SKI Report 02:61

Research

SKB's Project SAFE for the SFR 1 Repository

A Review by Consultants to SKI

Neil A. Chapman
Philip R. Maul
Peter C. Robinson
David Savage

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SKI perspective

Background

The Swedish repository of low and intermediate-level radioactive waste, SFR 1, is used for final disposal of waste produced by the Swedish nuclear power programme, industry, medicine and research. The repository is located near to the Forsmark nuclear power plant about 160 km north of Stockholm.

As part of the license for the SFR 1 repository a renewed safety assessment should be carried out at least every ten years for the continued operation of the SFR 1 repository. The safety assessment shall include both the operation and long-term aspect of the repository. SKB has during year 2001 finalised their renewed safety assessment (project SAFE) which evaluates the performance of the SFR 1 repository system. The current safety assessment is the first renewal carried out by SKB for the SFR 1 repository.

Purpose of the project

The purpose of this project is to provide SKI with expert opinion from consultants to SKI on the long-term aspect part of the SKB's Project SAFE Final Safety Report and on the supporting documents to SKB's SAFE-project. The results found by the experts are summarised in a progress document (this document) which serves as a support to SKI's own review of SKB's SAFE-project.

Results

Below are some of the key issues that have been identified by the consultants:

- There is no clear statement of SKB's overall safety concept for SFR 1 in the documents that have been reviewed.
- One aspect of system description that needs to be treated in more depth is the way in which final closure of the repository will be achieved.
- It is difficult to identify which variant of the evolution of the SFR 1 system and its environment investigated in relation to the Base Scenario is considered by SKB to represent the expected evolution.
- It is not always possible clearly to identify which choices of parameter values can be regarded as 'conservative'. Because, there are a number of different time scales and rates relevant to processes operating within the SFR 1 system that can affect the magnitude of radiological impacts.
- SKB has given more emphasis to evolution of the chemical properties of engineered barriers than processes that could lead to their physical degradation.
- No systematic approach has been taken to the incorporation of sensitivity or uncertainty calculations within the performance assessment.
- The probability figures that have been assigned to scenarios and scenario variants are generally arbitrary.

Project information

Responsible at SKI has been Benny Sundström.
SKI ref.: 14.9-010238/01064 and 14.9-020065/02023

Relevant SKI report: Maul P. R., Robinson P. C., Exploration of Important Issues for the Safety of SFR 1 using Performance Assessment Calculations, SKI Report 02:62, Swedish Nuclear Power Inspectorate, Stockholm, Sweden, 2002.

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Neil A. Chapman[1]
Philip R. Maul[2]
Peter C. Robinson[2]
David Savage[2]

[1]Quintessa Limited Associate Consultant
Dalton House
Newtown Road
Henley-on-Thames
Oxfordshire RG9 1HG
United Kingdom

[2]Quintessa Limited
Dalton House
Newtown Road
Henley-on-Thames
Oxfordshire RG9 1HG
United Kingdom

June 2002

Executive Summary

The SFR 1 repository at Forsmark is used for final disposal of low- and intermediate-level radioactive waste produced by the Swedish nuclear power programme, industry, medicine and research. It was granted a conditional permit for operation in 1988 and has been receiving wastes since that time. In 1992 it was granted a full-scale operating permit following additional reporting on long-term safety aspects by SKB, including the first in-depth safety assessment in 1991. The repository has an intended operational life of about 40 years, although there are plans for it to be extended, possibly around 2015, to provide capacity for the disposal of waste concrete from the decommissioning of nuclear power plants (with the repository then being closed in around 2060). This would require the addition of further vaults, in an 'SFR 3' phase. A possible second Silo is no longer considered necessary by SKB. It is also proposed that parts of SFR 1 could be used a temporary store for other decommissioning wastes (e.g. reactor components) until such time as a deep repository for long-lived low- and intermediate-level waste (SFL 3-5) is available.

It was stipulated as part of the full-scale licence for SFR 1 that a revised safety assessment should be carried out by SKB at least every ten years during the continued operation of the facility. The first 10-year SKB re-evaluation (after the 1991 'in-depth' assessment), called 'Project SAFE', was submitted to the regulators (SKI and SSI) during the first six months of 2001, as a series of connected reports. The Final Safety Report was received by the regulators at the end of June 2001.

The review of Project SAFE presented in this report is the culmination of several years' work with SKI, comprising a number of individual work packages, including:

1. The extension and application of SKI's 'systems' approach to set up a description of the SFR 1 repository using Process Influence Diagrams (PIDs).
2. Participation in the development of a flexible Performance Assessment (PA) software tool (the AMBER code) that enables time-dependent analyses to be made of system behaviour.
3. Use of the PID database to explore, from first principles, issues that are likely to be important in the safety performance of SFR 1 and thereby to identify topics to be explored by PA modelling.
4. Peer review of the main SKB Project SAFE supporting documentation to evaluate quality, completeness and the implications of the results.
5. An independent PA exercise, using the AMBER code.

6. A review of an English translation of Section 5 of SKB's Project SAFE Final Safety Report.

The present report covers only items 3 to 6, and a separate report provides a more detailed description of item 5. Issues that might be of significance in assessing he safety of SFR 1 arose at various stages of the review process, some of them going back to previous regulatory evaluations. The report is structured so that these issues can be tracked through the various stages of document review and independent PA modelling. Significant aspects that remain to various extents unresolved are highlighted in the conclusions. The results of this review are intended only to assist SKI and SSI with their own regulatory assessment, and the views expressed are those of Quintessa staff and other consultants and are not necessarily those of the regulators.

SKB has deployed its latest techniques of PA to carry out a comprehensive systems evaluation for Project SAFE; the outcome represents a very considerable advance on the previous evaluation of safety for SFR 1 in terms of the depth of analysis that has been undertaken. The assessment addresses key issues identified in earlier reviews and is based on a much more rigorous examination of the safety performance of the repository than has hitherto been undertaken.

Notwithstanding this increase in rigour and complexity, neither SKB's improved techniques nor the exploratory PA studies carried out for this review on behalf of SKI have identified any new factors or interpretations that indicate safety is other than was envisaged at the time SFR 1 was originally licensed. Our interpretation of the results of both sets of PA calculations is that the projected radiological impacts of SFR are broadly similar to those indicated in previous studies. In particular, when uncertainties are taken into account in describing the future evolution of the disposal system, it is possible to derive estimates of individual exposure for members of the hypothetical critical group via a well that lie in the range of natural background exposures. Although SKB has tried to show that SFR 1 could meet current risk standards, the uncertainties in the likelihood that such exposures (in the region of 1 mSv) could occur are sufficiently large that we believe such an argument cannot easily be sustained on the basis of PA approach adopted by SKB. However, there are in-built reserves of performance that have not been deployed in the safety assessment and which could be investigated more closely in future.

As a result of this review, the key issues that the regulatory authorities will need to address when reviewing SKB's safety case for SFR 1 have been identified as:

1. There is no clear statement of SKB's overall safety concept for SFR 1 in the documents that have been reviewed. It is therefore difficult to judge the

results of the PA against general expectations for how the disposal system has been designed to function, or with respect to the intended roles of individual system components in providing safety assurance. Our interpretation is that long-term safety performance is largely dependent on containment by immobilisation of longer-lived radionuclides as a result of chemical sorption within the two highest-inventory vaults, the Silo and the BMA. By comparison, long-term (> 300 year) physical containment plays a subordinate role, provided that groundwater movement through the waste materials is within reasonably expected limits.

2. One aspect of system description that needs to be treated in more depth is the way in which final closure of the repository will be achieved. SKB states that technical solutions have not been finalised and imply that the details of closure are not critical to the evaluation of safety performance. It is indeed important not to finalise closure plans too soon, in order to retain a measure of flexibility in future operations. However, it is not too early to begin to consider, as part of the ongoing development of the safety case, the possible implications of alternative management, backfilling and sealing options.

3. The projected evolution of the SFR 1 system and its environment has been examined in detail within Project SAFE, and the uncertainties associated with developing such a description are discussed. However, it is difficult to identify which variant of those investigated in relation to the Base Scenario is considered by SKB to represent the expected evolution. Linked to a well-defined safety concept, an explanation of expected evolution ('design basis') is a clear way to explain and understand system performance and associated uncertainties. Our interpretation of the supporting documentation is that the Main Case (Intact Barriers) variant of the Base Scenario is regarded as 'expected evolution'; however, our review results suggest that the Degraded Barriers variant of the Base Scenario may in fact be a more appropriate reference position.

4. There are a number of different timescales and rates relevant to processes operating within the SFR 1 system that can affect the magnitude of radiological impacts. These include: repository resaturation and gas evolution timescales; the rate at which changes in local sea level take place; the rates of engineered barrier degradation; and groundwater transport times through the geosphere. Therefore, it is not always possible clearly to identify which choices of parameter values can be regarded as 'conservative', and any such assertions by SKB need to be treated cautiously.

5. One exception to SKB's intended use of conservative parameter values is the specification of water flow rates through the vaults, where it is argued that values assumed as a basis for the PA calculations are realistic. However, even though we understand that SKB is aware of calibration problems involved in deriving the flow data, which could mean that flow rates have been underestimated, the SAFE assessment does not investigate the implications of higher values. Independent PA calculations carried out in support of this review have illustrated the sensitivity of calculated impacts to this parameter. In addition, higher water flow rates could lead to increased microbial activity and rates of corrosion, more rapid gas production and accelerated physical degradation of reinforced concrete. In practice, this means that SKB has given more emphasis to evolution of the chemical properties of engineered barriers than processes that could lead to their physical degradation.

6. No systematic approach has been taken to the incorporation of sensitivity or uncertainty calculations within the PA, and some of the claims for pessimistic parameter choices would appear to be difficult to sustain. The use of probabilistic calculations to address uncertainties in the biosphere but not in the rest of the disposal system reflects an incoherent approach to the quantitative treatment of uncertainty in the PA as a whole.

7. The probability figures that have been assigned to scenarios and scenario variants are generally arbitrary. Indeed, a case could be made for higher or lower probabilities in each case, or for the evaluation of combinations of situations that have not been addressed in the SAFE assessment. In particular, the use of a probability of less than one for the 'well' scenario is questionable. We do not believe it enhances the credibility of either SKB or the regulators to embark on somewhat sterile arguments regarding the likelihood of future human actions, expressed in probabilistic terms, as a basis for quantitative estimates of 'risk'. Instead, we suggest that the values of dose calculated in the assessment should be taken at face value as 'what if?' illustrations of the implications of different actions or types of behaviour, and recognition should then be given to implications of these results (including the size of the corresponding hypothetical critical group) in the light of judgments that certain behaviours are considered less likely than others.

8. SKB has undertaken calculations for a 10 000 year period after repository closure. Independent PA calculations suggest that overall risks posed by the repository will be highest within this period, even though peak impacts associated with some scenarios may not be achieved until after this time, and that radiological impacts are therefore unlikely to have been underestimated as

a result of the time cut-off used in the SAFE assessment. Nevertheless, consideration of longer timescales, particularly for the expected 'normal' evolution of the system, would have been helpful in illustrating the long-term safety implications of waste disposal in SFR 1, as well as demonstrating SKB's understanding of the processes that are expected to determine the eventual fate of the repository.

9. The nature of the software tools used by SKB has meant that the some continuous processes (such as the degradation of engineered barriers) have been represented in a discontinuous step-wise manner. Independent PA calculations have therefore been undertaken to investigate the possible importance of being able to represent continuous changes more explicitly. Whilst these calculations did not identify any factors that may have been misinterpreted in the SAFE assessment's stepped approach, nor suggest significantly different radiological impacts, they do illustrate that step-wise calculations can lead to physically unrealistic estimates of radionuclide transport.

10. Long-lived actinide radionuclides may be retained by sorption processes (particularly in the Silo) on very long timescales. If this is the case, peak impacts are likely to be dominated by long-lived fission and activation products (beta-gamma emitting radionuclides) such as Mo-93, Nb-93m, Ni-59, Cl-36, Se-79, Cs-135 and C-14. Having identified which are likely to be the most significant radionuclides in terms of potential impacts in the wider environment, it is important that assumptions made in relation to their behaviour are scrutinised to ensure that possible discrepancies or in-built biases are identified. Inventory issues were not addressed in this review, as this is being assessed separately by the regulatory authorities. For many of the PA calculations, C-14 (in organic form) appears to be the dominant radionuclide; hence, in the review of the SKB inventory by the regulatory authorities, particular attention needs to be given to assumptions about the magnitude of the C-14 inventory, as well as to assumptions about its chemical speciation, both in the wastes and upon mobilisation from the wastes into the engineered barrier system and groundwaters. In particular, the basis for the assumption that 10% of C-14 is in organic form needs to be checked. This topic appears to merit a definitive study.

Contents

1 Introduction

The SFR 1 repository at Forsmark is used for final disposal of low- and intermediate-level radioactive waste produced by the Swedish nuclear power programme, industry, medicine and research. It was granted a start-up permit for operations in 1988 and has been receiving wastes since that time. The repository has an intended operational life of about 40 years, although there are plans for it to be extended, possibly around 2015, to provide capacity for the disposal of waste concrete from the decommissioning of nuclear power plants (with the repository then being closed in around 2060). This would require the addition of further vaults, in an 'SFR 3' phase. A possible second Silo is no longer considered necessary by SKB. It is also proposed that parts of SFR 1 may be used to store temporarily certain decommissioning materials (reactor components) until such time as a deep repository for long-lived low- and intermediate-level waste (SFL 3-5) suitable for their final disposal is available.

As part of the licence for SFR 1, it was stipulated that a revised safety assessment should be carried out by SKB at least every ten years during the continued operation of the facility. The original ('preliminary') SKB safety assessment preceded SFR 1 licensing and was presented to the regulators in 1982, with supplementary studies being presented in 1983. This was reviewed by SKI, who also carried out independent calculations to verify the safety case, and a report was produced in 1984 (SKI, 1984). The initial licence (start-up permit) was granted in 1988, but was limited to waste emplacement in the rock vaults. The next ('final') SKB assessment was made in 1987, updated and submitted in 1991 as the 'in-depth' safety assessment, with a further review report being issued by SKI in 1992 (SKI Teknisk Repport 92:16, , which was translated to English in SKI & SSI, 1994). On the basis of this review, SKI recommended that, subject to certain measures being taken by SKB (see below) a full operational licence should be granted (i.e. the 1988 limitations should be withdrawn).

The first '10-year on' (from 1991) SKB evaluation, called 'Project SAFE', was submitted to the regulators (SKI and SSI) during the first six months of 2001, as a series of connected reports. The Final Safety Report was received by the regulators at the end of June 2001.

The regulators intend to base any decisions or recommendations relating to the SAFE assessment, in part, on an independent safety assessment of SFR 1. This is regarded as a more robust alternative to a regulatory review based solely on an appraisal of the documentation submitted by SKB. The independent assessment calculations, described by Maul and Robinson (2002), are based on the regulators' own tools and methodology, and the use of peer-reviewed SKB data. Because it is intended mainly as a means of checking models, assumptions and results, and of exploring specific issues identified during the course of the review, the performance assessment (PA) work supporting the regulatory review is not required to be as comprehensive as the Project SAFE analysis undertaken by SKB.

The review of Project SAFE presented in this report is the culmination of several years' work with SKI by Quintessa and several other consultants (see Figure 1.1), comprising a number of individual work packages, including:

1. The extension and application of SKI's 'systems' approach to set up a description of the SFR 1 repository using Process Influence Diagrams (PIDs) (Stenhouse et al., 2001).
2. Participation in the development of a flexible Performance Assessment (PA) software tool (the AMBER code) that enables time-dependent analyses to be made of system behaviour, and trial applications of this software.
3. Use of the PID database to explore, from first principles, issues that are likely to be important in the safety performance of SFR 1 and thereby to identify topics to be explored by PA modelling.
4. Peer review of the main SKB Project SAFE supporting documentation to evaluate quality, completeness and the implications of the results.
5. An independent PA exercise, using the AMBER code (Maul and Robinson, 2002).
6. A review of an English translation of Section 5 of SKB's Project SAFE Final Safety Report provided by SKI (2002).

