide inventories, concentrations and doses derived from objects by exposure pathway.

Transparency in the model description is promoted by attention to detail and a serious attempt to describe the mathematical as well as scientific basis for the model. The difficulty for transparency, however, is that the biosphere synthesis and model description are separate documents. The synthesis compares unit release results for dose in earlier assessments with corresponding values in SR-PSU. This illustrates that there are differences, it does not sufficiently explain the new features that are responsible for the differences. The model description is just that - details of the models are presented but there is no discussion of their role in the DAM. So, although the Synthesis is a very welcome feature of the documentation, there is insufficient linkage to the model itself.

Despite the "realism" of the radionuclide transport model SKB acknowledge that simplifications are necessary. These are dealt with by means of cautious assumptions. In particular, estimation of doses from cultivated soil employs more simplifications than natural ecosystems. This is a feature that needs to be investigated – is the approach taken to modelling agricultural soils compatible with the other parts of the dose assessment modelling? The justification for this (Saetre *et al*., p28) is not complete and should be clarified.

Much of the *enhanced* detail in the new DAM relates to the structure of the model in terms of compartments and the incorporation of the ^{14}C model in the main code. While the justification for much of this can be dealt with in the review of (selected) FEPs and their implementation there are some FEPs that deserve special mention at this stage for the effect that they have on the model.

The greater complexity of the natural ecosystems models relative to the agricultural ecosystem models (from which the highest doses are obtained) is such that primary producers are modelled as a dynamic part of the system. This is justified (on page 27 Saetre *et al*., 2013) since "for a few elements (e.g. non-metals like Br and Cl) the inventory in terrestrial primary producers makes up a substantial fraction of that in soils in natural terrestrial ecosystems in Forsmark (Löfgren 2010)". The possible implications for agricultural ecosystem models should be considered, with a detailed review of the material. Related matters concerning uptake are also discussed in Chapter 7 of this report.

The lack of Redox modelling in assessment-level models has been of concern in recent years. The inclusion of specific *organic* compartments in the structure of the transport model was driven by the need to incorporate ^{14}C into the mainstream modelling framework. However, there are clear benefits arising from this approach – notably that "mire peats have strong vertical gradients with respect to e.g. oxygen content, hydraulic conductivity and organic matter quality" (Saetre *et al*., p28). The implementation and implications of this approach need to be reviewed.

A final example of the enhanced, almost fractal, level of detail now present in the model is taken from Section 5.2.3 of Saetre *et al*. and concerns *litter production*. The litter compartment is newly included (as improved "realism") in the natural terrestrial ecosystem (ie, "mire" modelling). This can be welcomed, but with reservations. Litter production is written (page 63) as:

$$litter_{prod,terr} = \begin{cases} AC_{PP,ter}^{^{14}C} NPP_{ter} area_{obj,ter} f_{refrac,ter} & {}^{14}C \\ AC_{PP,ter}^{RN} NPP_{ter} area_{obj,ter} \left(1-\left(1-f_{refrac,i}\right) df_{decomp,ter}\right) & other\ radionuclides \end{cases}$$

with units Bq year^{-1}. The radionuclide concentration in mire vegetation (ie, primary producer, *PP*), net primary production (*NPP*) and object area are clearly recognisable. The newly introduced parameters for the process are indicated in blue. Not only is the justification for this expression missing in the documentation but the availability of the database for these and other parameters must be questionable. The *fraction of refractory organic matter of mire vegetation [kgC kgC^{-1}]* is $f_{refrac,ter}$ (a misprint is suspected, so that $f_{refrac,ter} = f_{refrac,i}$ is likely). The *discrimination factor during decomposition [Bq Bq^{-1}]* is $df_{decomp,ter}$. SKB should be required to produced better justification for this level of detail and to show that this level of detail is *necessary* for optimum functioning of the dose assessment model. The provenance of the numerical data can then be addressed.

Much attention is focussed on advective water fluxes in the regolith. Diffusive processes in the aqueous phase (more so for ^{14}C in gaseous form) are also an important feature of the SR-PSU model. Page 32 of Saetre *et al*. states:

> *As the rate of diffusion is strongly dependent on distance, diffusion is only considered to be a [sic] quantitatively important at scales below metres. Consequently, this process was only considered a relevant mechanism for vertical transport of radionuclides between adjacent regolith layers with large (>100,000 m^2) contact areas.*

This is an example of where the implications of the modelling assumptions need to be investigated. In the section on the mathematical implementation there is no indication of how this condition is implemented. Clarification of these matters should be sought from SKB.

As a development of the SR-Site model the improved model for SR-PSU deals with specific areas within the hydrologic basins. The characterisation of the parts of terrestrial ecosystems that are contaminated is better described than previously. In particular there is a clear geometrical interpretation of the object within the wider basin. The implementation of this is an essential part of the model description and requires deeper review. The methodology for the delineation of the objects has not yet been investigated in detail and is closely tied to the description of the release from the bedrock. Documentation for this part of the model is in the geosphere report (Odén *et al*., 2014). In order to fully understand the way in which the geosphere and biosphere models are integrated in the assessment this report as well as Werner *et al*. (2014) need to be reviewed to establish the credibility of the geosphere-biosphere interface *as modelled*.

Implications of the selection of the geometry of biosphere objects in relation to the releases from the bedrock are further discussed in Chapter 3 below. This also impacts the sensitivity analyses reported in the Biosphere Synthesis document in respect of alternate object delineations. Attention should be directed to how the hydrology of the variant object areas is derived for the modelling.

The object in the SR-PSU landscape from which the highest doses are derived is identified as Object 157_2. Unlike most of the objects in SR-PSU (and SR-Site for that matter) the discharge location to the regolith is *not* at the at the local topographic minimum (this is in object 157_1 – see *Figure 1* above). A similar situation with respect to the highest dose consequences was seen in SR-site, where object 121_3 featured a similar upslope release. It is interesting to note that each of these upslope release locations are situated on either side (approximately 250 m north and south respectively) from the SFR harbour pier, used to unload shipments for the current SFR repository. As a matter of interest SKB should state how common, in the future landscape, are such upslope releases in the SR-PSU landscape. Furthermore they should clarify if the releases in SR-Site and SR-PSU are linked and whether (and how) the SFR pier plays any role. Alternate modelling should be considered.

During the SR-Site review SKB made Excel versions of databases available to SSM. This proved to be invaluable in ensuring the SSM's review used the correct data. Additionally, the detail provided in the appendices of the biosphere model description (Avila *et al*., 2010) allowed SSM to produce a functioning copy of key parts of the dose assessment model. While the standard of reporting in SR-PSU is significantly better than at the time of SR-Site The mathematical description in the Biosphere Synthesis and biosphere model description are not sufficiently comprehensive to allow SSM to carry out a similar procedure for SR-PSU. SKB should provide a working version of the Ecolego code used to perform the dose assessment calculations or should produce a detailed description to perform the same function as the Appendices in Avila *et al*. (2010).

In this initial phase of the review the detailed descriptions in the Appendices B (Fraction of CO_2 in soil pore gas), C (Fraction of radionuclide inventory in crops), D (Degassing from unsaturated soils) and G (Ecosystem properties and fluxes). have not been considered in detail. These will be reviewed in the main phase.

3. Hydrology in the dose assessment

As discussed in the previous chapter, there is interest in understanding how the releases come about in the locations specified, in particular the upslope releases associated with the highest radiological impact. The main interest in the hydrological support for the dose assessment model is in the characterisation and representation of numerical water fluxes in the hydrologic basins as the system evolves.

As might be expected the desire for "realism" in the model means that the hydrological network in the DAM's representation of radionuclide transport is more sophisticated than during the SR-Site modelling where an "average object" was constructed as the mean of fluxes in a set of six current lake-mire basins using the flow system estimated by MIKE-SHE at 5000 CE. This averaging approach is now replaced by detailed object specific flux maps for each of the objects as calculated by MIKE-SHE at three times in the future evolution: 3000 CE, 5000 CE and 11000 CE.

There remain a number of issues that need to be reviewed in greater detail during the main phase of the review. On page 61 of the synthesis document, the approach used is summarised as:

> *Modelling of future hydrology was conducted on a local spatial scale, supported by regional-scale boundary conditions (the model areas are shown in Figure 4-6). MIKE SHE water-flow models were developed for the times 2000 AD (present conditions), 3000, 5000 and 11,000 AD,* ***using locally measured meteorological data for a selected one-year period referred to as the normal year (Werner et al. 2013a). This year has an accumulated precipitation that is close to the estimated annual average for the so-called reference normal period (1961–1990)****, and is also close to the locally measured annual average for the period 2004–2010. [Emphasis added].*

The flow systems for the objects are available in Werner *et al*. (2014). They give an impressive amount of detail for the objects that SKB have selected and will allow detailed forensic review, as required. There are a number of issues that require clarification and deeper investigation.

Saetre *et al*. gives snapshots of fluxes at the three times mentioned and these are interpolated in the DAM, presumably at run time. This needs to be confirmed either by deeper review or directly as an RFI.

Changes between the three snapshot times can be reasonably expected to be smooth and the linear interpolation assumed in the DAM is expected to be sufficient. SKB should be requested to confirm

i. how the interpolation is performed

ii. that the interpolated flow systems correspond to the MIKE-SHE flow systems at intermediate times.

Part of the deeper review will investigate the implementation of the flow systems in the post 11000 CE period and particularly for the hydrology of agricultural systems.

There are four climate driven scenarios in SR-PSU. The main report (SKB, 2014a) lists them with the total annual dose arising as:

CCM_GW 5.6 µSv Global warming (reference) case

CCM_EP	0.2 μSv	Early periglacial case (periglacial conditions between 17500 CE and 20500 CE)
CCR_EX	5.4 μSv	Extended global warming scenario, modified climate conditions to represent a warmer climate for the duration of the modelled period.
CCR_GC	2.9 μSv	Glacial conditions at start of calculation, no release until 59600 CE with extended submerged conditions at the site.

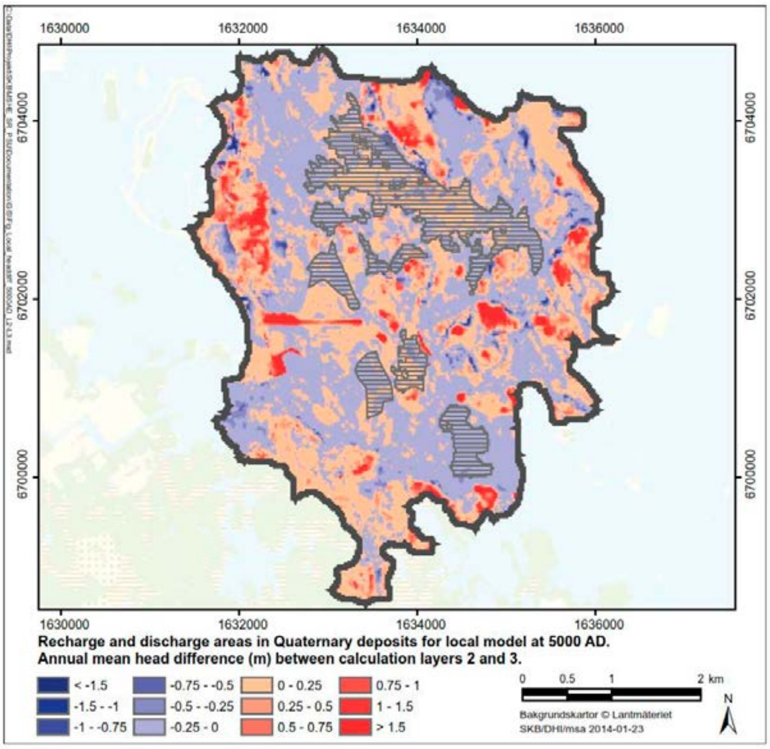
These four cases illustrate the range of climate determined doses in SR-PSU but more importantly they illustrate the relative *insignificance* of the periglacial state as modelled. Doses in this scenario are dominated by the hunter-gatherer exposed group with inherently high spatial dilution in the landscape (see also Chapter 8 here). Despite the extensive documentation it is not clear how the BCC3 (talik) biosphere is implemented in the overall assessment, though it is apparent from the page 99 of the Biosphere Synthesis that "Odén et al. (2014), see also detailed presentation in Vidstrand et al. (2014), used the bedrock hydrology modelling code DarcyTools to simulate steady-state groundwater flow in rock and taliks in a periglacial system with permafrost".

As noted in Chapter 2, above, it is the transition periods that are likely to be of greater interest since there is the potential for higher transient doses to occur with the change in hydrology. It would appear to be unlikely that a simple linear interpolation approach from full temperate to full talik conditions would be appropriate since onset of periglacial conditions and the changes to be expected as the climate then warms are unlikely to be smooth. These concerns are not discussed at all. The implications need to be considered. In the transition regime it might be possible for dammed concentrations of radionuclides in the bedrock and regolith interface to be suddenly released, with potentially much higher doses than are calculated in SR-PSU. At this stage the approach presented in the SR-PSU is not persuasive.

From the documentation it is apparent that SKB have not addressed these issues. It is recommended that some alternate calculational scenarios be investigated by SSM using their in-house modelling capabilities. These would be able to scope the possibilities and enable a more informed discussion with SKB. Flow system representative of talik conditions in the future landscape need to be reviewed in greater detail.

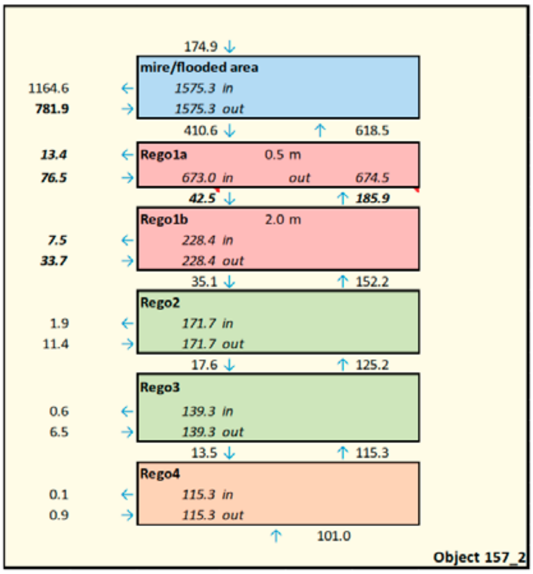
The scope of the SR-PSU documentation has been praised in the earlier part of this review document. In particular, the part of the sensitivity analysis that addresses the alternate object delineations is particularly interesting (Synthesis Document Section 6.4). In respect of the hydrological description however it remains unclear how the water fluxes for these alternates are generated. The flow systems in Werner *et al.* appear to be predicated on the boundaries of objects determined by the release maps in Odén *et al.* (see Chapter 4 below). A detailed investigation of the translation of MIKE-SHE flow vectors into the flow system maps used in the DAM is required. It is likely that this will require information from SKB concerning the numerical values available in the MIKE-SHE results database. Because there is not sufficient information in the current documentation to formulate request more clearly at present, it is suggested that the most efficient method would be to request a direct meeting between reviewers and SKB to resolve these (and similar) issues.

Figure 2: Illustration of the published output from MIKE-SHE. Results for 5000 CE.



[Figure 4-7 from TR-14-06]. MIKE SHE-calculated annual average vertical hydraulic-head differences in the regolith at 5000 AD. Blue colours represent areas with upward flow (discharge) and red colours areas with downward flow (recharge). Dashed areas indicate the delineated biosphere objects (see Chapter 6).

Figure 3: Extracted hydrological details for object 157_2 at 5000 CE as used in the DAM. How is the information in Figure 2 translated into these values. Details are needed.



[Figure A1-42 from R-13-19]. Water balance for biosphere object 157_2 at 5000 AD (normal year).

Figure 4-7 from the Synthesis Document (reproduced here as Figure 2) shows the recharge/discharge areas in the MIKE-SHE modelling at 5000 CE. To get an adequate understanding of the hydrological modelling a request should be made for the data on which this map (and the situation at 3000 CE and 11000 CE) is based – both as mapping files **and** as the numerical data from the MIKE-SHE model itself. Derivation of the numerical fluxes (shown in Figure 3) would then be possible in principle. It seems that this is done by a subroutine within MIKE-SHE. The details should be presented since it seems likely that they are contingent on where the boundaries of the object are placed. Again interface with SKB would probably be needed to expedite this RFI.

Appendix 1 of Werner *et al*. therefore needs to be reviewed in some detail. There are the familiar "Christmas Tree" plots, as used in SR-Site. These appear to give overall water balance for the landscape at different times and so are not necessarily useful in describing the individual biosphere objects. Their role and interpretation in relation to the information in Figure 2 and Figure 3 here need to be explained by SKB.

Detailed interpretation of the water fluxes as presented remains difficult. On page 58, Werner *et al*. note

> *During wet periods, some groundwater discharge areas in the regolith switch into recharge areas. Specifically, in some areas evapotranspiration causes an upward groundwater flow during average and dry conditions, whereas during wet periods such areas switch into recharge areas.*

Could there be scenarios were decreasing water fluxes over time leads to extra high accumulation in land that are later on used for agriculture?

Hydrology for the talik systems is not addressed in the same detail:

> *… periglacial conditions are not considered in the MIKE SHE model setup of the SR-PSU project. The locations and extents of future lakes and streams (Section 3.2.3), which control the locations of taliks, are similar to those of SR-Site. The results of the MIKE SHE modelling of periglacial conditions and permafrost presented by Bosson et al. (2010) are therefore considered to be relevant also for the SR-PSU project,*

(page 82 of Werner *et al*., 2013). The SR-Site details (Bosson *et al*., 2010) are still used for SR-PSU but with some reinterpretation (Bosson *et al*., 2013). The brief discussion in Sections 5.8.2 and 5.8.3 of Werner *et al*. (2013) illustrate the nature of the gap between the requirements of a radiological dose assessment and the abilities of the hydrology team to perform interesting scientific calculations but which are of less importance for the DAM. There are no equivalents of Figure 2 and Figure 3 for the periglacial biosphere. For this reason it is unlikely that entry to and exit from periglacial hydrologic conditions can be modelled in a reasonable manner using interpolated flow systems. It is recommended that SSM consider alternate interpretations.

The hydrology of the evolving system is evaluated using data for the "normal year" (Werner *et al*., 2013, p27) for the temperate climate, and with modifications for the warmer wetter conditions assumed in the extended global warming period. it appears that these data are employed as repeated time series in the MIKE-SHE modelling. It would be useful to know how different the snapshots of hydrology would be at 3000, 5000 and 11000 CE if credible alternatives where used, possibly using time series for meteoric inputs to MIKE-SHE. Further review is required to establish the implications of these assumptions and a possible RFI will likely arise in the course of the main phase review. It is too early to be precise at this stage.

The MIKE-SHE modelling is conditioned by the results from the geosphere domain using DarcyTools. There is a considerable overlap in the domains of the models. while DarcyTools is the principle too for the particle tracking to the top of the bedrock from repository depth and below (-634 m: p19 Werner *et al*., 2013), MIKE-SHE also includes this domain with fluxes in the bedrock conditioned by the vertical and horizontal hydraulic conductivities passed from DarcyTools.

The SR-Site site investigation programme is used in SR-PSU. There are uncertainties in the modelling and Öhman *et al*. (2013) suggest “that uncertainties in the hydrogeological model are studied in the safety assessment SR-PSU by means of a large number of calculation cases”. From a biosphere dose assessment perspective, at this stage of the review, it is not clear how results from the “large number of calculation cases” are evaluated to generate the data and results that are used in the SR-PSU biosphere calculations. It remains an open question how different the release distribution in the biosphere (at the base of the regolith) could be. Additional information should be sought from SKB but further investigation is required before a specific RFI can be formulated.

The potential role of the SFR pier was noted in the previous chapter. On page 148 of Werner *et al*., this feature of the modelling is briefly addressed:

> *In the DarcyTools modelling, most particles released from SFR 1 discharge at the interface between rock and regolith in biosphere object 157_2, which is located within a low-lying area north of SFR 1, in the vicinity of the junction between two steeply dipping deformation zones. Discharge locations for particles released from SFR 3 are located north of the SFR facility but also southeast of SFR 3, **which likely is due to the influence of the SFR pier on groundwater flow in the vicinity of SFR**.*

Emphasis added. It would be helpful if SKB would explain in greater detail the role played by the SFR pier in determining the releases to 157_2 (as well as Object 121_02) in SR-PSU and also if similar considerations apply to the release to Object 121_3 in SR-Site. There is clearly an overlap between the geosphere and biosphere modelling in the assessment arising, not least, from the linking of the transport regimes. For this reason the biosphere side of the dose assessment model needs to be more aware than in previous assessments of the nature of the geosphere/hydrological modelling associated with discharges – not only should Odén *et al*. (2014) be part of this review but also familiarity with the modelling described in Öhman *et al*., (2013) might also be necessary.

Finally, Page 148 of Werner *et al*. notes:

> *In particular, net fluxes are largest for biosphere object 157_2 (more than 100 mm/y) at 5000 and 11,000 AD,*

so the relatively high “net flux” in this object may account for the radiological importance of this object. There is much to investigate.

4. Releases from the geosphere, object delineation and geosphere-biosphere interface

For the several distinct basins in the future landscape, the analysis of particle discharge locations carried in Odén *et al*. (2013) provides the basis for identifying which basins are likely to be involved and an approximation of the key parts of the objects themselves that SKB consider necessary to be evaluated. These locations are the are Biosphere objects that are carried over into the dose assessment modelling.

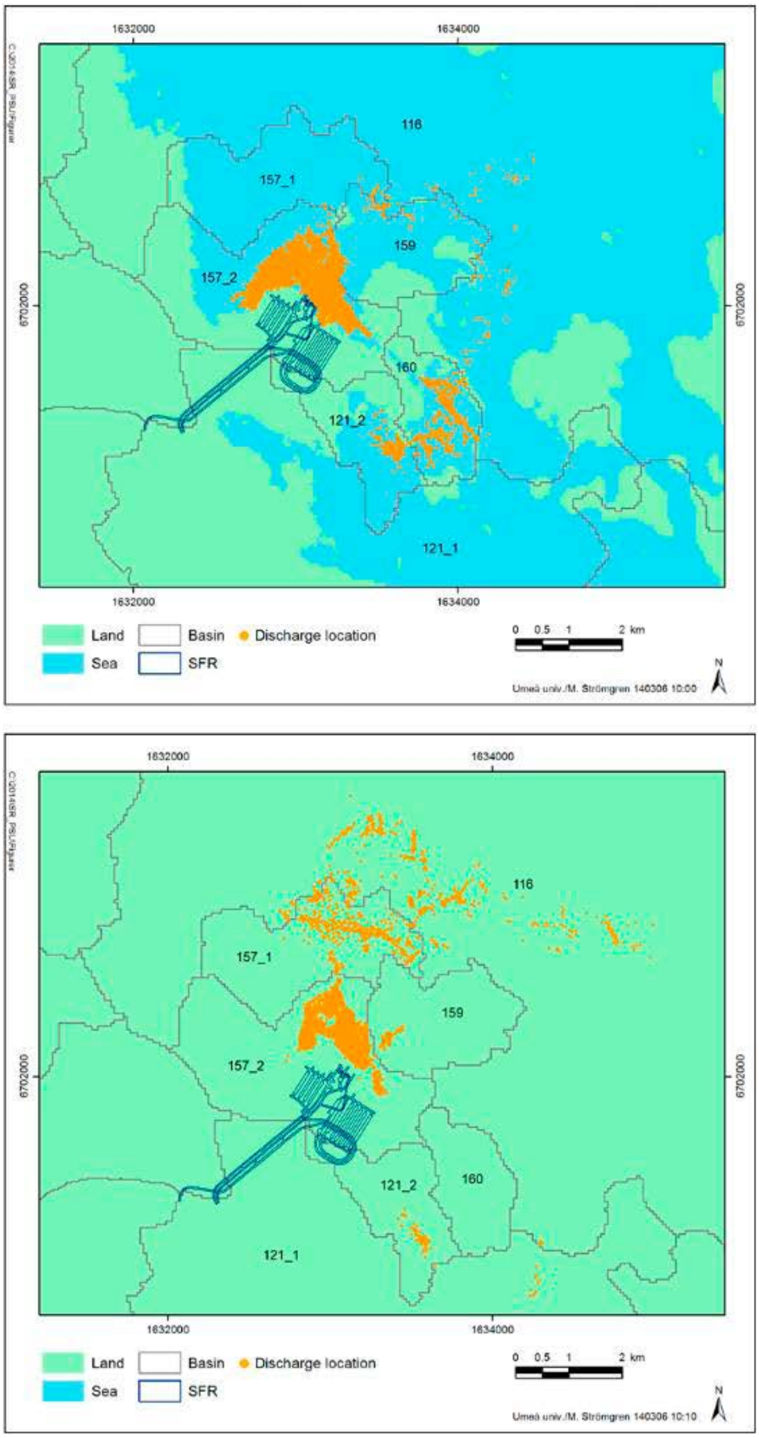
MIKE-SHE modelling also has an impact on the choice of biosphere objects – see Figure 2 above, where the recharge/discharge areas can also be used to identify object boundaries. Definition of the object delineations has a potentially important role to play in the dose assessment since too large an object can result in unwarranted spatial dilution of the release. The procedure for the object boundaries from the surface hydrology (Werner *et al*., 2013), the deep geology and particle tracking (Odén, 2014) and topographic maps (Strömgren & Brydsten, 2013) is not fully revealed in the documentation reviewed so far and therefore is an area that requires deeper review. As part of the review it would useful to have access to the object-defining characteristics in GIS-format files so that the reviewers would be able interrogate maps for themselves. These data should be requested from SKB. These details will be of use in any alternate modelling that SSM should require as part of the main phase review.

There are a number of datasets the should be requested:

- Boundaries of basins and biosphere objects (eg, Appendix 1 of Synthesis document).
- Release points as a function of time as calculated by Odén *et al*. (2014), as illustrated in Figure 4, below. Bothe temperate and periglacial release points should be included.
- Radionuclide release rates from the bedrock to the base of the regolith as a function of time and space. Data for three biosphere scenarios, BCC1 (temperate – global warming case), BCC3 (extended global warming) and BCC3 (periglacial case). This should include how the release points are converted to release rates in Bq year^{-1}.
- The digital elevation model (DEM) of the model area (from Strömgren & Brydsten, 2013).
- Total regolith depth (Strömgren et al., 2013).
- Surface expressions of lineaments at the top of the bedrock (eg, Figure 1-1 of Odén *et al*., 2014).
- GIS data to allow the location of the SFR1 and SFR3 structures to be mapped (eg, Figure 1-1 of Odén *et al*., 2014).

Overall, the procedure by which the boundaries are determined is not explicit in the documentation so for reviewed. There is evidently a requirement to combine information from a number of different sources, surface hydrology, release distribution and topography but how the procedure is carried out is well hidden. Figure 6-10 of the Synthesis document (reproduced here as Figure 4) provide some indication of how object boundaries might be identified. Clarification is required.

Figure 4: Releases locations by particle tracking in hydrologic basins at two future times.



[Figure 6-10 from TR-14-06]. Locations of discharging particles from SFR obtained with models for 3000 AD (top) and 9000 AD (bottom) displayed on maps showing the basins.

In the case of releases to local topographic minima the method can be approximated by considering closed contours in the topography. The situation with respect to the two objects for which there is upslope release (157_2 and 121_2, on either side of the SFR pier) is less clear. The discussion of the implications for the landscape dose factors of alternate object delineations (discussed in Section 6.4 with results in Section 10.8 of the Synthesis report) gives some idea of the interaction between the three controlling factors. There are important considerations for uncertainty here, not least of which concerns any potential alternate modelling that SSM may wish to consider in the main phase review.

For the periglacial simulation the distribution of release locations in the landscape is significantly more restricted. The snapshot nature of the periglacial hydrology again raises concern. Because the hydrology of the periglacial simulation is fixed and because changes to flow systems with onset of and return from periglacial are not represented. How this information is coded into the dose assessment model needs to be investigated, perhaps with an alternate modelling scoping study carried out on behalf of SSM. As stated on page 87 of Werner *et al*.,:

> *Areas that for temperate conditions act as inland groundwater-discharge areas can for permafrost conditions constitute recharge areas associated to through taliks. For such conditions, through taliks are the only available inland pathways through the permafrost and they tend to be located to topographical low points in the landscape. Hence, a shift from temperate to periglacial conditions with permafrost changes recharge-discharge patterns at the ground surface and the exchange between deep and shallow groundwater. Theoretical and empirical studies indicate that for periglacial conditions with permafrost, topographical differences between taliks govern the spatial pattern of groundwater recharge and discharge (Bosson et al. 2013). The main groundwater discharge occurs at the most downstream through talik (the sea bay in the Forsmark case).*

So the changes in the flow system are acknowledged but not implemented in the dose assessment modelling. The potential for enhanced accumulation and concentration of releases in the evolving landscape as a results of the modified and transient flow regime remains unaddressed. The presence of, for example, the Börstilåsen glaciofluvial deposit (Synthesis, p40) is testament to the role of the transition periods extant from the previous glaciation.

5. Development of landscape, climate and ecosystems

Climate evolution during the modelled period is an important new feature of the SR-PSU modelling. The timescale for the numerical assessment is now up to 100 kyear AP and the possibility of a periglacial episode is included. Previous assessments have been restricted to the first 10 kyear for detailed biosphere dose modelling over which timespan temperate conditions were assumed to prevail. With this extended timescale it is important that the consequences of periglacial conditions be understood. There is a need for SSM to be able not only to understand the details of SKB's modelling approach in the assessment, but also for SKB to have some idea of the possible scope of dose arising from the evolution into and out of this climate state. As noted in previous sections, the static, non-evolving approach implemented by SKB in SR-PSU is not sufficient.

Aside from the extended timescale of the biosphere dose assessment, the SR-PSU documentation emphasises a number of FEPs over and above what was included in the SR-Site model. The need to better incorporate ^{14}C into the DAM compared to bot the SR-Site and SAR-08 assessments is one driver for these improvements. Chapter 2 here notes the impact of the new ^{14}C-related FEPs. This chapter deals, in part, with the representation of carbon fluxes as they impact on the landscape development. For example, the Brydsten and Strömgren (2013) study presents a model that can predict the surface geology, stratigraphy, and thickness of different strata at any time during the period considered in the safety assessment. They apply this model to the Forsmark site. Topography is central to the definition of biosphere objects (see Chapter 4 above). A request for data from SKB has been suggested above in respect of the initial-state DEM topographic surface. A further request should be made regarding the modified topography at the times at which the hydrology simulation in MIKE-SHE are produced, namely 3000, 5000 and 11000 CE. How the topography evolves over the subsequent 89 kyear should also be described.

From this there is a sub-model that represents the growth and development of carbon in mires that is a clear "realistic" improvement of the net-sedimentation approach used in SR-Site. Carbon content of the upper layer of mires is given by a first order linear ordinary differential equation:

$$\frac{d}{dt}P_C = b_C A_{ter} - m_r P_C \text{ [kgC year}^{-1}\text{]}$$

where

P_C = mass of stable organic carbon (SOC) in the peat kgC,

b_C = areal burial rate of SOC, kgC m^{-2} $year^{-1}$,

A_{ter} = area of the terrestrial part of object, m^2,

m_r = the mineralisation rate of refractory organic carbon in the anoxic environment of the peat [kgC kgC^{-1} $year^{-1}$].

This is an interesting development that should be explored in any developments of the SSM alternate modelling capability since the mass of carbon accumulated in mires has a direct impact on the concentration of radionuclides in mire material and subsequent agricultural soils. Growth and burial of gyttja is also better described and needs to be understood and taken into account.

Taliks in the periglacial environment are an important feature of the post 11000 CE world. It is not clear how taliks form during the transition period from full temperate to full periglacial conditions. This contrasts with the details word-picture of the development of mires in temperate landscape (see Section 4.7 of the Biosphere Synthesis document). A request for a description of the changes to the landscape during talik formation should be requested.

The impact of some of the newly added modelling details are addressed in the context of the dose model in Chapter 2 of this document. What appears to be a significant feature of the evolving landscape has been mentioned in several places above, and it has impact on the radionuclide specific database addressed in the following Chapter. This is the chemical evolution of the emergent soils in the landscape. A selection of related comments from the Synthesis are listed here:

- *Compared with most other parts of Sweden, regolith in the Forsmark area has been subjected to soil-forming processes only for a relatively short time and most of the soils are therefore immature and lack distinct soil horizons (Lundin et al. 2004). Till and glacial clay in Forsmark have high contents of calcium carbonate ($CaCO_3$), and originate from Palaeozoic limestone that outcrops on the sea floor north of the Forsmark area. The high content of $CaCO_3$ in the soils strongly affects their chemical properties. [p40]*
- *The high content of calcium carbonate in the regolith and the recent emergence of the area above sea level affect the chemistry of surface waters and shallow groundwater. Specifically, surface water and shallow groundwater in Forsmark are generally slightly alkaline (pH 7–8) and have high concentrations of major constituents, caused by marine and glacial remnants deposited during the latest glaciation. Calcite has had a strong effect on the development of terrestrial and limnic ecosystems at the site. For instance, secondary calcite precipitation and co-precipitation of phosphate contribute to the development of the nutrient-poor oligotrophic hardwater lakes that are characteristic of the Forsmark area (Andersson 2010). The rich supply of calcium also influences soil formation and the development and structure of the terrestrial ecosystems (Löfgren 2010). [p46]*.
- *Due to the calcareous regolith, the field layer is characterised by herbs, broad-leaved grasses and many orchid species. [p49]*
- *During the forthcoming thousands of years, the present soils will successively develop into more mature soil types. At present, the most commonly occurring soils have developed on till and are often rich in calcite and consequently have high pH. In the future, the soil pH will decrease as the calcite is leached out. [p59]*
- *In contrast to peat, areas with minerogenic deposits can probably be cultivated for many thousands of years. Most of the regolith used as arable land today is dominated by minerogenic material. Erosion and weathering are slowly affecting these deposits. Erosion may be a fast process, but most likely not on the generally flat landscape discussed here (Cerdan et al. 2010). Chemical weathering is a slow process releasing nutrients needed for primary production. As long as the soils contain significant amounts of calcite, the elevated pH means highly fertile soils, but the calcite dissolution will in the long run lead to a lowered pH and a decreased productivity. [p76]*

There are other similar notes and comments sprinkled through the SR-PSU documentation, each pointing out the anticipated change in the chemistry of soils in the future landscape as $CaCO_3$ is slowly leached from the newly emerged soils with the impact on vegetation and ecosystems. Because soils emerge from the Baltic and then age and evolve over time there is a gradient of analogue conditions from the present day coastline inland. Indeed, the soils at Laxemar, that have been extensively studied as part of the site investigation programme for the spent-fuel disposal programme, provide practical analogues for matured soils at the Forsmark site.

It is strange, therefore that SKB choose not to model evolving soil chemistry in the SR-PSU assessment models but to represent it by a single probability distribution function (pdf) for each radionuclides in the assessment (see discussion in the following chapter). The transitory nature of ecosystems in the Forsmark area is also noted on page 47 of the Synthesis document:

> *Present-day lakes in the Forsmark area are small and shallow (mean depth typically below 1 m, Figure 3-6). They are characterised as oligotrophic hardwater lakes, with high levels of calcium and low nutrient levels.* ***This lake type is common along the coast of northern Uppland region where Forsmark is situated, but rare in the rest of Sweden****.*

Emphasis added.

The main review phase needs to ensure that the modelling deals with the evolving ecosystem characteristics effectively. It is suggested that alternate calculations be carried out in this respect, particular in respect of the evolving soil K_ds.

6. Element and radionuclide specific data

A major difference in the SR-PSU assessment, as distinct from SR-Site, is the emphasis placed on using site-specific parameters, including K_d and CR data. This represents a logical development from SR-Site, in which large volumes of site-specific data were collected but not used specifically in assessment modelling as part of that exercise. "The radionuclide model for the biosphere has, as far as possible, utilised the site-specific data both for describing parameters and populating parameter values. Compared to earlier SKB assessments, large amounts of site data are available for the SR-PSU biosphere assessment" (SKB, 2014b). It is also stated in TR-14-06 that "This dataset is probably one of the most detailed collections of synchronised surface data ever produced in Sweden". The site-specific data sets from Forsmark and Laxemar are certainly unique when viewed in the context of other environmental radiation protection exercises around the world, and it is unlikely that there has ever been a comparable data set amassed for the purposes of understanding the impacts of contaminants of any type in environmental systems. Given this large investment by SKB it is encouraging to see that full use is now being made of this rich resource.

However, despite placing a strong emphasis on site-specific data, the SR-PSU assessment still uses literature-derived data, where appropriate, for key parameters such as K_d and CR. Nevertheless, using K_d as an example, Tröjbom et al. (2013, p. 21) emphasise the IAEA (2010) position that "literature K_d values must be considered as approximate values that are suitable for screening purposes only and not for specific risk assessments". This is an important consideration in the 'new' SKB focus on site-specific values in which "Site data are generally prioritised over literature data" and "literature data usually have limited value other than for screening purposes and that site-specific data should be utilised when available". Tröjbom et al. (2013, p. 24) make the key justification that "Literature data have an important role as reference for comparisons and **plausibility control** of selected site data in this report". This is entirely reasonable.

Literature-derived data have been obtained from three major sources – IAEA (2010), ERICA (Beresford et al. 2008a, Hosseini et al. 2008) and ICRP (2009). It is possible that data within these individual sources overlap with one another. For example, the IAEA's (2010) 'Handbook of parameter values for the prediction of radionuclide transfer in terrestrial and freshwater environments' may have used the ERICA database as one of its key sources. The particular question of how much overlap exists between these sources and how much this might have influenced parameter choice in SKB's 'K_d/Cr compilation' is suggested as an area for deeper review. This would provide reassurance that multiple entries have not been made for K_d and CR values with common original sources.

Aside from the impressive collection of data on ecosystem-specific properties (Grolander, 2013), it is the radionuclide-specific transfer parameters which will control the ultimate radiological impact of the Forsmark facility in the biosphere. Accordingly, the focus of this review is on the K_d and CR values described in detail by Tröjbom et al. (2013) in report R-13-01.

Although they have been used in radiological assessment models since at least the 1970s, the solid-liquid distribution coefficient (K_d) has numerous shortcomings which limit its reliability as a measure of the geochemical mobility of radionuclides. It is refreshing that Tröjbom et al. (2013) have carefully enumerated (Section 2.3, p.

20) the assumptions underlying the K_d and the possible (probable) violations of these assumptions. This part of the report provides a much more thoughtful critique of this key parameter than has been evident in previous SKB reports. Tröjbom et al. (2013) also consider the effect of spatial and temporal scales on K_d estimates, specifically stating that “upscaling from site-specific samples or laboratory tests to landscape level introduces uncertainties regarding representativeness” and that “the variation assigned to specific K_d values should also account for the variation in the chemical environments among the possible discharge points in the model area”.

On the topic of temporal variability of K_d “If the estimated K_d values represent processes that would not reach equilibrium within the resolution of the dynamic model, the model might underestimate the mobility. The overall variation assigned to specific K_d values should also account for the long-term landscape evolution that will change the environmental conditions over time”.

Together these statements capture several areas of concern surrounding the use of both K_d and CR estimates in radiological assessments, particularly over the long timescales relevant to the SR-PSU. Specifically, the problem of using point-scale or local measurements of K_d and CR and applying these to a much larger spatial scale(s) is recognised. In the case of K_d the applicability of values derived from short-term studies (in laboratory or field) to the very long timescales of assessment calculations is also recognised. The translation of these details into the ranges (specifically GSD) in the dataset needs to be evaluated.

The solution to these concerns is to represent the variation in K_d and CR over the appropriate scales of time and geography within a single PDF, in the form of a log-normal distribution of K_d or CR estimates. This approach is by no means new, but it is reassuring that the variation in K_d and CR for the purposes of SR-PSU has been constrained within *plausible* limits using a formalised method which is exhaustively described by Tröjbom et al. (2013). The need to address these non-evolving K_d/CR values has been noted in earlier chapters here. The argument presented by Tröjbom is also less persuasive, however, if it is really the case (page 34 here) that only ten sample sets for the biosphere are considered.