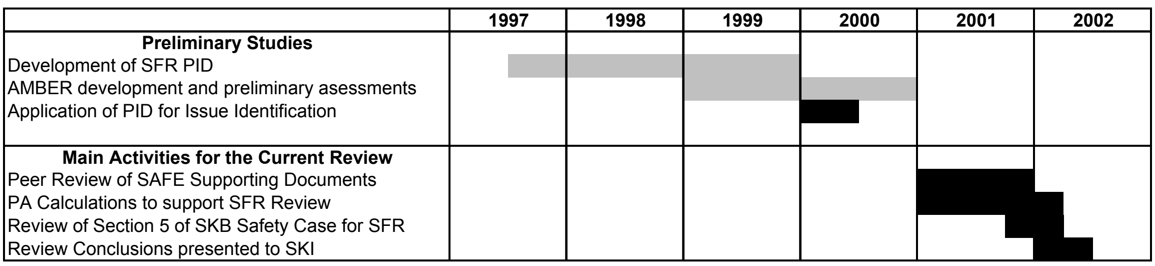

Figure 1.1 *Programme of activities related to SKI's review of SAFE. The activities described in this document are shown in bold*

As can be seen from Figure 1.1, only activities 3 to 6 are reported in this document, with activity 5 being more fully reported in Maul and Robinson (2002). The review process for these four activities is illustrated schematically in Figure 1.2. The reviews that were undertaken of SKB's supporting documentation were carried out before the relevant sections of the Final Safety Report had been made available in English. In September 2001, members of the review team were able to clarify questions that had arisen from their reviews, during a short visit to SFR 1 and a meeting with SKB staff. Subsequently, an English translation of Section 5 of the SKB Final Safety Report was made available by SKI, and this was reviewed in January 2002. These imposed limitations have resulted in a less than ideal review process. Nevertheless, it is believed that the key issues have been identified and, while it has not been possible in the present project to follow up each issue in depth, the results should form a useful support to the regulators' own internal review exercise later this year.

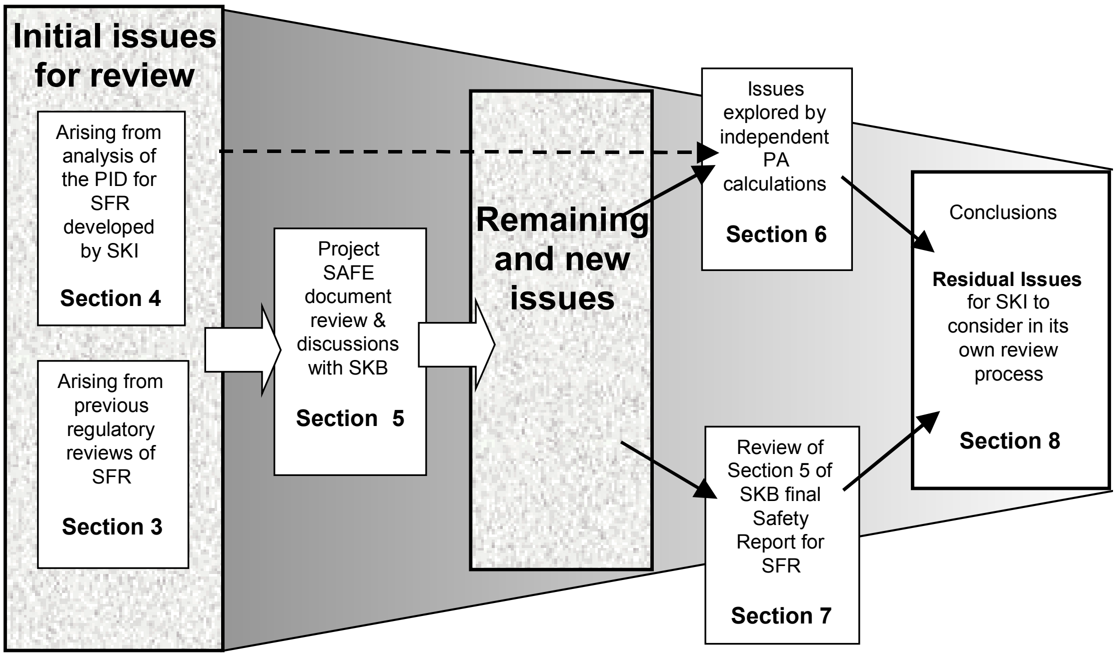

Figure 1.2 *Schematic illustration showing the structure of the review and the links between the various Sections of this report. The progressive identification and reduction of issues is indicated.*

As can be seen from Figure 1.2, the outcome of the first and third activities identified above (i.e. those relating to the development and use of the PID database), together with issues left from earlier regulatory review (SKI & SSI, 1994), provided the foundation for the main review of the SAFE documents, in the form of a set of initial issues. Review of the SAFE documents identified some new issues and partially resolved others. Since it was possible, based on the earlier explorations of the SFR 1 system, to identify important factors, some of the independent PA analyses were made before the SKB documents and data were available, with the remainder being carried out shortly afterwards.

It is important to note that the PA calculations have not attempted to address all the issues identified in the review, only to look at some of those that appeared likely to have more significant impacts on estimated performance. In this respect, there remains scope for further pursuit of incompletely resolved aspects of SFR 1 performance.

The final stages of the review involved bringing together the results of the independent PA calculations with the final review of Section 5 of the final Safety Report, to produce the conclusions of the present study in the form of residual issues for SKI to consider in its own review process.

The present report is intended to contribute expert opinion to SKI and SSI, based on the outcome of the above tasks, in order to assist them with their regulatory review. The views expressed are those of Quintessa staff and other consultants and are not necessarily those of the regulators.

The report is structured as follows (see also Figure 1.2):

- Section 2 provides a brief description of some important features of the SFR 1 facility relevant to the present review.
- Section 3 summarises some important issues that have arisen from previous assessments of the safety of SFR 1.
- Section 4 summarises the output from the workshop that was held in January 2000 to evaluate the PID for SFR 1.
- Section 5 gives details of the review of main SKB SAFE supporting documents and summarises the main findings of this document review.
- Section 6 summarises some of the main findings of the independent PA calculations that have been undertaken.
- Section 7 brings together a discussion of key issues arising from the whole review process, taking account of the subsequent review of Section 5 of the SAFE Final Safety Report.
- Finally, Section 8 presents the overall conclusions of the review.

To facilitate tracking of issues through the review process shown in Figure 1.2, this report gives important review issues an identifier code related to the stage at which they were brought up. Tables show how and when these issues were dealt with, either within SKB's SAFE documents, or by SKI's independent analyses. Issues that still remain open, or would benefit from additional consideration, propagate through to the end of this report.

2 The SFR 1 Repository

This section provides a brief description of some important features of the SFR 1 facility. Additional details are given in Stenhouse et al. (2001).

The SFR 1 repository at Forsmark comprises a Silo and four vaults, known as BMA, BLA, 1BTF and 2BTF, constructed in hard, crystalline bedrock at a depth of about 60 metres under the Baltic seabed, just off the coast, where the water depth is about 6 metres (Figure 2.1).

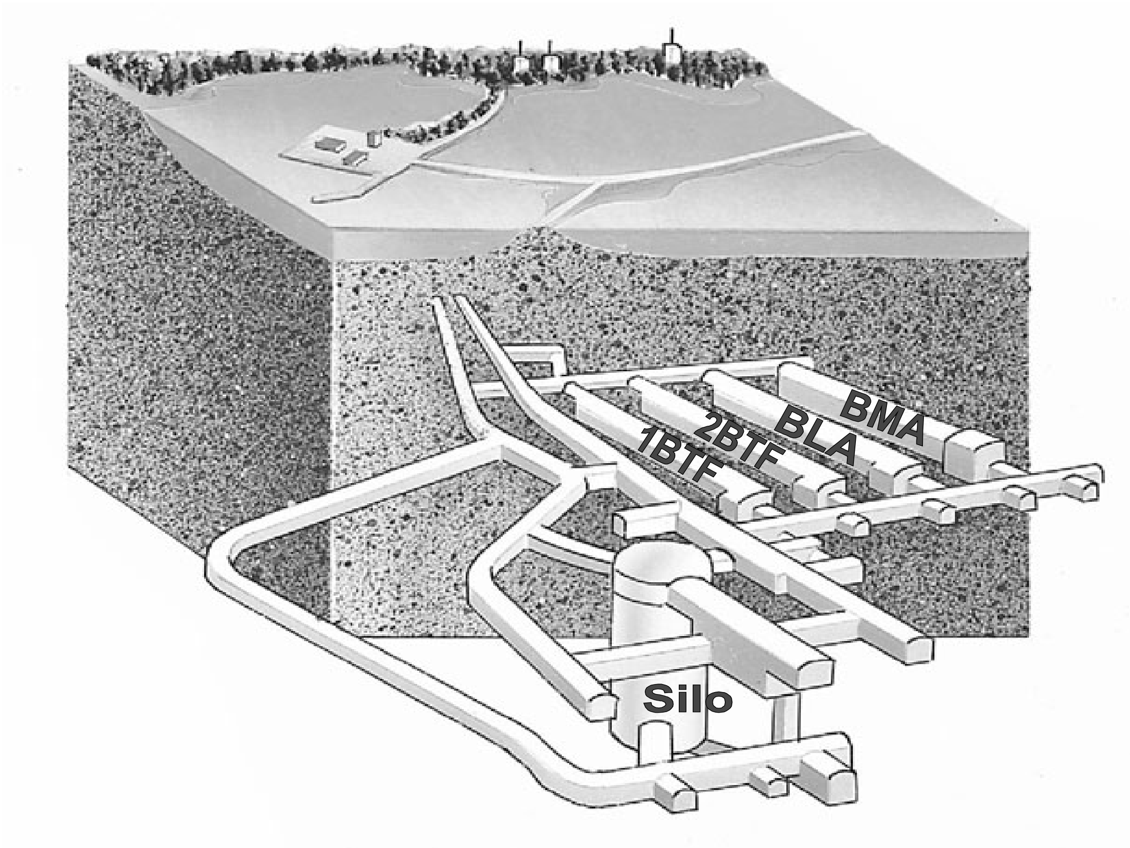

Figure 2.1 *Schematic illustration of the SFR 1 repository, showing the various vaults and the Silo*

The Silo, which contains the higher activity wastes, is 53 m high and 28 m in diameter and is intended to hold about 18 500 m^3 of solid wastes packed in concrete and steel moulds and steel drums. It is constructed of concrete, surrounded by a layer of bentonite clay at the sides and a bentonite-sand layer above and below. The vaults are each 160 m long and vary in height from about 10 to 16 m.

The BMA vault contains an inner concrete structure that holds waste containers. Remote handling is used to emplace packages and a small layer of grout is placed on the top of completed sections. It is possible that the remaining crown space between the top of the vault and the host rock could be used for miscellaneous large items of waste, although this would require a licence change. SKB will probably not fill the small spaces between waste containers, except where this has been done for operational reasons.

The BTF vaults are used to stack waste in concrete tanks or steel containers and the BLA vault is used simply to stack ISO transport containers. The BLA vault contains a number of full and half-height ISO containers; these can be inspected from the side, and are beginning to corrode. Each of the vaults can hold about 12 000 m^3 of wastes.

An important issue in design is that SKB's generic concept of using concrete vault structures surrounded by bentonite (as with the Silo) has changed since SFR 1 was built. It had originally been intended to use the same concept for the SFL 3-5 repository for ILW, although this is still many years in the future. SKB is now moving towards the use of the 'hydraulic cage' concept for SFL 3-5 (SKI, 2000), based on their experience with a similar design in the BMA vault at SFR 1. SKB has not stated clearly why this change has come about.

SKB wish to keep their options for final repository sealing open, as far as possible, but have documented the assumptions that were made in the SAFE assessment as part of the latest safety case. It is assumed that a gravel/sand mixture or crushed rock will be used to backfill the vaults (no backfill is planned for the BLA) and that concrete plugs will be used to seal the vaults and access tunnels. No backfilling or sealing will be undertaken until all waste has been emplaced.

The licensed inventory of SFR 1 is 10^{16} Bq of radioactivity. SKB estimates that it will contain about 10^{15} Bq by the time of closure in 2030. However, because there is uncertainty about which wastes might be directed to the repository over the next thirty years, SKB's safety evaluation assumes an inventory based on the upper limit defined by the licence conditions.

When the repository is closed, it is expected that the whole system will become resaturated as a result of groundwater ingress over a relatively short period. Groundwater movement in the repository host rock takes place within the network of fractures that characterise the rock. Its rate and direction are controlled by the variable hydraulic conductivity and connectivity of this fracture network and the hydraulic gradient and flow field boundaries, themselves a function of the location and properties of major structural features of the area (fracture zones) and the topography. Within the repository, flows will be strongly influenced by the highly transmissive vaults and tunnels and will also be affected by the locally enhanced transmissivities in the excavation damage zone around the vaults, silo and tunnels.

SFR 1 is designed to provide containment for the wastes, and much of the radioactivity initially disposed is expected either to decay in situ or to remain in the wastes for as long as the repository remains undisturbed. However, it is anticipated that some radionuclides will be leached from the wastes over the hundreds and thousands of years following closure, at rates depending on their chemical properties, the manner in which the concrete structures and other engineered features in the repository degrade and the rate of water flow through the system. In addition, gases will be generated by corrosion of metals and biodegradation of some types of organic wastes, with a fraction of the total gas production being derived from radioactive elements present in the waste. Both gases and any leached radionuclides can then make their way to the biosphere through the surrounding rock.

The land surface of central Sweden is rising as a result of ice unloading at the end of the last glaciation, some 10 000 years ago. This process continues today and results in an apparent fall in sea level, with the Baltic coastline receding. The position of the coast will move progressively further east, passing over the repository, which will consequently lie beneath dry land within 5000 years. Hence, whereas the environmental transport pathways followed by releases of radioactivity from the repository will initially emerge into surface waters (first via the sea bed, then lake sediments), at later times releases could occur at the exposed land surface, or via wells that may be established in the area some time in the distant future.

3 Issues from Previous Regulatory Evaluations

The 1984 SKI evaluation (SKI, 1984) identified a number of issues that would need to be kept under review during the operational lifetime of SFR 1 and addressed in future SKB assessments. These included:

- the evolution and movement of a gas phase (largely from metal corrosion) within the Silo structure and its mode of escape into the rock (and, to a lesser extent, the same issue within the vaults);
- the swelling of ion-exchange resins within bitumenised waste containers and its impact on the physical integrity of the concrete Silo walls;
- SKI's view that the voids in the vaults should be backfilled; and
- uncertainties in the geological and hydrogeological understanding of the site, which necessitated the use of conservative assessment approaches by both SKB and SKI.

Responses to these issues were included in SKB's 1987 final submission for a full operational licence. However, in 1990 the regulatory authorities asked for more information. The topics identified were (in brief):

- time dependence of corrosion and gas formation in the Silo;
- time dependence of changes in the land-sea transition, and its impact on the possibility of well drilling;
- flow around the repository and dilution impacts on recipients;
- a full and consistent scenario analysis;
- water displacement, gas release through bentonite and cracking impacts on Silo performance;
- organic materials (including additives in concrete);
- complexing agents from organic degradation products;
- sulphate attack on concrete;
- parameter variance analysis; and
- a biosphere model description.

This led to supplementary submissions from SKB in 1991. The 1992 evaluation of the submissions (SKI and SSI, 1994) found that SKB had, on the whole, satisfactorily supplemented the earlier analyses as well as answering questions about gas formation and grout properties. It was concluded that the radiological impacts of projected releases of radionuclides from the repository would ‘probably lead to negligible dose consequences’, although this ‘may be difficult to prove’. This was determined on the basis of conservative calculations for hypothetical critical groups showing that a few individuals, at some time in the future, might receive doses of about 1 mSv y^{-1}, or possibly (‘improbably’) up to 10 mSv y^{-1} if uncertainties are taken into account (compared with the reference value of 0.1 mSv y^{-1} used in the assessment). The risk of limited groups being exposed to radioactivity through operation of SFR 1 was considered to correspond to the risk that is currently accepted by society for naturally occurring radioactive substances.

Despite these conclusions, the regulators’ evaluation identified topics where more work was still required (and which consequently would need to be addressed in future assessments). These were (shown with an identifier code for the purposes of the current review):

R-1 land uplift and well scenarios;

R-2 uncertainties in data related to the formation of organic complexes and their implications for contaminant transport; and

R-3 combinations of scenarios (based on groupings of ‘not too conservative’ parameter variants).

The 1992 evaluation concluded by stating that residual uncertainties could be reduced if certain measures were adopted. The following measures were identified as conditions in the granting of the full operating licence:

- the limitation and control of the quantity of organic materials in different parts of the repository;
- research into complex formation with degradation products from cellulose; and
- the establishment of regulations for recording information relating to the repository.

An important issue that arises when considering the results of SKB’s safety assessment calculations is the definition of performance measure(s) for evaluating the significance of projected radiological impacts. Since SFR 1 was licensed, SSI has issued new risk criteria (SSI, 1999) for application to radioactive waste repositories. We understand that the regulators consider these new criteria would only apply if SKB were to seek approval to put other types of waste into SFR 1 or to increase or significantly modify the licensed radioactivity inventory. In the absence of such changes, the older dose-based reference value that applied at the time of original licensing (i.e. 0.1 mSv y^{-1} individual dose) is considered to remain appropriate.

4 Issues Identified from the PID Evaluation

SKI held a workshop in January 2000 to scope the review work and to identify potentially safety-relevant issues from the current understanding of the SFR 1 system. Part of this evaluation involved using the Process Influence Diagram (PID) for SFR 1 that had been set up using the SPARTA code (Stenhouse et al., 2001). The PID, which identifies diagrammatically all the key features and processes that describe the repository system and its behaviour and the way that they influence each other, is a means of stimulating discussion, improving understanding and ensuring that the system is being evaluated comprehensively. The workshop was organised around a group of 'clearing houses' that dealt with specific regions of the repository system. Chapman et al. (1995) described how this approach was first developed and applied by SKI in its SITE-94 project. The six clearing houses, each of which had three to nine members, were:

- regulatory requirements
- inventory
- vault (repository system and the near-field)
- rock (geology and hydrogeology)
- environment (biosphere and environmental change and evolution)
- performance assessment.

Each clearing house looked at the scope of information available and considered issues that might need to be taken account of in evaluating the behaviour of their part of the system, in carrying out the review of forthcoming SKB documentation, or in independent PA activity. The rock and vault clearing houses utilised the PID to focus their discussions and to identify uncertainties and performance related issues. Each group identified topics where they considered that it would be important for SKI to carry out its own assessment calculations. The regulatory requirements clearing house identified in particular the need to review SKB's approach to time cut-off in their assessment and to the treatment of uncertainty.

The main review issues identified by the workshop are outlined below, categorised according to different aspects of the repository system. They are numbered and given an identifier prefix of 'SKI'.

4.1 System Description

In the overall description of the SFR 1 system the following key issues arose:

SKI - 1 The nature of vault roof backfill. The Phase 1 SAFE documentation (SKB, 1998) indicated an absence of backfill, but earlier SKB reports and diagrams had indicated the use of crushed rock. Decisions on backfilling could affect groundwater flow, groundwater mixing, the pH plume and possible vault cave-in.

SKI - 2 Uncertainty regarding the mode of repository closure, and the justification for the concrete lid over the Silo.

SKI - 3 What types of cement were used and how they would perform in terms of physical and chemical degradation over long times.

SKI - 4 The distribution of the SFR 1 inventory (partitioning between different parts of the repository). Was it possible for different amounts of waste to be placed in different parts of the repository to the situation described in the original licence application (e.g. more activity in the BMA than was originally planned?).

4.2 Geology and Hydrogeology

The following key issues arose from the 'rock' Clearing House:

SKI - 5 The effects of land uplift on the composition and flow of groundwater. Would groundwaters become more or less saline, thus affecting near-field processes in the vaults? Groundwater in the repository rock volume has become less saline over the past ten years, possibly due to varying contributions from different groundwater sources. The composition of the groundwater saturating the bentonite could therefore be variable. Would the flow field change significantly with time, affecting pathlengths to discharge points and the environments into which discharge could occur?

SKI - 6 Implications of an updated geological model on the hydrogeological model that underpins the PA calculations. Assumptions made about the properties and the location of major fracture zones could affect the flow field. The methodologies used to identify structural features would need to be reviewed: for example, the geological interpretation of structures beneath the Baltic Sea. Alternative models may be possible with respect to these inferred or conjectural structures that are difficult to test or characterise.

SKI - 7 Stress field and seismic activity in the region, with respect to the likelihood of fracture movements in the next few thousand years.

4.3 The Biosphere and Environmental Evolution

The following key issues were identified by the 'environment' Clearing House as points to look out for in the review of SKB's SAFE documents:

SKI - 8 Human-induced climate changes (e.g. acid rain and greenhouse gases) and their implications for environmental change. Different biosphere models might be appropriate for warmer and wetter conditions.

SKI - 9 Future human actions. The treatment of intrusion, wells and other possible human impacts on the surface environment and shallow groundwater system that could affect performance.

SKI - 10 Repository-induced changes in the biosphere (e.g. possible effect on groundwater pH). If the water leaving the repository and entering possible wells is always too alkaline to be potable or useable for agriculture, this may need to be taken into account in any assessment of risk.

4.4 Near-field Evolution

In support of the review and the independent PA calculations, an SFR 1 'vault database' was being finalised by SKI (Savage & Stenhouse, 2001). Development of this document had helped to identify potential uncertainties that would need to be tracked. The following key issues arose from the 'vault' Clearing House discussions, as items to look for in the review:

SKI - 11 Cement and cement barrier properties: chemical evolution of pH buffer and the cement phase; cracking of concrete and the potential for sulphate attack; possibility of degradation of the Silo base given evidence of cracking in the roof of the observation tunnel beneath it; potential impact of an alkaline plume on rock properties (same as SKI – 3).

SKI - 12 Bentonite properties: alteration by high pH fluids from the cement; effect of variable resaturation of bentonite in the Silo on development of the bentonite barrier function and the stability of the concrete structure.

SKI - 13 Organics and colloids: degradation of organic components of the waste form (effect on K_d, pH buffering and potential radionuclide complex formation); formation of colloids and the location where they might be formed (e.g. within engineered barriers, in the near-field rock etc.)

SKI - 14 Structural and conceptual aspects: potential effect of cave-in (where there is no tunnel/vault backfill) on vault performance; evidence for a conceptual model for the safety functions of the different barriers.

SKI - 15 Near-field hydrogeology: variations in the groundwater flow pathway in the near-field as a result of different degradation rates of the vaults; possible differences in the evolution of chemical conditions within the vaults under saline, brackish Baltic and fresh water conditions as environmental conditions change.

4.5 Gas Generation and Behaviour

The following key issues on the specific topic of gas behaviour arose from the 'vault' Clearing House:

SKI - 16 Microbial activity effects on redox conditions and gas generation, although these may be unimportant at high pH.

SKI - 17 Gas generation and potential gas leakage pathways (especially in and from the Silo). The possibility of a cyclic build-up of gas pressure and subsequent escape, the effects of which could potentially damage the engineered barriers.

SKI - 18 How to estimate radiological impacts of gas mediated releases with respect to the potential for localised release of gas to the biosphere.

4.6 Suggested Calculations

Many of the issues discussed and considered important to the review were items to look out for in the forthcoming SAFE documentation. In addition, the workshop was invited to identify calculations that could be undertaken by SKI, independently of the SKB SAFE project, to explore some of the issues raised in more depth. These suggested calculations were intended to provide input to the regulators so that they could have more informed discussions with SKB, specifically concerning:

1. The influence of different completion designs and backfill options (Issues SKI - 1 and 2).
2. Gas generation and movement (Issues SKI - 17 and 18).
3. The implications of the distribution of waste between the vaults on radionuclide releases (Issue SKI - 4).
4. The characteristics of a high pH plume and its influence on the host rock (Issue SKI -11).

5. The effects of different modes of concrete cracking on radionuclide transport (Issues SKI -3 and 11).

6. Effects of organics present in the waste (including super-plasticisers used in grouts and backfill material) on radionuclide behaviour (Issues SKI-13 and R-2).

These suggestions, and the 'SKI' and 'R' issues, were revisited almost one year after this workshop and as the first SAFE documents were being received and entering review. A new, prioritised set of topics was defined that could be addressed in independent PA calculations during 2001, within the resources then available (Maul and Robinson, 2002).

In the PA calculations, topics 2, 5 and 6 were carried forward in the new priority list. It is considered that insufficient information is available at the present time for independent PA calculations for topics 1 and 3 to be useful, but it might be valuable to do this in future. An independent assessment of topic 4 would require the use of detailed supporting level codes rather than PA codes.

5 The Project SAFE Supporting Documentation Review

SKB has produced a series of reports in support of the SAFE Final Safety Report. These relate to the SKB's overall approach, the compilation of models and data, and the results of calculations of specific aspects of repository performance. At the time that these reports were reviewed, the reviewers were not aware that the Final Safety Report was being produced. Moreover, many of the supporting reports that were reviewed were available at that time only as draft versions.

The approach adopted for the review was to carry out formal, detailed reviews only of those documents that were identified as being the key supporting reports. The remaining 'underlying' reports were used as reference material for these detailed reviews. In particular, a large number of reports on the SKB approach to biosphere modelling were produced from 1998 – 2000, partly in support of the SR 97 project on the SFL-2 spent fuel repository. Some of this material is directly applicable to SFR 1 and was evaluated in the current project, but was not reviewed in detail.

Each key report was evaluated by one or more reviewers and the findings reported using a standard pro forma. The project management team (the authors of this review) also carried out a more cursory overview of the full range of reports, but it is emphasised that this project does not represent a comprehensive review of all of the reports produced by SKB. Rather, the intention has been to assist the regulators by identifying issues that require further consideration and, where possible, to provide a preliminary exploration of these using PA analyses.

The reports that have been reviewed are listed in Table 5.1, together with the names of the reviewers. Individual reviews are appended to this report. In addition, the structural geology of the SFR 1 site was identified as a key area requiring review on behalf of the regulators. This technical area has therefore been the subject of a separate appraisal by Tirén et al. (2000), and the results of that review have been taken into account here.

This Section draws out the main findings of the individual reviews of supporting documentation given in the Appendix, and discusses their significance for the assessment of the performance of the SFR 1 repository. Additional issues raised in discussions among the project team are also included here. As noted in the Introduction, it was possible to question SKB representatives about some of the issues raised by the reviews part way through the review process, during the course of a workshop that took place in September 2001. Information provided by SKB at that workshop is included where appropriate and Section 5.11 gives some more general comments about the outcome of those discussions.

The key points arising from the reviews are arranged under the following headings:

1. geological structure of the site;
2. groundwater flow;
3. waste form behaviour;
4. microbial activity;
5. gas production and movement;
6. stability of concrete structures;
7. the biosphere;
8. scenarios and systems approach;
9. data used in the SKB safety assessment; and
10. radionuclide release and doses.

At the end of this section, the issues identified previously in Sections 3 and 4 are revisited and classified according to whether the SAFE documents are considered to have cleared them up, advanced knowledge significantly but still left questions, or left them incompletely addressed. In addition, further issues that have arisen from the SAFE document review are tabulated and matched with the topics prioritised for SKI's independent PA calculations.

5.1 The Geological Structure of the Site

The separate review of SKB's structural model for the SFR 1 site (Tirén et al., 2000) concluded that most of the geological structures identified in previous models could be confirmed. However, the review did identify two additional zones that could affect performance: one inclined zone, situated just above the Silo, and another steep to vertical zone that transects the four vaults. Evidence for whether these additional features exist or not should be sought in investigations of the cavern walls, while the possible implications of such features for groundwater flow should be evaluated by SKB in future hydrogeological modelling of the site.

Table 5.1 *SKB SAFE Reports included in the Review of Supporting Documentation*

Report No.	Title & Authors	Status at Time of Review	Reviewer*	Date of review	Appendix / Section
R-01-02	Modelling of future hydrogeological conditions at SFR, Forsmark. (Holmen & Stigsson)	Draft	J Geier	April 2001	A1/6.2
R-01-21	Details of predicted flow in deposition tunnels at SFR, Forsmark. (Holmen & Stigsson)	Draft	J Geier	Dec 2001	A2/6.2
R-01-03	Project SAFE: Low and intermediate level waste in SFR-1: reference waste inventory (Riggare & Johansson)	Draft	Being reviewed by SSI as a separate project. The results were not available at the time the present review was completed.		
R-01-26	Characterisation of bitumenised waste in SFR-1. (Pettersson & Elert)	In Press	W Miller	July 2001	A3/6.3
R-01-04	Project SAFE: Complexing agents in SFR. (Fanger)	Published	M Stenhouse	June 2001	A4/6.3
R-01-05	Project SAFE: Microbial features, events and processes in the Swedish final repository for low and intermediate-level radioactive waste. (Pedersen)	Published	J West	May 2001	A5/6.4
R-01-11	Project SAFE: Gas related processes in SFR. (Moreno, Skagius, Sodergren & Wiborgh)	In press	P Robinson	Aug 2001	A6/6.5
R-01-08	Modelling of long-term concrete degradation processes in the Swedish SFR repository. (Hoglund)	Draft	D Savage	June 2001	A7/6.6
R-01-27	The biosphere today and tomorrow in the SFR area. (Kautsky, editor)	In press	M Egan	Dec 2001	A8/6.7
TR-01-04	Models for dose assessments. (Karlsson, Bergstrom & Meili)	In press	M Egan	Sept 2001	A9/6.7
TR-01-15	A transport and fate model of C-14 in a bay of the Baltic Sea at SFR. (Kumbland)	Draft	M Egan	Dec 2001	A10/6.7
R-01-13	Project SAFE: Scenario and system analysis. (Andersson & Skagius)	Draft	N Chapman	July 2001	A11/6.8
R-01-14	Project SAFE – Compilation of data for radionuclide transport analysis. (Anon)	Draft	P Maul	Nov 2001	A12/6.9
R-01-18	Project SAFE: Radionuclide release and dose from the SFR repository. (Lindgren, Pettersson, Karlsson & Moreno)	Draft	N Chapman	July 2001	A13/6.10
* Information on the review team is included as Appendix A14					

The review did not identify specific issues that should be addressed in PA calculations, although it was observed that the zone above the Silo could possibly be significant for the release of gas or radionuclides

5.2 Groundwater Flow

The review of the SKB groundwater flow studies focussed on two main topics: groundwater flow in the site as a whole and flow through the individual vaults. The results of the reviews are presented separately below.

Site Scale model

The review (Appendix A1) identified what appear to be a number of weaknesses in the SKB model:

- it omits significant heterogeneity that is manifested on the local scale and appears to have disregarded evidence for significantly higher permeabilities in the shallow part of the rock;
- it has been calibrated with respect to a very limited amount of data for a single hydrogeological situation that is significantly dissimilar from the situation for which predictions are sought, so the parameter estimates are poorly constrained;
- no convincing demonstration is given that the model is able to predict hydrogeological parameters for situations other than the case that has been used to calibrate the model;
- sensitivity studies have not addressed the significant uncertainty that remains. Alternative distributions of conductivity among fracture zones and the rock mass have not been ruled out, which affects estimates of flow through the tunnels;
- alternative hypotheses for the configuration of large-scale structures have not been considered;
- alternative possible values of porosity (which is poorly constrained) would affect estimates of breakthrough times and groundwater velocities.

The effect of these shortcomings would appear to be that:

- predictions of flow rates through the vaults over the long-term are likely to be underestimates;
- calculations of possible radionuclide capture by a well may be underestimates because wells were considered using an unrealistic, homogeneous model of the rock mass;
- alternative flow velocities would affect the evolution of near-field chemical conditions and degradation of engineered barriers (so far as these are impacted

by infiltration rates for meteoric water) and transport times for non-sorbing radionuclides;

- the ratio of flow wetted surface area to transit times (which controls radionuclide retardation by sorption and matrix diffusion) may have been overestimated;
- conclusions regarding the unimportance of tunnel plugs and the Singö fracture zone should not be relied upon for the safety case;
- the uncertainty in the calculations must be assessed as high.

Repository-scale Flow

A number of technical issues were identified in the review of flow calculations for the vaults (see Appendix A2):

- There is insufficient justification for the hydraulic conductivity values that were chosen for the two sensitivity cases (failed BMA section and failed Silo barriers). It is implied that these are *ad hoc* values. The discussion of the hydraulic conductivity value chosen for a failed Silo implies that the assumed value is to be regarded as conservative, but the arguments given are not sufficient to establish that this is the case. For the BMA sensitivity case, it might reasonably be asked why a higher value (e.g. 1×10^{-4} m s^{-1}) should not have been considered as within the range of realistic values. A clearer justification ought to be given for these 'assumed' properties and whether they can be regarded as conservative or even realistic for the designated scenarios.
- The BMA sensitivity case geometry is not entirely conservative: the net effect of assuming an incomplete rather than a complete breach along Fracture Zone 6 is arguably no worse than a factor-of-two underestimation of the flows predicted from this scenario. However, it is felt that this issue is of less significance than the uncertainty in the properties of the failed waste encapsulation, discussed above.
- There is insufficient documentation of the specific formulae that were used to convert from the basic model output to the presented results. The type of averaging used to calculate the 'average specific flow' values is not stated.

The weaknesses identified above in the review of the site-scale flow modelling give rise to the following concerns in interpreting the detailed flow predictions:

- The model treats the rock mass and fracture zones as homogeneous domains, although site data indicate the presence of at least three orders of magnitude variation in 'point' measurements of hydraulic conductivity within both the rock mass and the fracture zones. It is considered almost certain that the variability of flows to tunnel sections has been underestimated by a model that assumes homogeneous properties within each structural unit. No meaning can be attached to predictions that any specific tunnel section will have greater flows than another specific tunnel section. At best, these detailed predictions can be viewed as illustrative of which tunnel sections are most likely to experience greater flows than others, owing to unfavourable positions relative to the flow boundaries and the main fracture zones. The presence of heterogeneity also introduces uncertainty into the assessment of the sensitivity cases. For example, the coincidence of a failed tunnel segment with a relatively high-conductivity portion of Fracture Zone 6 would result in higher flows than have been predicted using the homogeneous model.