In the SR-PSU assessment, K_d values are presented for:

- nine different ‘soil’ types (actually ‘regolith compartments’)
- limnic particulate matter
- marine ecosystems particulate matter

CRs are presented for 55 terrestrial, limnic and marine types of non-human biota. The calculation of CRs is made unnecessarily complex by normalising activity concentrations of radionuclides in organisms’ tissues to their carbon content. The justification for this approach needs to be stated in the description of the parameter calculations, otherwise it simply adds confusion to what should be a deliberately simple empirical parameter.

There are some omissions in the preliminary material (p. 26 – 31, section 2.7). While this is a generally well-considered section describing the physico-chemical properties of relevant elements and their analogues there are some problems. Te is considered to be a suitable analogue for Se, but no account given of either Se or Te. By the same token, S as an analogue for Se when there is likely to be significantly more data for S. Similarly, it can be questioned why Bi or Pb are considered as analogues for Po – rather than Te, which is in the same group?

The ‘transfer coefficient’ is used to quantify radionuclide transfer from the feed of domestic animals to their meat and milk of cows. This is slightly more complicated than the simple concentration ratio, but is in keeping with many previous assessments and databases. The transfer coefficient accounts for the feed intake of animals, which is relatively well-known for domestic animals but can only be estimated for wild animals. Hence, appropriate transfer parameter types have been used for animals of different types in SR-PSU.

Given the large new dataset available to SKB following the SR-Site and related investigations, it is to be expected that the choice of K_d and CR values for SR-PSU will be much more defensible than in previous assessments. However, this is only likely to be true if the wider data set is scrutinised carefully and judicious selection of K_d and CR values made based on a carefully systematised method. This is exactly what Tröjbom et al. (2013) have set out to achieve. The stated aim of their parameterisation process "…is to find the best available and most probable element-specific parameter values for featured elements, based on various data sources in combination with general information on chemical analogues".

The starting point of this process is the compilation of a database (using Microsoft Access) which is referred to as the "K_d/CR compilation"

A three stage process has been implemented, consisting of:

- Data selection (from the K_d/CR compilation)
- Comparison of data
- Manual evaluation and selection

This is a significant departure from the method used in the SR-Site assessment which took a purely statistical (Bayesian) approach to define PDFs for K_d and CR, based on a much smaller available database. This change of approach represents a worthy aim to make the parameter definition process as transparent as possible and to ensure ‘uniform handling’ of parameter values.

The Access database within the which the ‘K_d/CR compilation’ is held is claimed to provide a "traceable link between the original concentration measurements and the final output parameters". As part of a deeper review it would be useful to scrutinise at least a sub-set of the database. This would involve a data request for a minimum of several illustrative examples of database content. In a previous review (of SR-Site) we made requests to access data in Sicada and these proved useful in understanding the type, volume and quality of data used in compiling K_d values from original concentration measurements from the Forsmark and Laxemar sites. In the context of SR-PSU it would be useful to make the same kind of analysis of data held within the ‘K_d/CR compilation’ and to develop an insight into how the new database relates to Sicada. One feature of the ‘K_d/CR compilation’ is that not all data/elements contained within it are used in the SR-PSU analysis, but they are used to check plausible GSD variation (see below). Again, scrutiny of the database would allow us, as reviewers, to form a better understanding of the suitability of the database for such checks.

One of the features of the K_d and CR selection process in SR-PSU is that avoids sophisticated statistical methods in an attempt to make the process as transparent as possible. One example of this straightforward approach is that no attempt is made to deal with concentration data which fall below analytical limits of detection using statistical methods, even though such methods exist (as acknowledged in R-13-01).

This approach is presumably possible because the data set is large enough to allow the stringent selection of data which, inevitably, means reducing the sample size of paired concentration measurements from which K_d or CR can be calculated. In practice, this is a robust and defensible approach.

Less defensible is the procedure described in section 4.2.1 of R-13-01 which seeks to maximise the number of K_ds obtained from paired measurements of soil and liquid concentrations obtained from several replicate samples.

> *"Kd values calculated from such measurements represent true concentration pairs sampled at selected sampling sites at specific depths. If several replicates are available ratios are formed for all possible combinations between pore water and the solid fraction" (p. 41)*

Calculation of K_ds should strictly be based on paired samples, since paired solid and liquid samples are assumed to be at physico-chemical equilibrium. The practice of using "all possible combinations" of pore water and solid phase concentrations is an artificial method to generate a larger number of ratio values than the measurements actually support and could introduce significant uncertainty into the K_ds thus obtained.

A similar approach is used for CR, although this is probably unavoidable for this parameter ("exact spatial and temporal matching of concentration samples are usually not possible") and probably less likely to introduce uncertainty in the ratio obtained since the equilibrium relationship between a biological compartment (eg. vegetation) and an associated physical compartment (eg. soil) is less precisely defined. For both K_d and CR, the pairing of as many combinations of concentration measurements as possible (ie. not necessarily just 'true' sample pairs) within the K_d/CR database leads to confusion in the definition of *N*, which is important in the later process of assessing data confidence (see below). The most straightforward definition of *N* would be the number of **ratios** (K_d or CR) calculated from paired samples, but this does not appear to be the definition used in R-13-01 (4.2.1, p. 42). An assessment of the impact on pdfs should carried out as part of the review, and/or with a request to SKB to justify (at least clarify) the methods used.

Perhaps the key step in the process of assigning appropriate and defensible PDFs to K_d and CR in SR-PSU is the definition of **plausible parameter variation** (section 4.3, p. 43).

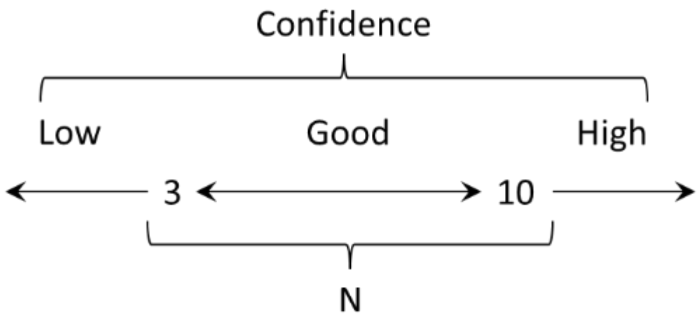
Analysis of the 'plausible' variation in GSD of parameters is based on site-specific data. However, the analysis seems to examine the range of GSDs of different elements including those not examined in the SR-PSU analysis. This implies, though is not clearly stated, that K_ds and CRs for different radionuclides/elements were lumped together when analysing the variation in each parameter (eg. K_d*_PM_lake* or *CR_lake_fish*). This approach requires clarification but, if our interpretation is correct, it raises the question of the validity of comparing, for example, GSDs for K_ds of Cs with those for U.

Having established that GSDs for each K_d and CR vary substantially Tröjbom et al. (2013) conclude that "no general assumptions of the nature of the GSD distributions can be made; therefore, the plausible limits for the GSD are defined as **percentiles** of the empirical distribution of the GSD for each parameter (or group of parameters)" The choice of 5^{th} and 95^{th} percentiles to delineate the lower and upper bounds of the GSD range is arbitrary but could be regarded as statistically 'conventional'.

What is less conventional is that each GSD appears to be calculated for a lumped collection of nuclides/elements for each parameter (eg. *Kd_ter*). **GMs and associated GSDs should only be calculated for individual elements/nuclides**. This should be confirmed and alternative derivation of values considered.

As stated above, Tröjbom et al. (2013) have aimed to make the parameter definition process as transparent as possible, compared with previous assessments. However, further reading of Chapter 4 of R-13-01 suggests that the Bayesian method of PDF construction for K_d and CR in SR-Site seems to have been replaced with a somewhat arcane empirical method to constrain parameter variability – transparency has not been achieved and the method warrants deeper scrutiny. It is true to say that "GM values and best estimates of parameter values are not affected by the estimate of the uncertainty of a parameter obtained by this method" but combining original concentration data in all possible combinations is not defensible.

Criteria for selecting (*GSDmin*, *GSDmean*, *GSDmax*) are based on 'confidence' based on the number of samples *N*, but *N* = 3 to 10 is taken as being 'relatively good'! They have produced a systematic method but *N* values used as confidence criteria are all rather low (see diagram below) and the exact procedure used to calculate (*GSDmin*, *GSDmean*, *GSDmax*) is far from clear at this stage. Even the exact definition of *N* remains uncertain (see above).



7. Special radionuclides

There is the "standard" model for radionuclide transport, accumulation and dose and there is the carbon-14 model for transport accumulation and dose. The two are distinct in the assessment but they are both incorporated into the coding for the assessment calculations. This is not a problem and carbon modelling is understood to be part of a parallel review. However, there are several instances where carbon fluxes are incorporated directly into the current "standard" model employed by SKB (for example the growth of mires discussed in Chapter 5. SSM may wish to consider the integration of a ^{14}C modelling capability into their current standalone dose assessment model and to use some of the refined description of FEPs in their own modelling tools.

There are other areas for which deeper review and familiarisation is necessary. One such is found in the discussions on page 61 of the biosphere model description (Saetre *et al*., 2013) and arises because, now, the modelling include distinct organic and inorganic compartments:

> *As plants primarily access elements in inorganic form (Kabata-Pendias 2011), root uptake is modelled exclusively from the inorganic pool. However, as empirical plant-soil relationships are traditionally defined by concentration ratios between the plant and the total soil concentration, including elements in organic form, [the approach applied here] may yield unrealistic or even impossible rates of plant uptake.* ***This is particularly a problem for parameter combinations that yield a high rate of biological uptake (high CR and NPP)*** *and a large accumulation in organic matter in surface peat (i.e. a high litter production and a low rate of mineralisation and/or burial, see below). Therefore the equation for plant uptake was modified to include an upper limit on the uptake.*

The added emphasis shows that there are important FEP interactions at work within the model as applied that need careful analysis. Here they are a combination of the carbon modelling included in the new model but have implications for other radionuclides. The "pools and fluxes" approach seen over the last decade in various SKB ecosystem-related documents may at last be bearing fruit.

Also dealing with plant uptake, Saetre *et al*. go on to say (also on page 61):

> *The plant tissue concentration of essential elements (nutrients) such as chlorine is often regulated (Van den Hoof and Thiry 2012). Consequently, the chloride concentration varies significantly between plant species, but has little to do with the concentrations in boreal soils (Edwards et al. 1981). Thus, the plant nutrient concentration can be used to derive an upper limit for net uptake of chlorine, and the Cl-36 concentration in newly synthesised biomass can be approximated from the specific Cl-36 activity concentration of dissolved inorganic chloride in the surface peat layer.*

Review of the models for such details should be part of the main phase review to ensure comprehensive coverage of topics.

8. Exposure pathways and exposed groups

In SR-Site, the characterisation of the most exposed population was a complex feature of the modelling, with the modelling defining the maximally exposed individuals. In SR-PSU there is a return to a more traditional method of defining exposed groups based on credible lifestyles in the future landscape. This greatly promotes transparency in the documentation of exposures to environmental concentrations of radionuclides.

Where site-generic biosphere dose assessment have traditionally used a “subsistence farmer” as the “critical group” the approach taken to this highly site-specific modelling is much more tailored to fit the potential of the Swedish landscape. The groups identified and used in SR-PSU therefore represent a detailed translation of the traditional approach to the Swedish context and are useful in scoping the potential interaction of particular lifestyles with the contaminated ecosystems that might arise.

The exposure groups are defined using the FEP analysis in SKB (2014g) . Unfortunately this report “Handling of biosphere FEPs and recommendations for model development in SR-PSU” does not yet appear to be available and so has not featured in this initial review. It needs to be part of the main phase review, not least for the identification of the exposure groups deployed in SR-PSU.

The four groups are (p123 of the Synthesis document):

- *Hunter-gatherers (HG) – A hunter and gatherer community using the undisturbed biosphere for living space and food. A typical hunter-gatherer community is assumed to be made up by 30 persons that utilise a forage area of approximately 200 km^2.*
- *Infield-outland farmers (IO) – Self-sustained agriculture in which infield farming of crops is dependent on nutrients from wetlands for haymaking (outland). A self-sufficient community of infield-outland farmers is assumed to be made up by 10 persons. A wetland area of 0.1 km^2 (10 ha [=10^5 m^2]) would be needed to supply winter fodder to the herd of livestock corresponding to the need of manure for infield cultivation of this group.*
- *Drained-mire farmers (DM) – Self-sustained industrial agriculture in which wetlands are drained and used for agriculture (both crop and fodder production). A self-sufficient community of drained-mire farmers is assumed to be made up by 10 persons. A wetland area of 6 ha [6×10^4 m^2] would be needed for food production.*
- *Garden-plot households (GP) – A type of household that is self-sustained with respect to vegetables and root crops produced through small scale horticulture. A garden plot household is assumed to be made up by 5 persons and a 140 m^2 area garden plot is enough to support the family with vegetables and root crop.*

The Hunter-Gatherer group is a non-agricultural community and therefore requires large areas of the natural environment to sustain itself. This is a major factor in the low doses from periglacial climate conditions. For this reason it is unlikely that this lifestyle would ever dominate over temperate-conditions agriculture where it is possible to source all consumed foodstuffs from the same location, which can have high concentrations in a relatively small area.

The Drained-Mire farmer group – with its relatively small footprint gives rise to the highest doses in most calculational scenarios. The smaller (in numbers and area exploited) Garden Plot group does not have particular prominence in the results as far as doses are concerned and this is despite well water usage (which is much better described in the SR-PSU documentation) being included for irrigation as well as water consumption.

There are, therefore numerous subtleties and interactions with other parts of the dose assessment modelling that need to be investigated more fully in the main phase. This will be in addition to a review of how well the groups fit into the landscape context assumed for the hydrology and landscape development modelling. As ever, the potential for exposure groups interacting strongly with any potentially high concentrations that may arise in the transition between climate states and their associated hydrological representations should be considered.

For any independent modelling that SSM may wish to carry out, implementation of these (and perhaps other) groups (and pathways – such as burning of biomass) can be considered.

Recent SSM independent modelling (Kłos *et al*., 2015) have illustrated the potential for accumulation in lower parts of the regolith that can be used for well extractions, with importance for calculated doses. In the present day biosphere "there are some private wells (dug in regolith or drilled in bedrock) in land areas along the coast. Analyses of the well water show that the water quality varies, such that some wells contain potable water and others non-potable water. Consequently, some wells are not used as drinking-water supplies but instead for other purposes, e.g. irrigation of garden plots" (Werner *et al*., p49. Evidently then, the regolith can be considered for well water and this appears to be justification for their inclusion of the garden plot group.

At present there is no clearly identified requirement for any RFIs, though this may change during the course of the main review phase.

9. Treatment of non-human biota

Impacts on non-human biota are an integral part of the assessment. The methodology for the calculation is standardised in that it based on the ERICA methodology (Beresford *et al*., 2007). The Biosphere Synthesis refers the reader to the Saetre *et al*., (2013) model description for details of the implementation of the ERICA methodology.

Details of the calculations of the applicable dose rate for each organism are given in Chapter 10 of Saetre *et al*. and, as reported in the radionuclide transport report (SKB, 2014d), the results show that calculated dose rates are invariably well below the ERICA screening dose rate of 10 μGy hour^{-1}. The headroom is often several orders of magnitude and even the most highly exposed species in some of the less probably scenarios (Table 8-1 SKB, 2014d) are more than two orders of magnitude below the screening level.

At this stage of the review it has not been possible to verify all the assumptions used in the calculations and it is recommended that a further review be carried out. This is needed to ensure that the compartmental concentrations in the media of the ecosystems re calculated in the model appropriate way. It is possible that, if the concentrations used are the average concentrations over a large spatial volume (as used, say, in the evaluation of doses to the human population) doses to populations of NHB with small ranges would not be correctly calculated. This needs to be checked. Inclusion of NHB calculations into SSM independent modelling might also be considered. Some calculations to investigate these matters should be considered.

10. Miscellaneous issues

The SR-PSU calculations are inherently probabilistic. Results in the Main Report (SKB, 2014a) reflect this; since the aim is evaluate risk to future populations

$$Risk_{Total} = Risk_{MainScenario}\left(1 - \sum_{\substack{less\ probable\\ scenarios,i}} P_i\right) + \sum_{\substack{less\ probable\\ scenarios,i}} P_i Risk_i$$

The risk and the probability of the scenarios are required, with the main scenario having probability $P_{MainScenario} = 1 - \sum_{\substack{less\ probable\\ scenarios,i}} P_i$. The "risk" in each of the dose scenarios is the product of the total dose over all nuclides in the scenario multiplied by the ICRP risk factor of 0.073 Sv^{-1} for death from fatal cancer or genetic detriment to future generations. However, the risks as calculated are available as probability distribution functions since the calculations are produced from

> *Monte Carlo simulations with Latin-hypercube sampling (McKay et al. 1979) were performed using 100 iterations for the near-field and far-field. The data set from these calculations was used as input to Monte Carlo simulation of the biosphere and dose calculations, using 1,000 iterations. Each realisation of a set of input parameters for the near-field and far-field is matched with 10 realisations of input parameter sets for the biosphere resulting in a sample of size 1,000 of input parameter sets for the entire modelling chain. In this way the near-field and far-field model only have to be run 100 times for the probabilistic assessment for each calculation case.*

(page 61 of the Radionuclide Transport Model report.

This total of 1000 overall simulations is reasonable number and, indeed, given the efficient way Latin-hypercube sampling covers the sample space 100 samples for the geosphere and near-field models is plausible. However, the entirety of the biosphere and dose evaluation calculations is covered by only ten samples. Given the many parameters in the biosphere modelling database (Grolander, 2013) it seems highly unlikely that an effective idea of the variability in the overall distribution of doses resulting from the uncertainty and variability in the biosphere component of the model can be adequately covered by such a small sample. SKB should justify this apparent choice (confirming that the interpretation here is correct). Additional review should be undertaken to estimate the impact that this small sample size might have.

The review of data carried out in this initial phase (Chapter 6) has focussed primarily on the radionuclide specific details. Parameters and pdfs are considered in isolation. In evaluating the pdfs of dose that are used to calculated risk, it is often that case that inter-parameter correlation matrix and how it is applied that is important in constraining the resulting pdfs to realistic values. This issue should be addressed in the main phase review.

The intricacies of the biosphere database raise another uncomfortable issue with respect to the biosphere side of the assessment. In another context Haldane (2003) notes two competing worldviews – the *Spartan Meritocracy* and the *Baroque Monarchy*. In the former each modification to understanding is tested with the overall picture consisting with a modified set of (what are effectively) FEPs at each stage in a continuous iteration. The resultant "model" therefore contains the necessary and sufficient elements relevant to the current phase of understanding. In the *Baroque Monarchy* elements are added as seems necessary with not attempt to fine tune to "model" and with no consideration to the overall purpose of the "model".

The *Spartan Meritocracy* is essential to maintaining a model's fitness for purpose as it evolves. The essential element is the testing – checking comparing with previous version, in short understanding the impact of the changes and upgrades to previous capability. This comparison of old and new models is an important part of the justification of the new model since it demonstrates how the new model works and provides a clearly traceable path of model development. It may even be concluded that a newly considered feature is a trivial detail that, for practical purposes, is not required.

This element of the SR-PSU documentation is lacking. Many of the additions to the modelling capability demonstrated at SAR-08 appear as "baroque" features – curlicues and epicycles – the importance of which is not clear and has not been demonstrated. Ideally the definition of the mathematical model used in the assessment should be identified and justified with the following steps, some of which are covered in sufficient detail in the SR-PSU documentation but many are not and will need to be requested:

(a) FEP review → the necessary and sufficient content of the model coupled to the assessment context, etc.: dealt with in the documentation.
(b) Derivation and documentation of the conceptual model. *Not documented in complete form in biosphere reports*.
(c) Mathematical model identification and justification; the assumptions, simplifications and compromises with respect to conceptual model. *Partial coverage, fragmented throughout the documentation.*
(d) Illustrative results: selected inventories, concentrations, doses in time and space. **This should be backed up with a detailed sensitivity analysis designed to show the importance and relevance of the new material, as well as the important FEPs in the dose assessment**. *Partially covered in the Synthesis document but in insufficient detail. Cannot, at this stage, say that all the nuances of the new model are fully understood.*
(e) Application of the model for the performance assessment as a whole. This will be the focus of the main phase review.

As one of the RFI suggestions relating the SR-PSU dose assessment model is to request intermediate information and justification, the corresponding RFI will follow these points as far as possible. As with several of the potential RFIs, it is suggested that a meeting be arranged with SKB in which a set of preliminary RFIs can be used to establish common ground for the final set arising from this initial review. it is anticipated that more RFIs will rise during the course of the main phase.

The aim of the documentation is transparency and completeness such that the reader should be able to reproduce the results independently. The modelling relies heavily on coding of the mathematical models – seemingly all in the Ecolego (ecolego.facilia.se) modelling environment. To maximise transparency, it would be useful if a functioning version of the model were to be made available to SSM and its reviewers.

11. Conclusions

Three main aims for this initial phase review were identified by SSM:

1. a broad understanding of the SKB's license application,
2. an assessment of how understandable and complete is SKB's documentation,
3. identification of key topics for deeper review in the main phase.

In the course of the review two further aims have been identified:

4. identification of items to be forwarded to SKB as RFIs – Requests for Further Information, and
5. items that might be carried forward to SSM's independent modelling.

Appendix 1 lists the reports that have been included in the review and sets out the degree of coverage. Appendix 2 lists the potential RFIs identified at this stage and Appendix 3 gives the list of topics that require deeper review, arranged according to themes. A further Appendix sets out potential areas for model development at SSM.

Performance assessment is an iterative process with each new submission being a development from the previous one with enhancements and details. The previous assessment published by SKB was a license application for the construction of a deep geologic repository for spent fuel at Forsmark. Much of the detail development for this (the SR-Site) assessment are included in the SR-PSU license application of the extension of the SFR I/LLW repository at Forsmark. However, there are many instances where new material and approaches are included in the SR-PSU reporting. There is significantly more material in the SR-PSU documentation than was the case even for the highly detailed SR-Site assessment.

The standard of documentation and description in SR-PSU is good. There are some gaps and these will be addressed in the main review phase, in part with the responses to the RFIs. Because there is so much *detail* in the SR-PSU reporting this initial phase report has been relatively superficial. However, it confirms that the reporting is understandable, reasonably transparent and complete in terms of themes discussed if not yet in respect of the totality of the material presented.

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Tröjbom M, Grolander S, Rensfeldt V, Nordén S, 2013. Kd and CR used for transport calculation in the biosphere in SR-PSU. SKB R-13-01, Svensk Kärnbränslehantering AB.

Van den Hoof C, Thiry Y, 2012. Modelling of the natural chlorine cycling in a coniferous stand: implications for chlorine-36 behaviour in a contaminated forest environment. Journal of Environmental Radioactivity 107, 56–67. [Reference in Saetre *et al.*, 2013]

Werner K, Sassner M, Johansson E, 2014. Hydrology and near-surface hydrogeology at Forsmark – synthesis for the SR-PSU project. SR-PSU Biosphere. SKB R-13-19, Svensk Kärnbränslehantering AB.

APPENDIX 1

Coverage of SKB reports

Following reports have been covered in the review.

Table A1 – Reports and coverage in the initial phase review

Reviewed report	Reviewed sections	Comments
TR-14-01 - Safety analysis for SFR. Long-term safety. Main report for the safety assessment SR-PSU	4. Initial state (Climate, surface systems, hydro-geology) 6. Reference evolution 7. Selection of Scenarios 8. Description of calculation-al cases (biosphere) 9. Radionuclide transport and dose calculations 10. Assessment of risk 11. Conclusions	Main review report – Overall description of calculated scenarios and results for risk. Scene-setting for the review, background material
SKB TR-14-06, Biosphere synthesis report for the safety assessment SR-PSU	All	Overview of biosphere com-ponent of modelling: bio-sphere in overall probabilistic risk assessment.
SKB TR-14-09, Radionuclide transport and dose calcula-tions for the safe-ty assess-ment SR-PSU	All, superficial	Results for complete model-ling chain (including ranges). Background material on model integration.
SKB R-13-46, The biosphere model for radionuclide transport and dose assess-ment in SR-PSU	All main text (Substantive appendices for Main Phase review)	Description of the origin, role of the biosphere DAM. Math-ematical model.
SKB R-13-19, Hydrology and near-surface hydrogeology at Forsmark - synthesis for the SR-PSU project	All	Description of MIKE-SHE modelling, water fluxes and water balance for biosphere objects at snapshots
R-13-25, SR-PSU Bedrock hydrogeology. Groundwater flow modelling methodology, setup and results	4. Temperate climate do-main 5. Periglacial climate domain 6. Integration of climate conditions and disciplines	Material in support of R-13-19. Release locations and object identification and delineation

Reviewed report	Reviewed sections	Comments
SKB TR-14-10, Data report	Superficial	For information only

for the safety assessment SR-PSU		
SKB R-13-18. Biosphere parameters used in radionuclide transport modelling and dose calculations in SR-PSU	All, superficial	Identification of text to be investigated in greater detail in main phase review.
R-13-01, Kd and CR used for transport calculations in the biosphere in SR-PSU	All	Main report for key radionuclide-specific data
SKB TR-14-12, Input data report for the safety assessment SR-PSU	Partial – biosphere material only	Identification of data sets to be requested
SKB TR-14-07, FEP report for the safety assessment SR-PSU	Limited – Section 4.4 biosphere FEPs	Biosphere detail limited. Background information.
R-13-43, Components, features, processes and interactions in the bio-sphere	All, Superficial	Biosphere FEPs – To main review as reference material for main biosphere model.
R-12-03, Digital elevation model of Forsmark. Site-descriptive modelling. SR-PSU biosphere	All, Superficial	Identification of data sets to be requested
R-13-22, Depth and stratigraphy of regolith FRS	All, Superficial	Identification of data sets to be requested

Missing report :

R-14-02 - Handling of biosphere FEPs and recommendations for model development in SR-PSU	Not available at 16.09.2015.	Required for main phase review

APPENDIX 2

Suggested needs for complementary information from SKB

Two types of complementary information are identified and are listed separately. The first is material that clarifies material in the text of the documentation. the second category lists dataset that have been identified or material that it is clear SKB hold as datasets but for which the *precise* reference (that would allow a direct request) has not yet been identified.

The items identified for RFIs re preliminary set and the details of the requests to be forwarded to SKB have not yet been finalised. A short period for discussion with SSM is anticipated. It is further understood that additional material is likely to become necessary as a result of the main phase review. Consideration should be given to arranging a meeting with the SKB team to make information exchange smoother.

Requests for Further Information: Datasets and codes
The following list is in order of priority. In most cases the SKB data is in the form of a GIS file and can be identified from the source map in the SR-PSU documentation. In other cases there is a need to refine the specification of the required datasets. This will be addressed prior to the start of the main phase review. Such instances are indicted.

1. **Access to selected records from the SICADA database for SR-PSU**. Details for selected radionuclide K_d and CR values *will be requested prior to the main phase review* (page 26.)
2. **Initial DEM + perturbed DEM as a results of landscape evolution (if possible)**, see page 18, above. SKB to provide the DEM file as used in Figure 3-1 of R-12-03 (Strömgren & Brydsten, 2013).
3. **Regolith depth map**, see page 18, above. SKB to provide the DEM file as used in Figure 5-1 of R-13-22 (Sohlenius *et al*., 2013).
4. **Biosphere object boundaries and topographic basins**, see page 18, above. Exact detailed reference to file required not yet found, GIS format files for the objects as displayed on map in Appendix 1 on page 235 of the Synthesis document, TR-14-06 (SKB, 2014b).
5. **Release point locations**, see page 18, above. The “exit point” locations as plotted in Figure 4-12 on page 50 of R-13-25 (Odén *et al*., 2014). GIS format files giving release locations at a range of time points.
6. **Radionuclide release rates as a function of time**, see page 18, above. Results from the output from the geosphere component of the model into the biosphere for all radionuclides and all biosphere objects re needed. Data for Global Warming, Extended Global Warming and Periglacial climate conditions are requested. *Tables of release vs. time re requested for each radio-*

nuclide in the calculated release. Alternatively, a selection of key radionuclides can be considered. This item should be discussed with SKB prior to the formal request being made.

7. **Low-magnetic lineament locations and surface expressions at top of bedrock**, see page 18, above. Also indicted in Figs 4-11 and 4-12 of R-13-25 (Odén *et al*., 2014) are black and grey areas. From Fig 2-1 of the same report, the black lines are "low-magnetic lineaments". Data for these should also be provided. They grey areas are associated with the boundaries of the hydraulic domains. These are also requested.
8. **Working version of the SR-PSU modelling code**, see pages 12 and 34, above. This should be provided for use in conjunction with the model description in Saetre *et al*. (2013) as an aid to clarity. *Details to be clarified with SKB.*
9. **Additional GIS objects for mapping.** For reference the location of the repositories SFR1 and SFR3 (as in Appendix 1 of the Synthesis document, TR-14-06, SKB, 2014b) would also be useful.

Requests for Further Information: Clarification

In order of priority, the request for clarification are set out below. Discussions with SKB regarding this material is recommended.

1. **Upslope releases and the SFR pier**. Two objects in the SR-PSU future landscape have "upslope" releases (Objects 121_2 and 157_2. SKB should clarify how common this type of groundwater discharge is in the present-day and future landscape. They should also clarify the influence of the SFR pier in bringing releases to these two objects (as well as about Object 121_3 from SR-Site). (Page 12.)
2. **Validity of interpolated flow systems**. MIKE-SHE is used to generate steady state flow systems at 3000, 5000 and 11000 CE. The flow systems for the biosphere objects change in time in the doses assessment modelling by linear interpolation. SKB should show how (and where in the code) the interpolation is carried out and should verify that the interpolated flow systems match the "reality" of MIKE-SHE models for intermediate times. (Page 13.)
3. **Derivation of object water fluxes from MIKE-SHE modelling**. Comparing the details in Figure 2 and 3 in the report, SKB should illustrate how the SKB results for the landscape (illustrated by Figure 2) are converted into the detailed inter-compartment numerical values quoted in Figure 3. Because the water balance for each object will be contingent on where the object boundaries are placed, results should be provided for the whole of Object 157_2 as well as the subareas featured in the assessment of alternative object delineations reported in Section 10.8 of the synthesis document. At the same time SKB should explain the origin of the numbers in the "Christmas tree plots (eg, Appendix 1 of Werner *et al*., 2013, Figure A1-1, etc.) as well as how they are used in the assessment. (Pages 14, 16.)
4. **Clarification (confirmation) of the method used to generate pdfs for K_d / CR**. SKB should produce a brief description – with worked examples – of how the database for a selected radionuclides is populated. (Page 27.)

5. **Number of distinct sample sets for biosphere modelling**. SKB to confirm if, in the sampled datasets, there are 100 sets of near-field-geosphere data coupled with 10 sets of biosphere data. (Page 33.)
6. **Narrative of radionuclide transport across the geosphere-biosphere interface**. SKB should provide a word-picture description of geosphere-biosphere interface geosphere biosphere interface transport of radionuclides from the end of the fractures in the geosphere model to the top of the regolith. The example give should discuss releases to Object 157_1 (lake/mire) and Object 157_2 (mire only). Reference should be made to conditions in the alternative object delineations study. (Page 18.)
7. **Alternative hydrological interpretations**. Flux systems for the objects are constructed on the basis of the "normal year". SKB should provide for a range of credible variants so that the robustness of the "normal year" results can be verified. (Page 17.)
8. **Biosphere dose assessment model: identification and justification**. The influence of the new modelling approaches needs to be illustrated with documentation of how the newly added or remodelled FEPs influence the results. Details to be finalised but will probably require intermediate results (compartmental inventories, concentrations pathway doses, etc.) to be provided. (See pages 10, 11.)
9. **Agricultural soils vs. Natural soils**. SKB to provide a justification as to why the agricultural soil model is simpler than the Natural soil model when agricultural ecosystems tend give the highest exposures. (Page 10.)
10. **Implementation of Diffusion in the biosphere model**. If not apparent from the main phase review, the details of how the process of diffusion between contiguous compartments is modelled in the model code. (Page 12).
11. **Transient flow systems associated with temperate-periglacial-temperate transitions**. SKB should comment on the likely changes to the flow systems for objects during these changes, and should address whether there could be a reservoir of contaminants built up during the periglacial period. (Page 21.)
12. **Topography – perturbations and evolution**. The DEM for the landscape is requested in the data section below. This is understood to be the present day best estimate of the topography of land and sea areas. SKB should evaluate how different is the topography at the times of the snapshots of water fluxes, namely 3000, 5000 and 11000 CE. some indication of the likely changes between 11000 CE and the end of the simulation period should also be provided. (Pages 21, 22.)

APPENDIX 3

Suggested review topics for SSM

Summary from the text

The following set of topics for deeper review are compiled from the material identified in the main section of this report. The list is rather lengthy and the

Topics from the SR-PSU documentation

<u>*Main focus*</u>

Hydrology:

1. **Interpolation of hydrology in the DAM**. The implementation and suitability needs to be checked for the temperate and temperate-periglacial-temperate climate sequences, including how the hydrology of periglacial conditions is implemented in the model. (Page 13, 20, 21.)
2. **Derivation of object specific flow systems at 3000, 5000 and 11000 CE**. Review of how information in Figure 2 is used to produce the numerical flux values in Figure 3. (Page 14, 16.)
3. **Impact of climate variability – alternatives to the "normal year"**. the use of the "normal year" smooths out all variability on the hydrology modelling. Review of the generation, usage and implications for the "normal year" is required.(Page 16, 17.)
4. **Hydrology of the geosphere-biosphere interface**. this initial phase review has concentrated on the biosphere side of the geosphere-biosphere interface with far less attention given to the geosphere expressed in Odén *et al*. (2014). Deeper review of Odén *et al*. is required because of the close connection between the bedrock and regolith geology. (Page 17.)

Radionuclide specific database

5. **The role of varying redox conditions.** The new structures of the SKB regolith sub-model should be reviewed in respect of the potential for chemical changes between media in the soil column. (Page 11.)
6. **Chemical evolution of soils**. As the chemical evolution of soils is discussed in the documentation in several places a deeper review of the material is suggested to better understand the details of the changes. (Page 23, 25.)
7. **K_d / CR values and ranges**. Deeper review of the origin values for these key parameters and the derivation of the statistical data carried forward to the SR-PSU database is required. To be carried out in conjunction with the RFI for access to the SR-PSU database. (Page 25, 25, 27, 28.)
8. **Probabilistic database**. The small sample size for some of the radionuclide specific parameters needs to be given more attention. Similarly the interparameter correlations need to be reviewed. (Page 33).

New FEPs

9. **Detailed review of Appendices in Saetre *et al*. (2013)**. Appendices B, C, D and G (respectively fraction of CO_2 in soil pore gas, fraction of radionuclide inventory in crops, degassing from unsaturated soils and ecosystem properties and fluxes)) need to be considered in detail for relevance. (Page 12.)

Additional areas of interest:

10. **Object delineation**. The exact procedure of defining the object boundaries used in SR-PSU has not yet been identified in the text. This needs to be reviewed in detail and the results for alternate object delineations need to be reviewed in detail. (Page 12, 14, 18.)
11. **Tracing of selected FEPs (to be determined) through the documentation from FEP review documentation to model implementation**. (Page 10, 29.) The aim is to
    i. verify traceability of documentation
    ii. investigate suitability of key FEPs affecting doses
12. **Comparison of model for agricultural and natural soils**. (Page 10.)
13. **The role of diffusion in the biosphere model.** Diffusion plays a role in mixing with compartments as well as between compartments. Review of the selective choice to limit intercompartment diffusive transfers to large areas of contact needs attention. (Page 12.)
14. **Exposure Groups in the future landscape**. The update to modelling in SR-PSU that deals with the identification and characterisation of potential exposed groups is reported in some detail. Detailed review should be carried out. (Page 30, 31.)
15. **Habitat concentration for NHB**. Review of how the concentrations of radionuclides in environmental media in the ecosystems inhabited by selected NHB should be investigated in detail. (Page 32.)

APPENDIX 4

Options for SSM's independent biosphere modelling

The following set of issues arise in respect of SSM's independent dose modelling capability, suggesting areas where current models might benefit from improvements that would improve their ability to represent FEPs in the main phase review.

1. Alternate modelling of Object 157. Development of model for the "upslope" release. (Page 12, 19, 21.)
2. Interpretation of the temperate – periglacial – temperate transition. (Page 14, 16, 21.)
3. Implementation of selected FEPs. (Page 22.)
4. Time varying k_ds vs. constant k_ds. Implementation of a test to see what impact the different approaches have on dose. (Page 24.)
5. Integration of the SR-PSU model in the SSM model. (Page 30.)
6. Implementation of alternate exposed groups. (Page32.)
7. Investigation of the potential for concentration gradients relevant to NHB habitats – evaluation of radionuclide concentration in the NHB modelling. (Page 33.)

These items can be reclassified in terms of priority:

<u>Priority 1</u>

Update to GEMA-Site. These items are required to enable the GEMA-site model to most effectively review the numerical results from SR-PSU.:

1. Modelling of upslope release in GEMA-site
2. Revised description of landscape development
    - Time varying land uplift rate – modify parameter *ldot_uplift* to be a lookup table in Ecolego
    - Variable peat growth: $\frac{dP_C}{dt} = b_C A_{ter} - m_r P_C$
3. Revise treatment of overburden wells in GEMA-Site

Sensitivity analyses with the SR-PSU version of GEMA-Site

1. To identify key features of the upslope release cases
2. Sensitivity and uncertainty associated with time-varying k_ds as $CaCO_3$ is leached from the new soils

<u>Priority 2</u>

Transient hydrology associated with talik formation under periglacial conditions with subsequent return to temperate hydrology as climate warms. This is a new area od biosphere research, as illustrated by the simplistic treatment in SR-PSU. It is potentially important for longer-timescale assessments but requires that some preliminary analysis be performed to assess what steps might need to be taken in future models.

Priority 3

1. Review and implementation of additional exposed group habits
2. Investigation of concentration gradients around release points that might impact calculation of radiological impact on NHB

3

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Review of dose assessment - biosphere models for specific radionuclides – SR-PSU

Activity number: 3030014-1007
Registration number: SSM2015-1021
Contact person at SSM: Shulan Xu

Abstract

SKB has submitted an application to SSM for expansion of the final repository for low and intermediate level radioactive waste at Forsmark (SFR). SSM has contracted a number of organisations to support its review of SKB's safety analysis (SR-PSU), with each organisation contributing to the review of a different technical area. SSM has divided its review activities into an initial review phase and a main review phase. This report describes the findings of Quintessa Limited's initial review of the analysis of biosphere modelling for specific radionuclides in SR-PSU.

A broad understanding of the biosphere component of SKB's application for extension to the SFR facility has been achieved. The SR-PSU assessment is directly supported by over two thousand pages of reports concerning the biosphere alone. This results in a large amount of information that needs to be assimilated and is reflected in a complicated SR-PSU assessment. The standard of reporting is good, with the documents being generally well-written and understandable. However, the documentation supporting the assessment has been published in a protracted way, with misleading publication dates on reports and some reports remaining unavailable at the time of initial review. The SR-PSU assessment is therefore not complete and the way in which it has been published causes concern to the review team with regards to the way in which the overall assessment has been managed by SKB.

The dose assessment methodology is well described in the SR-PSU documentation. The context for the assessment is also well presented, in particular, with regards to regulatory guidance, regulatory feedback on previous SKB assessments and comparison against international practice. The complexity of the biosphere modelling approach reflects both a site that is projected to evolve from marine to terrestrial ecosystems over the time scale of relevance, as well as a disposal system (waste, engineering and geosphere) that requires careful assessment of the potential impacts.

Notwithstanding the above, the initial review highlights issues in relation to the biosphere modelling that merit consideration when interpreting the assessment results. Some of these issues would tend to increase calculated doses in comparison to the central results presented in the SR-PSU assessment (including a potential increase in the reference inventory for a key radionuclide, delineation of biosphere objects, modelling radionuclide releases from time zero, modelling distributed releases to the biosphere, and increased well capture fractions). Other points reflect on the degree of confidence that can be placed on the numerical results, implying additional bounds of uncertainty that need to be taken into consideration.