- There is reason to believe that the calibrated parameters of the model are subject to significant residual uncertainty stemming from, for example, the non-uniqueness of the calibration with respect to the available data, and neglect of skin effects in the rock mass (which result from, for example, unsaturated conditions in air-filled tunnels). This will affect the detailed predictions of flows to tunnel segments. Calibration errors could affect both the total predicted flow through tunnel segments, and the distribution of flow among different tunnel segments. Thus both the average value and the variability of the predicted flows could be affected.

The main issues of relevance for the assessment of the safety case for SFR 1 are thus:

- The omission of heterogeneity from the underlying hydrogeological model very likely results in an underestimate of the variability of flows to tunnel segments. Correlations between flows and transport distances to the biosphere could also be affected if these were evaluated from the flows and transport distances for particular tunnel sections.
- Weaknesses of the calibration of the underlying site model will carry over as uncertainty in the predicted flows to individual sections of the repository. Flow rates through the vaults over the long-term are likely to have been underestimated. In that case, detailed flow predictions would also be systematically biased toward lower flow rates.
- If the BMA or Silo failure scenarios are critical to the safety case, further attention should be given to the parameter values that were assumed for these scenarios. These appear to be *ad hoc* choices, and should be better justified to establish that they are conservative or at least realistic.

Discussion with SKB

The SKB flow calculations show a divide so that flow paths from the vaults diverge from those from the Silo. Measured inflows to different components of the repository have been used to calculated effective hydraulic conductivities for the rock mass (around 6×10^{-9} m s^{-1}). Known fracture zones are represented directly. The uncertainty associated with this calibration procedure is the subject of some debate. It can be argued that the inclusion of skin effects might have resulted in significantly different values for the derived rock conductivity. SKB found it necessary to use a skin effect factor for Fracture Zone 6 in order to fit the known information from packer tests. It was argued that excess head measurements were unreliable and so the fact that the model does not reproduce them is not a concern.

SKB argues that the regional flows used in its previous assessment for SFR 1 were too large. The calculated flows through the vaults are much lower. SKB stated that the uncertainty in the repository flows (averaged over each vault) is about a factor of two, although this is much less than the difference between the ‘old’ and ‘new’ calculations. The review team believes that it is difficult to sustain such a low overall uncertainty factor, particularly when account is taken of rock heterogeneity.

Detailed flows through the vaults depend on the assumptions made for changing hydraulic conductivities. For example, the Silo bentonite barrier is assumed to have a hydraulic conductivity of 10^{-8} m s^{-1} after degradation (comparable with the value for the rock mass). The calculated flows through the vaults do not vary as much as might be expected with changes in hydraulic conductivities, as it is the overall resistance along the flow path that is important.

Calculated breakthrough curves from the repository to the biosphere are presented in the hydrogeology report. Typical timescales are in the region of 30-1000 years. Effective porosity calculations come from the observed times for sea-water ‘break-through’. The flow calculations are thought by SKB to be realistic and are carried through directly to the radionuclide transport calculations. The review team note that this appears to be in contradiction to claims that the overall approach to the safety assessment is to take pessimistic values for key parameters that affect performance.

5.3 Waste Form Behaviour

The main reports reviewed in this area concern the behaviour of bituminised waste (identified in previous SKI reviews as an issue that needed to be tracked in future assessments) and the role and importance of complexing agents in determining the behaviour of radionuclides released from the wastes.

The bituminised wastes (see Appendix A3) are considered first. Some potential for changes to the near-field physical properties as a consequence of bitumen swelling is acknowledged by SKB. For a few waste packages, the maximum potential volume expansion due to water uptake is greater than the available void spaces. In the case of the Silo, these waste packages are grouped together in the centre region and, therefore, the potential swelling of these packages may have some physical effects on the stability and hydraulic properties of the silo, although this was not quantified in the SKB report. Consequently, this issue appears to remain unresolved.

The evaluation of work on complexants (Appendix A4) suggests that sufficiently high concentrations of iso-saccharinic acid (ISA) exist in some waste streams to affect the sorption of bi-, tri- and tetravalent elements. In this context, it would be useful to consider in more detail the possible implications of enhanced concentrations of complexing agents carried through to dose calculations, to determine the significance of the findings. The SKB analysis gives no clear guidance on how this type of information should be carried through to PA calculations, e.g. as a reduction in K_d values, or increase in solubility, of certain elements such as Pu. Other assessments (e.g. the Nagra evaluation of Wellenberg L/ILW repository (Nagra, 1994)) have attributed such reduction/increase factors to broad groups of wastes in a generally conservative fashion, and it would be useful to apply this type of approach to SFR 1, for example to specific vaults. In discussion, SKB argued that the critical level for ISA is 10^{-4} M, and that it is relatively easy to demonstrate that these levels are unlikely to be maintained because of sorption on cement. In any case, the sorption values used in the PA calculations are low.

The concept of surrounding certain (unconditioned) waste packages in the BMA section with cement, to promote sorption of ISA and thereby decreasing the concentration of ISA in pore-waters, could be considered further.

5.4 Microbial Activity

This review is reported in Appendix A5. Whilst the SKB report correctly identifies the environmental controls on microbial life in SFR 1, along with all the likely microbial processes that could affect the integrity of the repository and are thus directly relevant to the safety case, it is a purely qualitative document. None of the information can be used directly in the overall safety case. Simple scoping calculations would have proved to be a useful first step.

There is considerable uncertainty about how the system evolves, yet the dominant role of microbial processes in most degradation mechanisms is clear. Microbial activity is acutely sensitive to groundwater flow through the vaults, the rates of which were found to be uncertain by the groundwater review (see Section 6.2). At higher flow rates, microbial activity increases: this could be important.

Consequently, there still seems to be a significant shortcoming in SKB's understanding of the significance of microbial activity in waste form degradation.

5.5 Gas Production and Movement

This review is reported in Appendix A6. The report on gas production presents various conceptual models, data and calculation case results but lacks a clear overall thread. It is unclear why the only gas effect that is considered is the expulsion of contaminated water. The potential impact of the gas itself and the potential for gas pressure to damage the repository structures are ignored. The origin of the scenarios (or calculation cases) appears to be ad hoc and no reference is made to the overall scenario report; hence, rather than presenting a coherent exploration of the topic SKB has instead discussed a collection of potentially relevant items. The primary assumption throughout the report is that gas generation starts after the repository is resaturated. This is clearly not the case (it begins earlier, as the timescales given for corrosion of aluminium indicate) and it may distract attention from the important processes that may occur.

The results of the SKB analysis indicate that the effect of gas generation is essentially a short-term issue. With the sub-sea location of the SFR 1, doses in the short-term are low in any case. The direct impact on flows beyond the first few years in not important.

Of more interest to the longer-term safety case would be the potential damage to physical integrity of the flow barriers. This is not discussed by SKB, except in the context of a potential escape route for gas, where a few small cracks are enough to allow all the gas to escape. The least favourable case would be cracking after the sea has receded. Thus, SKB do not provide enough information for useful input to the evaluation of the physical degradation of barriers. In addition to cracking caused by large-scale over-pressurisation, the effect of corrosion of reinforcement on the integrity of barriers should have been considered.

SKB provide no discussion on whether gas release has a chemical effect on the system, although this seems to be unlikely.

Although not impacting directly on the overall safety case as such, the lack of any formal FEP analysis or systematic approach to looking at uncertainties in the area of gas production and movement might be indicative of a wider issue in the assessment work that has been undertaken.

The conclusions section ends with strong statements about the importance of the adequate functioning of evacuation pipes in the Silo, the gaps between lid and wall in the BMA and the use of backfill in the BMA. These should be carried forward to the overall safety report and it should be shown that there is reasonable confidence in the correct functioning.

5.6 Stability of Concrete Structures

This review is given in Appendix A7. The long-term stability of the concrete structures in SFR 1, in the Silo in particular, is a very important aspect of the safety case, as it controls the rate at which water can move through the wastes. The SKB documentation looks principally at time-dependent conditions of pore fluid composition and chemical impacts on the physical properties of the concrete barriers. The SKB PA calculations would seem to be conservative in their treatment of these effects, although there are some weaknesses concerning:

- the completeness of the conceptual model;
- the applicability of the results to all portions of SFR 1 repository, which is not homogeneous in its cement content;
- a lack of calculations for the fresh water period;
- extrapolation of the results to the timescales of relevance to safety assessment, which involve considerable uncertainty owing to the lack of good analogues for validation; and
- the potential alteration of bentonite properties by cement pore fluids, which has not been addressed (other work indicates up to 50% of a 1 m thick layer of bentonite could be altered in 1000 years).

The implications of the results of the SKB study are that:

- pore fluids are likely to have pH > 10 for times ~ 10 000 years, thus justifying the use of sorption and solubility data for radionuclides under hyperalkaline conditions;
- the porosity of the concretes is unlikely to increase above 15%, the value which SKB has conservatively chosen for its safety assessment work;
- concrete alteration is unlikely to proceed deeper than 10 cm beneath exposed surfaces; and

- diffusivities could increase by a factor of 30 due to changes in pore geometries.

A key problem is that the SKB work has not looked at other (non-chemical) mechanisms for the physical degradation for the concrete structures. The SKI review of SKB's SFL 3-5 ILW repository assessment (SKI, 2000), which uses much of the same conceptual basis as the SFR 1 designs, identified a similar weakness:

'The general experience with steel-reinforced concrete is that such material experiences severe localised cracking soon after immersion in water. While this cracking may provide rapid pathways for the escape of gases generated by anaerobic corrosion, cracking could also lead to a much higher hydraulic conductivity for this material. Large cracks, in turn, might invalidate some of the assumptions regarding the relative contrast in permeabilities among the concrete structure, the gravel backfill, and host rock, and the assumption that aqueous radionuclide release from the concrete vaults is diffusion-dominated.'

This motivates some evaluation of the sensitivity of performance to concrete hydraulic properties.

A further matter has been identified concerning the impact of cementitious pore waters on local groundwater chemistry. This has not been considered by SKB. An obvious question is whether the well water (for the well intrusion scenario) would actually be potable. If not, then the scenario could be considered more conservative than has been assumed in reporting the results of the PA.

5.7 The Biosphere

Three SKB reports relevant to the biosphere were reviewed. Appendix A8 reviews the report on how the SFR 1 biosphere is expected to develop, Appendix A9 reviews the report on biosphere modelling and Appendix A10 reviews the report on the ecosystems model developed for C-14.

Development of the SFR 1 Biosphere

This report draws together a comprehensive, scientifically-justified basis for the identification and description of biosphere systems relevant to evaluation of long-term radiological impacts of SFR 1 and summarises the results of a substantial number of research and environmental characterisation reports that have been produced within the BIOSAFE project. The emphasis is on those parts of the biosphere that represent potential discharge areas or regions where a significant fraction of any potential release may migrate and accumulate in radiologically significant concentrations.

There is limited discussion of the uncertainties associated with the projections of future environmental change. It is not evident to what extent the underlying research has addressed the sources, or implications, of uncertainty associated with either the main drivers of change, or the implications of such change that become propagated through the biosphere system.

Comparatively little emphasis is given to factors that might cause the location (or rate) of contaminated groundwater discharge to change with time. Assumptions made in relation to the location of, and dilution at, the geosphere-biosphere interface are potentially a very significant part of the overall radiological assessment and it is not evident how the implications of biosphere change on the groundwater flow system have been taken into account in developing the flow and transport assessment calculations.

Biosphere Modelling

The models that have been developed by SKB evaluate the transport and distribution of radionuclides in a broad range of ecosystem types, representative of the potentially contaminated environment under present-day conditions as well as those anticipated as a result of landform evolution over the next 10 000 years. Discussion is also provided of the methods used to evaluate radiation dose rates to individual members of hypothetical critical groups.

The models are described as dynamic, but the model system is not itself time-dependent because individual model components and the rate constants representing transfers between them do not change with time. Evolution of the biosphere system is therefore represented by a sequence of distinct, time-invariant models for the individual ecosystem types.

Residual contamination from earlier stages in the sequence of landscape evolution (e.g. sea bed and lake sediments) may become a secondary source in the new ecosystem. However, no detailed consideration is given to how such transitions would be simulated in practice within the PA.

The system is configured for probabilistic analysis of the implications of parametric uncertainty, based on the specification (and, in some cases, correlation) of statistical distributions of parameter values, including assumptions about human habits and diet. Models for calculating doses from a range of exposure pathways are based on standard techniques. The use of a probabilistic approach is limited to the biosphere - it is not used in other parts of the system. This difference is bound to lead to questions about the compatibility of parameter value selection in different parts of the system.

The specification of physical parameters for the lake system is an example of where care needs to be taken in the use of the probabilistic approach. The area, depth and turnover rate of the lake are based on rough estimates, reflecting the difficulty of making precise predictions of future surface hydrological conditions in a dynamically-changing environment. However, these parameters are presented as distributions, implying an intention to consider the implications of such uncertainty as part of the overall probabilistic analysis, rather than seeking to justify a particular set (or sets) of assessment assumptions as providing suitable indicators of radiological impact.

In summary, the biosphere modelling undertaken by SKB is detailed and well presented. The main outstanding queries relate to consequences of using a sequence of time-invariant models, and the way that the probabilistic approach has been applied to some key parts of the system.

Ecosystems Modelling for C-14

Given the potential importance of C-14 to the overall safety performance of SFR 1, SKB has developed a detailed dynamic ecosystem model to provide a basis for investigating some of the contributions to uncertainty associated with calculated radiological impacts. This represents a novel piece of work. Because of its complexity, the model is necessarily founded on a range of assumptions that do not appear to have been fully tested. The requirement for detailed model testing and validation is stronger where the evaluation of contaminant transport and accumulation is based on a dynamic process model rather than empirical equilibrium relationships used in traditional biosphere modelling. At the present time this work can be viewed as being a useful input to the discussion of the importance of C-14 releases to the environment, although not sufficiently developed to provide a direct input to the safety case.

5.8 Scenarios and the Systems Approach

This review is given in Appendix A11. The methodology applied has been developed and tested before by SKB and is judged to be sound, and appropriate for the SFR 1 safety study. The methodology generates a significant ‘paper trail’. It is recommended that SKI carry out a QA check to examine the supporting documentation to confirm the depth and comprehensiveness of the process.

A number of shortcomings have been identified in the SKB application of the methodology that they present:

- the overall 'Safety Concept' for SFR 1 is not described in the underlying reports reviewed to date; this is a serious omission, as it is hard to judge how the system is designed to behave and what is the intended performance function of individual components or mechanisms;

- the SKI-SSI review of SR 97 asked for more discussion on combinations of scenario initiators: SKB do not appear to have looked at this matter comprehensively for SFR 1 either *(in discussion, SKB stated that no useful scenario combinations had been derived from the scenario analysis*);
- SKB does not define in sufficient depth how particular processes and scenarios should be analysed in the PA, so it is not possible to check whether the suggestions for what needs to be evaluated have actually been followed: the impression is given that most of the PA decisions had already been taken before the systematic evaluation described by SKB had taken place and developed the justification for their possible importance, or lack of it.

The Base Scenario appears to be a sensible and feasible basis for the PA work, but other scenarios are not described in any detail. The Base Scenario consists of a number of variants. There is no single scenario/variant that represents SKB's expected evolution of the system. (Linked to a well-defined safety concept, an explanation of expected evolution ('design basis') is a clear way to explain and understand system performance and associated uncertainties). For example, the Degraded Barriers variant is based on the assumption that full degradation occurs from 1000 years after closure because this was considered most pessimistic, in view of the timescales for the sea to retreat, rather than being based on a quantitative consideration of the likelihood of different possible degradation rates. Confusing statements are also made about scenarios that are said to need to be developed, but discarded later on. Some points about particular scenarios and how they are treated in the R-01-18 ('results') report are:

- It is not clear why discontinuous permafrost is less important than complete freezing, or why it is 'well covered by assumptions made in the Base Scenario'. (*In subsequent discussion, SKB argued that it was not worth pursuing the permafrost scenario any further, e.g. to consider discontinuous permafrost, based on the results obtained from the calculations that had been undertaken (these did not add to overall risk). It was also argued that tectonic events would be covered by the Initial Defects scenario.)*
- It is not clear that the suggested analysis of a magnitude 7 earthquake at 7000 years has been 'at least qualitatively assessed' by a relevant calculation case;
- Releases to wells have been considered. Only wells that penetrate the repository itself (BLA or BMA void space) or intersect the plume of contaminated groundwater can have any significant contamination. The annual probability of a well being present is derived from present day well

densities. The well intrusion analysis is stated to require evaluation of effects on both water flow and transport and it is not clear that the former has been done;

- The consequences of direct intrusion into the repository (e.g. drilling contact with the wastes, rather than exposure via an 'intrusion well') are not analysed. SKI and SSI need to be content with this position: the recent ICRP Publication 81 provides some useful views on appropriate measures to assess the significance of intrusion impacts.

The SKB analysis says little about the evolution of plugs and seals, as no decision has been taken about them. This is a topic in which SKI ought to take an interest, as their significance to the overall performance in untested. In addition, confidence that the repository can be adequately plugged is something that should not be left until a late stage.

More discussion of scenario initiation conditions and their likelihood is needed, which would be easier if the scenarios were properly and systematically described. The reason for doing this would be to follow recent ICRP 81 suggestions for providing decision-makers with disaggregated 'dose plus likelihood' data, as an alternative to risk figures. Providing more information about how and when scenarios might occur and combining this with information about impacts at different times, allows consideration to be given to overall resilience of the repository system.

SKB motivates a sensible set of scenarios for analysis, but does not give much guidance on how to analyse them. Moreover, it is not apparent that the set is comprehensive, since, despite going through a complex and, presumably, time-consuming process of setting up the system description, some rather weakly justified jumps have then been made in deciding what to analyse.

Two additional scenarios are suggested for possible analysis:

- the roof fall scenario in BLA; and
- an 'end point' scenario (beyond 10 000 years) associated long-term erosion processes, when the repository contents might become exposed at the surface.

The latter scenario would provide an illustration of the final 'fate' of the repository and the wastes, which is a useful end-point to any assessment and demonstrates that both implementor and regulator have considered the ultimate impacts of disposal.

In discussions with SKB, it was emphasized that the work on scenario definition was undertaken early in the project, but had not been formally written up until very recently.

It was also emphasised that the main advantage of the structured approach, at whatever stage, was to check that nothing important had been overlooked.

5.9 Data used in the SKB Safety Assessment

The review of data identification and abstraction for the safety assessment work identified a number of issues that can be summarized as follows (see Appendix A12):

- There appears to be an over-reliance on precision in the specification of groundwater flows through the different components of the repository, with insufficient information being provided on the uncertainties associated with these calculations.
- Parameter choices are sometimes based on arguments of conservatism. In a complex system like SFR 1 it is not always possible to determine in advance what assumptions are actually going to be conservative.
- The SKB calculations are based on calculations that extend over a 10 000 year period. Some of the assumptions made will not be valid if it proves necessary to consider impacts on longer timescales.
- The lack of some site-specific data for SFR 1 reflects the low importance placed on the geosphere in the overall safety case.

5.10 Radionuclide Release and Doses

This review is given in Appendix A13. Although the link between the derivation of scenarios and model calculations is not particularly well presented, the dose calculations provide very useful illustrations of possible future impacts. However, they omit, or give only selective treatment to, a number of potentially important aspects:

- as noted in Section 5.6, the mechanisms for concrete cracking do not account for physical degradation processes: barriers could degrade earlier than the 1000-year post-closure initiation time assumed in the SAFE study;
- the issue of roof-fall in the unfilled vaults and its potential impact on release paths is not addressed;
- a larger well (presumably feasible: the large void space in some vaults collects inflows from a large volume of rock), for a larger exposed population group, which could affect flow, release and doses;
- the potential for focussed flow in the more likely scenario of discontinuous permafrost might be more significant than the continuous case;

- the uncertainties in flow through the vaults highlighted in Section 5.2 suggest that sensitivity to increased flows through the various parts of the system needs to be assessed (the variants identified by SKB appear insignificantly different from the base values);
- a sensitivity analysis should be undertaken to address the implications of varying proportions of organic and inorganic carbon, as ^{14}C is the critical radionuclide in the dose calculations. *(In discussion, SKB stated that the estimate of 10% for the fraction of carbon that is likely to be in an organic form derives from measurements in reactor water. Although this figure is uncertain, they consider it reasonable. Wherever possible organic wastes have been placed in the BLA.)*;
- the fractured Silo base scenario is omitted on the basis (not stated in the source scenario report) that even if it were fractured, the bentonite would continue to limit flow: this needs to be checked, as it is potentially the most problematic scenario.
- the ‘initially degraded barriers’ scenario is unaccountably not accompanied by dose calculations; and
- the permafrost scenario uses the present day biosphere and then incorporates 'significant dilution' in a body of water that will not be present at 12 000 AD.

A number of observations can be made on the results of the SAFE calculations performed by SKB:

- the results presented for the 'downstream well' are in many cases close to, or in excess of, SSI's 10^{-5} Sv y^{-1} individual dose rate criterion for a repository (were the new regulations to be applied to SFR 1);
- BLA and BTF appear to dominate the well doses (and thus the radiologically significant releases) from the whole repository;
- partial combination of scenarios (e.g. the case cited of combined chemical and degraded barriers in BMA), gives doses approaching 1 mSv for the well recipient.
- the 'intrusion well' doses (which are not explored for sensitivity to well size and consumption) are several tens of mSv: current ICRP advice is that the significance of intrusion doses should be weighed against a dose range of 10 – 100 mSv y^{-1}, the upper end of which might require some form of action to be considered.

- there is a need for discussion about whether and how SKB should evaluate acute doses to intruders and how the results of the prolonged exposures from well-intrusion should be viewed.

A key concern is that the SKB analysis has not carried forward a discussion of the impacts of uncertainty and variability in some key safety-sensitive parameters (e.g., inventory and water flow rates), yet the results indicate, compared to many other international repository safety assessments, some relatively high doses at short times into the future, for scenarios that appear quite likely.

5.11 Clarification of Issues in Discussion with SKB

Most of the questions that had arisen from the review of the SKB documents supplied by SKI were satisfactorily dealt with at a meeting with SKB in September 2001. On the basis of the discussions with SKB, the overall approach to the safety of SFR 1 would seem to be based on the following main arguments:

- The primary role of the geosphere is to control the flow of groundwater through the repository.
- Much more detailed hydrogeological calculations have been undertaken than were performed in support of the original safety case calculations for SFR 1. These demonstrate much reduced flows of groundwater through the vaults, even after barrier degradation.
- Owing to uncertainties in the retarding effect of the geosphere, no allowance is made for this in the overall risk assessment.
- Although significant doses are calculated for some scenarios/variants, arguments based on the probability of those doses actually being incurred show compliance with a risk target of 10^{-6} y^{-1}.

5.12 General Observations at the End of the Document Review Stage

The key concern about the approach that has been taken by SKB is the uneven use of conservative assumptions. In several instances, unnecessarily pessimistic assumptions have been employed, whilst there are instances where assumptions have been made that could be non-conservative. Key issues include:

1. SKB has not presented within its Base Scenario a variant that they consider to represent the expected evolution of the system. Irrespective of the need to address regulatory criteria, this would have been extremely valuable in expressing SKB’s understanding of the safety of the system.

2. SKB have put forward arguments for undertaking calculations for a 10 000 year period after repository closure. Although it is considered that overall risks are unlikely to have been underestimated as a result, the arguments for this cut-off time are not convincing. Consideration of longer timescales, particularly for the expected evolution of the system, would have been helpful in demonstrating the long-term safety of the system.

3. The calculations are critically dependent on the calculated groundwater flows through the repository. The hydrogeological work that has been undertaken is impressive in its depth and detail, but there is an unrealistic expectation of the accuracy with which these can be calculated given the limited calibration data used, and there are concerns over the appropriateness of some of the methods that have been used. SKI's own PA calculations have explored a wider range of possible repository flows depending on the timing of barrier degradation (see Section 6).

4. Because of some of the conservative assumptions that have been made in the overall risk assessment (e.g. no allowance of the retarding effect of the geosphere even for short-lived radionuclides from the BLA) some convoluted arguments (e.g. on well drilling likelihood) have had to be introduced to try to demonstrate compliance with the overall risk target. Some of the assumptions made are questionable, particularly with regard to the interpretation of regulatory requirements and the assignment of probabilities to scenarios.

5. Because of the software tools employed, SKB have had to represent some continuous processes (e.g., engineered barrier degradation) in a discontinuous step-wise way. It is difficult to ascertain how this has affected the calculated potential radiological impacts. It is recommended that future software tools be chosen that enable such process to be represented continuously.

6. The detailed work that has been undertaken on the evolution of the biosphere is impressive, and the ecosystem modelling studies provide valuable supporting arguments for the behaviour of organic C-14 in the environment.

Partly because of the complexity of the models used for the near field, it is not easy to undertake a systematic sensitivity and uncertainty analyses for key parameters. This makes it difficult to ascertain how the overall safety of the system is affected by uncertainties in different areas. It is suggested that in future studies the structure of the calculations should be designed to enable straightforward sensitivity and uncertainty analyses to be performed.

At the completion of the document review it was found that some of the issues identified in the January 2000 SKI workshop and PID evaluation had been dealt with within the SAFE project, although many aspects were not fully resolved (see Table 5.2). Some issues had not been addressed by SAFE. The document review also identified several new matters for consideration by SKI, either in their own review or in future work by themselves or SKB (see Table 5.3). As indicated, some of these were carried forward into the final stage of the independent PA calculations described in the next Section.

Table 5.2 *Treatment in SAFE of Issues Identified by Previous Regulatory Review and January 2000 SKI Workshop*

Identifier	**Issue**	**Treatment in SAFE Supporting Documents**		
		Cleared Up	**Advanced Understanding**	**Aspects Outstanding**
R – 1	Land uplift and well scenarios		Much more detailed treatment provided	Inflow to well using a heterogeneous model
R – 2	Organic complexants	Partially	Critical level of ISA	Sensitivity to uncertainty in ISA concentration; conservativeness of K_d values
R – 3	Scenario combinations		Limited consideration only	Arguments for treatment of feasible combinations
SKI – 1	Vault backfill			Still an open issue
SKI – 2	Repository closure plans		Partial analysis of flow resistance of plugs	Still an open issue
SKI – 3	Cement longevity	Partly	Chemical degradation well characterised	Potential for physical degradation not dealt with
SKI – 4	Inventory distribution	Not evaluated as part of this review:being evaluated separately by the regulatory agencies		
SKI – 5	Land uplift impacts on flow and chemistry	Partly	Future environmental and biosphere states and evolution; biosphere modelling approach; ecosystem models for ^{14}C	Uncertainty in impact on discharge location variation with time
SKI – 6	Geological structural model	Largely		Significance of two conjectural fracture zones
SKI – 7	Seismic activity	Partly	Justifications for lack of impact provided	Quantitative assessment of M7 at 7000a not located
SKI – 8	Human induced climate change		Assumed addressed by natural sea-level change scenario	Potential changes to biosphere receptors

Table 5.2 *Treatment in SAFE of Issues Identified by Previous Regulatory Review and January 2000 SKI Workshop*

Identifier	**Issue**	**Treatment in SAFE Supporting Documents**		
		Cleared Up	**Advanced Understanding**	**Aspects Outstanding**
SKI – 9	Future human actions scenarios	Partly	Well constructed into vaults analysed	Direct intrusion and other land uses impacts not evaluated
SKI – 10	Repository impacts on biosphere			Not evaluated, but likely to be beneficial to safety case (so conservative)
SKI – 11	Same as SKI – 3	See SKI – 3		
SKI – 12	Bentonite property evolution			Chemical influence of cement pore fluids not addressed
SKI – 13	Same as R –2, plus colloids			Colloids not treated explicitly
SKI – 14	Cave-in scenario		Mechanical analysis of likelihood and nature of potential cave-in	Open issue: not analysed as backfill plans not available
SKI – 15	Near-field flow and chemistry variation			See SAFE – 2 to 4 in Table 5.3
SKI – 16	Microbial impacts on gas and redox		Scoping and description of likely processes	Quantitative impacts not assessed; would depend on water flow, which is uncertain
SKI – 17	Gas generation and dissipation	Partly	Gas expulsion of water	Gas damage to vaults; time of gas production
SKI – 18	Radiological impacts of gas release			Not treated

Table 5.3 Additional Issues Identified from SAFE Document Review

Identifier	**Issues**	**See Section**	**Related to issue**	**Evaluated in SKI independent PA study**
SAFE - 1	Bitumen wastes expansion	5.3		
SAFE - 2	Treatment of rock heterogeneity on flow field	5.2		As repository groundwater flux sensitivity case (Section 6.2.2)
SAFE -3	Calibration of vault flow model	5.2	SKI - 15	
SAFE - 4	Sensitivity to conductivity and porosity distributions and values	5.2		
SAFE - 5	Potential physical mechanisms for cement degradation	5.6	SKI - 3	
SAFE - 6	Lack of clearly defined 'safety concept' and expected evolution variant	5.8		
SAFE - 7	Scenario definition weakly connected to and tracked through the calculation cases	5.8		
SAFE - 8	Direct intrusion impacts (on intruder) not evaluated….necessary?	5.8	SKI – 9	
SAFE - 9	'Fate of Repository' scenario would be useful	5.8		Evaluated (Section 6.2.3)
SAFE - 10	Uniformity of use of conservative parameter values in assessment	5.9		Partial sensitivity study
SAFE - 11	Justification and implications of 10 000 year cut off	5.9		Partly evaluated by 'fate or repository' variant (Section 6.2.3)
SAFE - 12	Possibility of a larger well	5.10		
SAFE - 13	More realistic treatment of permafrost biosphere	5.10		Evaluated (Section 6.2.3)
SAFE - 14	Sensitivity to ^{14}C inventory, speciation and behaviour	5.10		Significance verified (Section 6.2.1)
SAFE - 15	Impact of using a continuous rather than a step change model of time evolution of system properties	5.12		Evaluated (Section 6.2.3)

6 Independent PA Calculations

As discussed in the Introduction, independent PA calculations having been undertaken on the performance of SFR 1, and these have been reported by Maul and Robinson (2002). These calculations have been used to explore some of the key issues for the SFR 1 safety case referred to in the previous sections without reference to SKB's own PA calculations. A summary of this work is given in this Section.

6.1 The AMBER Model

The AMBER software has been used to model SFR 1. The general approach that is used can be summarised as follows:

- The SFR 1 system is represented by a number of compartments.
- The transport of contaminants between compartments is modelled, with information on the transport of bulk materials within the system being provided as input information.
- Potential radiological impacts are estimated from calculated radionuclide concentrations in environmental materials.

AMBER has a number of facilities that make it a powerful tool for undertaking this type of modelling. This approach enables the whole system to be modelled, with all time dependent processes being explicitly represented. In this Section a brief summary is given of the key features of the modelling of the SFR 1 system with AMBER.

6.1.1 The SFR 1 System

The SFR 1 system has been divided into four sub-systems as shown in Figure 6.1, with the corresponding screen shot in AMBER shown in Figure 6.2. Figure 6.1 shows the main processes by which radioactivity can be moved around the system.

The four sub-systems are:

- The Repository sub-system which includes models for each of the vaults (Silo, 1BTF, 2BTF, BMA and BLA), together with associated near-field rock;
- The Geosphere sub-system which represents the far-field rock.;
- The Terrestrial Biosphere; and
- The Marine Biosphere.

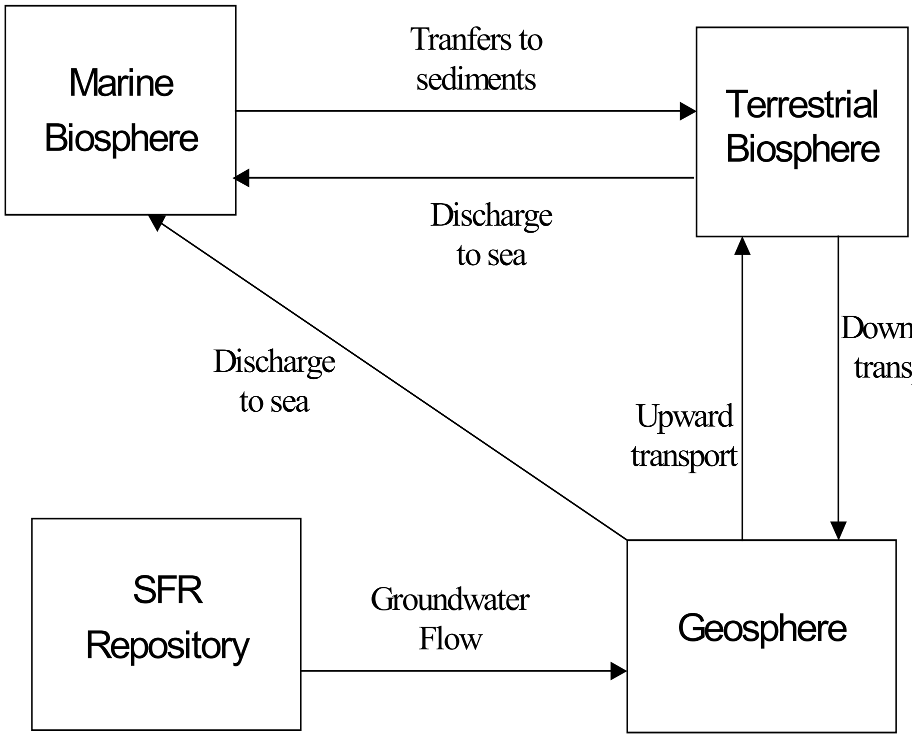

Figure 6.1 *The AMBER System Model for SFR 1*

Figures 6.3 and 6.4 show schematically how the groundwater flow direction is assumed to vary from generally upwards from the repository region to the overlying sea initially to almost horizontal when the Baltic has retreated and the lake referred to above is assumed to have formed. In the AMBER calculations it was assumed that this lake may persist for the period of interest of the PA calculations, or it may silt up; exposure calculations for both possibilities are considered.