Further issues have been identified that warrant consideration for the main review phase. These include review of the hydrological modelling used in support of SR-PSU, review of the probabilistic approach adopted, review of C-14 modelling, scrutiny of the parameter definition process for sorption and plant uptake, and review of assumptions for assessing doses top non-human biota. Additionally, it is recommended that an in-depth understanding of the representation of key radionuclides is achieved through implementation of SKB's models in an independent code, along with variants to develop understanding of the stylised way in which agricultural soils are represented in SR-PSU.

Contents

1. Introduction

SKB has submitted an application to SSM for expansion of the final repository for low and intermediate level radioactive waste at Forsmark (SFR). SSM has contracted a number of organisations to support its review of SKB's safety analysis (SR-PSU), with each organisation contributing to the review of a different technical area. SSM has divided its review activities into an initial review phase and a main review phase. This report describes the findings of Quintessa Limited's initial review of the analysis of biosphere modelling for specific radionuclides in SR-PSU.

In the context of this report, 'specific radionuclides' means radionuclides that are important to the consequence analysis of potential releases from the SFR.

1.1. Objective of the Initial Review

There are three main objectives of the initial review phase.

The first objective is to achieve a broad understanding of SKB's application. In the context of this report, this means obtaining a broad understanding of SR-PSU, focusing on biosphere modelling for specific radionuclides.

The second objective is to assess if SKB's documentation is understandable and complete with regard to the information needed to make an assessment of the application. Areas where complementary information may be needed are identified, enabling SSM to ask SKB for this information at the end of the initial review phase.

The third objective is to identify key review topics for the main review phase. These are topics that will have a significant impact on the assessment if the application fulfils relevant requirements. Furthermore these are topics that tend to be difficult to make judgements on. Detailed analysis of specific issues will be undertaken during any main review phase, with the detailed review tasks being defined at the beginning of that phase.

The initial review work has been undertaken independently by the individual reviewers. A structured collaboration between external reviewers and SSM staff will be needed during the main review phase so that multi-disciplinary issues can be handled in a more comprehensive manner than is required for the initial review. In the main review phase, SSM will also determine if SKB can be expected to fulfil all necessary regulatory criteria.

1.2. Scope of the Initial Review

The scope of the initial review of biosphere modelling for specific radionuclides is to consider:

1. If SKB's dose assessment methodology applied in SR-PSU for both humans and the environment is appropriate and adequate for its purpose.
2. If the approach of biosphere models used by SKB for specific radionuclides are appropriate and sufficient for its purpose.
3. If SKB's data collection and parameter derivation for specific radionuclides are appropriate and sufficient for its purpose.

The structure of this report reflects this scope:

- Section 2 presents the findings of the initial review of SKB's methodology for representing the biosphere.
- Section 3 presents the findings of the initial review of SKB's biosphere models for specific radionuclides.
- Section 4 presents the findings of the initial review of SKB's data collection and parameter derivation for specific radionuclides.

Section 5 presents the overall findings of the initial review of biosphere modelling for specific radionuclides.

The documents consulted as part of this initial radionuclide transport review are described in Appendix 1. Appendix 2 lists suggested questions to be addressed by SKB and Appendix 3 lists suggested topics for the main review phase.

The review has focused on the following SR-PSU reports:

- The Main Report: TR-14-01
- The Biosphere Synthesis Report: TR-14-06
- The Biosphere Model Report: R-13-46
- The Radionuclide Transport Report: TR-14-09
- The Biosphere Parameter Report: R-13-18
- The K_d and CR Report: R-13-01

While the objectives of this initial review are associated with taking a high level overview across SR-PSU to obtain a broad understanding and identify topics for the main review, we have examined some aspects of SR-PSU in more detail. The purpose of this is to investigate questions and topics of interest and determine whether it is possible to reach a conclusion at this stage, or whether further work is required as part of the main review. Commensurate with this being an initial review, it has not been possible to investigate all questions and topics of interest in detail at this stage. Therefore the depth of analysis underpinning the different aspects of this initial review varies, but we consider this to be a reasonable approach that is appropriate to an initial review phase.

2. Biosphere Modelling Methodology

The document structure relating to the biosphere modelling component of the SR-PSU assessment is described and discussed in Section 2.1. The methodology adopted by SKB in its biosphere modelling is described and discussed in Section 2.2.

2.1. SR-PSU Documentation

The Main Report for SR-PSU provides the top level description of the post-closure safety assessment studies relating to the proposed extension of SFR and draws on a substantial number of supporting documents. The SR-PSU reports relating to biosphere modelling are shown in Figure 1. It is evident that SKB has undertaken a large amount of work in support of understanding the biosphere at the Forsmark site and assessing post-closure safety. The biosphere reports (including the Climate Report, TR-13-05) supporting SR-PSU total over two thousand pages, these, in turn, draw on biosphere descriptions and reports that supported the SR-Site assessment, which themselves total over two thousand pages. Figure 1 therefore represents over four thousand pages of information supporting the biosphere component of the SR-PSU assessment.

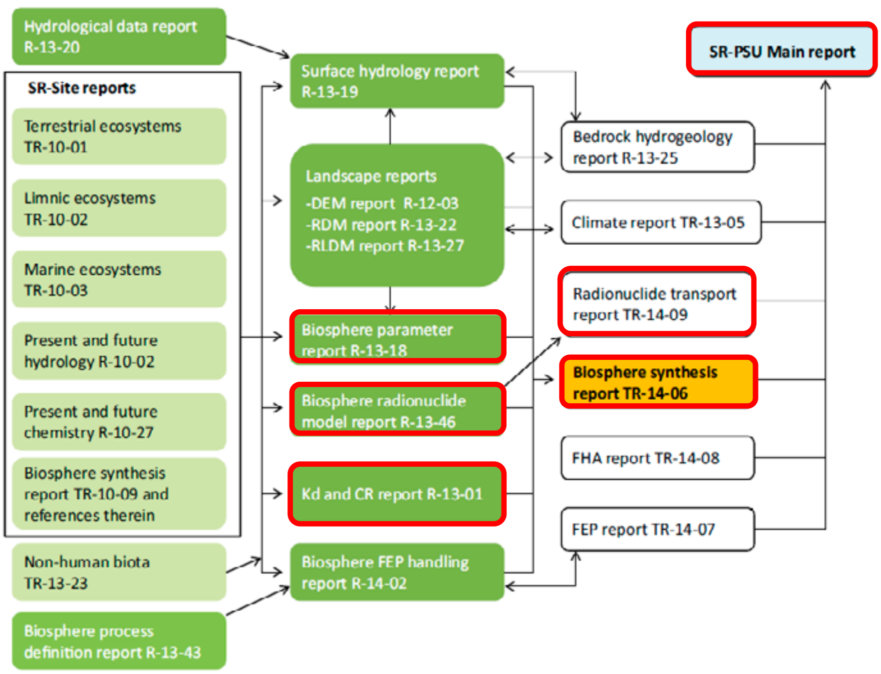

Figure 1: Biosphere reports produced in the SR-PSU project (based on Figure 1-4 from the Biosphere Synthesis Report), red boxes emphasise those reports reviewed as part of the present report.

The main report for the SR-PSU assessment was published in December 2014. The work undertaken by SKB relating to assessment modelling was complete at that point. However, not all of the supporting reports were published at that time. Notably:

- The Radionuclide Transport Report was not published until April, even though it is dated December 2014.
- The Biosphere Model Report was not published until June 2015, even though it is dated December 2013.
- The Biosphere Parameter Report was not published until June 2015, even though it is dated December 2013.
- The Biosphere Process Definition Report (R-13-43) was not published until June 2015, even though it is dated December 2013.
- The Biosphere FEP[1] Handing Report (R-14-02) has not been published yet.

The Biosphere FEP Handling Report is referred to over forty times in the Main Report, Biosphere Synthesis Report and Biosphere Model Report, in particular in relation to providing detailed justifications for modelling assumptions. The absence of this report has hampered the initial review and means that the documentation suite for the biosphere modelling component of SR-PSU is not complete.

The protracted way in which the reports have been published, plus the inconsistency between when the reports are published and the dates on the front covers is highlighted here. Good practice dictates that the underlying reports be published at the same time, or in advance of, the main report. In documenting assessments, including the review cycle for reports, issues can be identified that warrant changes in the assessment. In finalising documentation after the results have effectively been frozen, there is no longer an opportunity to address such issues. There is therefore the risk that the quality of what is delivered in the main assessment suffers as a result.

2.2. SR-PSU Biosphere Methodology

SKB has spent in excess of forty years characterising the area around Forsmark and has submitted a number of post-closure safety assessments relating to SFR (the most recent being SAR-08, SKB, 2008a,b), together with further assessments relating to a proposed geological repository for spent nuclear fuel in the same area (the most recent being the SR-Site assessment, SKB, 2011). SR-PSU therefore represents an iteration of assessments for SFR and builds on:

- understanding developed through previous assessment iterations and from further characterisation together with associated research and development; and
- developing regulations and dialogue with SSM.

Although the SR-PSU assessment stands by itself, it should be viewed in the context of the previous assessments, the regulatory requirements and the dialogue with the regulator in Sweden. To this end, it is very useful for SKB to have included commentary against SR-PSU's compliance with regulations SSMFS 2008:21 and SSMSF 2008:37 in Appendices A and B to the Main Report[2]. SKB has also usefully included commentary against SSM's formal response to the SAR-08 assessment and responses to review comments on SAR-08 in Appendices C and D of the main report. SKB also provide a summary discussion of previous assessments relating to

[1] Features, Events and Processes (FEPs).
[2] However, it is noted that SKB does not present a response to SSM's general advice on dealing with climate evolution in SSMFS 2008:37. The blue text on p408 of the Main Report simply reproduces the SSM guidance.

the Forsmark site in Section 2.5 of the Biosphere Synthesis Report, which provides useful context.

2.2.1. Methodology

Work supporting biosphere component of SR-PSU was divided into four tasks (p14, Biosphere Synthesis Report):

1. Identification of features and processes of importance for modelling radionuclide dynamics in present and future ecosystems in Forsmark.
2. Description of the site and its future development with respect to the identified features and processes.
3. Identification and description of areas in the landscape that may be affected by releases of radionuclides from the existing repository and its planned extension.
4. Calculation of the radiological exposure to a representative individual of the most exposed group of humans in the future Forsmark landscape, and the radiological exposure to the environment.

These work areas support the methodology that has been used by SKB to address the biosphere in SR-PSU. The Biosphere Synthesis Report provides a thorough representation of the methodology used by SKB, drawing on the supporting documentation. The methodology is illustrated in Figure 2.

Consistent with the SR-Site assessment[3], SKB discusses the way in which the biosphere has been addressed in relation to international experience, notably the guidance represented by the International Atomic Energy Agency's (IAEA) BIOMASS methodology. Although not framed in the same way as biosphere assessment is presented within the BIOMASS methodology, it is evident that the SR-PSU assessment takes account of international guidance and experience. This is notable, for example, (i) in the way that the Biosphere Synthesis Report clearly lays out the context within which the assessment has taken place[4], (ii) through the care taken to understand and describe the biosphere system and its evolution prior to defining scenarios and calculation cases, and (iii) in the way in which FEPs are used to support the assessment.

[3] See the equivalent discussion in Section 3.4 of SKB (2010).
[4] Section 2 of the Biosphere Synthesis Report.

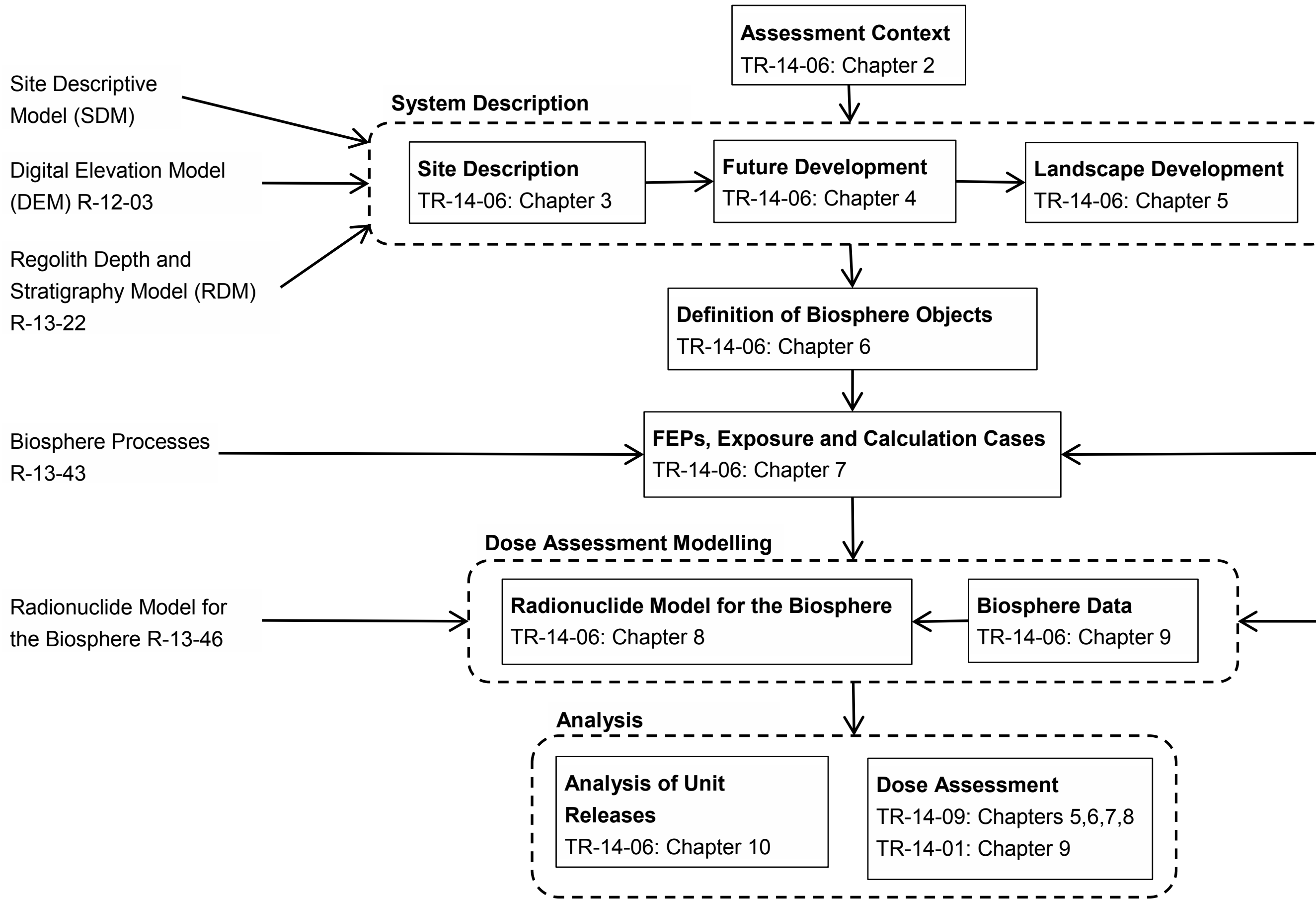

Figure 2: Illustration of the methodology used by SKB to address the biosphere in SR-PSU.

2.2.2. Modelling Releases to the Biosphere

A notable change in the approach to modelling the biosphere in SR-PSU is the way in which transient radionuclide releases in groundwater are fed directly into the biosphere model. Previous assessments, including the SR-Site assessment, used the biosphere model to calculate factors that convert groundwater releases (Bq y^{-1}) to doses (Sv y^{-1}) based on unit releases to the biosphere; these were termed Landscape Dose Factors (LDFs). LDFs assume equilibrium between radionuclide releases to the biosphere and losses from the biosphere system being represented. Equilibrium occurs relatively quickly for poorly sorbed radionuclides, however, for more highly sorbed species, equilibrium can take tens of thousands of years to be achieved (Walke et al., 2015). The Radionuclide Transport Report[5] demonstrates that calculated radionuclide releases from the near-field and geosphere are projected to fluctuate over time, such that feeding the calculated flux directly to the biosphere model provides a better and less abstract result in comparison to the use of LDFs.

In the SR-Site assessment, the LDFs were conservatively based on the maximum doses arising from potential releases to any of seventeen distinct hydrological basins/subcatchments (termed 'objects'). This reflected uncertainty both in where radionuclide releases might occur within the landscape and in what the landscape might look like where those releases to occur. In SR-PSU, the central calculations are based on radionuclide releases to a single biosphere object. This places a greater deal of confidence in SKB's ability to understand (i) the fracture network, (ii) groundwater flow characteristics and pathways, and (iii) the evolution and associated time scale for the object receiving the radionuclide releases. The Main Report notes that uncertainties in the development of the landscape configuration in Forsmark are not handled explicitly in the modelling[6]. This is an important difference in approach to the biosphere in comparison to the SR-Site assessment that merits consideration when interpreting the range of results presented for assessment calculations.

SKB has undertaken extensive particle tracking from the SFR to inform understanding about where radionuclide releases might occur in the landscape. This modelling indicates that a major fraction of releases is expected to occur to an area to the north of the SFR that is defined as biosphere object 157_2 in the landscape modelling. A distinctive characteristic of biosphere object 157_2 is that it does not go through a lake stage (i.e. it evolves from a marine system direct to a mire) and that during the mire stage there is no stream. This means that biosphere object 157_2 is not typical of catchments/sub-catchments in the Forsmark area. The discharge locations change with time, initially being closer to SFR and then migrating away as the sea retreats. Figure 3 shows the modelled distribution of discharge locations at 9000 AD, after the sea has retreated. Based on this analysis, SKB assign all of the radionuclide releases to biosphere object 157_2.

The analysis of the distribution of releases is based on one variant of the hydrological model, albeit with some variation in parameterisation. Results for other modelling variants and activities show less emphasis on releases to biosphere object 157_2[7]. Hydrological modelling for the Forsmark system in previous

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[5] Section 5 of the Radionuclide Transport Report.
[6] p178 of the Main Report.
[7] p112 of the Biosphere Synthesis Report.

assessments highlighted that discharge points concentrated on lakes, rivers and shorelines[8].

Given the above, it is not clear why SKB assign all releases to biosphere object 157_2 on its own in SR-PSU. Modelling of a case where releases were distributed resulted in a marginal increase in biosphere dose factors (see Section 3.2.7); that increase is observed even though less than 10% of the releases are distributed to objects other than 157_2[9].

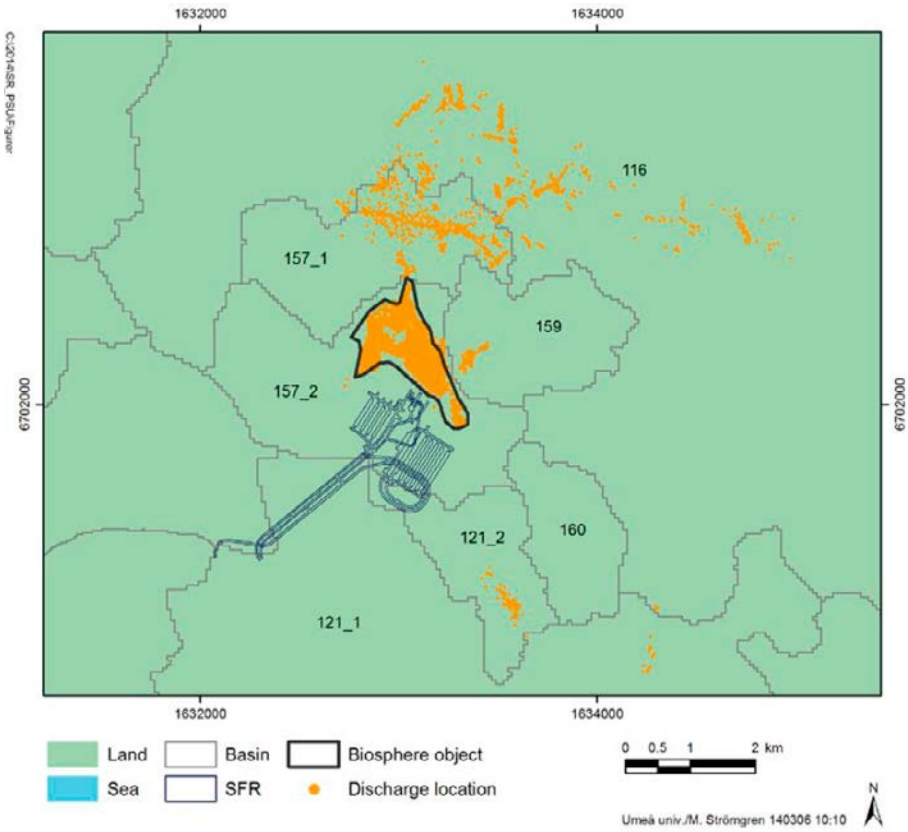

Figure 3: Locations of discharging particles from SFR at 9000 AD (Figure 6-12 from the Biosphere Synthesis Report). Basins are marked (grey outlines) and numbered, as is the explicitly modelled area of biosphere object 157_2 (black border).

2.2.3. Climate Change

SKB review climate related processes, past and modelled future climate in the Climate Report (TR-13-05), as a basis for defining three main climate cases for the SR-PSU assessment. A fourth case based on the Weichselian glacial case is also discussed in the climate report but does not feature significantly in the SR-PSU analysis because it is not a feasible case for the future. The three climate cases are summarised below and the temperature profile associated with each illustrated in Figure 4.

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8 p30 of the Biosphere Synthesis Report.
9 p199 of the Biosphere Synthesis Report.

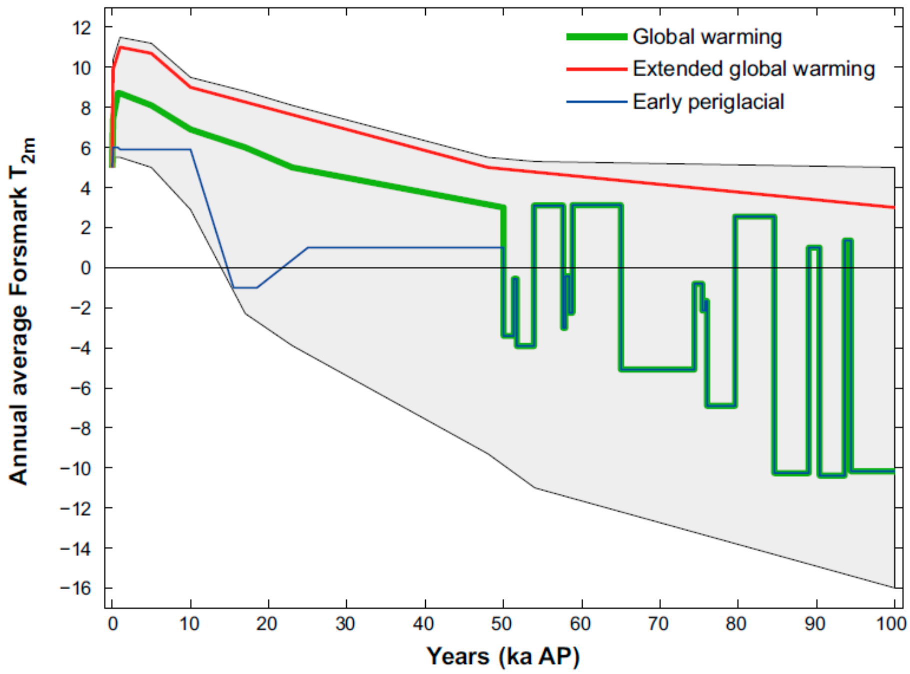

Figure 4: Generalised time evolution of annual average near-surface temperature (°C) in Forsmark (Figure 4-1 of the Climate Report).

The **global warming case** forms the basis of the main calculation cases for SR-PSU. The case is based on moderate human carbon emissions in the current and next century followed by a gradual decrease in the atmospheric CO_2 concentration. Growth of Northern Hemisphere ice sheets occurs after around 50 ka after present (AP). There is an increase in temperature of about 4°C above present-day annual average and it remains more than 2°C warmer than present-day for more than 10 ka.

The **early periglacial case** is based on low human carbon emissions plus a relatively fast decrease in the atmospheric CO_2 concentration. This combination results in climatic conditions that are cold enough for permafrost development at Forsmark after about 15.5 ka AP.

The **extended global warming case** is based on high human carbon emissions followed by a slow decrease in the atmospheric CO_2 concentration. Glacial inception does not occur until about 100 ka AP. The annual average temperature at Forsmark peaks about 6°C above the present-day value and remains warmer than present-day for about 50 ka AP.

In representing the global warming case in assessment calculations, the climatology and ecosystems are based on the present-day. Guidance from SSM (2008) states that today's biosphere conditions should be evaluated 'unless it is clearly inconsistent'. Warmer conditions are expected to be accompanied by increased precipitation, though that will likely fall outside the growing season. Increased temperatures would result in increased agricultural productivity and increased water demand, for example, from irrigation[10].

The Biosphere Parameters report is ambiguous as to the basis of the climate/hydrological data used in the central global warming case. It is stated that 'site data under present conditions, are used for the entire time period' for the global

[10] p58 of the Biosphere Synthesis Report.

warming case[11]. However, it is also stated that the water flows for a 'wetter and warmer climate' are used to parameterise the global warming climate case[12].

For the early periglacial case, hydrological flows reflect the presence of taliks beneath selected lakes. The presence of permafrost, together with significantly different climatology would presumably have a significant effect on water flows between the SFR and the biosphere. Nonetheless, radionuclide transport in the far-field is based on hydrological modelling for temperate conditions[13].

For the extended global warming case, shoreline displacement is taken to be delayed by 1000 years due to sea level rise and hydrological flows in the biosphere reflect a wetter and warmer climate. Other parameters are also modified for the extended global warming case, including primary productivity. Human behaviour is not, however, modified for the extended global warming case. Occupancy assumptions are not modified, in-spite of the warmer conditions, nor is the irrigation rate modified, even though the climate is expected to be warmer and drier during the growing period[14].

The hydrological modelling and its abstraction to the radionuclide transport model merit consideration for further review.

2.2.4. Sea Level Change

The sea level at Forsmark is determined by the rate of post-glacial uplift/rebound and global sea level change. At the present time, the rate of uplift exceeds the rate of sea-level rise, such that land at Forsmark is rising at a net rate of around 6 mm/y. The rate of uplift is slowly decreasing and is expected to become insignificant around 30,000 AD. The sea level is expected to fall to about 65 m below the present-day level over about the same period for all of the climate cases (Brydsten and Strömgren, 2013).

The sea level in the early periglacial cases is taken by SKB to be identical to that in the global warming case[15]; differences in global sea level between these two variants are neglected. In these cases, it takes about 1200 years for the land directly above the SFR to emerge from the sea. The absence of any perturbation in the relative shore-line around the time of early periglacial conditions is surprising. No discussion concerning the potential lack of significance in any perturbation on the time scale of the early periglacial conditions was found in the initial review.

For the extended global warming case, the rate of sea-level rise is taken to be greater, such that sea-level rise and uplift approximately cancel each other out during the first 1200 years after present[16]. After this period, land rise reflects a similar pattern as in the global warming case, such that the land directly above the SFR is anticipated to emerge from the sea about 2400 years after present.

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[11] p18 of the Biosphere Parameters Report.
[12] p53 of the Biosphere Parameters Report.
[13] Section 8.3.2 of the Main Report.
[14] p58 of the Biosphere Synthesis Report.
[15] Section 6.2.2 of the Main Report.
[16] p58 of the Biosphere Synthesis Report.

Uncertainty over sea level rise to 2100 AD is acknowledged as being very large and that beyond 2100 AD as even larger[17]. A stylised approach has therefore been taken to representing relative sea level change in SR-PSU. Uncertainty in the resulting shore level curve may be up to several tens of metres[18]. These uncertainties should be borne in mind when interpreting results.

2.2.5. Landscape Development

The landscape modelling undertaken in support of the SR-PSU assessment builds on that developed for the SR-Site assessment. The area of interest for SR-PSU is a sub-set of that considered for SR-Site, so the two studies overlap. The scale of many of the landscape development figure presented in the Biosphere Synthesis Report is appropriate to the larger SR-Site study area, but make it difficult to see the detail at the scale of interest for SFR (see Figure 5, for example).

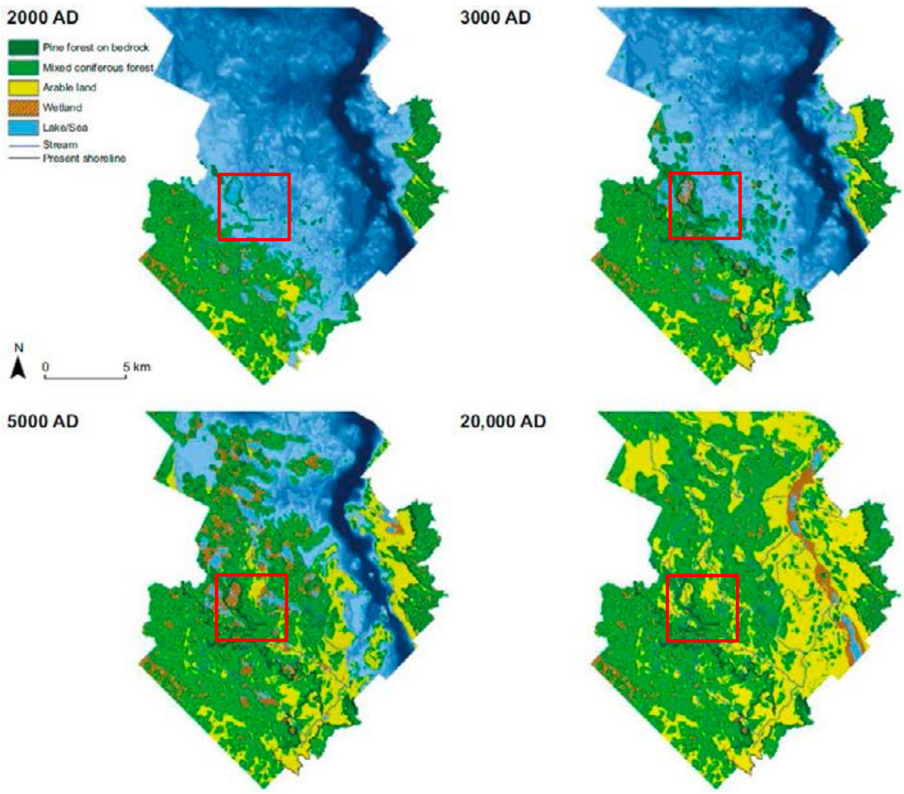

Figure 5: Illustration of landscape development for the global warming case (based on Figure 5-6 from the Biosphere Synthesis Report) with the approximate area of interest for the SFR highlighted in red.

Modelling of the future landscape development at Forsmark necessarily involves assumptions and uncertainties. The Biosphere Synthesis Report discusses the uncertainties[19], although these uncertainties are not handled explicitly in the modelling[20] and should therefore be borne in mind when interpreting the results.

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[17] p57 of the Biosphere Synthesis Report.
[18] p90 of the Biosphere Synthesis Report.
[19] Section 5.6 of the Biosphere Synthesis Report.
[20] p178 of the Main Report.

Uncertainties in the landscape modelling are exemplified by a comparison of a modelled reconstruction of the present-day landscape at Forsmark with the actual present-day landscape (Figure 6). The comparison shows a reasonably good reproduction of the landscape, although this is not necessarily surprising as the modelling has been calibrated to the present-day landscape (Brydsten and Strömgren, 2013). Notably, there are lakes in the present-day landscape that are not predicted in the landscape modelling (highlighted in Figure 6). These are explained in the Biosphere Synthesis Report as being 'small lakes' that are missing as a result of an assumption within the landscape modelling that small lakes are instantaneously filled-in. However, the approximate areas of the two lakes highlighted are 4.3 ha and 2.3 ha and are larger than some of the modelled lakes, so this does not satisfactorily explain the discrepancy.

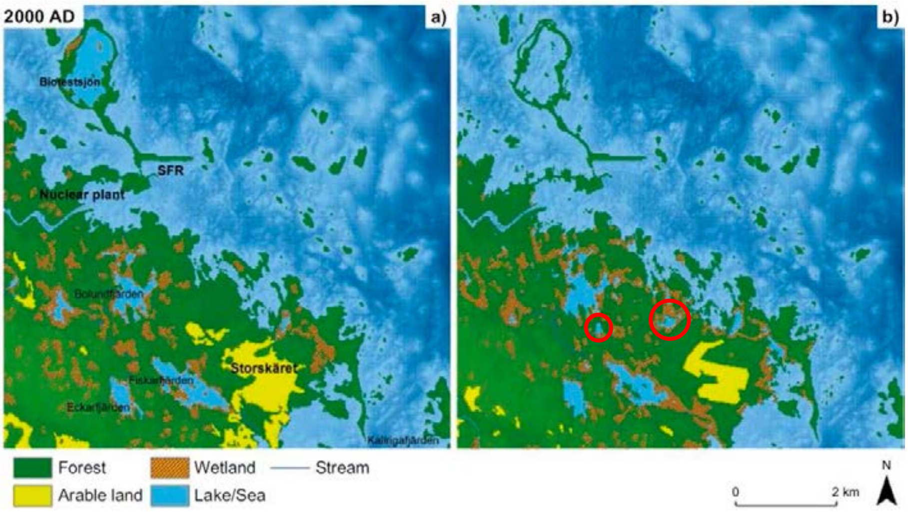

Figure 6: Modelled present-day landscape (a) compared to the actual present-day landscape (b), with examples of the lakes not predicted by the modelling highlighted in red (based on Figure 5-11 of the Biosphere Synthesis Report).

The lack of the capability of the landscape modelling to reproduce lakes that are present in the landscape today is highlighted because of the way in which the main SFR calculations assume that 100% of the radionuclide releases occur to biosphere object 157_2, which the landscape modelling 'predicts' will have no lake or even stream.

The landscape modelling is based on a natural progression of the landscape into the future. Human intervention is not explicitly modelled in the landscape development. The Biosphere Synthesis Report highlights that lowering of lakes for cultivation is not considered, which would allow cultivation somewhat earlier than simulated in the landscape modelling[21]. A similar point could also be made of the potential for humans to create lakes. The modelling 'predicts' that lakes are no longer present in the landscape after 40,000 years. However, in practice, if the area is populated on that timescale, then it is probable that artificial lakes will have been created for water management, water supply and/or amenity.

[21] p93 of the Biosphere Status Report.

2.2.6. Potentially Exposed Groups

Doses to humans are evaluated in SR-PSU through consideration of four potentially exposed groups that are based on past and present lifestyles that are considered by SKB to reasonably represent the range of exposure situations that might occur in the future. Each group allows a different combination of exposure pathways to be assessed.

- Hunter-gatherers: predominantly exposed via foraging in the landscape and drinking surface water; typically numbering 30 people and using an area of approximately 200 km^2.
- Infield-outland farmers: self-sufficient agricultural group with livestock and growing crops on areas not subject to groundwater discharge, but where the soil is fertilised through use of manure from animals fed hay from the wetlands; typically numbering 10 people and using water from a dug well or surface water. A wetland area of 10 ha is needed to provide winter fodder.
- Drained-mire farmers: self-sufficient agricultural group using drained mire for agriculture (crops and grazing/fodder) and drinking water from a well (dug or drilled) or from surface water; typically numbering 10 people and requiring an area of 6 ha.
- Garden-plot householder: self-sufficient household with respect to vegetables and root crops from small-scale horticulture, using a well (dug or drilled) or surface water for drinking and irrigation; typically numbering 5 people and needing 140 m^2.

The four exposure groups defined above demonstrate a reasonable range of different lifestyles, based on consideration of present-day and historical land use. The use of tangible and understandable lifestyles differs from that used in the SR-Site assessment, whereby land use was calculated based on the productivity of each biosphere object. The approach adopted in SR-Site, although understandable as a method, resulted in a lack of clarity with regards to exposure group assumptions The use of four stylised groups is considered an improvement in this regard. Stylised assumptions about the biosphere are unavoidable within such long-term assessments and these provide an example of where they help in the assessment of results and in the communication and explanation of those results.

2.2.7. Parameter Uncertainty

A probabilistic approach is used for the main calculations in which parameter distributions are used to reflect both uncertainty and variability in the input values. The Monte Carlo probabilistic calculations adopt a Latin Hypercube sampling approach based on 100 realisations for the nearfield and geosphere. Each of the nearfield/geosphere realisations is then run with 10 realisations of the biosphere model. This generates 1000 sets of results for which the mean result is presented as the representative value for comparison against the risk criteria.

The number of realisations used by SKB is small. Although presented as a sample size of 1000 in assessing the sample size[22], no nearfield and geosphere parameters were sampled more than 100 times. It is also not clear if the biosphere calculations used the same set of 10 realisations, or whether each of the parameter values within each of the 1000 calculations undertaken with the biosphere model were sampled independently. This highlights a lack of a specific description of how the

[22] p70 of the Radionuclide Transport Report.

calculations were undertaken in the SR-PSU reporting. The Model Summary Report (TR-14-11) includes some information, but nothing on sample seeds and about how output files are exchanged between the different Ecolego models, if that indeed what was done.

The arithmetic average result is presented for the significant majority of dose calculations. Relatively little discussion is devoted to the distribution of the probabilistic results[23] or confidence in the mean[24]. The overwhelming focus on the arithmetic average result means that a large proportion of the value in propagating uncertainty through the model is lost, as the reader is given relatively little information about the distribution of results. A mean result for a calculation where the full distribution is narrow is very different from the mean result for a calculation where the full distribution is large. The lack of value attributed to the distribution of probabilistic results is further illustrated by the statements that 'parameter variation had a limited effect' on the dose estimates when reviewing results for a sub-set of radionuclides in more detail (C-14, Cl-36, Ni-59, Mo-93)[25]. The statements are supported solely by comparison of the deterministic 'best estimate' dose factors and the mean of probabilistic calculations. The full range of results from the probabilistic calculations therefore seems to be largely ignored in the analysis.

The assessment of confidence in the mean noted above is assessed in SR-PSU using a bootstrap function based on 1000 samples. However, 100 nearfield/geosphere realisations multiplied by the 10 biosphere realisations does not equate to 1000 independent samples. The way in which this analysis was conducted therefore merits further review to determine its validity. It may be more appropriate to reflect the way in which the calculation is undertaken in the analysis of confidence, for example, by determining confidence in the release from the geosphere for key radionuclides separately from analysis of confidence in the subsequent biosphere modelling.

The Biosphere Synthesis Report includes comparison of biosphere dose factors calculated with the SR-PSU models with those calculated in SR-Site and in SAR-08[26]. The comparison is discussed further in Section 3.2.6, while the approach to the comparison is commented on here. The SR-PSU dose factors used in the comparison with SR-Site are based on deterministic 'best estimate' calculations, whereas the dose assessment in SR-PSU is based on the propagation of calculated geosphere fluxes through probabilistic calculations with the biosphere model. Comparison of the SR-PSU results for 'best estimate' and probabilistic biosphere calculations[27] shows that the mean of the probabilistic results differed in many cases from the 'best estimate' value. For decay chains, the comparison is further undermined because the SR-PSU dose factors used in the comparison exclude in-growth of long lived daughters[28], whereas such ingrowth is included in the SR-Site LDFs and can be important for some radionuclides. Analysis based on the deterministic 'best estimate' dose factors from SR-PSU is therefore of limited value.

[23] p292 of the Main Report.
[24] p70 of the Radionuclide Transport Report.
[25] Section 10.9.2 of the Biosphere Synthesis Report.
[26] Section 10.4 of the Biosphere Synthesis Report.
[27] Section 10.9 of the Biosphere Synthesis Report.
[28] p160 of the Biosphere Synthesis Report.

2.2.8. Key Radionuclides

Part of the scope of the current work relates to 'specific radionuclides'. This is interpreted within the report as those radionuclides that are shown to be important contributors to the primary biosphere endpoints, which are calculated doses to humans and to wildlife. A list of those specific radionuclides that merit particular review is given in Table 1. The list is distinguished into three tiers of importance. Justification for each of the radionuclides listed is given below.

Table 1: Specific radionuclides identified for SR-PSU review.

Tier 1	Tier 2	Tier 3
C-14	Ca-41	Cl-36
Ni-59	I-129	Cs-135
Mo-93	U-238	Ac-227

Tier 1: Most important contributors to calculated biosphere endpoints.

- C-14: Contributes up to about 25% of the peak calculated doses to humans for the global warming variant (Table 9-20 of the Main Report). Also important contributor to wildlife doses (Table 9-22 of the Main Report).
- Ni-59: Most important radionuclide for human doses in the central global warming case in the long-term[29] and key in the scenario involving high concentrations of complexing agents (Table 9-20 of the Main Report).
- Mo-93: Most important radionuclide, contributing up to about 50% of the peak calculated doses to humans for the global warming variant (Table 9-20 of the Main Report). Contribution of Nb-93m needs to be taken into account in any review.

Tier 2: Additional important contributors to variant calculations.

- Ca-41: Dominant contributor to human doses for a period of about 20,000 years in the central global warming case[30].
- I-129: Contributes over 70% of the peak calculated dose to humans during the periglacial phase of the early periglacial variant (Table 9-20 of the Main Report).
- U-238: Third most important contributor to the main cases (Table 9-1 of the Main Report) and important contributor to some wildlife doses (Table 9-22 of the Main Report). Contribution of radioactive daughters need to be taken into account in any review.

Tier 3: Other radionuclides of potential interest.

- Cl-36: Was an important contributor to results in SAR-08 (Bergström et al., 2008) and merits some review to understand the reduction in its relative importance.
- Cs-135: Was an important contributor to results in SAR-08 (Bergström et al., 2008) and merits some review to understand the reduction in its relative importance.
- Ac-227: Most important radionuclide for the scenario involving wells downstream of the repository (Table 9-20 of the Main Report). Presumably in-grown from U-235 and/or Pu-239.

[29] Figure 5-4 of the Radionuclide Transport Report.

3. Initial Review of Biosphere Models

This section describes the initial review of the biosphere modelling conducted in SR-PSU. The modelling chain is discussed in Section 3.1. The general radionuclide transport and human dose assessment model is discussed in Section 3.2. Specific consideration is given to C-14 in Section 3.3. Wildlife dose assessment is then discussed in Section 3.4.

3.1. Modelling Chain

SKB use a compartment approach to modelling radionuclide transport in the near-field, geosphere and biosphere. The SR-PSU assessment does not use a single integrated model of the disposal system, and biosphere, the three components are instead implemented in separate Ecolego models, with radionuclide transfer fluxes from one component being fed as input into the next component (see Figure 7). Equal care is needed in exchanging information and ensuring consistency between the three stages of radionuclide transport calculations as when separate codes where used, e.g. in SAR-08 and in SR-Site.

For the biosphere, the radionuclide transport, human and wildlife dose assessments are all included within the Ecolego biosphere model. The inclusion of the wildlife dose assessment within the Ecolego biosphere model differs from the approach adopted by SKB in the SR-Site, where the wildlife dose assessment calculations were undertaken separately using the ERICA tool based on calculated concentrations in environmental media. The approach adopted in SR-PSU has the advantage that time-dependent wildlife doses can be calculated as an output for any biosphere calculations. However, the approach comes at the cost of implementing an identical set of the large number of wildlife dose models and extensive dataset as already exists within ERICA, with the associated quality assurance overheads.

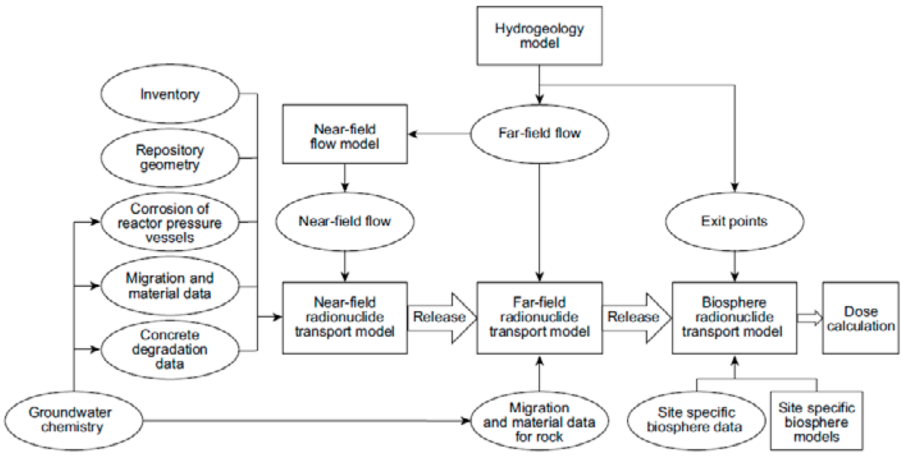

Figure 7: Flowchart illustrating the relationship between models (square boxes) and data (ovals) in the SR-PSU assessment (Figure 2-3 from the Radionuclide Transport Report).

3.2. General Biosphere Model

The general biosphere model for radionuclide transport and human dose assessment is discussed in the sub-sections below. Note that issues specific to modelling of C-14 are discussed in Section 3.3.

3.2.1. Biosphere Object Approach

Since the SR-Can interim assessment (SKB, 2004), SKB biosphere assessments have centred around representing radionuclide releases to and exchanges between a network of biosphere regions, termed 'objects'[30]. During the terrestrial stage, these objects are based on regions that receive discharging groundwater. At the initial point of the marine stage, the objects are space filling. On transition to a lake/mire stage, the objects solely represent those areas that receive groundwater discharge and delineate the initial boundaries of future lakes. This progression is illustrated for a single biosphere object in Figure 8.

For biosphere objects that go through a lake stage, a stream remains in the object once mire expansion is complete. However, no stream is present in the two biosphere objects that do not have a lake stage (157_2 and 121_2)[31]. The reason for excluding a stream from these two objects is unclear. The absence of a stream is also inconsistent with SKB's assumptions within the SR-Site assessment, whereby an object with significant overlap with 121_2 was represented specifically because it includes a stream (SR-Site object 121_3 and see Figure 11)[32].

During the marine stage, the boundaries of the marine water compartments are based on the boundaries of future catchment/sub-catchments and are not based on consideration of the marine system. Although this results in a discretisation that would not be chosen if modelling the marine system in isolation, it helps to facilitate modelling of transition to a terrestrial system. The relatively rapid exchanges between adjacent marine water compartments mean that the marine water discretisation is relatively unimportant. However, the model merits consideration for further review to ensure that exchanges reduce appropriately as uplift leads to embayment.

Another area of simplification within the marine modelling is the representation of the bed sediment area. The area that is used for marine bed sediments and underlying regolith reflects that of the future terrestrial object[33]. For biosphere object 157_2, the particle tracking indicates that, during the marine phase, radionuclides do not discharge over the area that is represented after isolation[34]. This approach again helps to facilitate modelling the transition to a terrestrial system and is claimed to be a cautious approach[35]. However, this is another aspect of the modelling that merits consideration for further review to understand both the way in which it is parameterised and the implications of this approach for radionuclide concentrations in marine water and sediments.

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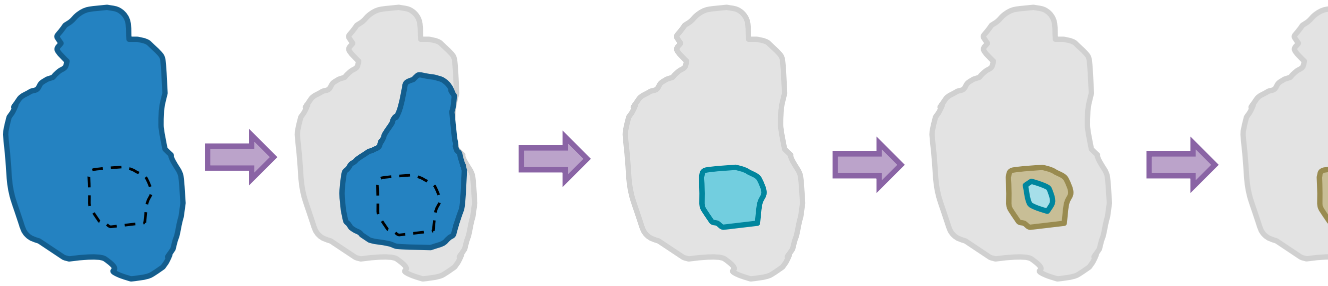
[30] Section 2.5.6 of the Biosphere Synthesis Report.
[31] p148 of the Biosphere Synthesis Report.
[32] See Figure 7-9 of Lindborg (2010) and accompanying text.
[33] Footnote 3 on p36 of the Biosphere Model Report.
[34] Figure 6-1 of the Biosphere Synthesis Report.
[35] p48 of the Biosphere Model Report.

The reference approach that has been used by SKB in identifying and delineating biosphere objects for use in the assessment calculations is summarised below[36].

1. The digital elevation model (DEM) was used to define future lakes and catchment geometries.
2. Hydrogeological simulations of water flow paths from the planned repository for a number of different times were used to identify discharge areas on the bedrock surface.
3. The discharge areas were used to define biosphere objects as sea basins, lakes or wetlands.

The information flow supporting this process is illustrated in Figure 9. The resulting biosphere objects that are identified as being of greatest relevance SFR are shown in Figure 10.

[36] Section 6.2.2 of the Biosphere Synthesis Report.



Initial marine stage. Boundary defined by future catchment. Dashed line indicates area of bed sediments and underling regolith, which is concurrent with the area of the future lake.

Marine area reducing due to uplift. Grey area no longer modelled.

Isolation of lake.

Ingrowth of mire around lake (light brown).

Fully ter

Figure 8: Progression of an illustrative biosphere object from a marine phase, through a lake phase to a fully terrestrial phas

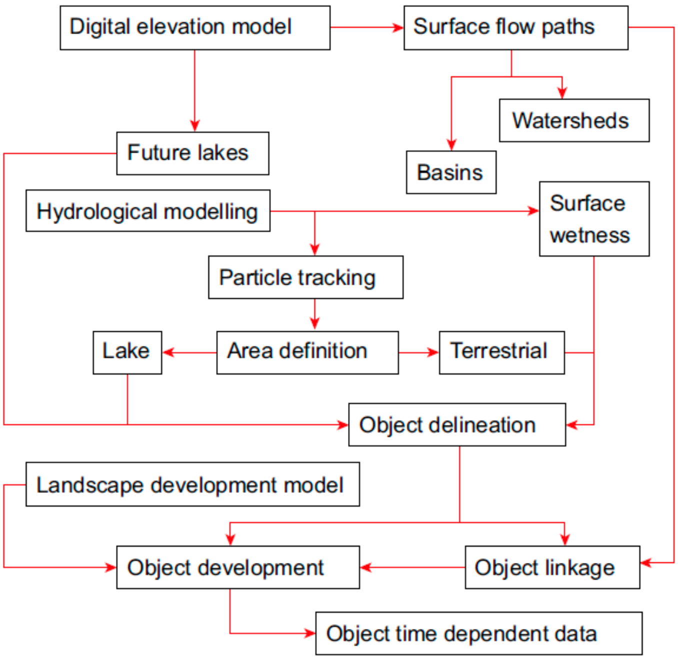


Figure 9: Information flow supporting the delineation of biosphere objects (Figure 6-6 of the Biosphere Synthesis Report).

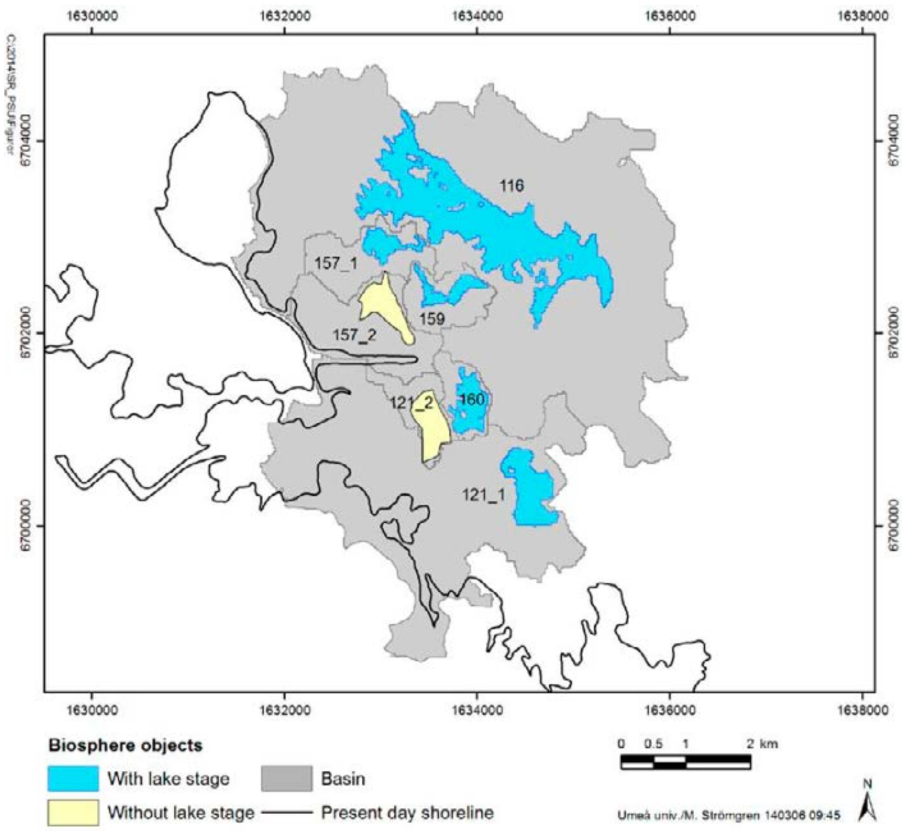


Figure 10: The seven biosphere objects identified as being of interest in the SR-PSU assessment (Figure 6-7 of the Biosphere Synthesis Report).

The process for identifying future biosphere objects is clearly elaborate and includes interpretation. For example, the same biosphere object approach was adopted in the SR-Site assessment, which encompassed the area considered in the SR-PSU assessment. However, there are notable differences in both the definition of sub-catchment/basin boundaries as well as in the presence or absence of future lakes (e.g. compare Figure 11 and Figure 10). Differences presumably include differences in the updated landscape development modelling (Brydsten and Strömgren, 2013), however they also help to emphasise the significant uncertainties involved in modelling landscape evolution and delineating biosphere objects.

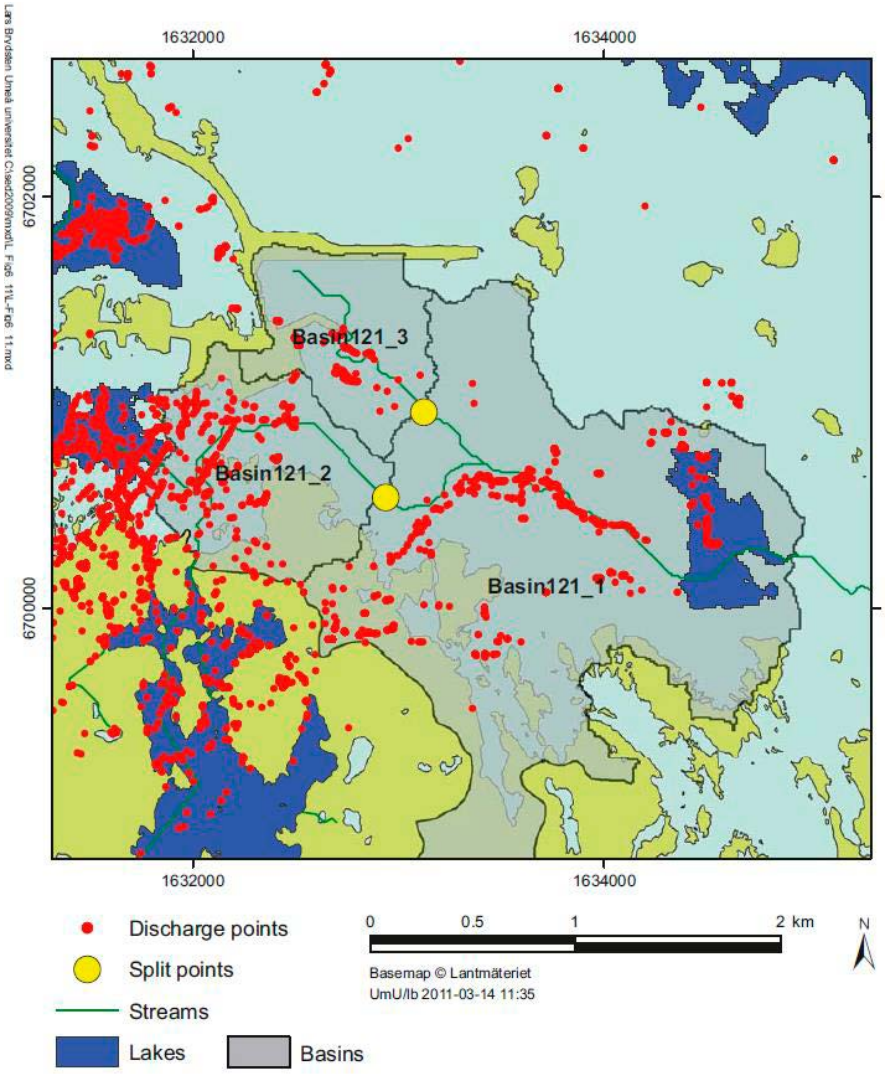


Figure 11: Sub-division of biosphere object 121 in the SR-Site assessment (Figure 7-9 from Lindborg, 2010).

The uncertainties associated with defining biosphere objects are recognised by SKB and the effect of alternative delineations explored[37]. Four alternative delineations were explored for biosphere object 157_2, which received 100% of the release from the geosphere in the reference calculations and has a reference area[38] of 1.5E5 m^2.

[37] Section 10.8 of the Biosphere Synthesis Report.
[38] Table C-5 of the Biosphere Parameter Report.

The alternative approaches (with the associated area of the object) are summarised below.

1. Areas with upward hydraulic gradients (UpwGrad) representing areas with a steady upward flux of groundwater from the bedrock through the geosphere-biosphere boundary and all regolith layers[39] (~ 1.3E5 m^2).
2. Wetland areas (Wetl) representing open wetland areas, with respect to predicted groundwater level and vegetation types (~ 8.4E4 m^2).
3. Main area for discharge points (HD-disch) representing an area with a high density of repository discharge points at the geosphere-biosphere boundary (~ 4.7 E4 m^2).
4. Potential arable land (Arabl) representing areas with a combined thickness of the arable regolith layers of at least 0.5 m (~ 2.9E4 m^2).

Comparison of the calculated concentrations in drained and cultivated soil for a unit release for four radionuclides (C-14, Cl-36, Mo-93 and Ni-59) are shown in Figure 12. This endpoint has been chosen here because calculated doses to the drained mire farmer dominate the peak calculated doses for the main calculations[40]. The comparison shows that the reference approach to delineating the biosphere object (labelled 'Ref' in Figure 12) almost exclusively results in the lowest calculated concentrations. Concentrations in the variant with the smallest area for the object were approximately an order of magnitude higher than those in the reference case for C-14, Cl-36 and Mo-93. SKB argue that it is unlikely for that radionuclides discharging in groundwater from the SFR would discharge into the 2.9E4 m^2 (2.9 ha) of the smallest variant. Nonetheless, the results are illustrative of the uncertainty associated with delineation of the biosphere objects and should be borne in mind when interpreting the results.

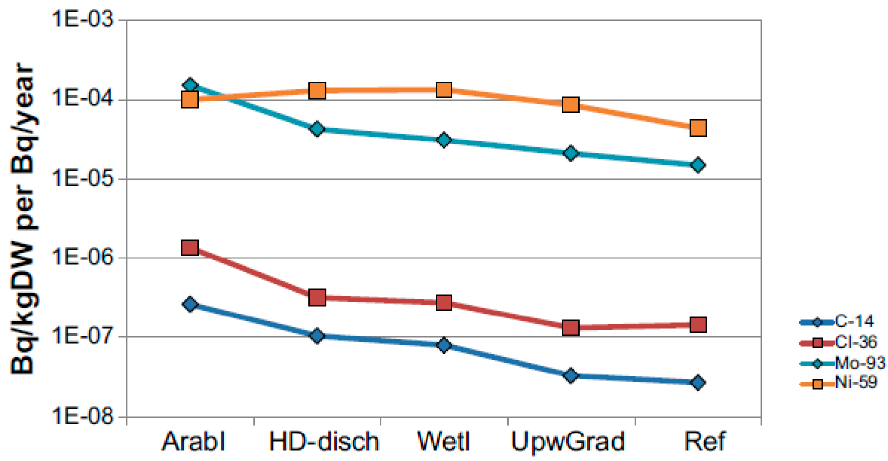


Figure 12: Concentrations of four radionuclides in drained and cultivated soil within biosphere object 157_2 with four different approaches to delineation of the biosphere object (Figure 10-31d of the Biosphere Synthesis Report).

[39] This is distinct from the reference approach which is based on the area of upward hydraulic gradient solely at the bedrock surface.
[40] Table 9-1 of the Main Report.

3.2.2. Compartment Model for Biosphere Objects

The compartment model for each biosphere object is illustrated in Figure 13. The terrestrial and aquatic phases are represented separately, with contaminants transferring across during terrestrialisation (transfers labelled '6' in the figure). The structure of the biosphere object model is refined further from that used by SKB in the SR-Site assessment (see Figure 14). Notable changes are highlighted below.

- The lower regolith is now represented distinctly for the aquatic and terrestrial parts on the objects. This helps to avoid the complexity of splitting transfers from the lower regolith.
- Organic pools are now explicitly represented in post-glacial sediments (PG), peat, the upper regolith and suspended particulate matter (PM). This reflects the importance of C-14 to the SFR assessment. The modelling of C-14 is discussed in Section 3.3.
- There is a greater degree of vertical discretisation in the regolith, with four (aquatic) or five (terrestrial) compartments as opposed to the three compartments used in SR-Site. The distinction between the compartments is made on physical grounds[41].

In review of the SR-Site assessment, one area of criticism of the compartment model for biosphere objects was the coarse vertical discretisation (Walke et al., 2015). The degree of vertical discretisation has been improved in SR-PSU, but remains relatively coarse, with, for example, the till and glacial clay layers, through which there is relatively slow vertical movement of groundwater, being represented with individual compartments. SKB acknowledges the coarse discretisation of the regolith[42] and claim that it is 'likely to be cautious' because it results in more rapid transport to the surface sediments. This is true of radionuclides without decay chains, particularly those with relatively short half-lives. However, the statement is not true for decay chains, especially where the daughters are more radiologically significant than the parent radionuclides, such as with U-238 and its daughters. This is because more rapid transport does not permit appropriate time for in-growth of the more radiological significant daughters. SKB's acceptance of modelling more rapid transport of radionuclides through the regolith than would be expected is in contrast with the care that is taken in understanding the timescales of landscape development and terrestrialisation.

Another aspect of the biosphere model for SR-PSU that is unusual is in the reduction in leaching from an agricultural soil compartment due to 'plant immobilisation'[43]. The process is intended to reflect that a fraction of the contamination in the biosphere will be incorporated into plant biomass and will be unavailable for leaching from the soil. The process is not described in the Biosphere Process Definition Report. In the absence of the Biosphere FEP Handling Report, the logic and arguments for its inclusion cannot be followed. It is recommended that plant immobilisation and its effect on the transport of key radionuclides be considered for further review.

3.2.3. Advective Transport of Radionuclides

Vertical advective transport is the major radionuclide transfer mechanism for radionuclides reaching a biosphere object in contaminated groundwater. Transport

[41] Section 3.1.1 of the Biosphere Model Report.
[42] p23 of the Biosphere Model Report.
[43] Appendix C of the Biosphere Model Report.

is represented vertically through the regolith column. There is potential sub-horizontal flow to adjacent regolith layers, however, this is expected to be small compared with vertical fluxes[44]. The SR-PSU model simplifies the horizontal flows so that only lateral flow from the top-most compartment (RegoUp) is represented as discharging direct to the adjacent water compartment. For biosphere objects without a persistent lake or stream, the lateral transfer is directed to water or the upper regolith in the adjacent, down-gradient object.

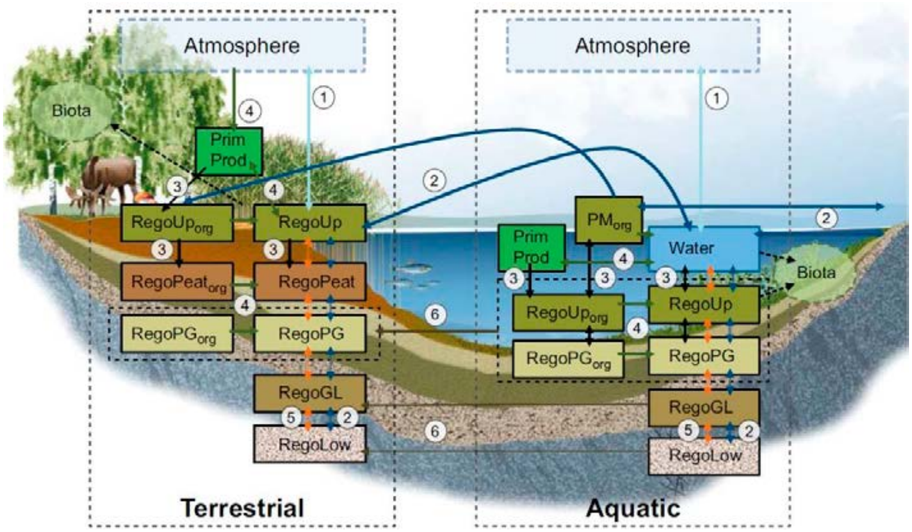


Figure 13: Illustration of the compartment structure used to represent each biosphere object in SR-PSU; arrows represent radionuclide transfers (Figure 3-1 from the Biosphere Model Report).

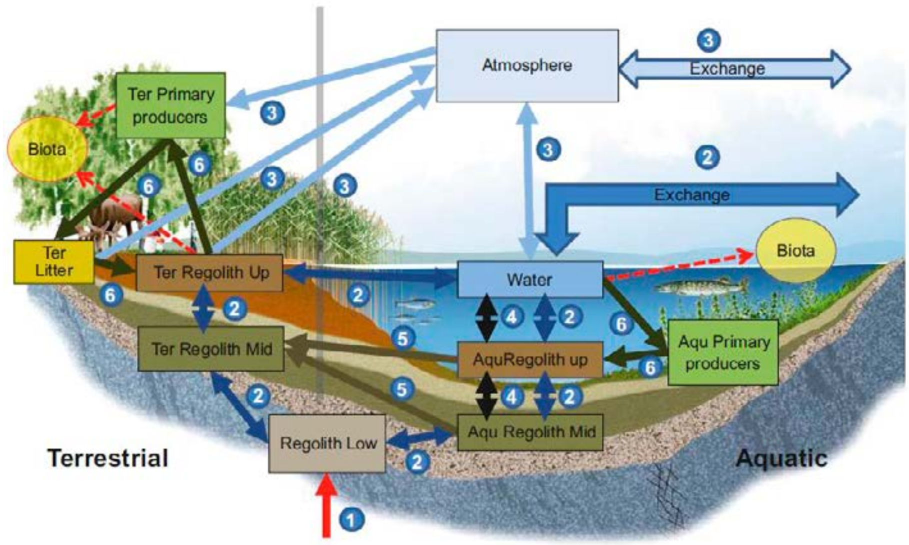


Figure 14: Illustration of the compartment structure used to represent each biosphere object in SR-Site; arrows represent radionuclide transfers (Avila et al., 2010).

Description of the till that dominates the Forsmark area highlights that it is significantly anisotropic, with a horizontal hydraulic conductivity that is 30 times

[44] Section 3.2.7 of the Biosphere Model Report.

greater than the vertical hydraulic conductivity[45]. There are also indications that the hydraulic conductivity is even higher at the rock-regolith interface than in the till itself. Given the significantly greater horizontal hydraulic conductivities in the till, coupled with the presence of a clay layer above, it is surprising that there is little horizontal groundwater flow and that it is ignored in the radionuclide transport modelling as a result. This is particularly true for objects that slope as they emerge from the sea such that they are considered by SKB to transition directly to a mire phase. One might expect sub-horizontal flow to occur at the rock/regolith interface or within the till such that the discharge would occur down-gradient, e.g. at a lake. It may be that the underlying geometry precludes this from occurring, but such evidence has not been found in this initial review so this remains a topic that merits consideration for further review.

SKB claim that exclusion of sub-surface horizontal advective transport is a cautious simplification, as it results in all radionuclides released from the bedrock being transported towards the upper regolith layers[46]. This claim is not universally true, for example, (i) if lateral transport results in a discharge to a lake, which might give higher dose factors for some radionuclides, (ii) if lateral transport means that radionuclides take longer to reach the surface, then dose rates can increase for decay chains within which the radioactive daughters are more radiologically significant than the parent, or, conversely, (iii) where horizontal hydraulic conductivity is substantially higher, then lateral transport may be quicker than vertical transport.

The absence of a stream in biosphere object 157_2 means that advective loses from the upper regolith compartment are represented as 'diffuse overland flow' to 157_1, down-gradient. The conceptualisation of such flows is uncertain, as there is no physical connection between the two objects (see Figure 10). The lack of a firm description of the connectivity and transfer necessitates some relatively arbitrary assumptions in characterising the exchange in the biosphere model[47]. Such assumptions would not be necessary if the transfer was characterised as a stream.

3.2.4. Modelling of Agricultural Groups

During interglacial periods, the highest calculated doses are obtained by those potential exposure groups making horticultural and agricultural use of contaminated land. The models for the infield-outland farmer, drainer mire farmer and garden plot groups therefore merit consideration for in-depth review. Some initial observations are provided below.

The general model for radionuclide transport and accumulation summarised in Section 3.2.2 reflects mire, lake and marine biosphere systems. Concentrations in agricultural soil are evaluated using side calculations based on radionuclide concentrations calculated in the general model (described in Section 7 of the Biosphere Model Report). No dynamic modelling of agricultural soil is undertaken[48]. Description of the calculation of soil concentrations is process based, but also relatively complicated.

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[45] p110 of the Main Report.
[46] p36 of the Biosphere Model Report.
[47] Described at the bottom of p40 of the Biosphere Model Report.
[48] p106 of the Biosphere Model Report, although this is not consistent with p164 of the Biosphere Synthesis Report which states that 'soil concentrations were modelled dynamically after drainage'.

Some observations with regards to the modelling approach for agricultural soil are given below.

- In-growth of explicitly modelled radionuclides is accounted for with a scaling factor, however, it is unclear if this adequately accounts for processes such as leaching whereby radioactive daughters will have differing retention characteristics.
- The garden plot exposure group irrigate soil. The model calculates an average concentration in soil for a 50 year period of cultivation[49]. However, radionuclide concentrations will continue to increase if irrigation were to continue beyond that timescale, particularly where a relatively well sorbed radionuclide is concerned. Irrigation for a period beyond 50 years may therefore have a significant effect on calculated concentrations.
- An accumulation period of 50 years is discussed for drained mire farmers (based on stability of organic soils) and for the garden plot group, however, the ingrowth calculation describes its application to all agricultural soils. This therefore implies a period of 50 years is represented for the infield-outland farmer, although this does not appear to be discussed.

On initial review, the following observations are made with regards to the model used by SKB to represent contamination of vegetables and tubers due to irrigation.

- The mathematical model allows for contamination of the plants by root uptake and by contamination remaining on leaf surfaces[50]. The model excludes the potential for foliar absorption and translocation of intercepted contaminants to tubers. Translocation is typically included in biosphere assessment models and may be important for those radionuclides that have a low degree of root uptake (Bergstrom et al., 2005).
- The model assumes that irrigation events are spaced equally during the growing season[51], even though the Biosphere Parameter Report notes that irrigation mainly occurs during the latter part of the growing season[52]. As a consequence, the model allows for 50 days of weathering of externally intercepted contamination[53], whereas, in practice, a period of several days would be more appropriate.

3.2.5. Modelling of Drilled Wells

The potential importance of groundwater wells as a pathway that by-passes some of the barriers means that the representation of wells in the assessment has received some attention during the initial review phase. The focus has been on drilled wells, which take contaminated water from a depth of about 60 m, as opposed to dug wells, which are shallow wells excavated into the till and are also represented in SR-PSU.

Radionuclide concentrations in drilled wells are calculated in the SR-PSU assessment by taking into account the fraction of release from SFR that may be intercepted by a well. For the main scenario calculations, the fraction intercepted by a well is defined separately for the different parts of the SFR facility and is very low (ranging from zero for releases from BLA1 and BMA1 to 0.3% for BLA3). These values are based on modelling of three wells in the vicinity of biosphere object 157_2 (those numbered 3, 5 and 11 in Figure 15). The locations have been chosen

[49] Section 7.3.10 of the Biosphere Model Report.
[50] p119 of the Biosphere Model Report.
[51] Equation 7-57 of the Biosphere Model Report.
[52] Section 9.14.5 of the Biosphere Parameter Report.
[53] Based on the average of the distributions used in SR-PSU.

to be ‘typical’ and reflect some consideration of historical wells (e.g. not on mires and within 100 m of an arable area)[54]. For the case of wells with a ‘well interaction area’, well interception fractions of 10% are used based on well locations within the area illustrated in Figure 16.

Discussion in Werner et al. (2013) notes that 80-90% of wells are located within 100-200 m of arable land. A circle of radius c. 200 m from arable land is shown in Figure 16, which highlights that there is notable overlap with the well interaction area. Although difficult to interpret from the figures in Werner et al. (2013), the modelled capture fractions for wells within the approximate region highlighted in Figure 16 is up to 17%[55]. It would seem equally reasonable for wells to be located in this region as in the region used to justify a capture fraction of 0.3% in the main scenario (note also that there is no requirement for the well for a garden plot group to be within a biosphere object).

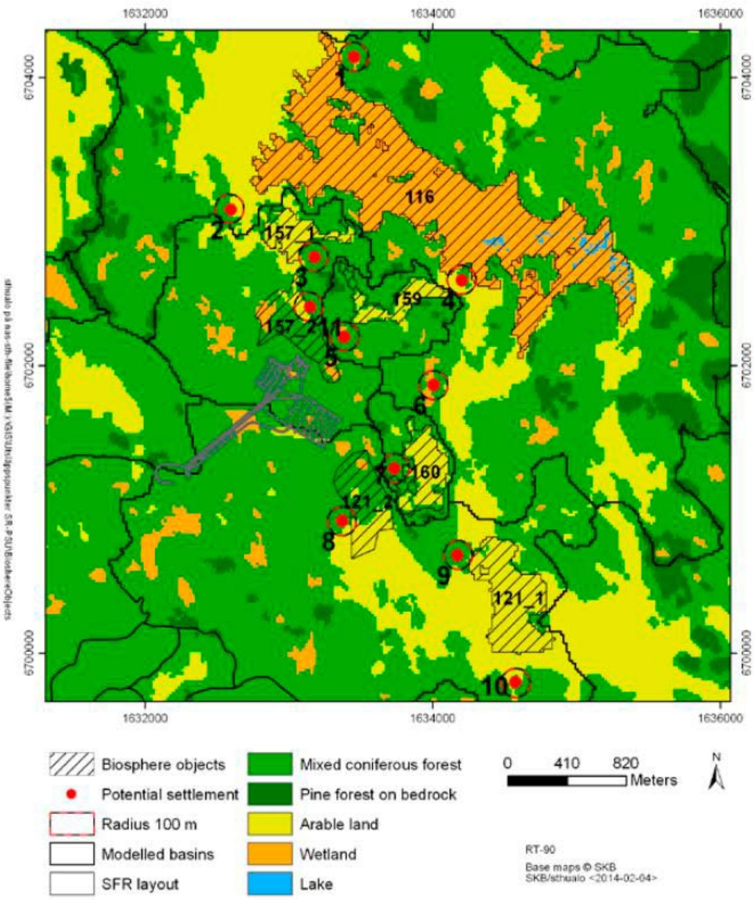

Figure 15: Potential settlement areas used as locations for drilled wells (Figure 6-10 from Werner et al., 2013).

A further issue that is highlighted with regards to wells is the inclusion of a well numbered 12 in the Biosphere Parameters Report[56]. It is of interest because it is associated with capture fractions of up to 32% from some parts of the SFR and its numbering indicates that it is located close to a potential settlement area associated

[54] Section 6.4.2 of Werner et al. (2013).
[55] Based on wells 23 and 26 in Tables A3-2 and A3-3 of Werner et al. (2013).
[56] Tables 12-1 and 12-2 of the Biosphere Parameters Report.

with a biosphere object. However, the well is not included in the averages and does not appear in the underlying Werner et al. (2013) report.

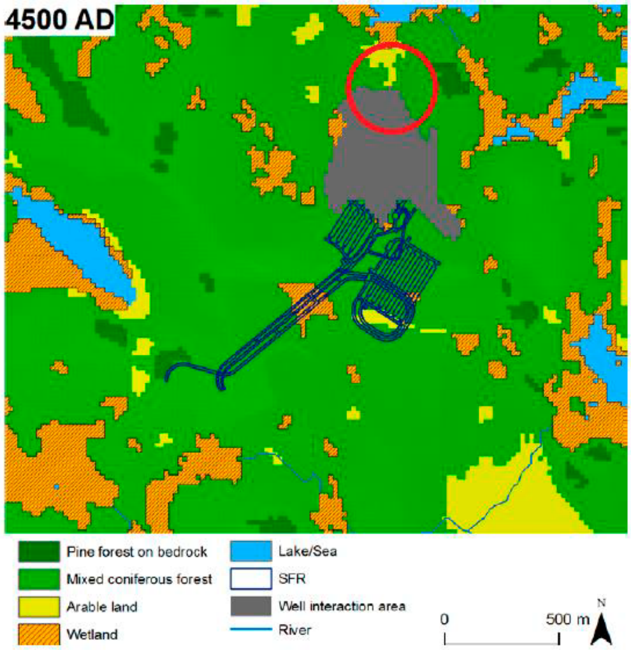

Figure 16: Well interaction area illustrated on the 4500 AD landscape map (based on Figure 6-12 of Werner et al., 2013). Red circle highlights area within c. 200 m of arable land.

3.2.6. Initial Review of Unit Release Results

The SR-PSU assessment compares results for the latest biosphere model with those from previous SKB assessments. Results for a unit release are compared against LDFs from SR-Site and from equivalent results from SAR-08[57], see Figure 17. The use of deterministic 'best estimate' results from SR-PSU in the comparison means that the results do not reflect the probabilistic biosphere modelling that is actually used in the dose assessment, as highlighted in Section 2.2.7.

LDFs are calculated by SKB for SR-PSU based on the global warming calculation case[58]. Unlike previous assessments, these are based on unit releases to a single biosphere object (157_2) and subsequent transport through the landscape (as discussed in Section 2.2.2). The drained mire farmers give the highest LDFs for 30 out of the 55 radionuclides modelled, followed by the garden plot holders (23) and then the infield-outland farmers and hunter-gatherers are highest for one radionuclide each. In 54 out of 55 cases, the highest LDF arises to groups using biosphere object 157_2 to which the releases are directed. However, for the key Mo-93, the highest LDF is calculated for biosphere object 157_1. This discrepancy for Mo-93 is of interest due to its importance to the dose assessment (see Section 3.2.8) and highlights the merit in considering detailed review of its parameterisation and representation in the biosphere.

[57] Section 10 of the Biosphere Synthesis Report.
[58] Table 10-1 of the Biosphere Synthesis Report.

Comparison with SR-Site is considered here as the most interesting, because both assessments explicitly represent environmental change (unlike SAR-08) and because most of the dose factors relate to radionuclide releases to similar biosphere objects (i.e., small objects that lack a lake stage). Figure 17 highlights that dose factors for several radionuclide of typical importance to disposal of radioactive wastes have reduced by more than an order of magnitude (and up to over three orders of magnitude in the case of Se-79) since the SR-Site assessment was submitted in 2010. The differences are mainly attributed to greater use of site-specific information in parameterising the biosphere for SR-PSU. In particular, these concern sorption coefficients in the till (Se-79, Nb-94, Sn-126) and soil-to-plant concentration ratios (Se-79 and I-129). The very significant difference attributed to the use of more site-specific data highlights the approach to data for key radionuclides as being a topic that merits consideration for further review.