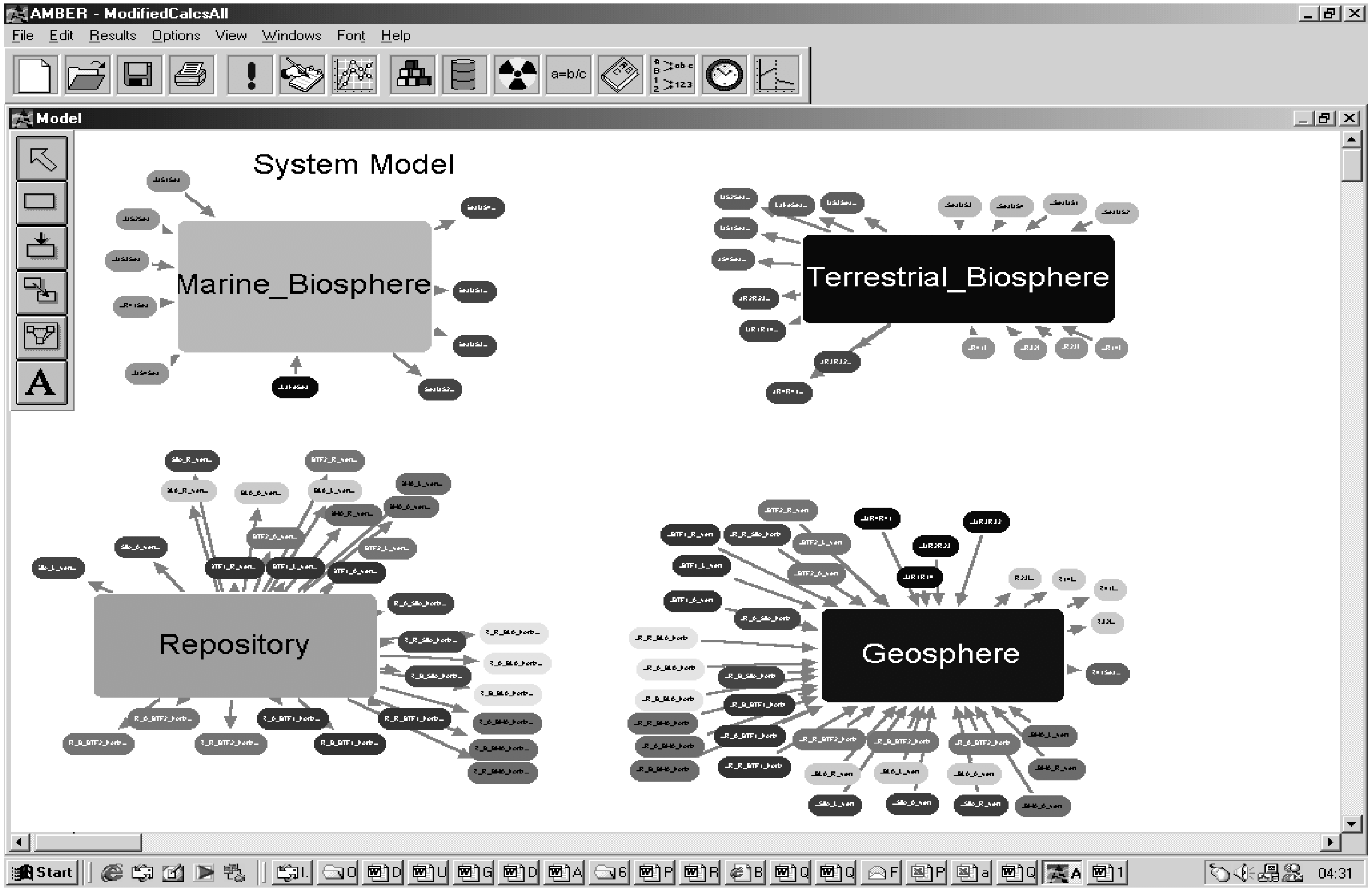

Figure 6.2 *Screenshot of The AMBER System Model for SFR 1*

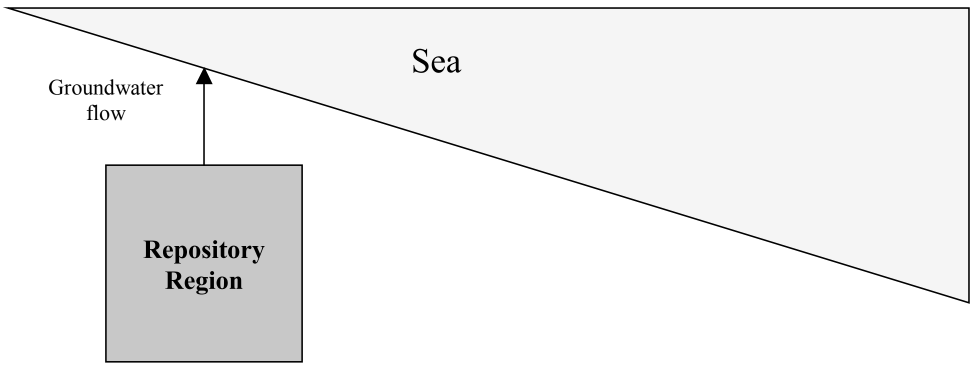

Figure 6.3 *Groundwater Flows when the Repository is below the Baltic*

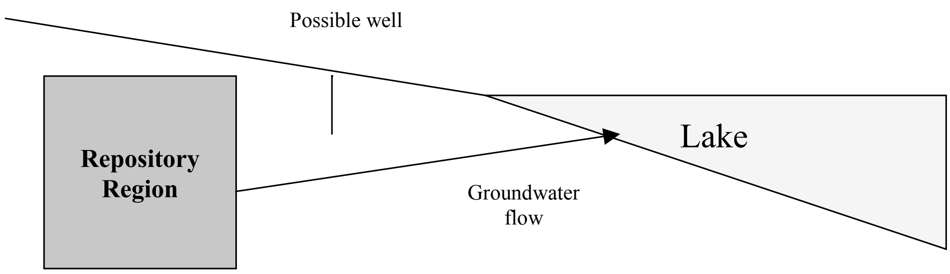

Figure 6.4 *Groundwater Flows when the Baltic has Retreated*

6.1.2 The Silo

AMBER models have been developed for each of the vaults making up the SFR 1 repository. Brief details are given here of the model for the Silo; the approach taken for the other vaults is similar. Figure 6.5 shows the arrangement of near-field rock compartments around the engineered part of the system in the AMBER model. Advective transfers out of the sub-model are to the Geosphere sub-model.

Figure 6.6 shows the representation of the engineered structure. All radionuclide transfers out of the sub-model are to the Silo near-field rock sub-model. The model includes representation of vault resaturation and gas generation. Groundwater flow through the Silo is assumed to increase as the engineered barriers degrade physically.

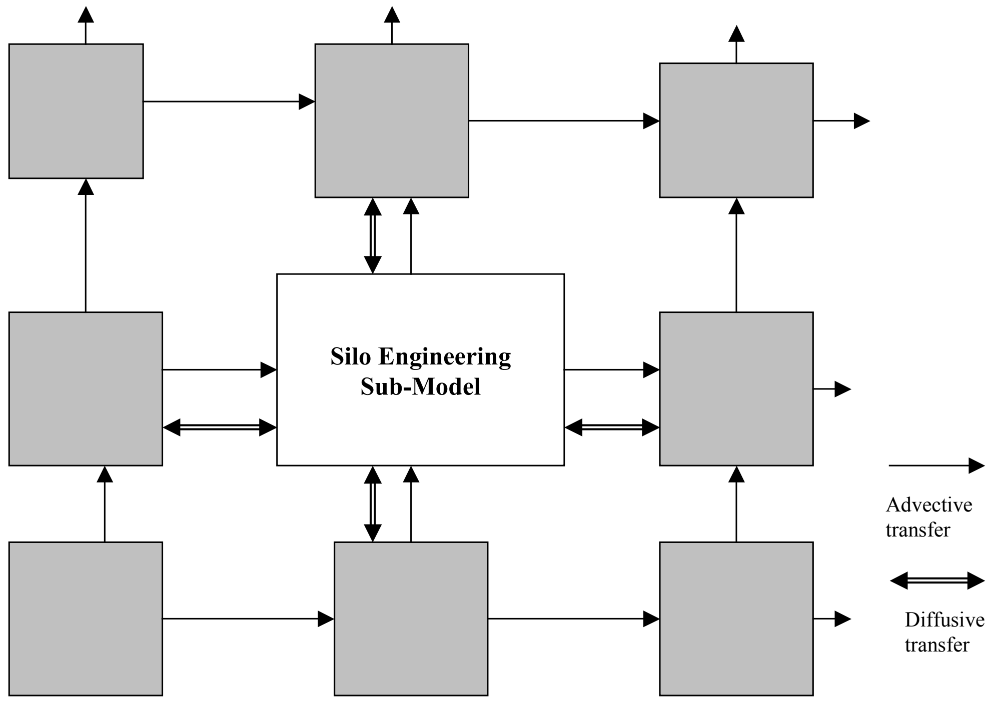

Figure 6.5 *The Silo Sub-Model*

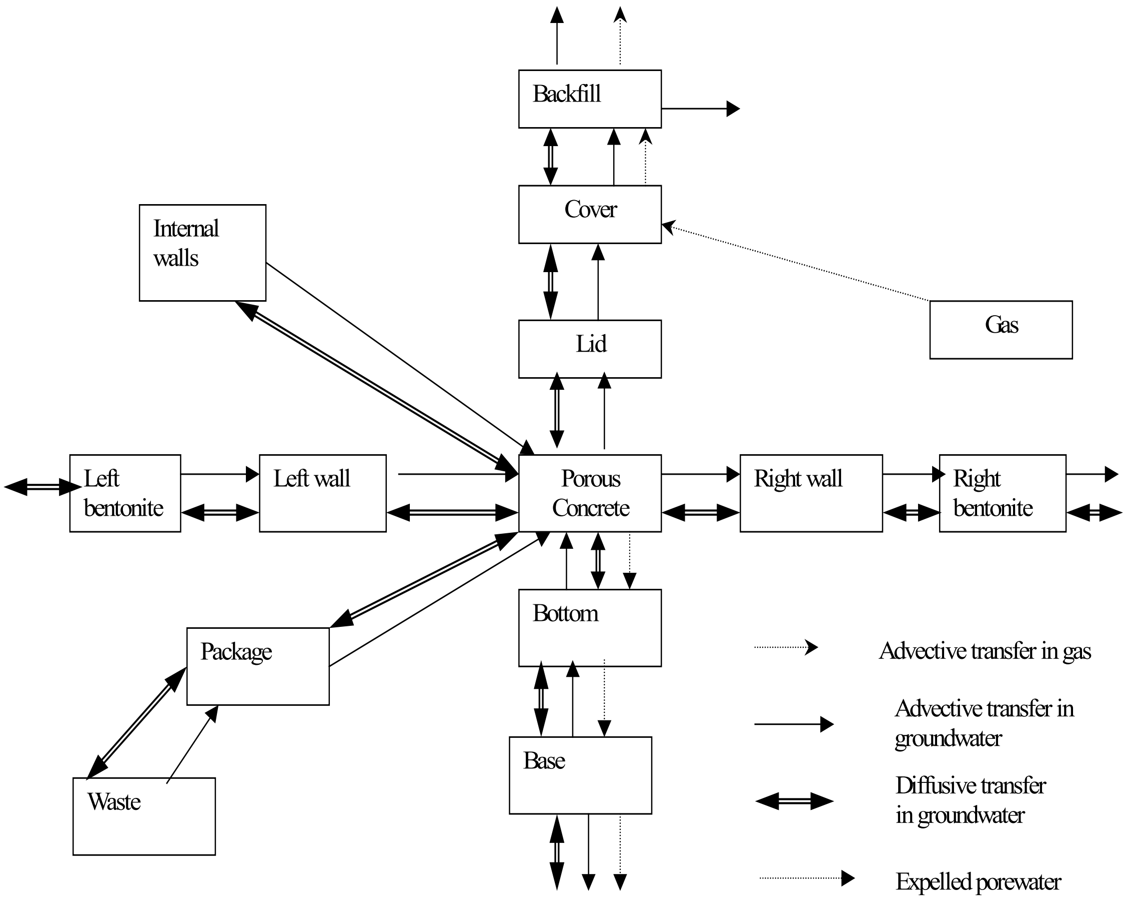

Figure 6.6 *The Silo Engineering Sub-Model*

6.1.3 The Geosphere

The structure of the Geosphere sub-system is shown in Figure 6.7. There are eight compartments representing regions of fractured rock, each with associated rock matrix compartments.

The compartments Rock13 and Rock14 are directly above the Repository sub-model. Groundwater transport through the crystalline rock is assumed to be rapid, so that only advective transfers between rock fractures (i.e., the 'Rock' compartments) are considered. Radionuclide transfers between the rock fractures and rock matrix (i.e., between the 'Rock' and 'Matrix' compartments in Figure 6.7) are diffusive.

Radionuclide sorption in the rock matrix is modelled, but sorption on fracture walls is neglected.

The degree of discretisation chosen for the geosphere was based on a desire to keep the representation consistent with the level of detail required for the calculations, enabling the importance of the variation of the magnitude and direction of the Darcy velocity with time to be investigated.

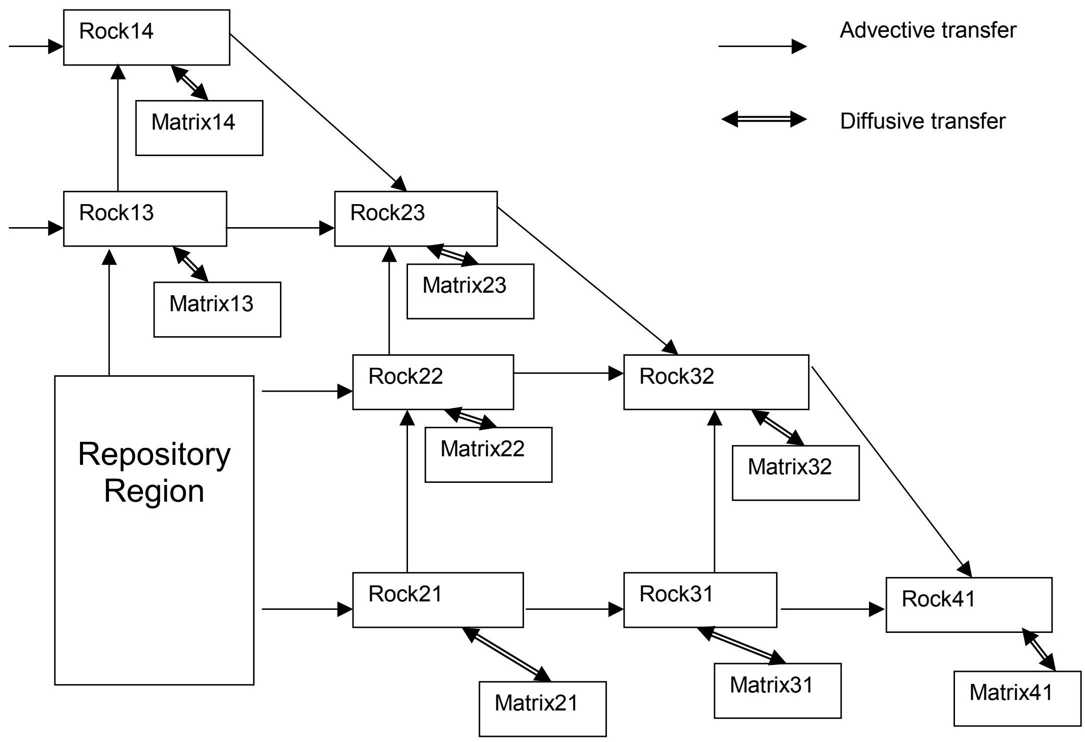

Figure 6.7 *The Geosphere Sub-System*

Note: The figure does not show transfers into the Terrestrial and Marine Biosphere systems

6.1.4 The Terrestrial Biosphere

The structure of the Terrestrial Biosphere sub-system is shown in Figure 6.8, with four areas of land being considered. The choice of the parts of the system that are included in the Terrestrial Biosphere sub-model is, to a large extent, arbitrary. Initially the whole of the system being modelled is under the sea, but subsequently individual areas become exposed as the land rises and relative sea level falls. The pragmatic choice has been made to include in the Terrestrial Biosphere sub-system the top-most parts of the land surface which may become partially saturated when the sea retreats; rock which is saturated at all times is included in the Geosphere sub-system, but rock which may become unsaturated at some time is included in the Terrestrial Biosphere sub-system. The sediment compartments represent marine sediments when the area concerned is under the sea; these become soil compartments when the sea has retreated.