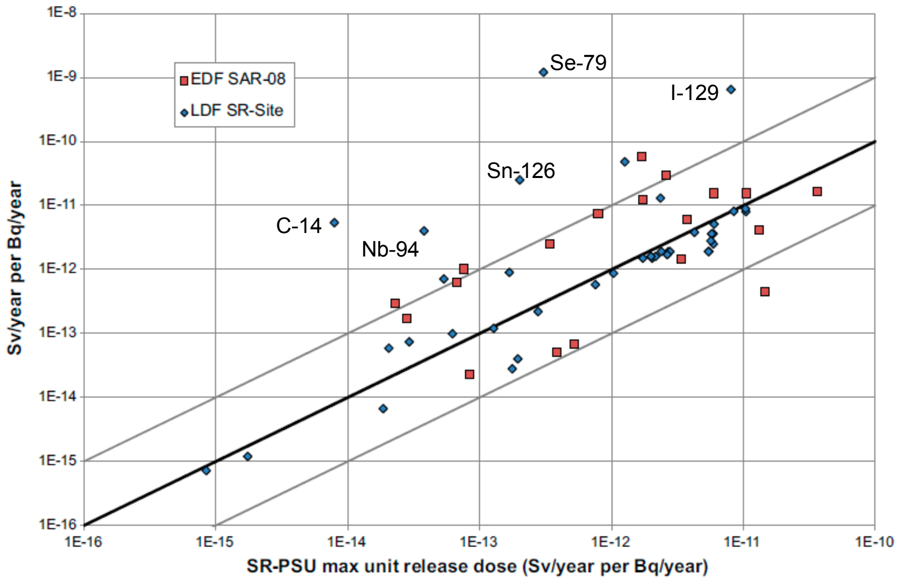

Figure 17: Maximum 'best estimate' biosphere dose factors from SR-PSU compared with those from SR-Site and SAR-08 (based on Figure 10-1 of the Biosphere Synthesis Report).

For C-14, the reduction in biosphere dose factor by a factor of over 680 between SR-Site and SR-PSU is not attributable to the site data. For C-14, a key exposure pathway in both SR-Site and in SAR-08 was the ingestion of fish due to the high water-to-fish concentration ratio exhibited by this radionuclide. In SR-PSU, ingestion of fish no longer dominates the maximum calculated doses for C-14. This is partly because, unlike SR-Site and SAR-08, the main scenario calculations in SR-PSU are based on the prediction that there will be no groundwater releases direct to a lake. Additionally, SR-PSU includes new constraints about the amount of fish that can be consumed based on consideration of protein toxicity.

Given its importance in previous assessments, assumptions concerning the fish pathway merit consideration for further review in SR-PSU. Some issues for consideration are noted below.

- The lack of any potential direct release of contaminated groundwater to a lake or even a stream in the main scenario is noted previously (see Section 2.2.2).
- The hunter gatherers are the only potential exposure group to ingest fish in the SR-PSU. This is a group of 30 individuals. The size of the group is

reflected in the yield of fish needed to sustain it[59]. The lake in biosphere object 157_1 is not large enough to provide the fish needed by the hunter-gatherer group[60], so the calculated concentration in fish is diluted with less or even uncontaminated fish from elsewhere. The results of the fish pathway may therefore be significantly greater if, for example, the garden plot household (of only five individuals) obtained fish from a nearby lake.
- Recourse to arguments based on protein toxicity reflect the way in which diets are abstracted to a carbon basis. Such recourse would not be needed were diets to be based directly (and more transparently) on habit data.

3.2.7. Unit Release Results for Distributed Releases

One of the assumptions underpinning the main dose calculations in SR-PSU is that all of the radionuclide releases occur in biosphere object 157_2. For four radionuclides (C-14, Cl-36, Mo-93 and Ni-59), SKB explore unit release results if the release from SFR is distributed amongst several biosphere objects, based on particle tracking calculations[61].

The analysis was based on releases from the 2BMA gallery, which demonstrated the widest spatial distribution of releases. Nonetheless, the majority of the release is still directed to biosphere object 157_2. The particle tracking calculations indicate that up to about 24% of the release from 2BMA might be directed elsewhere[62]. The releases were distributed to the biosphere objects in a time-dependent manner.

The unit release results show that, in most instances, accounting for the spatial distribution of releases gave an increase in the maximum calculated dose. Biosphere object 157_1 gave rise to the increases in the highest calculated LDF for Mo-93 and Cl-36 even though it only received up to about 10% of the release.

The results for the distributed releases indicate that assigning all of the release to biosphere object 157_2 does not necessarily result in the highest biosphere doses; this should be borne in mind when interpreting the results. The modelling of the releases is dependent on the ‘predictive’ capability of the landscape modelling, precision of the representation of the fracture network and reliability of the groundwater flow modelling that supports the particle tracking.

3.2.8. Initial Review of Dose Assessment Results

The risk criterion for harmful effects of 10^{-6} per year translates to an annual dose of 13.7 μSv. Where the most exposed group consists of just a few individuals, a risk criterion of 10^{-5} per year is applied (SSM, 2008).

Calculated results for the central case for the main scenario, which is described as ‘global warming’ and which prevents any radionuclide releases until the sea retreats after 1000 years, peak at 5.6 μSv/y. A variant to this case, where radionuclide releases are permitted from time zero, results in a peak calculated dose of 6.2 μSv/y. The highest calculated doses are received by the drained mire farmer in biosphere

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[59] Equation 9-13 of the Biosphere Model Report.
[60] p199 of the Biosphere Synthesis Report.
[61] Sections 7.4.6 and 10.7 of the Biosphere Synthesis Report.
[62] Table 7-5 of the Biosphere Synthesis Report.

object 157_2, with Mo-93 accounting for close to 50% of the peak, followed by C-14, which accounts for about 25%.

These results highlight that calculated doses are about 10% lower if releases from the wastes are prevented until the sea has retreated from above the SFR. This should be borne in mind when interpreting results for variant calculation cases where releases are prevented in the same way.

Between about 14,000 AD and 36,000 AD, calculated doses to the drained mire farmer in biosphere object 157_1 exceed those in 157_2. The switch in importance is associated with a switch in the relative contributions of radionuclides (see Figure 18).

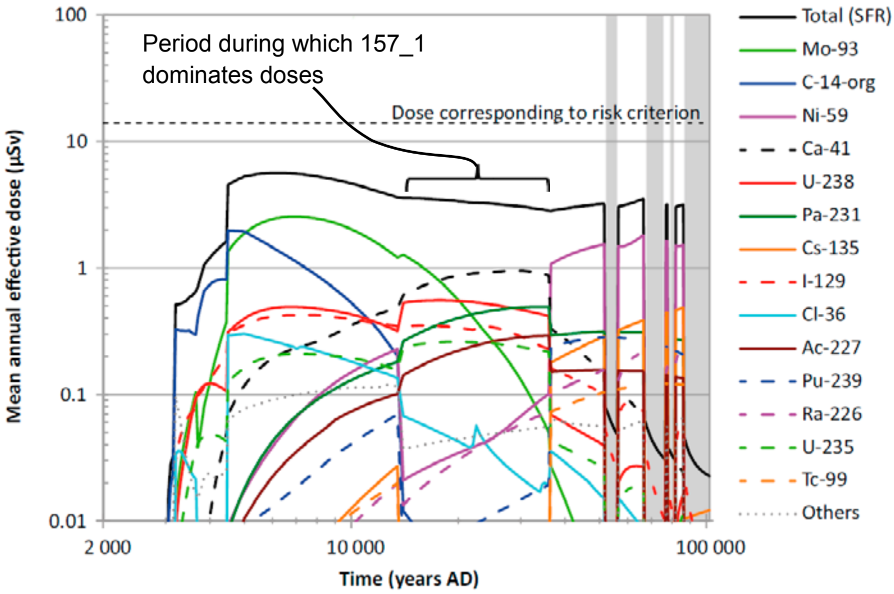

Figure 18: Arithmetic mean of the annual effective dose to the most exposed group in the global warming calculation case (Figure 5-4 from the Radionuclide Transport Report).

A calculation case with an early periglacial episode after 17,500 AD shows peak calculated doses of 0.24 µSv/y to the hunter-gatherer group (the only group active under these climate conditions). This dose is received from biosphere object 157_1, principally due to I-129, which accounts for about 70% of the calculated dose.

The extended global warming scenario is another that is interesting from a biosphere perspective and is represented in SR-PSU under 'residual scenarios'. The peak calculated dose for this case is similar to that of the main global warming case at 5.4 µSv/y. This is again due to Mo-93 (~40%) and C-14 (~30%) doses to the drained mire farmer in biosphere object 157_2.

3.3. Biosphere Model for C-14

In several cases, it is the organic C-14 inventory that is considered to be amongst the highest contributing radionuclides to annual dose[63]. As part of the SR-PSU assessment, the radionuclide transport model has been enhanced over that used in the SR-Site assessment to better represent the transport and accumulation of C-14 in the surface systems[64]. Rather than a dedicated section of a report outlining the C-14 conceptual model, the equations and their justification are integrated in the Biosphere Model Report, with the data contained in the Biosphere Parameter Report (see Figure 19).

A summary of the new atmospheric sub-model is provided in the Biosphere Model Report[65], the model having been developed specifically to address $^{14}CO_2$ exchange and uptake between soil-vegetation-atmosphere in the terrestrial ecosystem and water-atmosphere in the aquatic ecosystems. However, the supporting report that provides further description and justification of the new atmosphere model was not available at the time of this review (Avila and Kovalets, 2015).

As noted in Section 2.1, the Biosphere FEP Handling Report was also not available at the time of this review. This limits the extent to which the biosphere modelling can be reviewed because SKB state that whilst the radionuclide model is given in the Biosphere Model Report, the handling of C-14 in the SR-PSU modelling is described further in the Biosphere FEP Handling Report[66]. No mention is made in the Main Report of the new atmospheric exchange model.

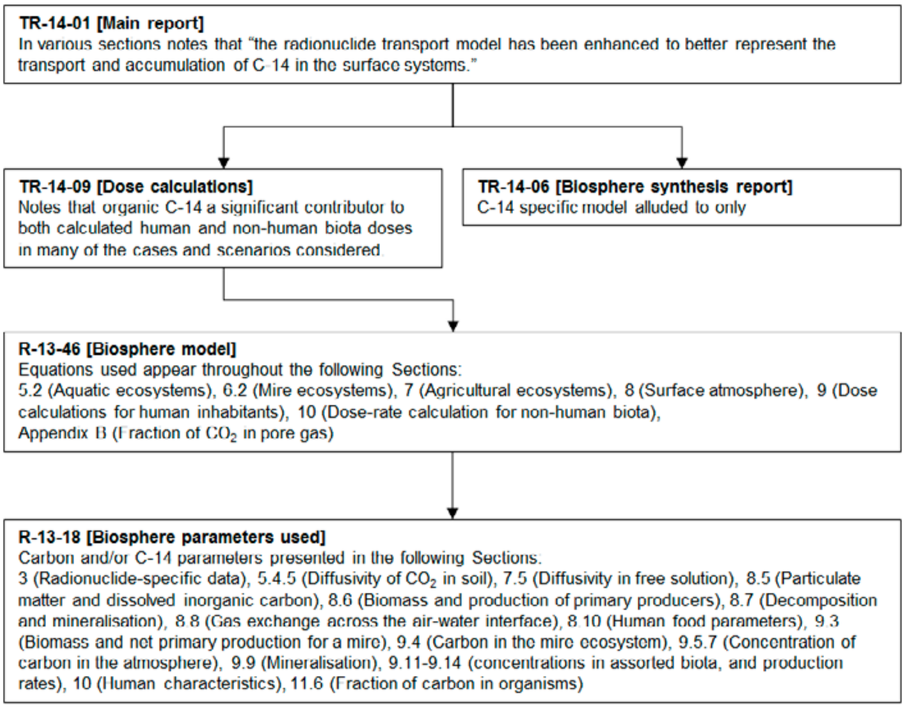

Figure 19: Schematic of C-14 biosphere model documentation with the SR-PSU assessment.

[63] Sections 5, 6 and 7 of the Radionuclide Transport Report.
[64] Section 1.5 of the Main Report.
[65] Section 8 of the Biosphere Model Report.
[66] p461 of the Main Report.

3.3.1. Overall Methodology for C-14

Given the absence of some of the more detailed reports during the initial review phase, an understanding of the processes included in the C-14 modelling was obtained by studying the equations listed in the Biosphere Model Report. The processes considered, in addition to advection and diffusion between the regolith layers, are listed in Table 2 below.

The terrestrial and aquatic ecosystem models have been redrawn from Figure 2-2 of the Kd and CR Report[67], with the exchange mechanisms named, in Figure 20 and Figure 21, respectively. With regards to the source term to the biosphere, the only mechanism considered for C-14 to enter the soil is in a dissolved form. This is because the gas pathway has been disregarded in the radionuclide transport modelling. The omission of this transport pathway has been highlighted as a topic that merits consideration for review in the initial review of the radionuclide transport modelling in SR-PSU (Towler et al., 2015).

One of the key differences between the new C-14 model and that used in previous SKB assessments is the explicit inclusion of organic carbon pools in the dynamic compartment models. However, the probable existence of C-14 in the form of $^{14}CH_4$ (methane) in regolith layers with low redox potentials has apparently not been considered in the SR-PSU assessment. The implications of this omission could be explored in a parallel modelling exercise as part of a deeper review into the SR-PSU methodology.

The different aspects of the C-14 model are discussed in more detail in the following sub-sections.

[67] Figure 2-2 of the Kd and CR Report.

Table 2: Processes considered in the biosphere model, indicating those which are C-14 specific.

Aspect of biosphere model	Processes with one equation for all radionuclides	Processes with C-14 specific equation
Aquatic ecosystem	Sedimentation Resuspension Burial Bioturbation Mineralisation	Plant uptake Litter respiration Litter production Degassing Gas uptake
Mire ecosystem	Burial Mineralisation	Plant uptake from atmosphere Plant uptake from roots Litter respiration Litter production Degassing Gas uptake
Agricultural ecosystem	Fertilisation Mineralisation Irrigation (garden plot only) Leaf retention (garden plot only)	Activity of C-14 in the soil (total and dissolved) Litter respiration Litter production Leaching Degassing Groundwater uptake Average activity over the first 50 years after drainage Leaf degassing (garden plot only)
Surface atmosphere	Flux to primary producers *[Turbulent and diffusive air fluxes]*	Specific activity of canopy layer Release to the canopy layer
Dose calculations for human inhabitants	Inhalation relates to dust concentration only	Inhalation relates to dust and atmospheric concentration Specific activity of foodstuffs
Dose-rate calculation for non-human biota		Specific activity in biota

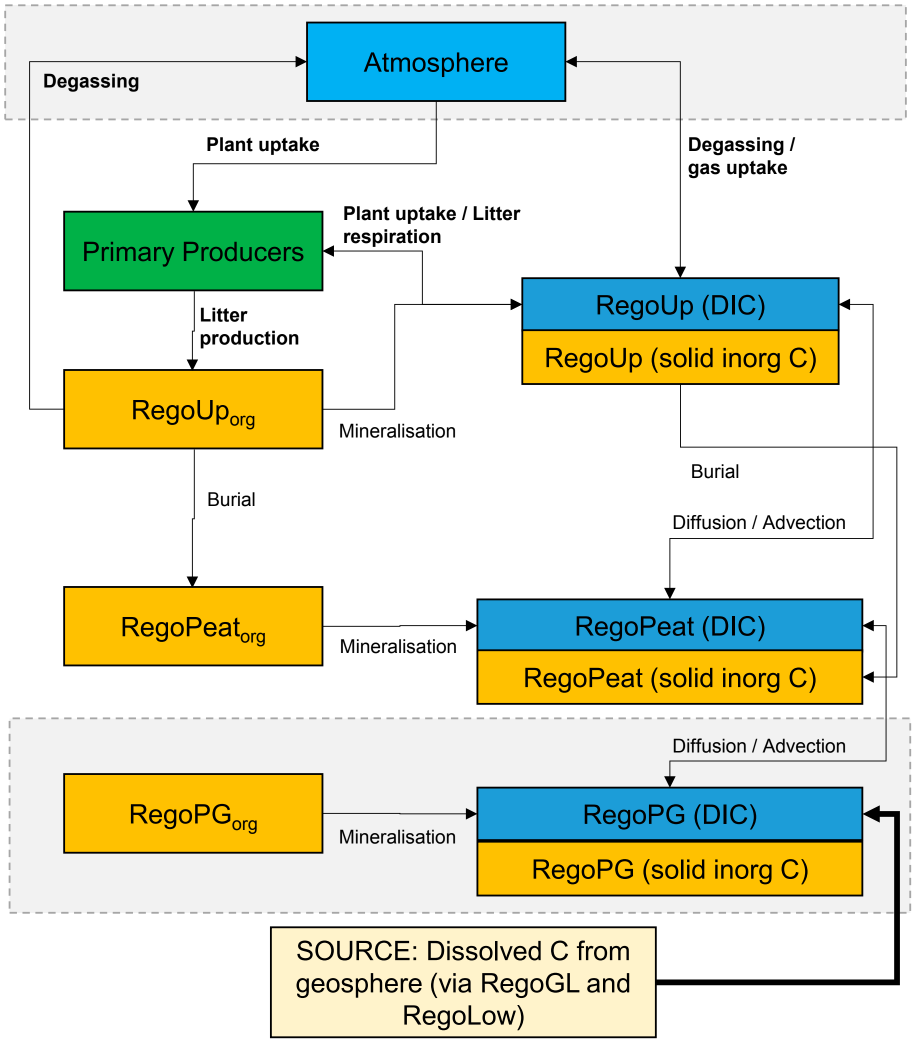

Figure 20: Schematic representation of the radionuclide model for the terrestrial biosphere, including source term (based on Figure 2-2 of the Kd and CR Report). Transfers highlighted in bold have a specific parameterisation for C-14.

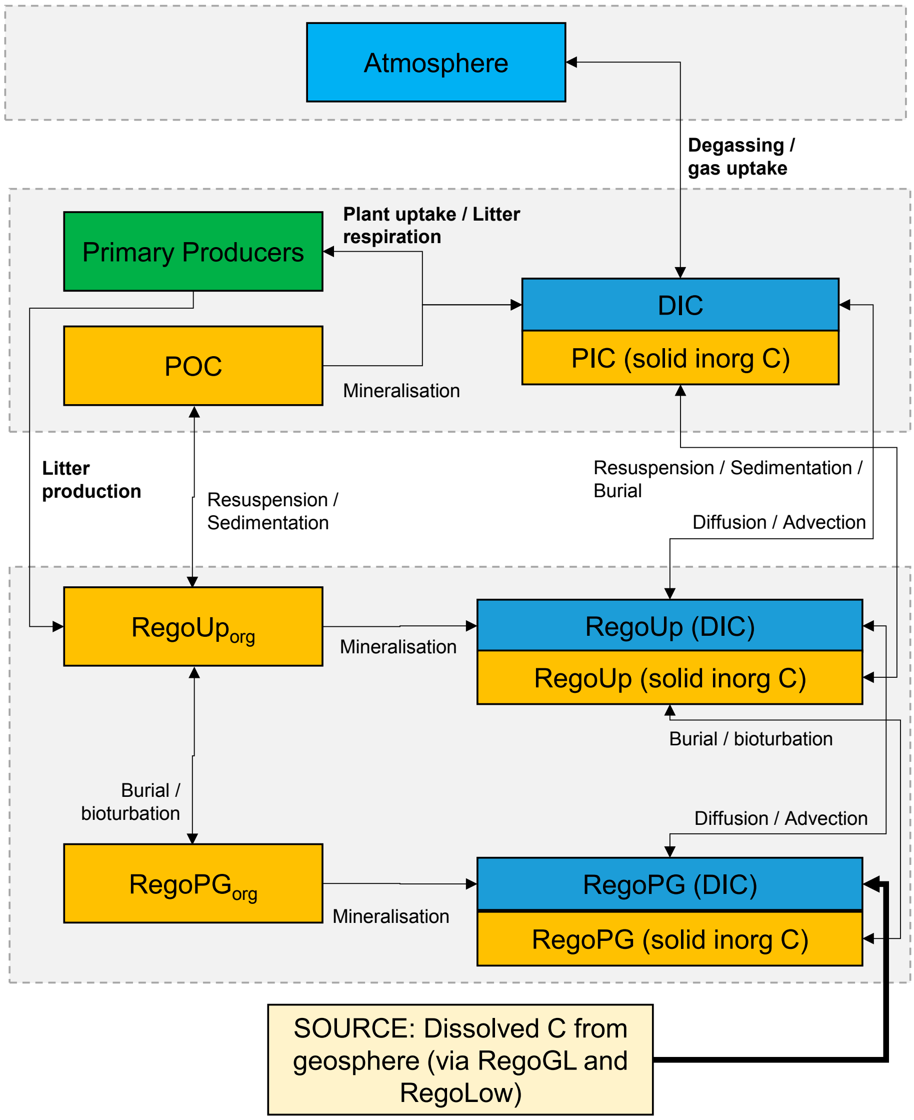

Figure 21: Schematic representation of the radionuclide model for the aquatic biosphere, including source term (based on Figure 2-2 of the Kd and CR Report). Transfers highlighted in bold have a specific parameterisation for C-14.

3.3.2. The Terrestrial Ecosystem

The Biosphere Model Report[68] considers the transport and biological assimilation of C-14 in the near-surface atmosphere, with the source term for this part of the model system being $^{14}CO_2$ which has outgassed from soil and leaf surfaces. As mentioned above, no consideration is made of possible outgassing of $^{14}CH_4$ from either of these surfaces. It is known that soils with low redox potentials can be a significant source of methane to the free atmosphere. As a result of their own investigations, SKB note that large amounts of methane have been found in sediments of lakes and shallow bays in the Forsmark area (Borgiel, 2004; Karlsson and Nilsson, 2007). There is also a substantial body of evidence for methane being present in, and released from, organic mire-like soils (e.g. Couwenberg and Fritz, 2012; Strömberg, 1998; Whalen, 2005). As such, SKB (2013) notes that excretion of methane, and

[68] Chapter 8 of the Biosphere Model Report.

carbon dioxide, from decomposers should be considered explicitly in the SR-PSU assessment. Furthermore, wetland plants growing in such soils can provide conduits for direct transport of methane from the sub-surface to the free atmosphere. C-14 outgassing from soil and vegetation surfaces as $^{14}CH_4$ represents a very small inhalation hazard and, unlike $^{14}CO_2$, will not be absorbed by photosynthesising vegetation canopies. The radiological impact of $^{14}CH_4$ is therefore likely to be less than $^{14}CO_2$ and this possibility could be reflected in a more comprehensive modelling approach.

Organic matter is explicitly modelled only in solid form (see Figure 2-2 of the Kd and CR Report). SKB argue[69] that dissolved low molecular weight organic carbon is typically mineralised within days or weeks (Howard, 1991), and, consequently, dissolved organic C-14 is assumed to be rapidly transformed to dissolved inorganic carbon on the time scale represented in the modelling. Whilst this may hold for low molecular weight organic carbon molecules, it is not clear that this statement is valid for heavier organic carbon molecules, and, as such, merits consideration for further review.

3.3.3. The Aquatic Ecosystem

As discussed in more detail in the review of the atmospheric sub-system (Section 3.3.4), the SR-PSU assessment differs from previous SKB assessments in as much as losses to the atmosphere above the water body are considered in the conceptual model, with a two-way exchange process invoked. The degree of potential reduction in calculated dissolved C-14 concentrations in water, and thus the reduction in exposure of aquatic biota, merits consideration for further review. The ingestion of C-14 contaminated fish provided one of the key potential exposure routes in the SAR-08 assessment (Bergström et al., 2008). In the SAR-08 assessment the peak dose from C-14 was associated with a lake receiving a direct flux of radionuclides from the geosphere.

Whereas, in the SR-Site assessment, the calculation of radionuclide concentrations in aquatic primary producers amalgamated the three groups (benthic microplankton, benthic macroplankton, and phytoplankton) together, they have been treated distinctly in the SR-PSU assessment. This means that with respect to the uptake of C-14 (and other radionuclides) into aquatic primary producers, each is modelled separately. With the exception of a retardation term in the SR-Site model, the equations used in the SR-PSU assessment to model the uptake of C-14 into aquatic primary producers are otherwise identical once both are converted to transfer coefficients (1/y) .

With respect to the specific activity of C-14 in fish and crayfish, the SR-PSU equates it to a weighted average of the specific activity of the three primary producers, whereas the previous SR-Site model equated it to the specific activity of the total mass of aquatic primary producers. Whether this, or the changes in assumptions with regards a water-atmosphere exchange of C-14, has a significant effect on calculated exposures to aquatic biota, and the human consumption thereof, and the magnitude of any changes, merits consideration for further review.

[69] Section 6.1.2 of the Biosphere Model Report.

3.3.4. The Atmospheric Sub-model

The Biosphere Model Report[70] provides a short description of the sub-models used to calculate the activity concentration of $^{14}CO_2$ in the near-surface atmosphere. A more complete description of the relatively simple models used in SR-PSU, together with a comparison with more detailed process-oriented models, can be found in Avila and Kovalets (2015), which has not been published at the time of this review.

The atmospheric model for C-14 developed for SR-PSU is very different to that used in the SAR-08 or SR-Site assessments, the latter being documented in Avila and Pröhl (2008). With regards to terrestrial ecosystems, whereas a single compartment was used for the aboveground atmosphere in the model developed by Avila and Pröhl (2008), in the SR-PSU assessment this has been effectively split into three compartments, with the total height (10 m)[71] being equivalent to that of agricultural land in Avila and Pröhl (2008). Plants take up their carbon (and C-14) from the lowest of the three compartments, the height of which varies depending on the vegetation present. When calculating inhalation exposure for humans, it is the concentration of C-14 in the middle atmospheric compartment that is used, which extends from the top of the vegetation canopy to 2.5 m.

With regards to aquatic ecosystems, in Avila and Pröhl (2008) the atmosphere above the water body was disregarded, whereas in SR-PSU there are two compartments[72], with a total height of 10 m, equivalent to that the of terrestrial atmosphere[73]. The lower layer, with a height of 1 m, is defined to provide an atmospheric concentration of C-14 to exchange with dissolved C-14 the water body.

The atmospheric sub-model for C-14 can only be reviewed once Avila and Kovalets (2015) is published; this is therefore a topic that is recommended for consideration in the main review phase.

3.4. Non-Human Biota Exposure

The dose assessment methodology for non-human biota is mentioned in several high-level reports within the SR-PSU documentation, with the details given in the Biosphere Model Report; see Figure 22. This detailed report was not published until May 2015.

The documentation makes it clear that the non-human biota assessment is based on the ERICA assessment approach, and that the ERICA model and data has been implemented in Ecolego. Jaeschke et al. (2013)[74] describes the November 2012 version of ERICA as the starting point for that used in the SR-PSU assessment.

[70] Section 8 of the Biosphere Model Report.
[71] Section 9.5.3 of the Biosphere Parameters Report.
[72] Section 8.2 of the Biosphere Parameters Report.
[73] Section 8.9 of the Biosphere Parameters Report.
[74] Appendix A of Jaeschke et al. (2013).

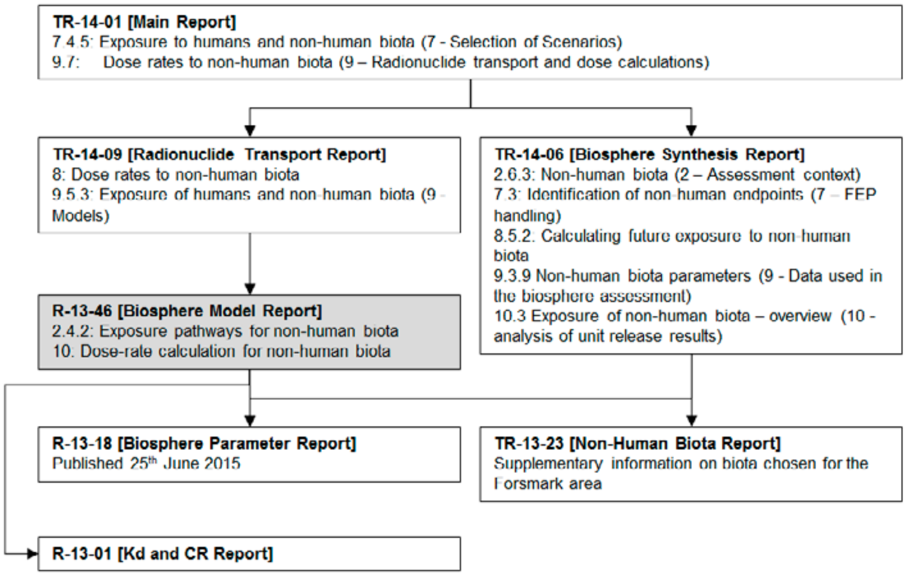

Figure 22: Hierarchy of SR-PSU documentation with respect to the non-human biota dose assessment. The report containing the details of the assessment approach is highlighted in pale grey.

With respect to non-human biota, the ERICA assessment approach is internationally accepted for the assessment of potential impacts to biota from radionuclides, excluding noble gases. A tool has been developed specifically for the calculation of doses to non-human biota using this methodology and is available from http://www.erica-tool.eu/. The tool calculates exposures for a given set of concentrations in environmental media, providing a snapshot in time.

The Biosphere Model Report[75] indicates that both the internal and external dose conversion coefficients were calculated in ERICA. In aquatic ecosystems SKB used total water (both the dissolved and particulate matter) radionuclide concentrations when calculating external exposures; in contrast, the ERICA methodology assumes external exposure comes only from the filtered water (Brown et al., 2008). The approach adopted in SR-PSU is therefore pessimistic in this regard.

Not all of the default parameters in ERICA were used in the SR-PSU assessment. SR-PSU specific data used includes the habitat occupancy factors (described in the Biosphere Parameters Report) and the concentration ratios (described the Kd and Cr Report). Since the SR-PSU assessment was undertaken, a new version of ERICA, Version 1.2, was released in November 2014. In the new version there have been several changes with regards assumptions about uptake into certain biota, and default model parameterisation.

ERICA (2014) notes that the new version of the software now includes a set of default parameter values for some radionuclides, such as Pa-231, that were not previously available, and that the Dose Conversion Coefficients for the external exposure of lichens and bryophytes were completely updated due to discrepancies in the original dataset. Therefore, there is merit in considering a comparison of assumptions in ERICA Version 1.2 and in the SR-PSU assessment for a selection of key organisms and radionuclides. Based on the results presented in the Main Report[76] and the key radionuclide highlighted in Section 2.2.8, key organisms and

[75] Figure 10-1 of the Biosphere Model Report.
[76] Table 9-22 of the Main Report.

radionuclides would be exposure of (wading) birds, lichens and bryophytes, with a focus on C-14 and U-238. In addition, Pa-231 would be of interest because it is listed as being an important contributor to some species and because it is a radionuclide that is subject to notable changes in the updated version of ERICA.

4. Initial Review of Biosphere Parameters

The question being addressed by this aspect of the review is whether the data collection and parameter derivation for specific radionuclides are appropriate and sufficient for its purpose. This has been considered in two stages. First, consideration is given to general approach adopted by SKB in the SR-PSU assessment and, where appropriate, changes from previous assessments. Second, an initial review of the biosphere parameterisation has been undertaken, with areas meriting further consideration in the main review phase highlighted.

4.1. Approach to Handling Biosphere Data

One of the most notable aspects of the documentation of the biosphere data in the SR-PSU assessment is that it is presented across only two reports (the Biosphere Parameters Report and the Kd and CR Report), supported by underlying Excel files containing raw data. This is in contrast to the SR-Site assessment, where environmental data was presented across the three ecosystem reports (Andersson, 2010; Aquilonius, 2010; Lofgren, 2010), and element specific data was presented in a separate report (Nordén et al., 2010), with underlying spreadsheet files containing the raw data. Time-dependent data used to represent biosphere objects are also fully documented in the Biosphere Parameter Report, whereas they were only available in spreadsheet files in the SR-Site Assessment. The reporting of the biosphere data is therefore improved in SR-PSU in comparison to the SR Site assessment.

Where data collected from studies in the Forsmark and Laxemar areas was available, this data was always used in preference to literature data. With the exception of one study to collect more Kd and CR data (Sheppard et al., 2011), the reports containing field data cited are the same as those used for the SR-Site assessment. Only in instances where no data from SKB field studies was available did SKB use literature data. Furthermore, the kinetic-allometric model used to assign CR values to some herbivores in the SR-Site assessment was not used in SR-PSU, with isotope, element or parameter analogues used instead[77].

In contrast to the SR-Site assessment, field data and literature data were never combined in the SR-PSU assessment. As such, the purely statistical Bayesian Inference methodology introduced for the SR-Site assessment (Nordén et al., 2010) was not used in the SR-PSU assessment. This is because, as noted in the Biosphere Parameter Report[78], "the Bayesian statistical methods could, in some cases where data were scarce, give unexpected results, as for example unrealistically large ranges". Instead, a hierarchical approach has been adopted in the selection of the data to use, including element or parameter analogues.

The use of site-specific data over literature data is an encouraging development, considering the efforts which were made in SR-Site to amass what is probably the largest site-specific database ever collected for radioecological purposes. As such, it is considered as an improvement in the handling of element and radionuclide specific biosphere parameters in SKB's assessments. In addition, the hierarchical

[77] Sections 2.6.5 and 2.7 of the Kd and CR Report.
[78] Section 7.1 of the Biosphere Parameter Report.

approach to parameterisation is more tractable than the Bayesian Inference methodology.

4.2. Initial Review of Parameterisation

It is evident that considerably more care has been taken over the selection of Kd and CR values in SR-PSU than in previous assessments. This is reflected in the careful consideration of the assumptions made when using Kds. Particular care has been taken to evaluate what the Kd and CR Report refers to as 'plausible' parameter variability, based on a highly systematic selection process. The baseline for this selection process is a combined Kd and CR database which is referred to as the 'Kd/Cr compilation', constructed in the form of a Microsoft Access database.

A three stage process of parameter selection has been implemented, consisting of:

- data selection (from the 'Kd/CR compilation');
- comparison of data; and
- manual evaluation and selection.

In the SR-Site assessment the Bayesian Inference approach was taken to define PDFs for Kd and CR, based on a much smaller available database. In SR-PSU, a more straightforward, less statistical, approach has been taken to make the parameter definition process as transparent as possible and to ensure 'uniform handling' of parameter values.

An important question concerning the Kd/CR database is the extent to which matched or complementary pairs of data have been used to calculate Kds and CRs. Strictly speaking, only solid and liquid samples from the same bulk soil sample should be used for the purpose of calculating Kd values. Similarly, radionuclide or element concentrations in matched vegetation and bulk soil samples should be used to calculate CR values. It is presumed that the 'Kd/CR compilation' database is large enough to allow this process to be carried out. The Kd and CR Report states that "Kd values calculated from such measurements represent true concentration pairs sampled at selected sampling sites at specific depths"[79]. However, the report goes on to say that "if several replicates are available ratios are formed for all possible combinations between pore water and the solid fraction". Access to the 'Kd/CR compilation' database would be required in a deeper review to determine the extent to which this approach has been used and whether it has led to an 'artificially' increased number of Kd values for the purpose of constructing PDFs.

Having calculated Kds and CRs from site-specific data from Forsmark and Laxemar, geometric means (GMs) and geometric standard deviations (GSDs) are established. Literature values of Kds and CRs, also entered into the 'Kd/CR compilation' database, are used to evaluate the 'plausibility' of the GSDs derived from site-specific data. This is a defensible approach, but it is not clear to what extent GSDs are established for single elements/radionuclides or combinations of elements/radionuclides. This approach should be investigated in a more detailed review.

The degree of confidence placed in estimates of maximum and minimum GSDs is evaluated based on N, the number of relevant Kds or CRs for specific radionuclides/elements within a specific biosphere compartment. However, the

[79] p41 of the Kd and CR Report.

threshold value of N for 'good' confidence is 3, which seems low but presumably reflects the available data within the Kd/CR database. This emphasises the need for further scrutiny of the database to improve the reviewers' understanding of data quality and the degree to which the selection process used by SKB optimises that quality.

Correlation between CR and Kd values is acknowledged, but is not taken forward to the parameterisation of any stochastic calculations. The Biosphere Synthesis Report notes that ignoring negative correlations between log-normally distributed Kd and CR permits more combinations of stronger sorption and higher uptake than might be expected[80].

There are several issues relating to the element or radionuclide specific biosphere parameterisation which merit further consideration in the main review phase. These are discussed in brief below. As with the SR-Site parameter review (Klos et al., 2014), access to the raw data files would facilitate the more detailed review of this aspect of the assessment, as well as potentially the more detailed review of other aspects of the biosphere modelling, including the use of alternative models.

1. When looking at site-specific data that SKB have collected, it is not clear how the data has been combined from multiple datasets. Note that a similar issue was raised in the SR-Site review (Klos et al., 2014). For example, the numbers of samples used from site data as reported in the Kd and CR Report are often difficult to tally up with the supporting data reports. Furthermore, whilst distributions are based on data from both the Forsmark and Laxemar sites when data are available, SKB state that the best estimates of element specific parameters are best represented by the GMs of the Forsmark only data[81]. For a selection of key radionuclides, an independent derivation of a parameter distribution could be undertaken, and consideration given to the implications of using only Forsmark data for the best estimate upon calculated risks.
2. In some instances, the data reported in the Kd and CR Report is based solely on field data collected since the SR-Site assessment, with that data reported in Sheppard et al. (2011). Noting that the data reported by Sheppard et al. (2011) is given in kg dw/kg dw[82], which needs to be transformed to kg dw/kgC for use in the assessment, there is potential for errors and/or inconsistencies in the conversion, such as was noted in Klos et al. (2014). This conversion could be reviewed for a selection of radionuclides and environmental media.
3. The main review phase could consider the appropriateness, or otherwise, of the use of element and parameter analogues in the gap-filling of missing or scarce data for the specific radionuclides of concern.

[80] p223 of the Biosphere Synthesis Report.
[81] Section 2.6.3 of the Kd and CR Report.
[82] Dry weight is abbreviated to 'dw'.

5. Overall Findings of the Initial Review

A broad understanding of the biosphere component of SKB's application for extension to the SFR facility has been achieved. The SR-PSU assessment is directly supported by over two thousand pages of reports concerning the biosphere alone. This results in a large amount of information that needs to be assimilated and is reflected in a complicated SR-PSU assessment. The standard of reporting is good, with the documents being generally well-written and understandable. However, the documentation supporting the assessment has been published in a protracted way, with misleading publication dates on reports and some reports remaining unavailable at the time of initial review. The SR-PSU assessment is therefore not complete and the way in which it has been published causes concern to the review team with regards to the way in which the overall assessment has been managed by SKB.

The dose assessment methodology is well described in the SR-PSU documentation. The context for the assessment is also well presented, in particular, with regards to regulatory guidance, regulatory feedback on previous SKB assessments and comparison against international practice. The complexity of the biosphere modelling approach reflects both a site that is projected to evolve from marine to terrestrial ecosystems over the time scale of relevance, as well as a disposal system (waste, engineering and geosphere) that requires careful assessment of the potential impacts.

Notwithstanding the above, the initial review highlights issues in relation to the biosphere modelling that merit consideration when interpreting the assessment results and others that warrant further review.

5.1. Interpretation of SR-PSU Results

The SR-PSU assessment is based on a probabilistic representation of each calculation case. However, the calculations are based on only 100 realisations for the nearfield and geosphere with a further 10 realisations for the biosphere. This is presented and analysed by SKB as if it represented 1000 independent samples. It is unclear if this approach is justified without further information from SKB.

Uncertainties associated with the many aspects of the assessment that are not treated probabilistically should be borne in mind when comparing calculated results against the risk criteria. Examples of uncertainties not treated explicitly in the main assessment results are noted below.

- Unlike previous SKB assessments, uncertainties in the landscape modelling are not handled explicitly in the modelling. A very large degree of confidence is instead placed on the landscape modelling such that it is predicted that no lake, nor even a stream, will be present in a key biosphere object that is represented as receiving 100% of the release.
- Significant uncertainties are acknowledged in the sea level curve but not explored.
- Results are shown to be sensitive to the way in which biosphere objects are delineated. Exploration of reasonable alternative approaches by SKB demonstrates that results for key radionuclides might increase by up to an order of magnitude if different assumptions are used.