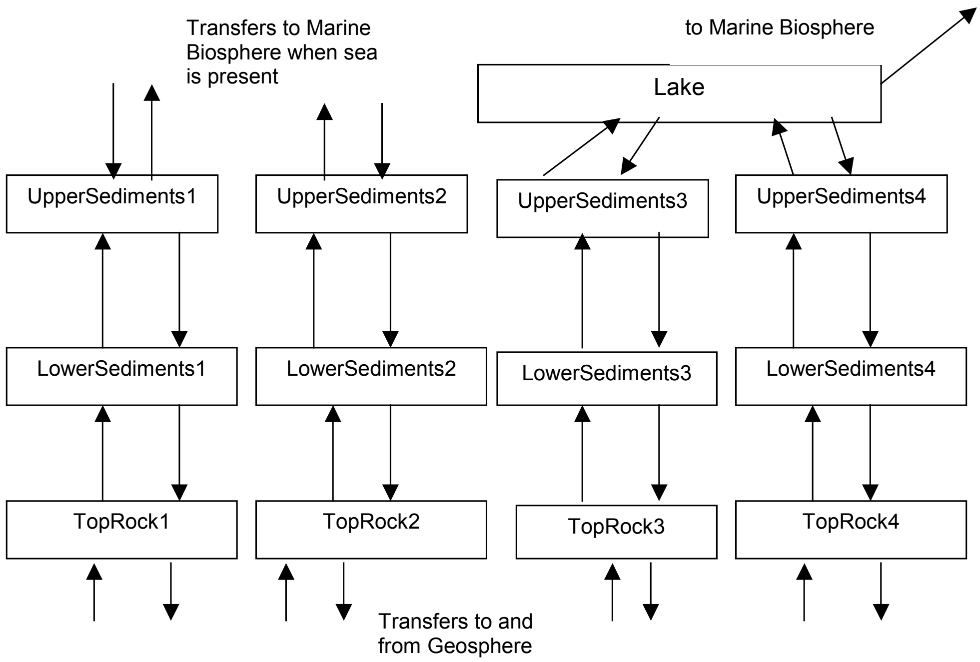

Figure 6.8 *The Terrestrial Biosphere Sub-System*

6.1.5 The Marine Biosphere

The structure of the Marine Biosphere sub-model is shown in Figure 6.9.

There are model compartments for an area of Regional Waters and the Baltic, each with associated compartments for bottom sediments. The compartment for other Oceans is effectively a sink compartment i.e. contaminants entering other oceans are assumed to have left the system of interest and are no longer considered. The simplicity of the Marine Biosphere sub-system reflects the fact that the most significant radiological impacts are likely to arise directly from radionuclide concentrations in environmental materials in the Terrestrial Biosphere sub-system rather than the Marine Biosphere sub-system

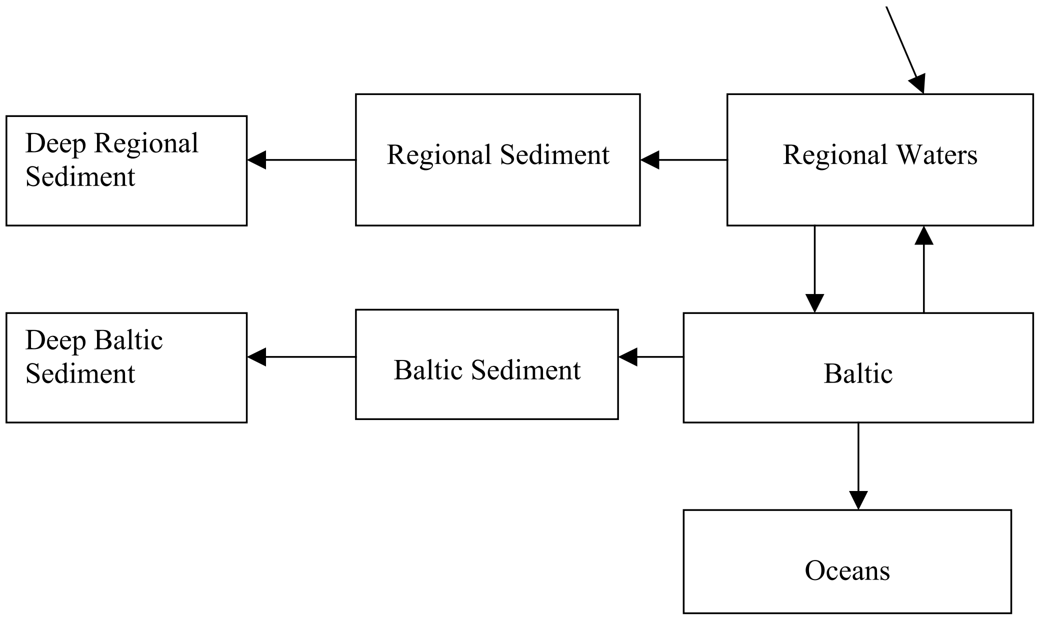

Figure 6.9 *The Marine Biosphere Sub-System*

6.1.6 Radiological Impact Calculations

Individual doses are derived from the AMBER calculations of radionuclide concentrations in environmental materials. The intention is not to undertake a detailed assessment of potential doses, but to use representative pathways to enable comparisons to be made between the impacts for different modelling assumptions. Consistent with this aim, the representative pathways considered are external exposure over contaminated soils or sediments, inhalation of contaminated soil or sediment, the consumption of drinking water from a well, and the consumption of lake and sea fish.

6.2 PA Calculations

A large number of model calculations has been undertaken using the AMBER model described in Section 6.1. In this Section a selection of these calculations is presented.

6.2.1 The Reference Scenario

A main calculation case was defined to provide the basis against which variant assumptions and calculations can be compared. Figure 6.10 shows the calculated flux of radionuclides from the different vaults for this calculation case. The peak flux from the Silo, 5.5E8 Bq y^{-1}, occurs at around 1600 years after repository closure. The peak flux from the BLA occurs at very early times and cannot be seen in the Figure. Except for the BLA, peak fluxes into the terrestrial environment occur at around the time that can be expected to result in the highest doses, relatively soon after the Baltic has retreated.

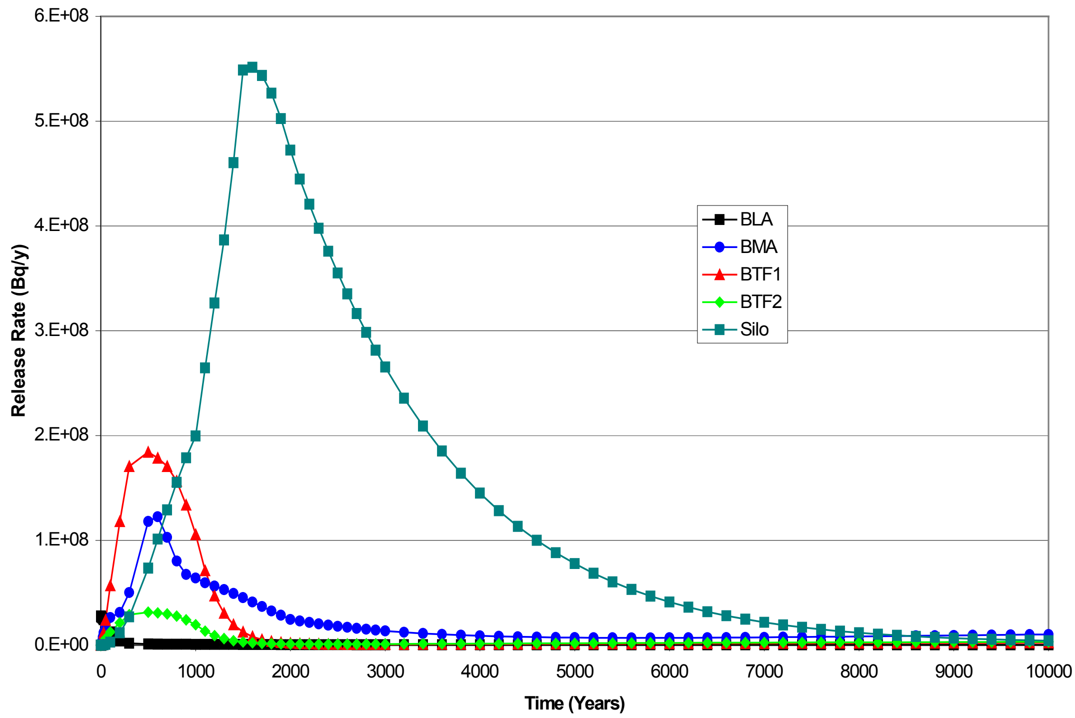

Figure 6.10 *Radionuclide Fluxes from the Vaults in the Reference Calculations*

Figure 6.11 gives illustrative dose calculations for the selected 'terrestrial' pathways. The doses appear to be dominated by organic carbon-14 (verifying the sensitivity to inventory and speciation of this radionuclide: see Issue SAFE-14). Other significant radionuclides are long-lived beta/gamma radionuclides such as Mo-93, Nb-93m, Ni-59, Cl-36, Se-79 and Cs-135. The consumption of drinking water from a well may be an important pathway, although the size of the calculated dose depends on a number of assumptions, including the degree to which the plume from SFR 1 is diluted with uncontaminated groundwater.

It is concluded that once the Baltic has retreated from above the repository (after 1000 years with the reference parameter values) dose rates of the order of 0.1 mSv y^{-1} are possible.

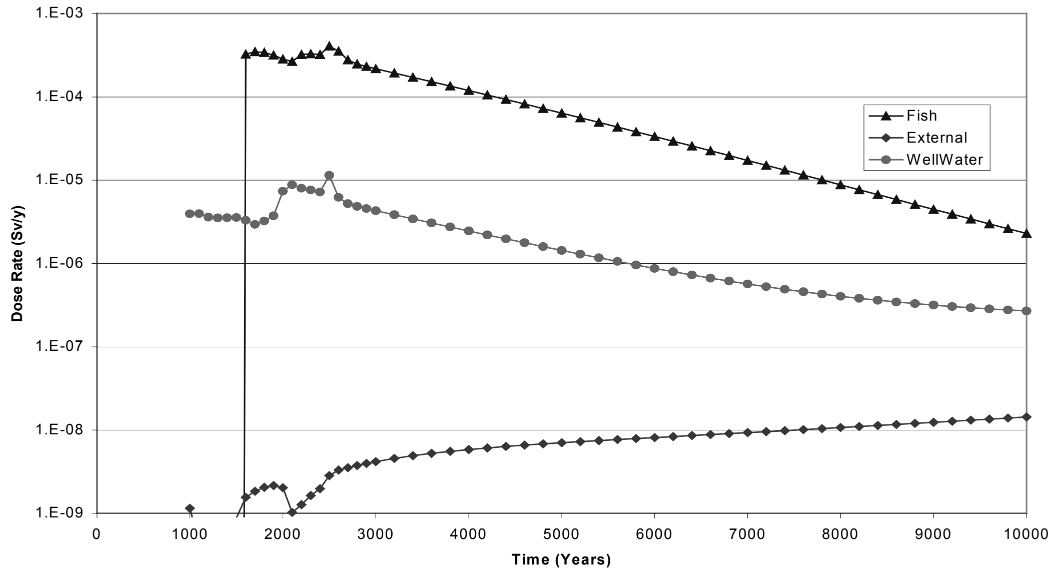

Figure 6.11 *Illustrative Dose Calculations for Terrestrial Pathways for the Reference Calculations*

Figure 6.12 gives illustrative calculations for the selected 'Marine' pathways. On the scale employed, only the dose for the sea fish consumption pathway can be seen. The doses are much lower than those calculated for the Terrestrial pathways. The sea fish consumption pathway is dominated by organic C-14 from the Silo.

With the reference parameter values chosen, retention in the geosphere by matrix diffusion is not an important process. The calculated dose rates shown in Figures 6.11 and 6.12 are little affected if matrix diffusion is 'switched off' by choosing a very low value of the flow wetted surface area. Matrix diffusion can be more important, however, for long-lived actinides on much longer timescales.

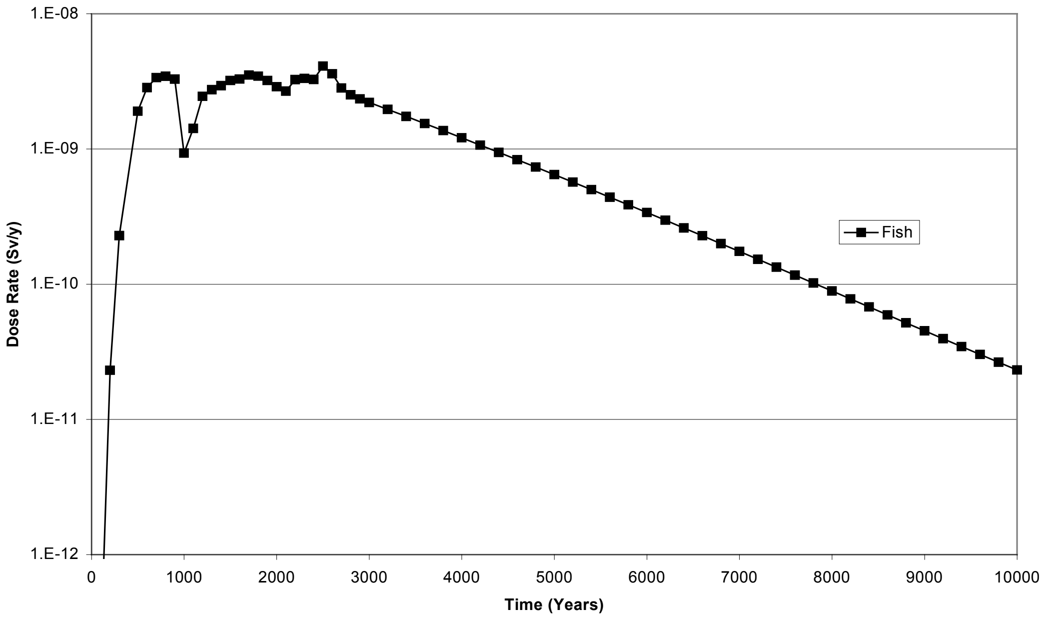

Figure 6.12 *Illustrative Dose Calculations for Marine Pathways for the Reference Calculations*

6.2.2 Sensitivity Calculations

A number of sensitivity calculations have been undertaken to explore how the calculated radiological impacts vary with key parameters. An example is the dependence of the peak dose rate on vault flows (Issues SAFE-2 to 4 and SKI-15) as shown in Figure 6.13. The final Darcy flow rate through the vaults is varied from 10^{-4} to 1 m y^{-1}. The peak dose rate increases steadily as the Darcy flow increases, but the two samples with the highest flow rates actually give lower peak dose rates. This is believed to be due to the very high flow rates resulting in a large fraction of the radionuclide inventories being transported into the Baltic before it has retreated from above the repository. This emphasises the importance of the timing of the radionuclide fluxes into the environment. It is clear that the assumptions made about groundwater flow rates through the vaults will be important in determining calculated radiological impacts.