- The main assessment calculations are based on a case where radionuclide releases are prevented for 1000 years, as it was assumed that early releases would have a low consequence due to marine dilution[83]. Variant calculations that, more realistically, allow radionuclide releases from the start of the assessment period show a 10% increase in the results.
- Distributing less than 10% of the releases to other biosphere objects results in higher calculated dose factors. Instead of exploring uncertainties in the distribution of releases, the main results are based on all releases going to a single biosphere object that is not typical of the Forsmark landscape.
- No uncertainty or variability is represented in the hydrological flows within the biosphere model. In addition, the effect of simplifying assumptions e.g. limited lateral flows, is not explored.
- Coarse discretisation of the regolith means that the timescales of radionuclide transport and accumulation are not modelled appropriately in a system for which time-dependent landscape evolution is considered of fundamental importance. This approach results in higher doses for shorter lived radionuclides, but underestimates results for decay chains.
- The representation of drilled wells in the main calculation cases is based on very small capture fractions (much less than 1%). Capture fractions greater than 10% appear feasible based on reasonable alternative assumptions.

In addition to the above points, SKB note that the inventory for Mo-93, which is shown to be the dominating radionuclide for the main calculation cases, may be underestimated by a factor of about one third[84].

Some of these points would tend to increase calculated doses in comparison to the central results presented in the SR-PSU assessment (increased inventory, delineation of biosphere objects, radionuclide releases from time zero, distributed releases to the biosphere, increased well capture fractions). Other points reflect on the degree of confidence that can be placed on the numerical results, implying additional bounds of uncertainty that need to be taken into consideration.

5.2. Issues Identified for Further Review

Issues identified for consideration during the main review phase are listed in Appendix 3. The suggestions are summarised below.

- The hydrological modelling used in support of SR-PSU warrants detailed review. Particular aspects of interest are (i) the near-surface hydrological modelling and its abstraction for use in the assessment modelling, (ii) the robustness of the fracture flow and particle tracking calculations that support the predicted discharge locations and well capture fractions, (iii) the modelling of nearfield and geosphere flows during periglacial conditions.
- Review of the probabilistic approach adopted in SR-PSU and the associated analysis of confidence.
- Gain in-depth understanding of the SR-PSU biosphere model for key radionuclides through its implementation in an independent software code. This will allow the results for key radionuclides to be verified as well as facilitate exploration of the significance of issues identified in review.

[83] p271 of the Main Report.
[84] p350 of the Main Report.

- Dynamically model agricultural systems for key radionuclides to gain an understanding of the simplifications adopted in the stylised way in which agricultural soils are represented in SR-PSU.
- When it becomes available, review the Biosphere FEP Handling Report and the way in which it demonstrates an audit trail from the Biosphere Processes Report to the Biosphere Model Report.
- The way in which the landscape evolution modelling is abstracted to support parameterisation in the radionuclide transport and dose calculations merits detailed review.
- Detailed review of the modelling of C-14 in the sub-surface, with particular emphasis on the potential importance of methane, which is omitted from the SR-PSU model.
- Detailed scrutiny of the parameter definition process for Kd and CR.
- Comparison of SR-PSU assumptions with regards to the non-human biota assessment with those in the latest version of ERICA for key radionuclides and wildlife species.

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APPENDIX 1

Coverage of SKB reports

Following reports have been covered in the review.

Table A1-1: Coverage of SR-PSU reports.

Reviewed report	Reviewed sections	Comments
TR-14-01	1, 2, 4, 6, 7, 8, 9, 10, 11 Appendices A, B	Broad review, but with particular focus on biosphere issues. See also editorial observations made in Appendix 4.
TR-14-06	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11	Thorough review. See also editorial observations made in Appendix 4.
R-13-46	1, 2, 3, 4, 5, 6, 7, 8, 8, 10, 11	Thorough review.
R-13-18	See comments column	Selected review in exploring issues identified in reviewing the top-level reports.
R-13-01	1, 2, 3, 4, 5, 6, 7, 8, 9, 10	Broad review in tracking data back to source.
TR-14-09	5, 6, 7	Targeted review in exploring issues identified in reviewing the Main Report.

APPENDIX 2

Suggested needs for complementary information from SKB

1. Ecolego models and supporting data files sufficient to reproduce the SR-PSU results.
2. Provide explanations for (i) the protracted way in which the SR-PSU reports were published, (ii) the inconsistency between the dates on the published reports and the publication dates and (iii) how SKB plans on handling issues identified in review and finalisation of the SR-PSU reports published after the SR-PSU Main Report.
3. Provide a response from SKB relating to 'Dealing with climate evolution' in relation to SSM's general advice relating to SSMFS 2008:37 (i.e. in place of the duplicated text on p408 of the Main Report).
4. Provide landscape modelling results at a scale that is more appropriate to the SFR assessment.
5. Provide an explanation for why the present-day lakes highlighted in Figure 6 are over-looked in the landscape modelling reproduction of the present-day landscape.
6. Provide further information to support SKB's confidence that no lake or stream will be present in biosphere object 157_2 in the future.
7. Provide further justification for the use of the mean result as the 'representative value' for comparison against the risk criteria.
8. Provide further description of the way in which radionuclide transport and dose calculations were undertaken for SR-PSU. In particular, (i) explain how data was passed forwards from each step in the modelling chain, (ii) explain where the same or different sequences of sampled parameters are used (i.e. relating to the use of sample seeds).
9. Provide an explanation for the presence of well number 12 in Tables 12-1 and 12-2 of the Biosphere Parameters Report when it is omitted from Werner et al. (2013).
10. Provide an explanation as to which set of hydrological data are used in support of the global warming calculation case. It is unclear if it is the data for the present-day, as suggested on p18 of the Biosphere Parameters Report, or if it is the data for a warmer, wetter climate, as suggested on p53 of the Biosphere Parameters Report.
11. Provide access to the 'Kd/CR compilation' database (Microsoft Access format). This should involve a minimum of 'several' illustrative examples of database content. Preferably, the entire database would be made available.

12. Provide clarification of what quality assurance and verification procedures were adopted for models implemented in the software codes (i.e. quality assurance of the implemented models, not the software codes[85]).
13. Provide clarification whether any verification of the implementation of the ERICA models and data within the Ecolego biosphere models was undertaken, e.g. by comparing ERICA results against non-human biota doses calculated by the Ecolego biosphere model.
14. Provide an explanation for the apparent discrepancy between p164 of the Biosphere Synthesis Report, which states that agricultural 'soil concentrations were modelled dynamically after drainage', and p106 of the Biosphere Model Report, which states that concentrations in cultivated soils were modelled 'without running dynamic simulations'.

[85] There are notes on the quality assurance of the software codes in SKB (2014c).

APPENDIX 3

Suggested review topics for SSM

1. When it becomes available, review the Biosphere FEP Handling Report and the way in which it demonstrates an audit trail from the Biosphere Processes Report to the Biosphere Model Report.
2. Several issues have been identified regarding the hydrological modelling and interpretation undertaken in support of SR-PSU.
    a. The near-surface hydrological modelling and its abstraction for use in the radionuclide transport calculations merits consideration for detailed review. For example, the way in which horizontal flows is neglected in the till.
    b. The robustness and accuracy of the fracture flow and particle tracking modelling that is used in support of the definition of discharge locations and in the well capture fraction calculations merits consideration for detailed review.
    c. The way in which groundwater flows are represented in the near-field and geosphere during periglacial conditions merits consideration for detailed review.
3. The way in which the landscape evolution modelling is abstracted to support parameterisation in the radionuclide transport and dose calculations merits detailed review.
4. Review of the probabilistic approach adopted in SR-PSU and the associated analysis of confidence.
5. Gain in-depth understanding of the SR-PSU biosphere model for key radionuclides through its implementation in an independent software code. This will allow the results for key radionuclides to be verified as well as facilitate exploration of the significance of issues identified in review. Those issues include those already identified, including those noted below. This topic also has the potential to be undertaken in conjunction with a parallel study of the near-field and geosphere modelling (Towler et al., 2015).
    a. Why the key radionuclide Mo-93 is the only one for which the highest LDF occurs outside biosphere object 157_2.
    b. The representation of the fish pathway.
    c. The accumulation period for agricultural systems.
    d. Plant immobilisation.
    e. The period between irrigation and harvest.
    f. Translocation.
6. Building on 5, undertake a detailed review of the SR-PSU biosphere model for agricultural systems, including dynamic representation for key radionuclides.
7. Modelling-based review of the relative importance of the C-14 source-term and the effect of carbon speciation in the sub-surface (methane *versus* CO_2).
8. Detailed scrutiny of the parameter definition process for Kd and CR, including investigation of practical processes involved in defining

'plausible parameter variation' and how this relates to the 'Kd/CR compilation' data-base.

9. Comparison of SR-PSU assumptions with regards to the non-human biota assessment with those in the latest version of ERICA for key radionuclides and wildlife species.

APPENDIX 4

Editorial Issues in SR-PSU Documentation

Editorial observations relating to the Main Report and Biosphere Synthesis Report are given in the tables below.

Table A4-1: Editorial observations relating to the SR-PSU Main Report.

Page	Text	Comment
288	[Title for summary dose tables]	Titles should emphasise that the peak values relate to the arithmetic mean.
324	The highest dose obtained for the on-site drilling crew was 250 **mSv** at year 3000 AD,	Comparison with Figure 9-44 suggests that there is a typographical error in the dose units and that they should be **μSv** rather than mSv.
326	The highest dose was 1 **mSv**	Comparison with Figure 9-46 suggests that there is a typographical error in the dose units and that they should be **μSv** rather than mSv.
331	Peak dose [**mSv**]	Should be **μSv**.
332	Peak dose [**mSv**]	Should be **μSv**.
408	[All highlighted text on 'Handling in SR-PSU']	The text is a reproduction of the last paragraph of regulatory guidance. Presumably, this is an editorial error.

Table A4-2: Editorial observations relating to the SR-PSU Biosphere Synthesis Report.

Page	Text	Comment
58	The present summary of regolith development in Forsmark **in** based on Lindborg (2010)	Should be '**is** based on'.
115	Figure 6-14	Needs a scale.
199	[Cross-reference to **Table 7-2**]	Should be to **Table 7-5**.

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4

Review of Quality Assurance in SKB's Safety Assessment SR-PSU

Activity number: 3030014-1010
Registration number: SSM2015-1078-4
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Abstract

This quality assurance (QA) review has considered SKB's overall approach to QA in the SR-PSU safety assessment. The review has focused on how SKB has implemented its QA plans and QA instructions, and has included model and parameter spot checks.

Generally, the QA instructions provide comprehensive coverage of quality-affecting issues relating to the safety assessment. However, the QA review has found that:

- SKB reviewed and approved many of the instructions after publication of the SR-PSU safety assessment and it is not clear what versions were used in the production of the safety assessment.
- The QA instruction concerned with the development of process descriptions does not cover biosphere processes.
- SKB takes a graded approach to code QA, which is good practice. However, there is no guidance on what constitutes evidence of acceptable QA for commercial or open source codes. Also, it is not clear if checks are undertaken to confirm that codes have been used correctly and there is no requirement to consider code validation.

The Ecolego code was selected for detailed QA review. The discussion of Ecolego in the Model Summary Report is not comprehensive and does not give a clear picture of the QA status of the code and how it has been used in the safety assessment. However, combined with material presented in other SR-PSU reports, sufficient information is provided to give confidence that Ecolego has an acceptable standard of QA.

Review of the Data Report focused on the metallic corrosion parameter. The discussion of the parameter in the Data Report fails to meet the detailed and thorough requirements set out in the instruction for supplying data. In particular:

- No specific references are made to the modelling activities that use the data, which hinders traceability.
- No detailed information has been provided on where corrosion rate data are located in background documents; such information is required according to SKB's instruction on supplying data.
- No information is given about how the data are qualified.
- There is no discussion of how uncertainty has been evaluated.
- There are inconsistencies in corrosion rates reported in different SR-PSU reports.

Generally, the information provided is insufficient to give the necessary confidence that the data on metal corrosion rates are suitably qualified for use in the SR-PSU safety assessment.

Contents

1. Introduction

On 19 December 2014, the Swedish Nuclear Fuel and Waste Management Company, SKB, submitted an application to the Swedish Radiation Safety Authority (SSM) for the expansion of SKB's final repository for low and intermediate level waste at Forsmark. SSM is in the process of reviewing the application.

SKB's assessment of the long-term safety of the repository is documented in the SR-PSU safety assessment (SKB, 2014a). SSM is undertaking a phased review of the safety assessment, which involves an initial review and a main review. Currently, the initial review phase is being undertaken, where the objectives are to develop a broad understanding of the application, to judge whether the application is complete and to identify key topics for the main review phase. Requests to SKB for any complementary information required to assess the application will be made by SSM at the end of the initial review phase.

In support of SSM's initial review of SR-PSU, Galson Sciences Ltd has been contracted by SSM to review SKB's safety analysis methodology and the approach to quality assurance (QA) in SR-PSU. This report presents the results of the review of QA in SR-PSU. The review of SKB's safety analysis methodology is presented in a separate report to SSM.

The QA review has considered SKB's overall approach to QA of the safety assessment and has focused on how SKB has implemented its QA plans. The review has included spot checks on one model referred to in the Model Summary Report (SKB, 2014b) and one parameter referred to in the Data Report (SKB, 2014c) to assess how SKB's QA procedures have been implemented.

2. QA Review

The Main Report of the SR-PSU safety assessment includes a discussion of the quality management system used by SKB in conducting the assessment (SKB, 2014a, §2.7 and §4.1.1). SKB (2014a, §4.1.1) states that the quality management system meets the requirements in ISO 9001:2000; although not stated in the report, it is presumed that this system is certified.

SKB (2014a, §2.7) lists a number of steering documents produced by SKB that reflect project management and safety audit procedures. In response to a request from SSM, SKB provided a number of these steering documents for this QA review. Although not provided for the QA review, SKB has indicated that the Project Decision, the Project Plan and the Document Management Plan for the SFR Extension Project (all in Swedish) would be available for SSM to see at SKB's offices. The steering documents are listed in Table 1, and the document language and whether the document has been provided by SKB for the QA review are indicated.

SKB's overall approach to QA has been assessed by reviewing the steering documents provided to determine whether they are sufficiently comprehensive that their application ensures that the expected requirements of a QA programme are met. For example, consideration has been given to whether appropriate application of these documents would ensure that transparency and traceability of information would be sufficient to enable judgments to be made regarding the reliability and validity of the safety assessment.

Table 1: SKB's steering documents for SR-PSU (SKB, 2014a, Table 2-2).

Object	Language	Comment
Project decision	Swedish	Not provided for the QA review, but available to review at SKB's offices.
Project plan	Swedish	Not provided for the QA review, but available to review at SKB's offices.
Quality plan for the SFR Extension project	Swedish	Provided, but not reviewed.
Document management plan SFR Extension project	Swedish	Not provided for the QA review, but available to review at SKB's offices.
Instruction for qualification of "old" references	English	Provided and reviewed.
Quality assurance plan SR-PSU	English	Provided and reviewed.
Instructions for developing process descriptions in SR-PSU	English	Provided and reviewed.
Instructions for development and handling of the SKB FEP database – Version SR-PSU	English	Provided and reviewed.
SR-PSU model summary report instruction	English	Provided and reviewed.
Supplying data for the SR-PSU Data report	English	Provided and reviewed.
Instruction for use of preliminary data used in SR-PSU calculations/modelling	English	Provided and reviewed.
Instruction for model and data quality assurance for the SR-PSU project	English	Provided and reviewed.

The steering documents for SR-PSU are similar to those used in preparation of SKB's SR-Site safety assessment for a spent fuel repository. The SR-Site steering documents were reviewed on behalf of SSM by Baldwin and Hicks (2009; 2012). Some of the findings from the SR-Site QA document reviews are relevant to the SR-PSU steering documents.

It is noted that, according to the document review and approval details, although the steering documents were written in the period 2010 to 2012, several of them were reviewed and approved in July 2015; that is, after the production of the SR-PSU safety assessment. Each steering document ends with a 'register of revisions' table, but details of the reviewer and approver are not stated explicitly for each version of the document where more than one version has been produced; reference is simply made to the header which only shows details for the final version of the document. Also, the revisions made between use of the steering documents in the production of the SR-PSU safety assessment and the versions supplied for the QA review are not apparent. It would have been preferable if the versions of the procedures applied in the safety assessment had been provided for SSM's QA review.

Findings from the review of each steering document are reported in the following sub-sections.

2.1. SDU-115 – Qualification of Old References in SR-PSU

This steering document is concerned with checking the quality of old SKB references or references external to SKB that are cited in the SR-PSU safety assessment reports, but which do not have a clearly documented factual or quality review.

The procedure requires that the qualification of such references is made and documented in the report that uses the cited information. Furthermore, the results and arguments from such references should be documented in the report, rather than just cited, such that the reliability of the arguments can be checked by reviewers without the need to consult the cited references. The procedure is, however, restricted to 'supporting references' that support or justify a decision and treatment of an issue; it does not apply to 'general references' that exemplify or describe an issue. Judgments about why supporting references are considered adequate from a quality assurance perspective are included in a dedicated section in the process reports.

It is noted that the steering document refers to the testing of this approach on the Fuel and Canister process report. Presumably this is referring to testing that was undertaken as part of the SR-Site safety assessment work, because such a report has not been produced as part of the SR-PSU safety assessment.

If it has been applied correctly, the approach to qualifying old SKB references or references external to SKB, as presented in the steering document, will give confidence in the reliability of safety arguments. However, this initial QA review task has only checked the scope of the procedure. The procedure's application in the SR-PSU process reports has not been checked in any detail, although the Engineered Barrier Process Report (SKB, 2014d), for example, indicates that the vast majority of supporting references are peer-reviewed articles or documents that have undergone factual review. It is recommended that subsequent SSM review tasks undertake detailed checks of how the procedure has been applied in the SR-PSU process reports.

2.2. SDU-501 – Quality Assurance Plan for the Safety Assessment SR-PSU

The Quality Assurance Plan aims to ensure that all factors relevant to long-term safety have been considered and handled appropriately in the SR-PSU safety assessment. The plan covers organisational aspects, QA audits, steering documents, demonstration that regulatory requirements are met, the selection of experts to contribute to the safety assessment, QA in report production, document management, feature, event and process (FEP) handling, and modelling (including data usage). Generally, the plan covers the range of QA issues relevant to the production of a safety assessment and makes suitable references to the QA steering documents for details of the procedures followed in each QA area.

It is recommended that two QA processes are checked to further build confidence in how SKB has applied its QA procedures in the SR-PSU safety assessment:

- The Quality Assurance Plan indicates that internal QA audits are conducted according to procedure SD-005 in SKB's management system. SSM could ask to inspect the QA audit reports and check them against the QA audit procedure, in particular, to confirm that any corrective actions have been implemented. Note that details of the QA audit procedure SD-005 are missing from the reference list in the Quality Assurance Plan.
- The Quality Assurance Plan states that all of the SR-PSU reports have been peer reviewed. SSM could ask to inspect the documentation that shows how peer review comments have been addressed for each report.

2.3. SDU-502 – Instruction for Developing Process Descriptions in SR-PSU

This steering document is concerned with the development of process descriptions for the SR-PSU safety assessment. The procedure applies to FEPs judged to be relevant to the safety assessment. Instructions on how to present process descriptions are provided, including on how to show couplings between processes and variables. The steering document also requires that an audit against the Nuclear Energy Agency (NEA) FEP database is carried out. The steering document presents comprehensive instructions on how processes judged as relevant in FEP analysis should be described in the process reports.

The procedure includes the requirement to discuss how the processes, including uncertainties, are handled in the safety assessment. There appears to be no requirement to ensure consistency between the process descriptions and the discussions of processes associated with the data presented in the Data Report.

Also, the instruction is not intended to apply to the development of biosphere process descriptions, but no indication is given as to what QA process is followed in developing the biosphere process descriptions. However, the Biosphere Synthesis Report (SKB, 2014e, §2.4.3) does discuss how SKB's approach to the treatment of the biosphere is consistent with the International Atomic Energy Agency's (IAEA) BIOMASS methodology.

2.4. SDU-503 – Instruction for Development and Handling of the SKB FEP Database – Version SR-PSU

The instruction on development and management of the SR-PSU FEP database relates to the activities of the SR-PSU FEP team. The instruction is based on the instruction developed for the SR-Site project. The development of the FEP database, including requirements for cross-referencing between FEPs and their treatment in SR-PSU reports (e.g. process reports), and links to NEA FEPs are covered by the procedure. With regard to documenting links between biosphere FEPs and processes, the procedure refers to the steering document on developing process descriptions, but the procedure on process descriptions explicitly does not cover the development of biosphere process descriptions (see Section 2.3).

Parts of the instruction are included in the quality assurance section of the FEP Report (SKB, 2014f, §2.3). The requirement to maintain an informal log of actions during the development of the database, as stated in the instruction, has not been re-stated in the FEP Report (SKB, 2014f, §2.3.4). Presumably this does not mean that the log of actions was not maintained.

A review of FEP handling in the SR-PSU safety assessment has been undertaken as part of the review SKB's safety analysis methodology noted in Section 0 and has been reported separately.

2.5. SDU-504 – SR-PSU Model Summary Report Instruction

The Model Summary Report instruction is included in the Model Summary Report (SKB, 2014b, §2) and is almost identical to that used by SKB for the SR-Site safety assessment, as reproduced in the SR-Site Model Summary Report (SKB, 2010a, §2). The instruction is concerned with procedures for ensuring that the computer codes used in the safety assessment are suitably quality assured and that the process of selecting codes and using them in the safety assessment is justified and recorded in the Model Summary Report.

The Model Summary Report instruction indicates that a graded approach to software QA has been taken. Under this approach, in order to determine the QA procedure to be applied, the codes have been categorised broadly as follows:

1. Commercial system software such as operating systems, compilers and data base software.
2. Software used to solve problems that can be verified by simple calculations.
3. Wide-spread commercial or open source codes.
4a. Modified commercial codes.
4b. Calculations performed with codes developed within the safety assessment.

This graded approach to code QA represents good practice and has been adopted by other radioactive waste management organisations, as discussed by Hicks (2005, §4.4) in a previous code QA review.

The Model Summary Report instruction also lists a number of basic requirements on QA of each code and its application. These requirements are summarised here as:

- Show that the code is suitable for its purpose – required for all categories of code.
- Show that the code has been used properly – required for all categories of code.
- Show that the code development process has followed appropriate procedures and that the code produces accurate results – required for Category 4a and 4b codes, but the developer's procedures are accepted for codes in Categories 1, 2, and 3.
- Describe how data are transferred between the different computational tasks. Although not stated in the instruction, this is presumably required for all categories of code.

A template is included for recording these code QA issues in the Model Summary Report, which broadly covers the following:

- A description of the code, its usage in the assessment and its categorisation.
- The suitability of the code for the application in the assessment.
- Information on code usage and documentation.
- A discussion of the code development process and code verification (for Category 4 codes).
- Handling of data (inputs and outputs).
- The rationale for using the code in the SR-Can safety assessment.

It is apparent that the use of Category 1, 2 and 3 software for assessment calculations implies that the QA procedures used by the code developer have been accepted by SKB. However, it is not clear what process SKB follows or what checks are undertaken to ensure that the developer's procedures meet SKB's software QA requirements. This is of particular importance for Category 3 (commercial or open source) codes. Broadly, there appears to be a general acceptance of QA based on the size of the user base of a Category 3 code; that is, a large user base implies sufficient code verification. A discussion of code development and verification is only required for Category 4 codes. There is no guidance on what constitutes evidence that a code can be classed as Category 3 with acceptable QA. Further, for Category 2 software, the Model Summary Report instruction does not state any minimum requirements for checking that the simple verification calculations have been undertaken and recorded. Furthermore, it is not clear if checks are undertaken to confirm that Category 3 and Category 4 codes have been used correctly (i.e. independent checks that the codes have been implemented to solve the equations and problem as intended). Similar observations were made by SKI&SSI (2008, §4) on the SR-Can approach and Baldwin and Hicks (2012, §2.6) on the SR-Site approach.

The requirement to document the suitability of a code for its application in the SR-PSU safety assessment essentially relates to code validation. However, the template (SKB, 2014b, §2.5.2) focuses on the need to present a description of mathematical models and solution methods rather than a discussion of any testing of code validity. The requirement could be expressed more explicitly in terms of the need to present an understanding of why the code is considered valid for the problem addressed in the safety assessment. For example, reference could be made to any analysis that has been done to show that the code can produce accurate representations of the types of problems being addressed in the SR-PSU safety assessment.

A review of the application of this instruction is given in Section 2.9.

2.6. SDU-505 – Supplying Data for the SR-PSU Data Report

The instruction on supplying data for the SR-PSU Data Report is reproduced in the Data Report (SKB, 2014c, §2) and is similar to that used by SKB for the SR-Site safety assessment, as reproduced in the SR-Site Data Report (SKB, 2010b, §2.3). The instruction is concerned with procedures for qualifying input data for the SR-PSU safety assessment calculations and is comprehensive in terms of the scope of what is expected with regard to data requirements, reporting (including uncertainties and variability) and qualification. Helpful examples are provided of how qualified and supporting data should be cited and tabulated, how data sets could be illustrated, and how recommended data, including uncertainties, can be documented.

Data are categorised as either qualified or supporting. Qualified data are data that have been produced "within, and/or in accordance with, the current framework of data qualification"; this includes data from peer-reviewed literature. Supporting data are data that have been produced "outside, and/or in divergence with, the framework". Data produced by SKB prior to the implementation of its quality assurance system, or data produced by other organisations are classified as supporting data. Note that there is inconsistency in the use of the term "supporting" within the SR-PSU safety assessment. With regard to references, supporting refers to information that supports or justifies a decision and treatment of an issue in the safety assessment and covers SKB references as well as old SKB references and references external to SKB (if suitably qualified for use) (see Section 2.1).

The instruction makes it clear that the Data Report is only concerned with data that are identified to be of particular significance for assessing repository safety, but how the significant data are identified is not discussed. However, the Data Report (SKB, 2014c, §1.3.2 and §2.1) clarifies that the data of particular significance for assessing repository safety and requiring qualification are those that relate to the safety functions provided by the technical barriers and geological environment. The safety functions together ensure that the safety principles of limiting the radioactive inventory and retaining radionuclides are met. On this basis, the scope of application of the instruction is appropriate.

A review of the application of this instruction is given in Section 2.10.

2.7. SDU-507 – Instruction for use of Preliminary Data used in SR-PSU Calculations/Modelling

The instruction for use of preliminary data is concerned with the qualification of data used in analyses and calculations that were undertaken prior to the qualification of data reported in the Data Report (SKB, 2014c) or other SR-PSU 'background reports'. A process is described for checking that the data used in the preliminary analyses are consistent with the data presented in the Data Report (or other reports) and the format of a table is provided for recording the results of the check and any actions required in the event of inconsistencies being found.

The documents produced as part of the data control process are stored on SKB's SKBdoc document management system. This data control process is an important step in ensuring consistency of approach throughout the SR-PSU safety assessment. It is recommended that a review is undertaken by SSM to check that the data control process has been implemented correctly and that qualified data have been used in the analyses and calculations reported in the safety assessment reports.

2.8. SDU-508 – Instruction for Model and Data Quality Assurance for the SR-PSU Project

The model and data quality assurance instruction is concerned with the management of model calculations and input data for the SR-PSU safety assessment. The instruction lists 'objects' that are important to model and data QA, which are: the Assessment Model Flowchart; Process Reports; the Initial State Report; the Data Report; the Data Storage; the Model Summary Report; the Model Storage; Planning Documents; the Calculation Reports; control of data used in calculations/modelling tasks; and the Issue Tracking System.

Not all of these objects are discussed as claimed in the instruction (i.e. Process Reports, the Initial State Report and control of data used in calculations/modelling tasks are not discussed). Furthermore, although instructions are available relating to procedures for most of these objects, an instruction for preparation of the Initial State Report has not been identified in this QA review.

The Planning Documents describe the planning and progression of work in the safety assessment, especially computational tasks. The coverage of the Planning Documents includes input data requirements, input storage, code specification, code storage, and how results are to be presented and stored. The results of calculations are presented in Calculation Reports, which include descriptions of the calculational approach, codes and hardware, the work performed and the results. The Planning Documents and Calculation Reports thus appear to be important objects produced in the development of the SR-PSU safety assessment. The instruction does not discuss any requirements on QA checking of Calculation Reports or verification of code implementation (i.e. independent checks that the code has been used as intended). Possibly the Issue Tracking system is intended to be used to record such checks but this is not clear and use of the system is optional. Also, it is not clear if the Calculation Reports are published by SKB. It is recommended that a review is undertaken by SSM to check the QA status of Calculation Reports and how the results are used, their content against Planning Document requirements, how SKB checks that a code has been used as intended (i.e. to solve the intended equations and problem), and how the Issue Tracking system has been used.

The Data Storage and Model Storage are storage areas for the large amount of data and the codes (including Excel spreadsheets and compiled codes) used in the SR-PSU safety assessment. The implementation of such a centralised storage area, with code version control, represents good practice. However, codes used and owned by contractors are not required to be stored in the centralised storage area. It is not clear how SKB checks that suitable version control and storage of codes is maintained by such contractors.

2.9. QA Review of a Selected Model

The Model Summary Report (SKB, 2014b) discusses the QA of 14 codes used in the SR-PSU safety assessment. These codes are listed in Table 2 and brief comments are given on the QA discussions in the Model Summary Report.

The approach to discussing code QA in the Model Summary Report is varied. In some cases, the discussion is brief and websites and other reports need to be consulted to gain a clear understanding of the QA status of the code (e.g. ArcGIS, Comsol Multiphysics and Ecolego). In contrast, other codes are described in clear detail and include information on code validation tests (e.g. LOVECLIM, Numerical GIA Model, Numerical Permafrost Model, and Numerical Ice Sheet Model). The tendency appears to be for less to be written about the QA of Category 3 codes. A consistent approach to documenting code QA should be followed, as exemplified by that for the Category 3 code LOVECLIM.

The Model Summary Report (SKB, 2014b, Table 2-1) lists the modelling activities for which each code presented in the report has been used. The modelling activities are as shown on the Assessment Model Flowchart (AMF) (SKB, 2014b, Appendix A). Numbers indicating AMF outputs are also listed in SKB (2014b, Table 2-1) and shown on the AMF, although the meaning of these numbers is not explained in the report or on the AMF. However, the Main Report (SKB, 2014a, §3.4.3) explains that each coupling between the assessment activities has been given a number that points to a chapter in the Input Data Report (SKB, 2014g) where data are described. Thus, the numbers shown in SKB (2014b, Table 2-1) are keys to code data outputs (which are inputs to other activities) as described in the Input Data Report (SKB, 2014g) (apart from number 212, which refers to the final calculation of dose and is not an input to another activity). These links should have been explained clearly in the Model Summary Report.

SKB (2014b, Table 2-1) is helpful in terms of providing links to the AMF, which engenders an understanding of where the codes fit in within the overall safety assessment. However, traceability of code usage and inputs/outputs would have been improved if the discussion of each code in SKB (2014b, §3) had included extracts from the AMF that showed the different activities for which the code had been used. That is, the boxes from the AMF showing the activities that involved the code, and the numbers indicating the immediate inputs and outputs as discussed in the Input Data Report (SKB, 2014g), could have been included.

A complete list of assessment activities is given in SKB (2014a, Appendix F), including numbers that show where the code inputs are discussed in the Input Data Report (SKB, 2014g). As well as the codes discussed in the Model Summary Report, SKB (2014a, Appendix F) includes activities described as literature reviews, expert judgements and analytical solutions. The code FastReact is listed as being used for geochemical evolution calculations, but the QA status of FastReact is not discussed in the Model Summary Report. SSM should request information on the QA of FastReact for the SR-PSU safety assessment and could also consider reviewing QA in the implementation of the various analytical solutions referred to in SKB (2014a, Appendix F).

Table 2: Codes used in the SR-PSU safety assessment and discussed in the Model Summary Report (SKB, 2014b). Code categories are noted (see Section 2.5) and general observations on the QA discussions provided in the Model Summary Report are given.

Code	Category	Comment
3DEC	3	Used in SR-Can and SR-Site. No discussion of validation testing. Verification discussed even though it is a Category 3 code.
ADINA	3	No discussion of validation testing. Verification discussed even though it is a Category 3 code.
ArcGIS	Not stated	No categorisation given, but appears to be a Category 3 code. Used in SR-Site. Discussion of the code is rather brief, especially regarding code usage in SR-PSU. No discussion of validation testing.
CCSM4	3	Previous version (CCSM3) used in SR-Site. Clear discussion of the code, including code validation. Verification discussed even though it is a Category 3 code.
Comsol Multiphysics (iDC interface)	3 (4a)	Not used previously by SKB in safety assessments. No information on the version of iDC used. Discussion of QA is brief, with reference to task reports for information on the suitability of the code and its development and verification.
DarcyTools	4b	Used in SR-Site. No clear description of how the code has been used in SR-PSU. Clear discussion of code QA, including code validation.
Ecolego	3	Used in SR-Site. Discussion of the code is brief. The code platform is not given. There is a reference to validation against other codes. Verification discussed even though it is a Category 3 code. The 'unit testing methodology' is mentioned but not explained.
LOVECLIM	3	No mention of any previous use by SKB in safety assessments. Clear discussion of code QA, including code validation. Verification discussed even though it is a Category 3 code.
MIKE SHE	3	No mention of any previous use by SKB in safety assessments. Clear discussion of code QA, but not code validation testing. Verification discussed even though it is a Category 3 code.
Numerical GIA model	4b	Used in SAR-08, SR-Can and SR-Site. Clear discussion of code QA, including code validation. No code version number given.
Numerical permafrost model	4b	Used in SR-Can and SR-Site. Clear discussion of code QA, including code validation.
Numerical ice sheet model (UMISM)	4b	Used in SR-Site. Clear discussion of code QA, including code validation. No code version number given.
PHAST	3	Used in SR-Site. Clear discussion of the code, but little on verification (although it is a Category 3 code) and no discussion of validation testing.
PHREEQC	3	No mention of any previous use by SKB in safety assessments. Clear discussion of the code, but little on verification (although it is a Category 3 code) and no discussion of validation testing.

As part of this QA review, a safety assessment model has been selected for review to assess how SKB has implemented its QA methodology. Given its importance to the safety assessment and its limited discussion in the Model Summary Report, the Ecolego code has been chosen for more detailed review. Ecolego has been used in four activities according to the AMF:

- Corrosion of reactor pressure vessels (waste category).
- Radionuclide transport in water phase (near-field category).
- Radionuclide transport in water phase (geosphere category).
- Radionuclide transport and dose (biosphere category).

In each case, SKB (2014b, Table 2-1) refers to the Radionuclide Transport Report (SKB, 2014h) for a discussion of the activity. A discussion of Ecolego QA is presented in Section 3.7 of the Model Summary Report (SKB, 2014b) and observations on Section 3.7 follow.

Introduction (SKB, 2014b, §3.7.1):

- The introduction simply states that Ecolego is used in SR-PSU for modelling and simulating radionuclide transport in the near-field, geosphere and biosphere; no references are given as to where these applications are discussed in SR-PSU. Reference to, or reproduction of, Figure 2-3 in the Radionuclide Transport Report (SKB, 2014h) (which is essentially a component of the AMF) would have provided a clear indication of how Ecolego had been used in a chain of model activities.
- It is stated that Ecolego was used in the SR-Site safety assessment, but the version of the code used in SR-Site is not given. Ecolego 6.0 was used in SR-PSU. No information is given on the code platform used in the assessment calculations.

Suitability of the code (SKB, 2014b, §3.7.2):

- There is no discussion of the suitability of the code for solving the problems for which it has been used in SR-PSU. Instead some useful features of the model are listed, but this does not provide any information to give confidence that the model solves the required equations and gives acceptable results over the parameter value ranges used in the assessment. Reference is made to the Radionuclide Transport Report (SKB, 2014h) and Saetre *et al*. (2013) for discussion of the Ecolego mathematical models. These documents do provide full descriptions of the Ecolego models (e.g. SKB, 2014h, §9).

Usage of the code (SKB, 2014b, §3.7.3):

- Reference is made to the user guide at www.ecolego.facilia.se, which does provide tutorials on constructing models.

Development process and verification (SKB, 2014b, §3.7.4):

- Although SKB's template does not require the code development process and verification information to be provided for Category 3 codes, some information has been provided for Ecolego. Code comparisons with analytical solutions and other software are noted, but no information has been provided on the types of problem for which Ecolego has been validated. Testing using the unit testing methodology is noted but not explained. The Radionuclide Transport Report (SKB, 2014h, §2.4.2 and

Appendix B) discusses successful comparisons of Ecolego with Simulink/Pandora and FARF31; it is surprising that these tests are not discussed in the Model Summary Report. The validation tests have not been checked under this QA review.

Handling of input data, computational results and scripts (SKB, 2014b, §3.7.5):

- There is no discussion of the inputs to the code or how the results are used by other codes. For Ecolego, it appears from the AMF that outputs from one Ecolego radionuclide transport modelling activity become inputs to another Ecolego radionuclide transport modelling activity.

Rationale for using the code in the assessment (SKB, 2014b, §3.7.6):

- A reasonable rationale for using the code is provided. Essentially, the code is designed for the type of risk assessment undertaken in SR-PSU.

In summary, the discussion of Ecolego in the Model Summary Report is not comprehensive and does not give a clear picture of the QA status of the model and how it has been used in the SR-PSU safety assessment. However, with the information presented in the Radionuclide Transport Report (SKB, 2014h) and Saetre *et al*. (2013), sufficient information is provided to give confidence that Ecolego has a standard of QA that is suitable for the assessment and that the code has been implemented appropriately.

2.10. QA Review for a Selected Parameter

The instruction for supplying data for the Data Report is concerned with data that relate to the assessment of the safety functions provided by the technical barriers and geological environment (see Section 2.6). A list of the ten data sets is included in Table 1-2 of the Data Report (SKB, 2014c) and these are consistent with the data requirements of the five safety functions defined in the Main Report (SKB, 2014a, §5.5).

Each of the safety functions has a number of associated safety function indicators (e.g. pH, redox potential, corrosion rate) (SKB, 2014a, Table 5-3) and these are shown in Table 3 for the combinations of data set and safety function discussed in the Data Report. However, not all of these safety function indicators are relevant to a particular data set and safety function combination. Comments in Table 3 relate to the reviewer's attempts to understand which particular safety function indicators are relevant to a particular data set and safety function combination. Greater traceability of information through the safety assessment would have been achieved if the Data Report had included discussion of the specific safety function indicators to which a particular data set pertains.

To improve traceability, for each data set presented in the Data Report (SKB, 2014c), explicit reference should be made to the modelling activities that use the data (i.e. the modelling activities for which the data form inputs in the AMF).

Table 3: Qualified data sets presented in the Data Report (SKB, 2014c), the safety functions to which they relate and the associated safety function indicators (SKB, 2014a, Table 5-3). The comments relate to the reviewer's attempts to identify which of the safety function indicators shown are relevant to the particular safety function/data set combination being considered.

Data sets	Safety functions	Safety function indicators	Comment
Radionuclide decay	Limited quantity of activity	Activity of each radionuclide in each waste vault	
Uncertainties in the radionuclide inventory	Limited quantity of activity	Activity of each radionuclide in each waste vault	
Metallic corrosion	Good retention	pH, redox potential, concentration of complexing agents, available sorption surface area, corrosion rate	Presumably the relevant safety function indicators are pH, redox potential, and corrosion rate (SKB, 2014c, Section 5) – gas pressure would also be relevant
Bitumen swelling pressure	Low water flow in waste vaults	Hydraulic contrast, hydraulic conductivity, gas pressure	Presumably the relevant safety function indicator is hydraulic conductivity, although this link is not made entirely clear in SKB (2014c, Section 6)
Bentonite and Concrete/Cement sorption data	Good retention	pH, redox potential, concentration of complexing agents, available sorption surface area, corrosion rate	Presumably the relevant safety function indicator is available sorption surface area (SKB, 2014c, Section 7)
Rock Matrix and Gravel sorption data	Good retention	pH, redox potential, concentration of complexing agents, available sorption surface area, corrosion rate	Presumably the relevant safety function indicator is available sorption surface area (SKB, 2014c, Section 8)
Concrete/Cement diffusivity data	Good retention	pH, redox potential, concentration of complexing agents, available sorption surface area, corrosion rate	There does not appear to be a safety function indicator relating diffusion to good retention
	Low water flow in waste vaults	Hydraulic contrast, hydraulic conductivity, gas pressure	Presumably the relevant safety function indicator is hydraulic conductivity, although this is not discussed in SKB (2014c, Section 9)
Concrete/Cement hydraulic data	Low water flow in waste vaults	Hydraulic contrast, hydraulic conductivity, gas pressure	Presumably the relevant safety function indicator is hydraulic conductivity (SKB, 2014c, Section 10)
Hydraulic pressure field in the SFR local domain	Low water flow in bedrock	Hydraulic gradient, hydraulic conductivity	Presumably the relevant safety function indicator is hydraulic conductivity (SKB, 2014c, Section 11)
	Low water flow to waste vaults	Hydraulic contrast, Hydraulic conductivity, gas pressure	
Shore-level evolution	Avoid wells in the direct vicinity of the repository	Intrusion wells, wells downstream of the repository	

As part of this QA review, a parameter has been selected for review to assess how SKB has implemented its QA methodology. The discussion of metallic corrosion in SKB (2014c, §5) appears brief, but the parameter affects several coupled processes in the evolution of repository conditions. Therefore, this parameter has been selected for more detailed QA review. Observations on each sub-section of SKB (2014c, §5) follow.

Modelling in SR-PSU (SKB, 2014c, §5.1):

- Brief information is given about why the corrosion rate data are needed (for redox modelling, gas generation modelling and modelling radionuclide release from metallic wastes). However, no reference is made to the modelling activities presented in the AMF or the reference numbers shown on the AMF that indicate where the data are discussed in the Input Data Report (SKB, 2014g). This hinders traceability of information through the safety assessment. The discussion fails to meet SKB's requirement of explaining how the data are used in specific models.

Experience from previous safety assessments (SKB, 2014c, §5.2):

- It is stated that the corrosion rates were used in gas formation calculations in the previous SAFE and SAR-08 safety assessments, but no information is given on the code used or whether it was the same code as used in SR-PSU. No references are given to the previous safety assessment documents for background information.
- It is indicated that in the previous assessment a correlation was assumed between gas generation and oxygen consumption by metal corrosion. No information is provided as to whether a similar correlation is assumed in the SR-PSU safety assessment.
- The discussion of data limitations should be about how data limitations were addressed in previous safety assessments. Instead, the discussion refers to the SR-PSU Waste Process Report and issues relating to the uncertainties in corrosion rates obtained from literature.

Supplier input on use of data in SR-PSU and previous safety assessment (SKB, 2014c, §5.3):

- This section is intended to be about learning from the experience of previous assessments and other modelling activities in order to avoid repeating any errors or misconceptions. It is unclear how the brief discussion of aluminium, zinc, carbon steel and stainless steel corrosion rates relates to learning from previous safety assessments.

Sources of information and documentation of data qualification (SKB, 2014c, §5.4):

- Information is only provided on the source of data on steel corrosion rates. No information is given in this section on aluminium and zinc corrosion rates. A corrosion rate for aluminium and zinc is given in the previous section (SKB, 2014c, §5.3), although the conditions for such a corrosion rate are not discussed.
- Numerous references are listed for supporting data sets. The instruction on supplying data for the SR-PSU Data Report requires that detailed information is provided on the section, table, etc. where the data can be

found. However, no such information has been provided, which does not help traceability.

- No information is given regarding whether the data are qualified or supporting. The data are from an external report and so appear to be supporting data, but no information is provided on the data qualification process used. No information is given to support any judgments that the data are suitably qualified for use in the SR-PSU safety assessment.

Conditions for which data are supplied (SKB, 2014c, §5.5):

- This section should discuss the conditions for which the corrosion rate data have been obtained and justified as relevant to the SR-PSU safety assessment. Presumably the corrosion rate data are directly relevant to the range of conditions expected in the repository, but this is not made clear.

Conceptual uncertainty (SKB, 2014c, §5.6):

- A reasonable discussion is provided of conceptual uncertainty in the method to measure and evaluate corrosion rates. Instantaneous and integrated techniques are discussed and it is noted that instantaneous techniques can give misleadingly high corrosion rates. However, no information is given on the method used to derive the corrosion rate data used in the SR-PSU safety assessment.

Data uncertainty due to precision, bias and representivity (SKB, 2014c, §5.7):

- Precision and bias uncertainties associated with the data used are not discussed. The discussion is actually more concerned with the conditions for which data are supplied (i.e. pH range, temperature range). The corrosion rate data shown in SKB (2014c, Table 5-3 and Table 5-4) claim to take account of uncertainty in the effects of chloride concentrations on general corrosion rates under oxic near-neutral conditions, but there is no discussion of how this uncertainty has been evaluated. There is no detailed discussion of any differences in data sets produced by different researchers.

Spatial and temporal variability (SKB, 2014c, §5.8):

- The effects of expected spatial variability in pH on corrosion rates and decreases in corrosion rates as anoxic conditions develop are discussed. Presumably these effects are accounted for, but it is not made clear.

Correlations (SKB, 2014c, §5.9):

- The discussion of correlations is not clear. It is implied that the corrosion rates are used to calculate gas generation, oxygen consumption, corrosion of reinforcement bars and radionuclide transport, but no details of the correlations are given.

Results of supplier's data qualification (SKB, 2014c, §5.10):

- Corrosion rates are provided for carbon steel, stainless steel, aluminium and zinc (SKB, 2014c, Table 5-3, Table 5-4, Table 5-5). Four values are given for carbon steel and stainless steel to cover alkaline and near-neutral oxic and anoxic conditions. A single value is given for aluminium and zinc for alkaline anoxic conditions, although a high corrosion rate is also assumed in the Main Report for aluminium and zinc under oxic conditions (SKB, 2014a, §6.3.7). Uncertainties in corrosion rates have not been evaluated.

Judgements by the SR-PSU team (SKB, 2014c, §5.11):

- Brief statements that the SR-PSU team agrees with the information and data supplied are recorded. No concerns such as those discussed above are raised.

Data recommended for use in SR-PSU modelling (SKB, 2014c, §5.12):

- Reference is made to the data in SKB (2014c, Table 5-3, Table 5-4, Table 5-5). No guidelines are given on how the data should be used in the modelling.

The presentation of corrosion rate data in the Input Data Report (SKB, 2014g) was checked for consistency with the data given in the Data Report (SKB, 2014c). The following observations are made:

- The corrosion rate data used for calculations of gas production are presented in the Input Data Report (SKB, 2014g, §2.5), but the data are not entirely consistent with those presented in the Data Report (SKB, 2014c, §5.10). The corrosion rate used in the gas production calculations for aluminium and zinc is given as 1 (mm/year), which is the same as that given in the Data Report. However a single corrosion rate of 0.05 μm/year is given for carbon and stainless steel rather than the ranges given in the Data Report.
- The Input Data Report (SKB, 2014g, §2.8) correctly refers to SKB (2014c, Table 5-3 and Table 5-4) for data on the corrosion rate of reactor pressure vessel steel.
- The Input Data Report (SKB, 2014g, §2.15) discusses the literature review activity shown in the AMF to obtain corrosion rate data for steel, stainless steel, aluminium and zinc. Reference is made to SKB (2014c, Table 5-3, Table 5-4 and Table 5-5) for the corrosion rate data.

In summary, the discussion of metallic corrosion in the Data Report is far from comprehensive and does not meet the requirements set out in SKB's instruction for supplying data for the Data Report. In particular, little information is provided to give confidence that the data are suitably qualified for use in the safety assessment.

3. Summary and Conclusions

SSM is undertaking a phased review of SKB's SR-PSU safety assessment involving an initial review and a main review. Currently, the initial review phase is being undertaken. This report presents the results of an initial review of QA in SR-PSU. The review has focused on how SKB has implemented its QA plans, and has included spot checks on one model referred to in the Model Summary Report and one parameter referred to in the Data Report.

Broadly, the review has found that the QA instructions do provide comprehensive coverage of quality-affecting issues relating to the SR-PSU safety assessment and, if implemented correctly, would generate confidence in the reliability of the safety assessment results. The QA instructions are similar to those used by SKB in the preparation of the SR-Site safety assessment.

Key points arising from the QA review of the steering documents are as follows:

- Many of the steering documents were reviewed and approved after publication of the SR-PSU safety assessment. The versions of the documents used in the production of the safety assessment should have been provided for the QA review.
- The steering document concerned with the development of process descriptions for the SR-PSU safety assessment does not cover biosphere processes, but no indication is given as to what QA process is followed in developing the biosphere process descriptions.
- SKB takes a graded approach to code QA according to the instruction on model QA, which is good practice. However, there is no guidance on what constitutes evidence of acceptable QA for a code classed as Category 3 (commercial or open source). Also, it is not clear if checks are undertaken to confirm that codes have been used correctly (e.g. independent checks that commercial or SKB codes have been implemented to solve the equations and problem as intended).
- Further, the instruction on model and data QA does not discuss any requirements on QA checking of calculation reports or verification of code implementation. An Issue Tracking system is referred to, but it is not clear if it is intended to be used to record such checks, and use of the system is optional.
- The instruction on model QA should include a requirement for code validation to be discussed. That is, information should be provided on analysis that has been done to show that the code can produce sufficiently accurate representations of the types of problems being addressed in SR-PSU.

The Model Summary Report discusses the QA of the codes used in the SR-PSU safety assessment. However, there is no discussion of the QA of the code FastReact, which has been used for geochemical evolution calculations. Also, the approach and level of detail provided is quite varied. The tendency appears to be for less to be written about the QA of commercial codes, but a consistent and thorough approach to documenting code QA should be followed.

The Ecolego code was selected for more detailed QA review to assess how SKB has implemented its QA methodology. The discussion of Ecolego is not comprehensive and does not give a particularly clear picture of the QA status of the model and how it has been used in the SR-PSU safety assessment. However, combined with material presented in other SR-PSU reports (e.g. the Radionuclide Transport Report), sufficient information is provided to give confidence that Ecolego has an acceptable standard of QA.

Review of the Data Report focused on the metallic corrosion parameter. The discussion of the parameter fails to meet the detailed and thorough requirements set out in the instruction for supplying data for the Data Report. Numerous problems were found with regard to the level of detail of information provided about metallic corrosion. Some of the main concerns are as follows:

- No specific references are made to the SR-PSU modelling activities that use the data, which hinders traceability.
- Learning from previous assessments is not documented.
- No information has been provided on the section, table, etc. in background documents where corrosion rate data can be found; such information is required according to the instruction on supplying data for the SR-PSU Data Report.
- No information is given about how the data are qualified or whether they are classed as qualified or supporting; the data are from work produced external to SKB for a different purpose to the SR-PSU safety assessment.
- There is no discussion of how uncertainty has been evaluated.
- There are inconsistencies in corrosion rates reported in the Input Data Report and the Data Report.

Generally, the information provided is insufficient to give the necessary confidence that the data on metal corrosion rates are suitably qualified for use in the SR-PSU safety assessment.

4. References

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SKB (2010a). Model Summary Report for the Safety Assessment SR-Site. SKB Technical Report TR-10-51. Svensk Kärnbränslehantering AB, Stockholm, Sweden.

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SKB (2014e). Biosphere Synthesis Report for the Safety Assessment SR-PSU. SKB Technical Report TR-14-06. Svensk Kärnbränslehantering AB, Stockholm, Sweden.

SKB (2014f). FEP Report for the Safety Assessment SR-PSU. SKB Technical Report TR-14-07. Svensk Kärnbränslehantering AB, Stockholm, Sweden.

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SKB (2014h). Radionuclide Transport Report for the Safety Assessment SR-PSU. SKB Technical Report TR-14-09. Svensk Kärnbränslehantering AB, Stockholm, Sweden.

SKI&SSI (2008). Review of SKB's Safety Assessment SR-Can: Contributions in Support of SKI's and SSI's Review by External Consultants. SKI Report 2008:16, SSI Report 2008:06. SKI, Statens kärnkraftinspektion, Stockholm, Sweden.

APPENDIX 1

Coverage of SKB reports

The following reports have been covered in the QA review.

Table A1:1

Reviewed report	Reviewed sections	Comments
TR-14-01, Safety Analysis for SFR Long-term Safety – Main Report for the Safety Assessment SR-PSU	Appendix F, Appendix G	Reviewed to understand traceability of inputs and outputs through modelling activities
TR-14-06, Biosphere Synthesis Report for the Safety Assessment SR-PSU	Section 2.4.3	Checked to understand QA processes in developing the biosphere model
TR-14-07, FEP Report for the Safety Assessment SR-PSU	Section 2.3	Checked FEP steering document against procedure shown in the FEP Report
TR-14-09, Radionuclide Transport Report for the Safety Assessment SR-PSU	Sections 2 and 9	Consulted to understand assessment approach in the context of Ecolego QA
TR-14-10, Data Report for the Safety Assessment SR-PSU	Sections 2 and 5	Spot checked metal corrosion parameter
TR-14-11, Model Summary Report for the Safety Assessment SR-PSU	All sections, with focus on Section 3.7	Spot checked Ecolego QA
TR-14-12, Input Data Report for the Safety Assessment SR-PSU	Sections 2.5, 2.6, 2.8 and 2.15	Checked traceability and consistency of metal corrosion rate treatment
SDU-115, Instruction for qualification of “old” references	All sections	
SDU-501, Quality assurance plan SR-PSU	All sections	
SDU-502, Instructions for developing process descriptions in SR-PSU	All sections	
SDU-503, Instructions for development and handling of the SKB FEP database – Version SR-PSU	All sections	
SDU-504, SR-PSU model summary report instruction	All sections	

Reviewed report	Reviewed sections	Comments
SDU-505, Supplying data for the SR-PSU Data report	All sections	
SDU-507, Instruction for use of preliminary data used in SR-PSU calculations/modelling	All sections	
SDU-508, Instruction for model and data quality assurance for the SR-PSU project	All sections	

APPENDIX 2

Suggested needs for complementary information from SKB

1. SKB is required to conduct QA audits according to its management system. Have any QA audits been undertaken? If so, could details of the findings and any corrective actions implemented be provided?
2. Could SKB provide information on what verification checks are made that codes have been used correctly? In particular, what checks are made that individuals who use commercial codes (such as Ecolego and COMSOL) or SKB codes have implemented the solution methods and solved problems accurately and as intended?
3. Could information be provided on the QA checking of Calculation Reports and on the use of the Issue Tracking system?
4. Could information be provided on how SKB checks that its contractors maintain suitable code version control and code storage?
5. Information on the QA of FastReact has not been included in the Model Summary Report. Could information on FastReact QA be provided?
6. Could information be provided on any validation studies performed (by SKB or externally) for 3DEC, ADINA, ArcGIS, MIKE SHE, PHAST and PHREEQC that support judgements on their suitability for application in the SR-PSU safety assessment?
7. There is insufficient information to give the necessary confidence that the data on metal corrosion rates are suitably qualified. Could a revised discussion of the metallic corrosion parameter be provided that carefully addresses all of the issues listed in the instruction for supplying data for the Data Report? In particular, could information be included on how the metal corrosion rate data were qualified for use in SR-PSU and on how uncertainties in metal corrosion rates are evaluated?

APPENDIX 3

Suggested review topics for SSM

1. It is recommended that a more detailed review of the implementation of SKB's QA procedures is carried out that covers the following:
    a. If QA audits have been carried out according to SKB's management system, SSM should review the results of the audits to confirm that any corrective actions have been implemented.
    b. The Quality Assurance Plan states that all of the SR-PSU reports have been peer reviewed. SSM should review the documentation that shows how peer review comments have been addressed for each report.
    c. SKB has a procedure for qualifying old SKB references or references external to SKB. SSM should check the procedure's application in the SR-PSU process reports. However, the Engineered Barrier Process Report indicates that the vast majority of supporting references are peer-reviewed articles or documents that have undergone factual review. SSM should check that cited documents have been subject to appropriate factual review.
2. SSM should undertake further reviews of model QA covering:
    a. QA review of the analytical solutions referred to in Appendix F of the Main Report.
    b. QA review of FastReact.
    c. Review of entries in the Issue Tracking system, if it has been used, in order to better understand the QA process followed in calculational work.
3. SSM should undertake further reviews of data QA covering:
    a. SKB's procedure for checking that the data used in preliminary analyses (prior to data qualification) are consistent with the data presented in the SR-PSU Data Report (or other reports). This data control process is an important step in ensuring consistency of approach throughout the SR-PSU safety assessment. It is recommended that a review is undertaken by SSM to check that the data control process has been implemented correctly and that qualified data have been used in the analyses and calculations reported in the safety assessment reports.
    b. Given the reviewer's concerns about the qualification of data on metallic corrosion presented in the Data Report, it is recommended that a full QA review is undertaken of all of the data presented in the Data Report against SKB's instruction for supplying data for the Data Report.

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5

Review of Safety Analysis Methodology in SKB's Safety Assessment SR-PSU

Activity number: 3030014-1010
Registration number: SSM2015-1078-5
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Abstract

This review has considered SKB's overall methodology for post-closure safety analysis in the SR-PSU safety assessment. The review has included a review of SKB's approach to the treatment of features, events and processes (FEPs), including spot checks for consistency within the FEP database. The review also includes comments on SKB's selection and use of safety functions and the development of scenarios for the safety analysis. A discussion of the overall treatment of uncertainty includes comments on how these are linked to requirements on the design, waste acceptance criteria and inventory.

SKB has used a project-specific FEP list derived from established FEP lists to develop scenarios for safety assessment. The review notes that SKB has used only FEP lists derived for high-level waste and spent fuel repositories and has not utilised FEP lists specific to near surface repositories. This introduces some concerns regarding the comprehensiveness of the starting FEP list, particularly with respect to processes affecting low-level waste forms.

SKB's assessment methodology includes the use of safety functions, but SKB has defined only a very limited set, with effectively only two safety functions being defined in a way that can affect assessment calculations. There are many more safety function indicators defined and the assessment would be clearer if some of these were defined as safety functions and used in the derivation of scenarios.

Overall, the set of scenarios identified and assessed in SR-PSU is sufficiently comprehensive to demonstrate compliance with SSM's risk criterion. However, additional calculation cases and less probable scenarios based on credible degradation of barriers or accelerated internal processes would be of value in understanding the behaviour of barriers.

The review concludes that SKB's overall safety assessment methodology is reasonable and similar to approaches used in other waste management programmes. There is, however, little evidence of a linkage between the safety assessment methodology and other aspects of an iterative design and assessment process that would allow for BAT/optimisation decisions and the setting of requirements.

Contents

1. SR-PSU – Review of safety analysis methodology

1.1. Introduction

On 19 December 2014, the Swedish Nuclear Fuel and Waste Management Company, SKB, submitted an application to the Swedish Radiation Safety Authority (SSM) for the expansion of SKB's final repository for low and intermediate level waste at Forsmark (SFR). SSM is in the process of reviewing the application.

SKB's assessment of the long-term safety of the repository is documented in the SR-PSU safety assessment. SSM is undertaking a phased review of the safety assessment, which involves an initial review and a main review. Currently, the initial review phase is being undertaken, where the objectives are to develop a broad understanding of the application, to judge whether the application is complete and to identify key topics for the main review phase. Requests to SKB for any complementary information required to assess the application will be made by SSM at the end of the initial review phase.

In support of SSM's initial review of SR-PSU, Galson Sciences Ltd has been contracted by SSM to review SKB's safety analysis methodology and the approach to quality assurance (QA) in SR-PSU. This report presents the results of the review of SKB's safety analysis methodology. The review of QA in SR-PSU is presented in a separate report to SSM.

1.2. SKB's safety analysis methodology

1.2.1. Approach

SKB's approach to safety analysis for the SR-PSU assessment of an enlarged SFR repository for low-level wastes is a development of the approach used in the SAR-08 and earlier assessments undertaken to demonstrate safety of SFR 1. The SAR-08 assessment [1] was a development of the SAFE assessment (Safety Assessment of Final Disposal of Operational Radioactive Waste) [2] taking account of comments from SKI and SSI relating to the overall safety concept (safety strategy) and the systematic formulation of scenarios.

SKB's approach to safety analysis for the SR-PSU assessment is also similar in many respects to the approach used for the SR-Site assessment for a spent fuel repository [3], although the differences in waste types, disposal concept and stage of development give rise to differences in the application of the methodology.

The approach to safety analysis includes ten key steps, from an analysis of features, events and processes (FEPs) to dose calculations and evaluation with regulatory criteria (Figure 1).

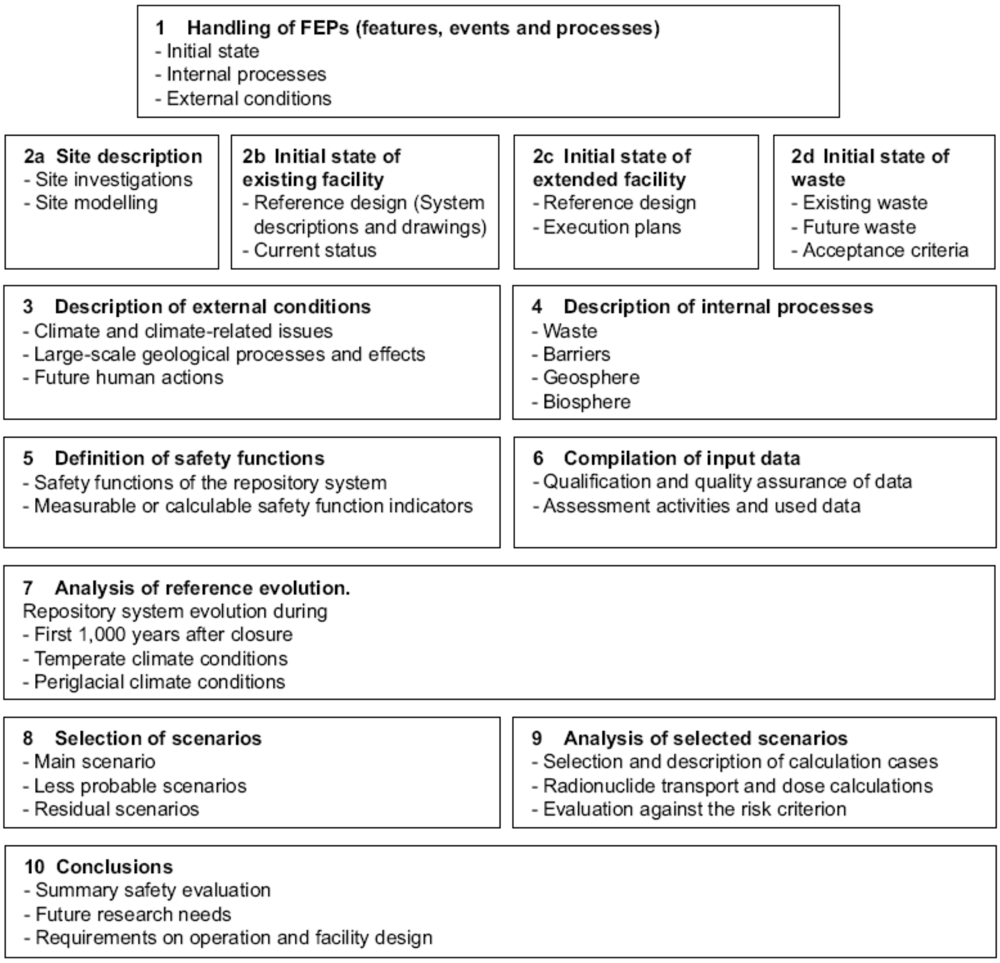

Figure 1 Overview of the ten steps in the methodology used for the long-term safety assessment SR-PSU.

This review, undertaken as part of the initial review of SR-PSU, focuses primarily on Step 1 (FEP handling), Step 5 (Definition of safety functions) and Step 8 (Selection of scenarios). It also considers how SKB has handled uncertainties in all parts of the assessment and the identification of future research needs.

1.2.2. Documentation

SKB's principal description of the approach to safety assessment is in the Main Report (TR-14-01). This is supplemented by a series of supporting reports describing the initial state of the disposal system, the processes that will affect the evolution of the system, and the models and supporting data that have been used to calculate the consequences of system evolution in terms of doses to members of the public and to non-human biota.

This review is based mainly on the information provided in the Main Report and in the FEP Report (TR-14-07) and corresponding FEP Database that document how

FEPs have been considered in the safety assessment. Reference has also been made to the Radionuclide Transport Report (TR-14-09) and the scope of the Data Report (TR-14-10) and Process Reports (TR-14-03, TR-14-04 and TR-14-05) have been assessed.

2. FEP handling

2.1. Introduction

Establishing whether the features, events and processes (FEPs) accounted for in a safety assessment are sufficiently comprehensive generally involves the use of established FEP lists at some point within the assessment methodology. The principal established FEP lists are the NEA'S international FEP list [4, 5] for high-level waste and spent fuel repositories and the IAEA's ISAM FEP list for near-surface repositories [6].

Two general approaches are available or using FEP lists:

- Bottom-up, in which FEP lists are screened to provide a project-specific FEP list that is used as the basis for scenario and model development;

- Top-down, in which FEP lists are used to audit the scenarios and models developed from a phenomenological understanding of the disposal system.

2.2. SKB's approach

SKB's approach to the handling of FEPs in the SR-PSU assessment is the same as that used for SR-SITE (3) using the NEA International FEP list as the basis. The approach comprises the compilation of an initial FEP catalogue, an audit of this catalogue against other FEP lists, designating FEPs as being relevant to the initial state of the disposal system or to internal or external processes acting on the disposal system, and allocating FEPs to particular components of the disposal system. These steps lead to the establishment of the SR-PSU FEP catalogue which comprises FEPs categorised as:

- Initial state FEPs.
- Processes in the system components waste form, packaging, BMA barriers, BTF barriers, silo barriers, BLA and BRT barriers, plugs and other closure components and the geosphere.
- Variables in the system components waste form, packaging, BMA barriers, BTF barriers, silo barriers, BLA and BRT barriers, plugs and other closure components and the geosphere.
- Biosphere FEPs, comprising biosphere processes, sub-systems and variables.
- External FEPs.

The expected initial state, long-term processes and a reference external evolution derived from the SR-PSU FEP catalogue are used to define the reference evolution for the repository system. Other external FEPs are used in the selection of scenarios.

The differentiation between variables and processes in the FEP catalogue has enabled the generation of influence and process diagrams that have in turn been used to ensure that the Process Reports describe all of the key processes and interactions. Interaction matrices, showing the couplings between variables and processes have also been prepared.

2.3. FEP consistency and traceability

In order to check the consistency and traceability of SKB's FEP documentation, a number of FEPs have been selected and their entries checked in the FEP Report.

SR-PSU FEP WM11 Diffusive transport of dissolved species

This waste form FEP is linked to NEA Project FEP A 1.27 Diffusion which is linked in turn to SR-PSU FEPs Pa07, BMABa08, BTFBa08, SIBa09 and BRTBa08. Transport in the BRT vaults is assumed to be by advection only and the FEP database therefore notes that FEP BRTBa08 is not addressed. For all of the other linked diffusion FEPs, the description notes that diffusion and its temperature dependence are addressed.

SR-PSU FEP WM11 is also linked to NEA Project FEPs E GEN-09 Diffusion and E SFR-09 Diffusion in the near-field. Although all of these linked FEPs have similar titles, the "aspects of the FEP addressed" entries in the SR-PSU FEP database differ, reflecting differences in the source databases and descriptions. The information presented has been edited from these original descriptions. For example, references in E SFR-09 to diffusion in bentonite around the silo have been removed for this waste form FEP and other descriptive text has been shortened.

SR-PSU FEP WM11 is also linked to NEA Project FEP I 300 Temperature effects (on transport). The associated comment states that temperature effects on diffusive transport are "addressed" but that they have been "neglected" due to the largely isothermal conditions in the SFR. This raises questions as to how to interpret the term "addressed" when it appears elsewhere in the FEP database.

As noted, diffusive transport potentially occurs in other components. SR-PSU FEPs Pa07, BMABa08, BTFBa08, SIBa09 all state that diffusion and its temperature dependence is addressed but none of these FEPs are linked to a temperature effects FEP. This suggests that temperature dependence can be neglected but also that there is a difference in the treatment of diffusion, or at least its screening, between the components.

SR-PSU FEP BMABa16 Gas formation

This FEP is linked to NEA Project FEP A1.35 Formation of gases which is linked in turn to SR-PSU FEPs WM19, Pa13, BTFBa15, SiBa23 and BRTBa15 all termed gas formation.

The description of the processes considered under each of these linked FEPs differs. Gas production from corrosion is listed for all the gas formation FEPs, radiolytic and methane production are mentioned for all of the vault components (BMA, BTF, BRT and Silo), and radiolysis is listed for the waste form (WM). There is a Microbial processes FEP for the waste form (WM17) which includes reference methane production

The comments associated with the gas formation FEP for three of the vault components note that further discussion of methane production is included under the corresponding microbial processes FEP for that component. There is no corresponding cross-reference to the methane production FEP for the BRT vault (BRTBa13) although the scope of this FEP appears identical to that for other vaults.

The NEA Project FEP A1.66 is linked to SR-PSU FEPs WM03 Radiolytic decomposition of organic material and WM04 Water radiolysis. There are no links to FEPs for the vaults corresponding to the references to radiolytic gas production above.

SR-PSU FEP Ge01 Heat transport

The influence table for this FEP shows that the handling of heat transport is limited to the modelling of permafrost. The process diagram for this FEP indicates interactions with the vaults and with the biosphere through "Heat exchange". The process diagram for the biosphere groups heat exchange with water, gas and mass exchange under a single FEP Bio32 Convection. The influence table for this FEP notes that the influence of convection on temperature is handled through the assumption that it reduces temperature differences. There is no indication of a FEP relating to heat exchange between the geosphere and the biosphere.

NEA Project FEP I 062d Concrete (degradation - natural, artificial)

This FEP relates to the premature degradation of concrete structures due to re-bar corrosion, freeze/thaw deterioration, thermal stress, shrinkage cracking, alkali-aggregate reactions, chemical attack, leaching, carbonation, acid rain, and the action of lithotropic molds. At least some of these processes are assumed to occur in the SFR and it is unclear as to why this FEP has been screened out as not relevant.

NEA Project FEPs A 1.08 Cave ins and S 004 Cave ins

Both of the NEA Project FEPs are linked to a range of SR-PSU FEPs. "Mechanical processes" in the various vault types are linked in both cases, but the corresponding FEPs for the waste form, package and plugs are only linked to from S.004. Conversely, the variables "Geometry" and "Mechanical stresses" for different vault types are only linked to from A 1.08. The original FEP descriptions do not provide sufficient information to explain these differences.

2.4. Summary

SKB has adopted a bottom-up approach to the use of FEPs, using established FEP lists as the basis for developing a project-specific FEP list. SKB has limited its consideration to the NEA FEP list and does not reference the FEP list specifically developed for near surface facilities by the IAEA [6]. Although comprehensive for high-level waste and spent fuel repositories, the NEA list may not include FEPs specific to the waste forms typical for low-level waste and near surface facilities.

SKB's overall approach to the use of FEPs is a bottom-up approach, using established FEP lists to derive a project-specific FEP list and to then use this as the basis for scenario and model development. This is in contrast to the top-down approach which uses a FEP list to audit scenarios and models developed using expert judgement and experience. There is an opportunity for SKB to use both approaches by using the ISAM FEP list as an audit tool for the models used in SR-PSU.

The FEP Report and associated FEP database have been reviewed through a series of spot-checks. These demonstrate that SKB has taken a methodical approach to establishing the relationships between FEPs from a number of sources. Efforts have been made to identify FEPs specific to the waste types concerned but the nature of the NEA FEP list introduces some concerns as to whether the derived SR-PSU FEP list is sufficiently comprehensive.

In addition to a list of FEPs, the FEP database also provides a description of how each FEP is handled in SR-PSU. Because of the several different disposal concepts within the SFR, there are separate descriptions for the scope and treatment of internal processes for each of the vault types as well as for the waste form and the packaging. This approach, rather than a single description covering all components of the engineered barrier system (EBS), helps to improve transparency in the treatment of FEPs.

The multiplication of FEPs arising from the separate consideration of EBS components does, however, increase the number of links between FEPs, including those to other FEP lists. In some of the FEPs checked there are differences in the links made for similar FEPs. This may be because of different assumptions regarding the scope of the FEPs or because the FEPs have been treated in different ways, but there is not always sufficient information available for this to be determined.

The significance of many FEPs in terms of post-closure performance is small. Such FEPs can reasonably be excluded from models, particularly where the range of uncertainty associated with other, more significant FEPs. SKB's terminology regarding these FEPs is not always clear. Some are categorised as "neglected", whereas others are "addressed" even where there is no explicit treatment described.

3. Safety functions

3.1. Introduction

In both the design and assessment of a disposal system, it is useful to consider each element of the disposal system in terms of its contribution to the overall safety of the system and how such contributions might be affected. In both cases, these contributions can be summarised in terms of *safety functions* for each element. At the design stage, this approach helps to ensure that different elements contribute effectively to the overall safety without undue emphasis on a single element. In assessments, a consideration of safety functions can help to ensure comprehensiveness in the scope of the analysis.

3.2. SKB's approach

SKB introduced safety functions into the safety assessment approach for the SFR in SAR-08, principally in response to comments from SKI and SSM relating to the overall safety strategy for the SFR and the demonstration of a systematic approach to scenario development. Further regulatory comments on SAR-08 have led to SKB modifying the approach and its implementation.

SKB has identified two safety principles for the SFR – *limitation of the activity of long-lived radionuclides* and *retention of radionuclides*. Safety functions, defined as "a *role through which a repository component contributes to safety*" are assigned to each repository component. The safety functions identified by SKB are listed in Table 1.

Table 1: Safety functions identified by SKB for the two safety principles (Main Report; Table 5-1).

Safety principle	Breaks down into safety functions
Limitation of the activity of long-lived radionuclides	Limited quantity of activity
Retention of radionuclides	Low water flow
	Good retention
	Avoid wells in the direct vicinity of the repository

The effectiveness of safety functions cannot necessarily be assessed directly, and so safety performance indicators, which provide a set of measurable or calculable properties, are also defined. Safety performance indicator criteria, which would provide a measurable indication of whether a safety function was satisfied, have not been defined. This contrasts with SKB's approach in SR-Site in which quantitative safety performance indicator criteria are defined.

For the reference evolution of the disposal system, SKB assumes that the safety performance indicators are satisfied throughout the assessment period and hence that the safety functions are maintained. The analysis of FEPs has been used to identify events or processes that could lead to changes in the safety performance indicators. The consequences of these changes are assessed through the definition of less probable scenarios. Residual scenarios are also used to assess the consequences of changes in the safety performance indicators where no potential initiating FEP has been identified.

3.3. Comments on the selection and application of safety functions

Both of the safety principles have been used to derive safety functions. However, the different nature of these principles affects how these safety functions are established and used in the assessment.

Controlling the inventory is a key element of the safety strategy for any near-surface disposal system. It is important that this limitation is considered in determining which waste streams can be consigned to a particular facility or vault within a facility, and also in setting waste acceptance criteria (WAC) for these waste streams. There are some uncertainties associated with the characterisation of waste streams and individual waste packages. Once consigned to the facility, however, the activity of the disposed inventory is not subject to change except through decay. The activity of the waste and associated uncertainties must be included in the description of the initial state, but inclusion of activity limitation in a functional analysis of the disposal system does not help in understanding long-term performance.

In its description and analysis of the *retention of radionuclides* safety function (Main Report; Section 5.4), SKB provides a more detailed breakdown of the contributors to safety, both by component and by process. Those applicable to components of the EBS are summarised as a set of “potential aspects that are considered for different components” (Main Report; Table 5-2), and provide the basis for the safety performance indicators. It is not clear why some of these have not been treated as safety functions as they are more directly applicable to the design, construction or operation of the facility than the general safety functions presented. For example, *mechanical stability*, listed as an aspect considered for all components other than plugs and other closure components, could be defined as a safety function within the safety assessment.

Not all of the contributors to safety presented are direct attributes of the repository components. For example, *favourable water chemistry*, listed for the waste and cementitious components, is the result of interactions between a repository component and the groundwater rather than an attribute of the component itself. Nevertheless, it is important that such contributors are considered in a similar manner to the direct attributes if there are processes that can affect them. Hence, although they may be best classified as safety performance indicators, their treatment within the assessment, for example in defining scenarios, may be similar to that of the safety functions.

Changing the terminology of the factors considered in the assessment might not lead to a more detailed consideration of the contributions to safety than is already presented in Section 5.4 of the Main Report, but it would help in demonstrating that the scenario development process has been systematic.

Given the comments above regarding the *limitation of activity* safety principle and associated safety function, SKB has effectively defined three safety functions: *low water flow, good retention,* and *avoid wells in the direct vicinity of the repository*. The last of these is distinct in the sense that it relates to siting and depth decisions rather than to waste form and vault design. However, as the siting and depth decisions have already been taken, at least for SFR 1, and there are no means of reducing the uncertainties associated with future wells, it is not apparent what is gained by defining “avoid wells” as a safety function.

There are other aspects of disposal system performance that are similarly related to siting and to repository depth such as the response to permafrost. In these cases there are design decisions, site characterisation and modelling studies that could affect the uncertainties and assessment conclusions. It would therefore seem appropriate to define a separate isolation safety principle and associated safety functions rather than adopt the over-simplification of relating all aspects of the disposal system to the retention of radionuclides.

Notwithstanding the suggestion above that SKB consider many of the detailed aspects of the various components as safety functions, there is a strong case for separating the current generalised safety functions into EBS and geosphere safety functions. Although the physical processes might be similar, there is a conceptual difference between the retention of radionuclides within the waste form, waste packages and other EBS components, and the delay or retardation of radionuclides being transported through the geosphere. Similarly, there is a conceptual difference in limiting water flow by selecting a region with a low hydraulic gradient and by constructing low permeability walls or other barriers. These differences between the EBS and geosphere result in different types of uncertainty and may therefore influence both the definition of scenarios and the resulting consequence calculations. It is recommended that in future iterations of the SR-PSU SKB more clearly separate the safety functions applying to the EBS and the geosphere and their analysis.

In the SR-Site assessment for a deep disposal facility [3], safety function indicator criteria are defined to determine whether or not a safety function is fulfilled under particular conditions. For the SR-PSU assessment, however, SKB argues that the performance of repository components does not change in discrete steps and hence that there is no clear distinction between acceptable and deficient performance. The same continuous evolution of many repository components applies to both types of facility and it is not clear why SKB has excluded the setting of criteria for all safety function indicators in SR-PSU.

In the iterative design and assessment process that is recommended for the development of a disposal facility (see, for example, the ISAM methodology [6]), a functional analysis of the disposal system is a key element. Not only does such an analysis allow a structured approach to safety analysis, it also allows the design of each component to be optimised in terms of its role(s) in providing overall system safety. Without such a functional analysis, there may be redundancy within the design or components that are not cost-effective in terms of their contribution to safety.

SKB originally introduced safety functions to the assessment of SFR after the start of construction and operation of SFR 1 and at that stage there were limited opportunities for design optimisation. At the current stage, in which the SR-PSU assessment forms part of a licence application for extending SFR, there is much more scope for design optimisation, including waste treatment and packaging. As described in the SR-PSU, the proposed new BLA and BMA vaults would be the same as the corresponding existing vaults. There may be a justification for these decisions elsewhere in the licence application, but there is no evidence that the safety functions presented in SR-PSU have been used to support the continuation of the SFR 1 disposal concept. This review has not examined the design requirements for the BRT vault (for reactor pressure vessels) but again there is no indication that the safety functions or safety performance indicators used in the performance assessment have been used in this context.

SKB does note that requirements relating to the cellulose content of wastes and to the amounts of potentially gas-producing material have been identified through the SR-PSU assessment. However, because safety performance indicator criteria have not been set, the links between these requirements and the safety functions and safety performance indicators are not clear.

One topic where the limitation of the number of safety functions makes their use unclear is gas pressure. The silo is surrounded by a bentonite buffer that has a low hydraulic conductivity intended to limit water flow through the silo and the low water flow safety function applies in this case. However, one potential mechanism for failure of this barrier is an over-pressure from gas formed inside the silo. SKB describes the various mechanisms for gas formation (reactive metals, corrosion, microbial activity and radiolysis) and notes that the consequent gas pressure will expel contaminated water into the buffer. A higher than expected gas pressure could then lead to gas reaching the geosphere.

The design requirements on the buffer to limit flow into the silo are not necessarily the same as those required to mitigate the effects of increased gas pressure within the silo. For example, the silo design includes gas evacuation pipes which are presumably intended to allow gas to escape from the waste domain without expelling any contaminated pore water.

SKB includes gas pressure as a safety function indicator for the low water flow safety function and notes that this is met through limits applied to the amount of reactive metals. Although limiting the potential gas pressure by this and other controls on waste characteristics is appropriate, linking this indirectly to the low hydraulic conductivity safety function hinders the optimisation process. It would seem more appropriate to establish safety functions relating directly to gas production and its effects.

SKB notes that BAT and optimisation issues are reported in other parts of the licence application. It is reasonable that the performance assessment is reported as an assessment of a particular design and inventory, with associated uncertainties, rather than for a range of potential designs and other options. Nevertheless, given that both the assessment and BAT/optimisation studies purport to be based on safety functions, a clearer explanation of the links between these parts of the application would help provide assurance that consistent assumptions have been made.

3.4. Summary

SKB has introduced the definition of safety functions as a step in the overall safety assessment methodology for the SFR (Figure 1, Step 5). Only four safety functions have been defined and only two of these, retention of radionuclides and low flow, can be regarded as safety functions in the sense that they relate directly to the design of system components. A much larger number of safety function indicators has been identified and it would be appropriate to consider some of these as safety functions. For example, safety functions related to the formation and containment of gas should be considered and distinguishing between the retention of radionuclides within the EBS and the retardation of released radionuclides would clarify some of the assumptions made.

SR-PSU is the latest in a series of assessments for the SFR and SKB acknowledges that further assessments will be required prior to construction and operation of SFR 3. At this stage, only preliminary steps appear to have been taken in defining the requirements for repository components through an analysis of safety functions. The optimisation/BAT process would again be aided by broadening the range of safety functions considered. The safety function indicators again provide the basis for this broader range.

4. Scenario selection

4.1. Introduction

In the context of safety assessments for disposal facilities, scenarios represent broad-brush descriptions of the characteristics and evolution of possible combinations of events and processes. As such, they provide a basis for safety assessments, with different scenarios representing different sets of events and processes and/or different evolutions. In general terms, there are two principal approaches to deriving such sets of scenarios for a particular assessment (scenario development), designated as *top-down* and *bottom-up* approaches.

A top-down approach is based on explicitly identifying FEPs that could affect the expected long-term performance of the disposal system. When applied to assessments based on the degradation of safety functions, the key stages of the top-down approach can be summarised as:

- identify the safety functions of the disposal system and their evolution;
- identify potentially-initiating FEPs;
- identify how safety functions are influenced by an initiating FEP (i.e., which functions are assumed to be degraded or affected) and generate profiles of safety function "states", giving due account to the timing of function degradation;
- compare similar profiles to evaluate if consequences of two or more events or processes can be covered in one scenario;
- develop alternative evolution scenarios to cover all relevant identified futures / function profiles.

In the bottom-up approach to scenario development, the key stages can be summarised as:

- identify the safety functions of the disposal system and their evolution;
- identify any dominant scenario-defining safety functions;
- identify relevant states for the remaining functions (e.g., not degraded, partially degraded, or fully degraded);
- construct a matrix of all potential combinations of function states;
- develop and apply rules to identify where combinations can be neglected as not relevant, or can be combined to be covered in one scenario;
- consolidate the selected set of scenarios.

The bottom-up approach to scenario development is based on a systematic treatment of safety function degradation, with no necessity to identify the actual cause of degradation. As the number of safety functions increases, and particularly if alternative timings and degradation states are considered, the number of scenarios increase rapidly, thereby requiring a process to screen and consolidate scenarios to a number manageable within an assessment. A significant number of these scenarios may not have feasible causes and would therefore be classified as what-if or residual scenarios.

A comparison of the advantages and disadvantages of the two approaches to scenario development is presented in Table 2.

Table 2: Comparison between top-down and bottom-up approaches to scenario development.

Top-down	Bottom-up
Straightforward	Potentially complex to implement – relies on ability to make simplifying rules
Comprehensiveness relies on identification of initiating events	Systematic and comprehensive
Limitation to number of possibilities, easier to track	More difficult to present and trace
No automatic generation of what-if cases	Potentially numerous what-if cases generated

As a consequence of these differences between approaches, the majority of waste management programmes base their scenario development methodology on the top-down approach but with some differences determined by the stage of the assessment or other factors.

4.2. SKB's approach

SKB's approach to scenario development is essentially a top-down approach as outlined above with some elements of a bottom-up approach used in deriving residual scenarios.

An important influence on SKB's approach to scenario development is the guidance provided by SSM (SSM 2008:21) which identifies three types of scenario for consideration. The **main scenario** should take account of future external events which have a significant probability of occurrence. **Less probable scenarios** are intended to explore uncertainties with respect to external and internal conditions in terms of type, degree and time sequence (scenario uncertainties). **Residual scenarios** are intended to explore sequences of events and conditions that are selected and studied independently of probabilities in order to illustrate the significance of individual barriers and barrier functions.

SKB has described a reference evolution for the disposal system and the main scenario is used to assess the potential consequences of this evolution. Two cases are considered within the main scenario to take into account alternative sequences of climate change.

SKB states (Main Report; Section 7.3.2) that less probable scenarios are selected "... by going through all possible routes to violation of each safety function, i.e. by examining the uncertainties in initial state, internal processes and external conditions and assessing if there is a possibility that the status of the safety function deviates from that in the main scenario in such a way that a lower degree of safety is indicated". In Section 7.4.6 of the Main Report, it is noted that "The wider ranges of conditions covered in the reference evolution, but not in the main scenario, are evaluated in the less probable scenarios. In Section 7.5 of the Main Report it is noted that "identified FEPs" are also considered in the selection of less probable scenarios.

The less probable scenarios arising from these selection processes are:

- High inventory scenario
- High flow in the bedrock scenario
- Accelerated concrete degradation scenario
- Bentonite degradation scenario
- Earthquake scenario
- High concentrations of complexing agents scenario
- Wells downstream of the repository scenario
- Intrusion wells scenario

SKB has defined a set of residual scenarios (Main Report; Section 7.3.3) in order to illustrate:

- The significance of individual barriers and barrier functions.
- Damage to humans intruding into the repository and the consequences of an unclosed repository, as required by SSM's guidance (SSM 2008:21).
- Consequences of external conditions within the range defined by the SR-PSU climate cases that are not included in the main scenario.

SKB notes that the residual scenarios are analysed regardless of their probability but provides no further information regarding a methodology for their selection.

The set of residual scenarios considered are:

- Loss of barrier function scenario – no sorption in the repository
- Loss of barrier function scenario – no sorption in the bedrock
- Loss of barrier function scenario – high water flow
- Changed repository redox conditions in SFR 1 scenario
- Extended global warming scenario
- Unclosed repository scenario
- Future human action scenarios
- Glaciation and post-glacial conditions scenario

The scenario development methodologies outlined in Section 4.1 above are generally based on the identification of external or initiating FEPs that are assumed to have a sufficiently low probability of occurrence to be justifiably excluded from the expected evolution of the disposal system. SKB has extended the methodology to also include the occurrence of more extreme parameter values as scenario-forming events. These may represent processes such as concrete degradation taking place at a faster rate than assumed for the expected evolution, or the effective occurrence of processes not otherwise considered, such as the loss of sorption capacity.

There is certainly a role within a safety assessment for considering uncertainties in parameter values. In a deterministic assessment, sensitivity studies can be used to explore these uncertainties. In a probabilistic assessment, parameter distributions are used to characterise the "normal" range of these uncertainties, and this is the approach taken by SKB for the majority of parameter uncertainties.
There is an issue as to how to treat extreme values or tails within parameter distributions. Extending a distribution to include more extreme values with very low probabilities can adversely affect the convergence of probabilistic calculations. Many more simulations will be required to provide a statistically converged mean of the output distributions and the tails may still remain sensitive to sampling seeds.

To avoid the issues of convergence, a case can be made for evaluating parameter values outside the "normal" range through standalone calculations but it is important to be clear about why such values are being considered. If there is evidence that such values are credible under some circumstances then there should be some form of initiating event that leads to these circumstances. In SKB's approach, these can be treated as a less probable scenario. If there is no evidence that the extreme values are credible, even if other events occur, then their inclusion is only warranted as part of a what-if case or residual scenario.

On this basis, it is considered that some of the less probable scenarios included in the SR-PSU assessment would be more appropriately classified as residual scenarios. Detailed comments on each scenario are presented in the following section.

4.3. Comments on the selection and definition of scenarios

4.3.1. Introduction

An assessment of the completeness of SKB's scenarios for the SR-PSU safety assessment requires consideration of the scenarios, calculation cases and modelling approaches in order to determine whether a sufficient range of calculations have been undertaken to demonstrate the safety of the disposal system. This review has not examined all of the information included within SKB's comprehensive description of the reference evolution, which has been used as the basis for identifying the processes to be accounted for within the main scenario, although some comments are made on the treatment of climate change. Instead, the focus has primarily been on the differences between the main scenario and the other scenarios and the additional events and processes considered.

If not already undertaken as part of the initial review phase, a detailed review of the reference evolution and the derivation of the main scenario could build confidence in the appropriateness of the assumptions made.

4.3.2. Main scenario

The main scenario represents the implementation, in terms of conceptual and computational models of the reference evolution. This implementation has not been considered in detail in this review; it is assumed that the FEPs identified in Step 1 of SKB's assessment methodology (Figure 1) as being likely to occur are accounted for in the appropriate models. If not already considered in the Initial Review Phase, this is a check that should be considered in the main review phase.

A group of FEPs that does require consideration in the assessment are those relating to climate change. SKB has presented a detailed analysis of the potential for climate change to affect the disposal system in the Climate Report (TR-13-05). From this analysis SKB concludes that climate evolution would be best represented by sequences taking account of anthropogenic climate change rather than by a repetition of past changes. Section 6.2 of the Main Report notes that three future evolutions of climate and climate-related issues, representing low, medium and high anthropogenic emissions of greenhouse gases are included in the reference evolution:

- The *global warming climate case*, representing a reasonable future climate evolution under the assumption of medium greenhouse gas emissions.
- The *early periglacial climate case*, representing low anthropogenic emissions and a relatively fast decrease in atmospheric CO_2 concentration.
- The *extended global warming climate case*, representing high anthropogenic emissions and a slow decrease in the atmospheric CO_2 concentration.

Although three climate cases are identified in the reference evolution, only the first two are treated as calculation cases in the main scenario. The third case, the extended global warming case, is excluded on the basis that its principal effect, prolonged periods of meteoric groundwater recharge, does not have a significant effect on disposal system performance. Given that this calculation case has in fact been considered, as a residual scenario, this is a weak argument. If the climate studies include three credible cases for the reference evolution, all three cases should be included within the main scenario.

The FEP analysis (see Section 2) and the description of the reference evolution (Main Report; Section 6) both indicate that gas formation is expected to take place within the vaults as a result of corrosion and microbial action. However, the description of the main scenario (Main Report; Section 7) and the radionuclide transport calculations (Radionuclide Transport report) do not make specific mention of gas formation or transport. SKB has identified gas pressure as a safety function indicator for the silo but did not identify a mechanism for its violation (see Section 3.3).

Overall, this initial phase review finds that the assumptions and modelling treatment of gas formation and transport, and its effects on groundwater flow and radionuclide transport in different parts of the repository, are not well explained. SKB has assumed however that it is reasonable to treat all of the uncertainties concerning gas formation and transport, including the performance of design features to facilitate gas flow, as part of the main scenario. A less probable or residual scenario to further explore these uncertainties would appear to be warranted. Examination of the assumptions regarding gas formation and transport could be the subject of a more detailed review in the main review phase.

4.3.3. Less probable scenarios

Although SKB's description of the derivation of less probable scenarios makes reference to "... all possible routes to violation of each safety function", it is clear that a scenario should only be categorised as less probable if there is a credible means for it to occur. As noted above, extreme values for internal processes beyond those considered "normal" may occur but these are only credible if there is an identified cause such as an external FEP.

The FEP analysis identifies four sets of external FEPs relevant to the SR-PSU assessment (Tables 5-12, 5-13, 5-14 and 5-15 in the FEP Report).

The first set of external FEPs relates to the components of the biosphere and these are not considered as initiating FEPs for scenario development.

The second set of external FEPs relates to climate and climate change. The evolution of climate is dominated by the assumptions made concerning the pattern of anthropogenic CO_2 releases and the majority of the external FEPs are assumed to be subsumed within these assumptions. An exception is the development of permafrost which is considered in a less probable scenario to degrade bentonite through formation of an ice lens.

The third set of external FEPs relates to large scale geological effects. The large-scale movements that take place in the FennoScandian shield are assumed to determine the boundary conditions for the long-term mechanical evolution of the repository's host rock. Earthquakes are considered in a less probable scenario.

The final set of external FEPs comprises those relating to future human actions. A residual scenario is used to consider the effects of such actions (as described in the FHA Report), but an intrusion well scenario has also been considered as a less probable scenario. Wells close to the repository following land rise and the exposure of the region above the repository are also considered in a less probable scenario.

SKB has used these external FEPs to identify less probable scenarios, but has also defined scenarios that are not based on the FEP analysis. Comments on each of the less probable scenarios are presented below.

High inventory scenario

There are no external FEPs that might lead to an overall increase in the activity of wastes within the repository. There are uncertainties relating to the characterisation of waste streams, particularly if these are derived by finger-printing rather than direct measurements. There are also uncertainties relating to the assay of individual waste packages. These uncertainties are not however uniform across the radionuclides considered in the assessment. It therefore seems inappropriate to derive a less probable scenario with an arbitrary increase in the overall inventory.

If a scenario of this type is considered useful, it would be more appropriate as a residual scenario as it does not seem credible to derive a probability for such a scenario. Investigation of the effects of an increased inventory would, however, be better implemented through the calculation of specific doses (i.e., the dose arising from a unit disposal activity). By calculating these for each vault type and each radionuclide, the effects of varying waste volumes, waste stream compositions, and of consigning wastes to different vaults can all be readily assessed. The sum of fractions approach could then be used to monitor disposals as they occur and ensure that the overall radiological capacity of the repository is not exceeded.

High flow in the bedrock scenario

SKB has introduced this scenario in order to assess the effect of degrading one of the two safety functions, low flow, applied to the geosphere. The scenario affecting the other safety function, retention of radionuclides, is categorised as a residual scenario because no credible FEP was identified to cause such an effect. Similarly, the high flow in bedrock scenario has been constructed not on the basis of an initiating external FEP or maximum parameter values. Rather, it has been generated by scaling results from flow calculations in a manner that SKB describes as leading to unphysical data (Main Report; Section 7.6.2). If a scenario of this type is considered useful, it would be more appropriate as a residual scenario as it does not seem credible to derive a probability for such a scenario.

Accelerated concrete degradation scenario

Concrete barriers are important elements in all of the vaults within SFR and contribute to both of the safety functions for the EBS identified by SKB. Under saturated groundwater conditions, concrete will degrade leading to both an increase in hydraulic conductivity and a decrease in the sorption capacity. SKB has modelled both these effects in the main scenario with step-wise changes in the properties at particular times.

For the accelerated concrete degradation scenario, SKB has assumed that the changes in hydraulic properties of concrete take place at earlier times than in the main scenario. No changes are made in the assumptions concerning sorption although the concrete degradation processes would be expected to affect all properties of concrete.

In order to understand the effectiveness of concrete structures within the disposal system, it is reasonable to assess the effects of different assumptions regarding the rate of degradation. Uncertainties regarding this rate would be best included within the main scenario but it appears that the underlying models do not provide results that can be used in this manner. Defining a less probable scenario to assess the uncertainty is a sensible alternative in this context, but it is not clear why only one of the effects of degradation has been treated in this manner. A complete loss of sorption capacity has been assessed as a residual scenario, which is useful in demonstrating the overall robustness of the disposal system. However, a less probable scenario with a change in the timing of sorption degradation would help to evaluate the uncertainties in concrete performance. A combination of the two accelerated degradation scenarios would then provide information on the overall effectiveness of the concrete barriers.

The disposal concepts within SFR include both concrete structures and the use of cementitious grout within these structures. The former are important in maintaining a low flow through the waste. In terms of radionuclide retention, however, it may be the grout, with a larger surface area, that is more important. From the information reviewed, SKB does not appear to have differentiated between these components and their potential degradation rates. Calculation cases within the accelerated concrete degradation scenario would allow uncertainties regarding potential differences between degradation of concrete and grout to be investigated.

This initial review has not assessed the assumptions regarding the timing of concrete degradation. If not already included in the initial review phase, a review of these assumptions, and whether the deterministic modelling of this timing is appropriate, would be a potential topic for the main review phase.

Bentonite degradation scenario

Bentonite is used between the concrete silo and the surrounding rock, in access tunnels to the silos and to the vaults, and in plugs within the access shafts. In the main scenario, the bentonite around the shaft is assumed to maintain a low hydraulic conductivity throughout the assessment period. One process that can affect the structure of the bentonite, and hence its hydraulic properties, is freezing and the possibility of this occurring during periglacial periods is assessed in this scenario.

SKB notes that the plugs are too small for growth of an ice lens and their properties are not changed in this scenario. It is unclear how the bentonite in the access tunnels to the silo and vaults has been treated – these regions are of comparable volume to the bentonite in the silo and may therefore be susceptible to freezing in a similar manner. Clarification of the treatment of these components and potential modification to the scenario assumptions are required.

This initial review has not assessed the assumptions regarding the growth of ice lenses in the Forsmark region under different climate conditions. These form the basis for determining whether this scenario is a less probable scenario or should be subsumed within the main scenario. If not already included in the initial review phase, a review of these assumptions would be a potential topic for the main review phase.

Earthquake scenario

Earthquakes are one of the few external initiating FEPs identified in the FEP analysis. A seismic analysis has provided an estimate of the probability of occurrence of an earthquake that could be included within a probabilistic assessment of the disposal system. However, the treatment of earthquakes through a separate less probable scenario is an appropriate approach provided the consequences are included within an overall risk summation.

An earthquake is assumed to affect the low flow safety function provided by both the geosphere and the EBS. However, it is unlikely that all components would be affected and the implementation of this scenario could be regarded as a residual scenario. Less extreme assumptions, and separate analyses of the effects on different components would help to evaluate the uncertainties in the effects of earthquakes and could help to establish whether design changes to increase mechanical stability would be warranted.

This initial review has not assessed the assumptions regarding earthquake frequency and magnitude, or the effect of earthquakes on the disposal system. If not already included in the initial review phase, a review of these assumptions would be a potential topic for the main review phase.

High concentrations of complexing agents scenario

The sorption of some radionuclides is affected by the presence of complexing agents in the waste or from other components of the disposal system. Complexing agents may be present at the time of disposal or they may from through the degradation of waste materials such as cellulose. Since 2010, SKB has restricted the use of strong complexing agents and is proposing to limit the quantity of cellulose in the new vaults. A scenario that supported, or otherwise, these decisions would be useful as part of the optimisation process. As defined, however, this scenario evaluates the assumption regarding the effect of complexing agents on sorption rather than the effects of different concentrations or types of complexing agents.

In the discussion on routes to violate the retention safety function (Main Report; Section 7.5.4) SKB notes that the "...cautious assumption with fast degradation [of cellulose] implies that the main scenario can be regarded as an upper boundary for the degradation process and hence it is not meaningful to select any additional scenario". Given this statement, it is unclear why this scenario has been introduced, particularly as a less probable scenario which implies that there is a credible mechanism by which it could occur.

Wells downstream of the repository scenario

SKB has introduced this scenario to address uncertainties in the pathways by which members of the public might be exposed. After 1,000 years of uplift, the site of the SFR will be above sea-level and any discharges of radionuclides that would have been diluted by discharge into the marine environment are assumed to be to new lakes. As uplift continues, the shoreline will migrate further from the repository site and the lakes will become infilled and transformed into mires that may then be drained and used for agriculture. This pattern of succession is assessed in the main scenario, with exposure via crops and other foodstuffs grown on contaminated soil.

By analogy with the present-day environment, it is assumed that any wells drilled near a newly emerged coastline will be into the regolith or will access non-potable water. There is therefore no drinking water pathway from wells in the reference scenario, although drinking from surface water sources is included. In this scenario, however, it is assumed that wells near the coast are drilled sufficiently deep to intercept groundwater containing radionuclides from the repository and that this groundwater is potable. SKB assigns a probability of 0.13 to the occurrence of this scenario, based on assumptions concerning the frequency of wells and their interaction area.

SSM's guidance on future human actions is concerned with more direct effects than drilling wells into contaminated groundwater. As such a well is virtually certain to occur at some time over the assessment timescale, this could be considered as part of the main scenario. However, given the uncertainties in future human habits, it is appropriate to consider the potential impact of a well intersecting contaminated groundwater as a less probable scenario and to add the risk to that for the main scenario. This requires a consideration of how the probability might vary with time, as the site retreats from the coast, or a demonstration that the single value selected is appropriate for the whole timescale.

Intrusion wells scenario

The assessment of residual scenarios evaluating the consequences of future human actions on the disposal system is a recommendation in SSM's guidance (SSM 2008:21). SKB has reported the details of this assessment in the Future Human Actions Report (TR-14-08). It is not clear why SKB has included intrusion wells as a separate less probable scenario rather than as part of the residual scenario assessing future human actions.

4.3.4. Residual scenarios

SSM's guidance (SSM 2008:21) identifies residual scenarios as an appropriate approach to assessing the effects of various "what-if" and similar assumptions concerning barrier behaviour. SKB has defined three residual scenarios that assume the loss of a safety function in the barriers, three that are recommended by SSM's guidance or comments, and two related to climate change. Comments on each of the residual scenarios are presented below.

Loss of barrier function scenarios

As noted above, the two safety functions identified by SKB relate to the retention of radionuclides and low water flow through repository component. SKB has defined residual scenarios that separately assess the role of retention in the repository components and in the geosphere. In the case of the low flow safety function, however, SKB has only assessed only a single residual scenario, with high water flow in the repository. High water flow in the bedrock has been treated as a less probable scenario. However, as noted above, there is no identified external FEP to warrant this categorisation and only poor justification of the probability assigned to this scenario. Depending on the realism of the assumptions underlying high flow in the bedrock, it would seem more appropriate to treat this case of "barrier failure" either within the assessment of hydrogeological uncertainties in the main scenario or as a further residual scenario.

Changed repository redox conditions in SFR 1 scenario

The redox conditions within the silo and vaults will affect the oxidation state of certain radionuclides which will in turn affect the extent of sorption of these radionuclides onto repository materials. SKB has demonstrated that corrosion of steel within the silo and vaults will be sufficient to ensure that reducing conditions persist. Nevertheless, SKB has assessed the effects of oxidising conditions as a residual scenario.

This scenario has been introduced in response to a comment from the regulators on the SAR-08 assessment. Given that, at the time the comment was made, SFR 3 had not been proposed, it is not surprising that this comment referred only to SFR 1. It is surprising that in SR-PSU SKB has limited the extent of the extent of changed conditions to just this part of the repository. There may be a justification for this in terms of the distribution of the radionuclides most affected by redox conditions but this is not made clear.

Extended global warming scenario

As discussed above, the *extended global warming climate case*, representing high anthropogenic emissions and a slow decrease in the atmospheric CO_2 concentration was identified as one of three credible climate evolutions in the Climate Report. SKB suggests that it was identified so as to lead to significant levels of meteoric water reaching the repository whereas the Climate Report appears to be based on general assumptions regarding climate change and not localised, repository-dependent assumptions.

Although the categorisation of extended global warming as a calculation case within the main scenario rather than as a residual scenario may not affect the calculated consequences, it is important that the main scenario in particular is well justified. Further explanation as to why extended global warming has been treated as a residual scenario is required.

Unclosed repository scenario

The assessment of a residual scenario based on the assumption that waste is emplaced but the repository is not then closed is a recommendation included in SSM's guidance (SSM 2008:21). The detailed implementation of this scenario has not been reviewed.

Future human action scenarios

The assessment of residual scenarios evaluating the consequences of future human actions on the disposal system is a recommendation in SSM's guidance (SSM 2008:21). SKB has reported the details of this assessment in the Future Human Actions Report (TR-14-08). It is not clear why SKB has included intrusion wells as a less probable scenario rather than as part of this residual scenario.

This initial review has not assessed the handling of future human actions in the Forsmark region. If not already included in the initial review phase, a review of the assumptions and consequence calculations would be a potential topic for the main review phase.

Glaciation and post-glacial conditions scenario

SKB identifies three alternative patterns of climate change in the reference evolution, based on different assumptions regarding the generation of global warming gases. In all three patterns, there is a delay in the timing of the next glaciation relative to the standard pattern of climate change that has been previously considered. The glaciation and post-glacial conditions scenario assesses the effect of the earlier onset of glacial conditions using the pattern of the last, Weichselian, glaciation as a model.

In this scenario, SKB assumes that permafrost in the early part of the glacial cycle degrades the hydraulic properties of the repository components but not the potential for retardation. These are the same assumptions as in the loss of barrier function scenario above. The difference between these scenarios lies in the assumptions regarding transport of radionuclides away from the repository. In the glaciation scenario it is conservatively assumed that there is no transport of radionuclides until the melting of permafrost during warm-base glacial conditions. Following this it is assumed that radionuclides are released to the Baltic Sea, although it is unclear whether there are releases during the initial period of warm-base conditions when the ice sheet margin is far from Forsmark.

Given the current interpretations of climate change over assessment time-scales, it is appropriate to treat this glaciation scenario as a residual scenario. The details of its implementation have not been reviewed in this initial review. A review of the assumptions and consequence calculations would be a potential topic for the main review phase.

4.3.5. Scenario combinations

In a scenario development process based on the identification of independent initiating FEPs, scenarios based on the occurrence of such FEPs will be independent. It is therefore possible for more than one scenario to occur simultaneously and SKB has addressed this by considering two combinations:

- High flow in the bedrock combined with accelerated concrete degradation.
- High flow in the bedrock combined with high concentration of complexing agents.

SKB categorises these scenarios as less probable and independent, such that the probability of them both occurring would be the product of their individual probabilities. The discussion above, however, notes that there do not appear to be credible initiating FEPs for the high flow and complexing agent scenarios and that these would be more appropriately categorised as residual scenario. Residual scenarios can of course be combined in terms of consequences, and the results of these combinations do provide some illustration of how safety function degradation in the geosphere and in the EBS might combine.

4.4. Summary

Overall, the set of scenarios identified and assessed in SR-PSU is sufficiently comprehensive to demonstrate compliance with SSM's risk criterion.

There are some issues relating to the scope and categorisation of scenarios that limit the use of the assessment for other purposes such as design optimisation and identifying requirements. For these purposes, additional less probable scenarios based on credible degradation of barriers or accelerated internal processes would be of value. For example, a scenario considering the effects of increased gas production and/or failure of the gas evacuation systems would be useful. Additional scenarios, or calculation cases within the accelerated concrete degradation scenario, would allow uncertainties regarding the timing of degradation and the effects of degradation on both flow and retardation to be investigated.

An alternative means of exploring the effects of different inventories should be developed. A less probable scenario with an arbitrary increase in the entire inventory is not an appropriate approach. Similarly, uncertainties in the extent of complexing agents should be explored in more detail than through a single, arbitrary scenario.

Climate change is a major source of uncertainty for the performance of SFR. It is not clear why some of the credible alternatives identified through SKB's research have been treated differently in the development of scenarios.

5. Handling of uncertainties

5.1. Introduction

The long time-scales and the heterogeneous nature of the geological environment are two key reasons why safety assessments for radioactive waste disposal require a consideration of uncertainties at all stages of the assessment process. The categorisation of uncertainties into different types can support this process and the different categories can be assessed in different ways.

A commonly used categorisation is to distinguish between scenario uncertainties, parameter uncertainties and model uncertainties. Simplistically, scenario uncertainties are associated with what might happen within the disposal system, or affect the system from the outside, parameter uncertainties are associated with the extent or magnitude of the events and processes affecting the system, and model uncertainties are associated with how the performance of the disposal system is assessed. As noted in SSM's guidance (SSMFS 2008:21) there may not be a clear distinction between these and other categories of uncertainty and an assessment should describe and handle uncertainties in a consistent and structured manner.

5.2. SKB's approach

SKB recognises the importance of uncertainties in the safety assessment and highlights three approaches for handling different categories:

- Completeness in identification of FEPs and scenario selection; addresses system uncertainty and scenario uncertainty.
- Conceptual uncertainty; addresses model and spatial variation uncertainty.
- Uncertainties in input data for calculations of radionuclide transport; addresses parameter uncertainty and spatial variability.

SKB has addressed system and scenario uncertainty through a systematic consideration of FEPs from internal and international FEP lists so as to ensure as far as possible that all relevant FEPs are considered. SKB acknowledges that it is not possible to guarantee a comprehensive choice of scenarios but has used safety functions to guide its scenario selection process.

Sections 2, 3 and 4 of this review comment on the approaches to FEPs, safety functions and scenario selection.

SKB does not explicitly address conceptual uncertainty in the SR-PSU assessment. Where there is conceptual uncertainty, SKB has generally adopted simplifying assumptions and adopted models or parameter values that they consider to not under-estimate releases or the transport of radionuclides. For example, in the case of processes leading to radionuclide release in unconditioned waste, SKB has assumed that the waste form does not contribute to the retention of radionuclides.

There is only a very general discussion of conceptual uncertainties in the Main Report and the bases for selecting models and justifying that they do not under-estimate releases are provided in the Process Reports. These have not been reviewed here and there are likely to be some aspects of these models and justifications that would warrant a more detailed review in the main review phase.

SKB uses a probabilistic approach to safety assessment and addresses data uncertainty through the specification of probability distribution functions (PDFs) for key parameters. There is only a very general discussion of data uncertainties in the Main Report and justifications for the parameter distributions used are provided in the Data Report. These have not been reviewed here and there are likely to be some aspects of these distributions and justifications that would warrant a more detailed review in the main review phase.

5.3. Comments on the handling of uncertainties

SKB's overall approach to the handling of uncertainties corresponds to established approaches are the basis of methodologies such as that developed by the IAEA's ISAM project, [6] and used in other waste management programmes.

In the overall presentation of results, however, there is comparatively little discussion or representation of uncertainties. The emphasis is on demonstrating compliance with SSM's risk criterion and this is done using the results from the main scenario and a risk summation incorporating the less probable scenarios. Some information concerning scenario uncertainties can be gained from the results for the residual scenarios but, as discussed above, these, and indeed the less probable scenarios, are based on extreme assumptions. This means that, although the system can be demonstrated to be robust, information on sensitivities is not readily available.

The majority of results presented in the Main Report are mean values from the probabilistic results. This is reasonable, as comparisons with a risk criterion should not “double-count” the uncertainties by using a higher percentile for the comparison. Nevertheless, probabilistic output distributions do provide information with regard to both modelling issues such as convergence and sensitivities to input parameters and more detail regarding the results should be made available.

More detail of the probabilistic results is provided in the Radionuclide Transport report, with diagrams showing the 5th, 50th and 95th percentiles as well as results from deterministic calculations. Many of these results are presented without commentary, however, and the key uncertainties in the calculations of dose are not discussed.

In the Main Report summary, there is reference to a detailed discussion of uncertainties in Section 10.6. That section presents the results of additional analyses that examine the contribution to calculated dose of different radionuclides and the distribution of these radionuclides between vaults. These are very useful analyses and will support decisions concerning waste acceptance criteria (WAC), the distribution of wastes between vaults and the requirements for further research. They do not, however, provide insights into the key uncertainties concerning system behaviour and hence topics that may benefit from additional site characterisation, modelling studies or experimental studies.

There is a further reference to Section 10.6 in the discussion of the assumptions in the assessment (Main Report; Section 10.3.4), this time referring to a detailed description of pessimistic assumptions. Once again, however, Section 10.6 does not provide the level of information that is implied. Section 11.5.1 of the Main Report does identify a set of key assumptions, in the context of where changes in future assessments may be made, but these are not necessarily pessimistic assumptions.

It appears that SKB considers the Main Report to include a discussion of the uncertainties and associated assumptions but it is not clear where information that fulfils this role can be found. SKB should be asked to clarify and develop this description.

5.4. Links to requirements

SKB acknowledges that the SR-PSU assessment represents an initial phase of an iterative programme of design, assessment, construction and operations. The proposed design for SFR 3 is based on the vault designs in SFR 1, and the future inventory is based on assumptions concerning the operation of nuclear power plants and estimates of waste arisings from decommissioning. These assumptions are likely to change, both during the design phase and construction, as more information is obtained regarding the behaviour and interactions between the components of the EBS and the geosphere, and during operations as waste is consigned and the final inventory is defined. All of these changes will require changes to the assessment, but there is also a role for assessment results to be used to define requirements and hence to influence the design, WAC and inventory.

SKB represents this iterative process in Figure 11-3 of the Main Report. This provides a reasonable summary of the process and its components. In future iterations of the assessment, SKB should consider providing some indication of the drivers for the process and the differences between "internal" information flow in the design, construction, operation cycle and the "external" interfaces could be highlighted in graphical terms.

In addition to the figure representing the iterative process, SKB highlights some of the requirements that have already been identified or inferred from assessment results (Main Report; Section 11.5.2), and topics where further R&D is needed (Main Report; Section 11.5.3).

As noted previously, the principle focus of the assessment presented in the SR-PSU Main Report and supporting documents is a demonstration of compliance with the risk criterion in SSM's regulations. For this purpose, it is reasonable to adopt conservative assumptions as a means of handling uncertainties. Optimisation decisions cannot, however, be made on the basis of such conservatisms, and setting requirements on the basis of such assumptions may not provide the most cost-effective design or disposal strategy. For demonstrating BAT/optimisation and setting requirements it is therefore necessary to review these conservative assumptions and provide a more robust representation of the uncertainties.

The R&D needs listed in Section 11.5.3 of the Main Report appear to address many of the areas where conservative assumptions have currently been made. This initial phase review has not however made a systematic comparison between these and the assumptions documented in the Radionuclide Transport and Biosphere Synthesis reports (TR-14-09 and TR-14-06 respectively). Such a comparison could be the subject of a more detailed review in the main review phase.

6. Summary

SKB's overall safety assessment methodology is reasonable and similar to approaches used in other waste management programmes. It is based on the assumption that a comprehensive project-specific FEP list can be derived from established FEP lists and then used to develop scenarios and assessment cases for safety assessment. SKB has, however, used only FEP lists derived for high-level waste and spent fuel repositories and has not utilised FEP lists specific to near surface repositories. This introduces some concerns regarding the comprehensiveness of the starting FEP list, particularly with respect to processes affecting low-level waste forms. It does, however, provide an opportunity for SKB to develop the methodology by introducing an audit step, comparing the implemented scenarios and models with an independent FEP list.

SKB's assessment methodology includes the definition of safety functions. It is clear from the history of assessments for the SFR that this step was introduced at a late stage of the assessment cycle. There is little evidence that safety functions have been used in design decisions or BAT/optimisation considerations. SKB acknowledge that further work will be done in this area. Prior to the use of safety functions in this manner, however, SKB will need to re-assess its treatment of uncertainty to ensure that overly conservative assumptions are not used for optimisation decisions.

SKB has defined a very limited set of safety functions, with effectively only two being defined in a way that can affect assessment calculations. There are many more safety function indicators defined and the assessment would be clearer if some of these were defined as safety functions and used in the derivation of scenarios. One example relates to the treatment of gas formation and transport which is not explicitly treated beyond the main scenario. Defining a safety function relating to gas would lead to a clearer assessment of its effects and potential for disruption.

Overall, the set of scenarios identified and assessed in SR-PSU is sufficiently comprehensive to demonstrate compliance with SSM's risk criterion. However, additional calculation cases and less probable scenarios based on credible degradation of barriers or accelerated internal processes would be of value in understanding the behaviour of barriers and allowing for BAT/optimisation decisions and the setting of requirements.

7. References

[1] SKB, 2008. SFR 1. Slutlig säkerhetsrapport, pärm 2. Svensk Kärnbränslehantering AB. (English translation: Safety analysis SFR 1. Long-term safety. SKB R-08-130, Svensk Kärnbränslehantering AB).

[2] SKB, 2001. Project SAFE. Scenario and system analysis. SKB R-01-13, Svensk KärnbränslehanteringAB.

[3] SKB, 2011. Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project. SKB TR-11-01, Svensk Kärnbränslehantering AB.

[4] Nuclear Energy Agency, Features, events and processes (FEPs) for geological disposal of radioactive waste: an international database, OECD/NEA, Paris, France, 2000.

[5] Nuclear Energy Agency, Features, events and processes (FEPs) evaluation catalogue for argillaceous media, OECD/NEA, Paris, France, 2003.

[6] IAEA (International Atomic Energy Agency) 2004, Safety Assessment Methodologies for Near Surface Disposal Facilities, Results of a Co-ordinated Research Project.

APPENDIX 1

Coverage of SKB reports

The reports that have been covered in this review are listed in table A1.

Table A1-1: Reports that have been covered in this review

Reviewed report	Reviewed sections	Comments
[*insert SKB report number and title*]	[*insert reviewed sections*]	[*insert comments, if any*]
TR-14-01 Main Report	1,2,3,5,7,8,10,11	
TR-14-07 FEP Report	All	

APPENDIX 2

Suggested needs for complementary information from SKB

1. SKB should be asked to explain more clearly the reasons for differences in the use of safety functions between the SR-Site and SR-PSU assessments and in particular why safety function indicator criteria have not been used in the latter.
2. SKB should be asked to explain how the safety functions presented in SR-PSU have been used to support the continuation of the SFR 1 disposal concept. If safety functions have been used only in an assessment role and not in a design or optimisation role, SKB should explain how the link between safety functions and design will be made and how BAT will be demonstrated.
3. SKB should be asked to document and justify the difference in assumptions regarding the growth of ice lenses in different bentonite components. Bentonite in the silo is currently treated differently to bentonite in plugs, and it is unclear how the bentonite in the access tunnels to the silo and vaults has been treated.
4. SKB should be asked to explain more clearly why high water flow in the bedrock has been treated as a less probable scenario, even though there is no identified external FEP to warrant this categorisation. SKB should justify why such conditions are not treated as a case of "barrier failure" either within the assessment of hydrogeological uncertainties in the main scenario or as a further residual scenario. If SKB retains a less probable scenario as an appropriate treatment of this uncertainty, further justification of the probability assigned to this scenario should be provided.
5. SKB should be asked to explain why the scenario relating to a change in the redox conditions within the repository has apparently been restricted to SFR 1 and not to SFR 3.
6. SKB should be asked to explain why the credible climate change alternatives identified through SKB's research have been treated differently in the development of scenarios, and in particular why the extended global warming climate case has been assessed as a residual scenario rather than as a calculation case within the main scenario.
7. SKB should be asked to clarify and develop the description of the uncertainties and associated assumptions referenced as being in Section 10.6 of the Main Report.
8. SKB should be asked for additional information relating to the results of the probabilistic calculations. Key uncertainties should be discussed and sensitivity studies that demonstrate relationships between input parameters and calculated doses should be reported. Evidence that demonstrates the probabilistic results are converged should be presented.

APPENDIX 3

Suggested review topics for SSM

Suggested topics potentially requiring substantial additional work on the part of SSM and SSM's external experts during the main review phase.

1. A detailed review of the reference evolution and the derivation of the main scenario could build confidence in the appropriateness of the assumptions made. This could include a check that all the FEPs identified in Step 1 of SKB's assessment methodology (Figure 1) as being likely to occur are accounted for in the appropriate models.
2. The assumptions and modelling treatment of gas formation and transport, and its effects on groundwater flow and radionuclide transport in different parts of the repository.
3. The assumptions regarding the timing of concrete degradation and whether the deterministic modelling of this timing is appropriate.
4. The assumptions regarding the growth of ice lenses in the Forsmark region under different climate conditions.
5. The assumptions regarding earthquake frequency and magnitude, and the effect of earthquakes on the disposal system.
6. The assumptions and consequence calculations relating to future human actions in the Forsmark region.
7. The assumptions and consequence calculations relating to glaciation of the site assuming a pattern of climate change similar to that during the Weichselian.
8. Selection of models and justifications that they do not under-estimate releases.
9. Justifications for the parameter distributions used in assessment models.
10. A systematic comparison between assumptions documented in the Radionuclide Transport and Biosphere Synthesis reports and the R&D needs identified by SKB.

2016:09

The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 300 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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