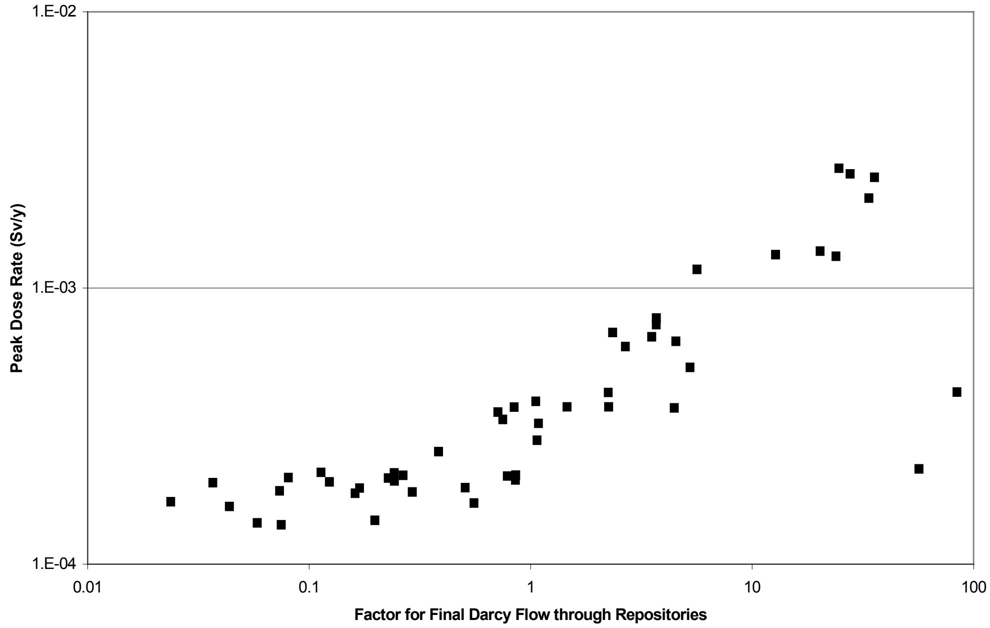

Figure 6.13 *Scatter Plot for Peak Dose Rate for Terrestrial Pathways against uncertainty factor for the Final Darcy Flow through the Vaults*

Other sensitivity calculations showed that calculated peak dose rates may not be very sensitive to assumptions about the timing of the physical degradation of engineered barriers (Issues SAFE-5 and SKI-3) because of the presence of the Baltic above the repository at early times. However, assumptions about the chemical confinement of long-lived radionuclides (by sorption onto near-field materials: Issue R-2) may be very important in determining long-term dose rates.

6.2.3 Other Calculations

Several other calculations have been undertaken including a Permafrost Scenario in which it was assumed that the engineered barriers remain physically intact until the repository is subject to permafrost (Issue SAFE-13). Following the thawing of the permafrost it is assumed that the barriers are degraded. This Scenario did not give significantly higher radiological impacts than the Reference Scenario.

A much simplified version of the AMBER Case was also used to investigate the hypothetical situation where all the radionuclides stay in the repository until activity reaches the surface on very long timescales due to surface erosion (Issue SAFE-9).

Figure 6.14 shows the calculated illustrative dose rates for Terrestrial pathways. These dose rates are much lower than those calculated for the Reference Scenario, not exceeding 1 μSv y^{-1}. The important radionuclides are now very different from those that dominate the doses in the Reference scenario. As one would expect, they are all very long-lived isotopes: Nb-94, Tc-99, Ra-226, Th-229, Th-230, Pa-233, Np-237, Pu-239 and Pu242.

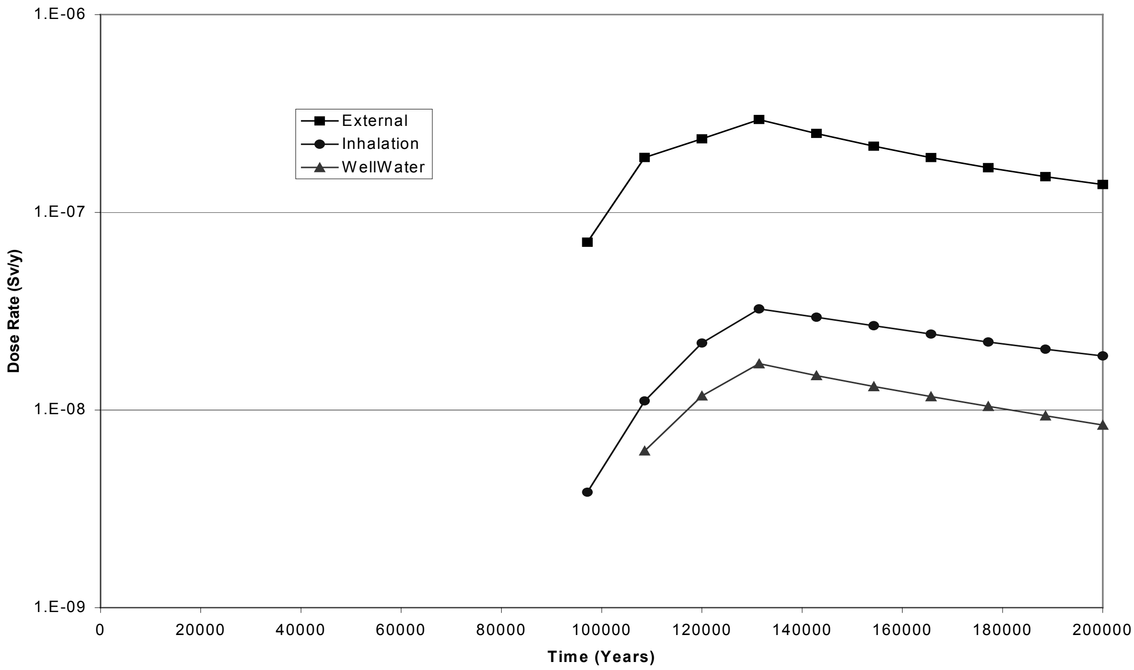

Figure 6.14 *Dose Rate for Terrestrial Pathways for Very Long Term Calculations*

A set of calculations was also undertaken to investigate specifically the potential importance of gas generated in the Silo (Issue SKI-17). These calculations showed that if overpressurisation of the Silo were to take place, some contaminated water could be expelled at early times, but the radiological impact of this would be small. The possible contribution of this process to the physical degradation of the engineered barrier could, however, be more significant.

Finally a set of calculations was undertaken to investigate how calculated impacts change if processes that are represented as continuous in the Reference calculations are instead represented by a discontinuous series of 'snapshots' (Issue SAFE-15); this is a common approach used in many PAs. These calculations illustrated that the 'snapshot' approach may lead to unphysical estimates of radionuclide transport, but for the SFR 1 system (because the repository is under the Baltic at early times) the calculated radiological impacts may not be significantly different.

6.3 Conclusions from Independent PA Calculations

The key issues that have been identified can be summarised as follows:

1. The timescales and rates associated with a number of different processes affect the magnitude of potential radiological impacts from the SFR 1 system. These include: repository resaturation and gas evolution timescales, the rate at which the Baltic is retreating, the rates of engineered barrier degradation, and groundwater residence times in the geosphere. It is important that all relevant time-dependent processes are represented in system modelling.

2. Owing to the complexity of the system, it is not always possible to define which choices of modelling assumptions and parameter values can be regarded as 'conservative'.

3. Radiological impacts when radionuclide discharges are to the Baltic are likely to be orders of magnitude lower than those when the discharges are to the terrestrial environment.

4. If overpressurisation of the Silo takes place due to gas generation, this could lead to increased early releases of short-lived radionuclides into the environment, but this is unlikely to lead to significantly increased radiological impacts as these releases would take place when the SFR 1 is below the Baltic. Physical damage of the engineered barriers, might, however, be important on longer timescales by affecting groundwater flows through the facility.

5. Dose rates of the order of 0.1 mSv y^{-1} are possible when radionuclides from SFR 1 enter the terrestrial environment. The precise value of the calculated maximum dose rate will depend upon a number of assumptions about biosphere characteristics, and critical group behaviour. The use of contaminated well water may give rise to significant exposures.

6. Long-lived actinide radionuclides (particularly in the Silo) may be retained by sorption processes on very long timescales. If this is the case, peak impacts are likely to be dominated by long-lived beta-gamma radionuclides such as Mo-93, Nb-93m, Ni-59, Cl-36, Se-79, Cs-135 and C-14.

7. For most of the PA calculations, organic C-14 appears to be the dominant radionuclide, primarily because it is assumed not to be sorbed in the near-field. Further consideration needs to be given to the behaviour of this radionuclide throughout the system, in order to be able to provide better estimates of potential radiological impacts.

8. Peak impacts are likely to be sensitive to the assumptions made about groundwater flow rates through the vaults.

9. Illustrative calculations to investigate the potential importance of permafrost suggest that impacts are unlikely to be greater than those calculated in its absence.

10. Calculations to investigate potential impacts on very long timescales when the wastes may be brought close to the surface by erosive processes have shown that such impacts are likely to be small, being dominated by very long-lived radionuclides and their daughters such as Nb-94, Tc-99, Ra-226, Th-229, Th-230, Pa-233, Np-237, Pu-239 and Pu-242.

7 Discussion of Key Issues

In January 2002 an English translation of Section 5 of SKB's Project SAFE Final Safety Report provided by SKI (2002) was reviewed by Neil Chapman, Peter Robinson and Philip Maul.

The issues that had been identified in the early review of the supporting SAFE documents (Tables 5.2 and 5.3, Section 5) were used to help focus the final review of the partial English translation of the SKB SAFE Final Safety Report. By this stage, the results of the independent exploratory PA evaluations (Section 6) were also able to shed more light on some of these matters.

For convenience of presentation, the overall findings are grouped as answers to the following broad questions:

1. Is the SFR 1 system, its safety concept and its evolution, adequately understood and described?
2. Are the key processes controlling performance identified and treated adequately in Project SAFE?
3. Have the most sensitive parameters been quantified either conservatively, or so as to test the impacts of uncertainty and variability on system performance?
4. Are the safety assessment methodology and the scope of the analyses appropriate?
5. Have previous concerns been addressed in the new study?
6. Has the safety assessment demonstrated robust performance for the repository?
7. What could be done (by either SKB or the regulatory authorities) to enhance future evaluations or further improve understanding of SFR 1?

The fact that the review of the Final Safety Report was based on a partial and draft translation may affect the significance of some of the conclusions.

7.1 The SFR 1 System

The question addressed here is:

Is the SFR 1 system, its safety concept and its evolution, adequately understood and described?

SKB has carried out a much more comprehensive assessment of the disposal system and its definition than in previous studies, and the SAFE project is large step forwards in this respect. A drawback for anyone trying to understand the basis for the design and management of SFR 1 is that SKB presents no 'safety concept' for the system, describing how the total system has been structured to provide adequate containment of radioactivity (at least in the documentation that has been seen by the reviewers).

Our interpretation is that the concept functions largely as a result of chemical containment of longer-lived radionuclides by sorption within the two highest-inventory vaults, Silo and BMA (the importance of the chemical containment is referred to in Section 5.4.4 of the Final Safety Report). Long-term (> 300 year) physical containment plays a subordinate role, provided groundwater movement through the waste materials is within reasonably expected limits. It is only in circumstances where that flow may be increased that physical containment becomes important in some regions (notably the Silo), and only for a few radionuclides (principally C-14). Consequently, the bentonite shield provided around the Silo appears to have a limited function to protect against situations where the engineered concrete structure degrades faster or more extensively than expected. We note also that the preservation of chemical stability in the vaults is predicated on generally low groundwater flow.

A second key aspect of the Safety Concept would appear to be dilution of any early releases (over the next 1000 years) in the Baltic Sea. Without this, the repository could have difficulties complying with both old and new regulatory standards. In fact, as the principal radiological impact at any time in the 10 000 years evaluated is from mobile but long-lived radionuclides (mainly C-14), the total system performs better if these are released early, to the sea. This is discussed in more detail later, in Section 8.6.

The evolution of SFR 1 is described in detail, but it is difficult to identify which variant of the Base Scenario SKB is considered to represent the expected evolution. Our interpretation is that the Main Case (Intact Barriers) variant of the Base Case is regarded as 'expected evolution', whereas our review results suggest that the Degraded Barriers variant of the Base case may be a more appropriate reference representation of the future. This is discussed further in Section 7.2.

One aspect of system definition and uncertainty that does not appear to have been well tested is the possibility of alternative structural models of the site, where SKB say that there is little uncertainty. The SKI review of this aspect (Tiren et al., 2000) suggests that there may be alternative interpretations of major fracture location, which, if correct, could impact on performance (for example, the possibility of a sub-horizontal zone above the Silo).

SAFE has treated the biosphere comprehensively, and the scope of the analysis, the description of pathways and future evolution is impressive, although not fully covering system uncertainties.

An aspect of system description that is not treated sufficiently is repository closure. Section 5.3.3 of the Final Safety Report notes that technical solutions have not been finalised, while Section 5.6 implies that the details of closure are not critical to the evaluation of safety in the PA. Whereas a measure of flexibility in future operations and closure is important, it is not too soon to begin to look at the impacts of different management and sealing options. The possibility that additional vaults may be built, that some materials may be emplaced in parts of the vaults not originally planned to hold wastes, and that there are already considerations of alternative backfill strategies (e.g. placing cement in BMA) suggest that more analysis will be needed in the near future. Such an approach would reflect prudence on the part of both SKB and the regulators.

7.2 Key Processes

The question addressed here is:

Are the key processes controlling performance identified and treated adequately in Project SAFE?

Whilst the key processes have been identified in the systems analysis, they have not been treated evenly; for example, there has been only limited consideration of physical degradation of the vaults on the basis that, as noted above, the main control on containment performance is chemistry. A wide range of phenomena that could cause physical degradation of the concrete structures and bentonite is discussed, but in the analyses it is assumed that none has a significant effect on the barriers during the first 1000 years after closure. Higher water flow rates (see Section 7.3) could cause enhanced microbial activity and corrosion, more rapid rates of gas production and accelerated physical degradation of reinforced concrete before the 1000-year barrier lifetime assumed in SAFE. A similar conclusion was drawn in the recent review of SKB's SFL 3-5 assessment.

Would this significantly affect performance? The answer, which can be deduced from the results of the exploratory PA studies (Section 6, and Maul and Robinson, 2002), is probably not. Provided that the chemistry of the vaults remains stable, then increased groundwater flow through, for example, the Silo and BMA in the first 1000 years would simply result in increased but still much diluted releases of mobile radionuclides to the sea. However, SKB has taken a narrow approach to the uncertainties in physical degradation (and some linked chemical degradation mechanisms, such as high-pH plume interactions with bentonite). The uncertainties are frequently acknowledged as being difficult to quantify (for example, in Section 5.6.2, chemical changes to bentonite) and are then effectively set aside (in Section 5.5.4 of the Final Safety Report), where there may be some justification in making more conservative assumptions that are then passed into the safety calculations.

Gas generation is clearly an important factor in early performance of the repository. SAFE does not look at sensitivity to different potential rates of gas production. Even a comparison with previous SKB estimates of gas evolution would have given some feeling for the uncertainty in this factor. Early production may be more beneficial than delayed gas production after the 'marine' period, provided the rate is not such as to affect the barriers physically (especially the bentonite around the Silo). There is no parallel evaluation of early gas production and resaturation. The possibility exists that slow or uneven resaturation of the Silo barriers could leave 'dry' pathways for gas movement. The reliability of long-term venting of gas from the BMA and Silo does not appear to have been addressed as part of the SAFE study.

7.3 Uncertainty and Variability

The question addressed here is:

Have the most sensitive parameters been quantified either conservatively, or so as to test the impacts of uncertainty and variability on system performance?

The validity of the SAFE results is predicated on the analysis making generally conservative assumptions and using conservative parameter values: this much is stated frequently in the supporting reports and a detailed justification of the pessimism in the chemical parameters used is given in the Final Safety Report, Section 5.6.5. In the great majority of instances, and certainly for most of the chemical data, this approach appears to have been followed rigorously, but there are some important exceptions as well as a practical difficulty. The difficulty was illustrated in the exploratory PA calculations, where it became clear that some factors that may appear conservative (e.g. late release or strong retention) do not necessarily give conservative estimates of impacts. This fact stems from the unusual nature of SFR 1 noted earlier, where early (marine) releases have lower impacts than later (terrestrial) releases. Consequently, it is not always possible to identify the degree of conservatism before a sensitivity analysis has been carried out. SAFE contains no sensitivity analysis, so SKB has not been able to explore this factor.

Two important exceptions to the selection of conservative parameter values have been identified. The first is the water flow rate through the repository, where SKB argues that the values they have taken are realistic. For reasons discussed earlier, the SKB values are thought to be potential underestimates, despite their awareness of the calibration problems involved in deriving their data (Final Safety Report Section 5.5.1). The SAFE PA does consider the potential implications of higher flows.

The second issue is inventory uncertainty. SAFE asserts that by using the original licensed inventory (whose activity is larger by a factor of ten than the expected final content today) in the safety analysis, then the overall result must be conservative. This may not be the case, as the relative uncertainties between different radionuclides can be substantial and it could still be possible to underestimate the amount of a safety-relevant radionuclide. C-14 and Cl-36 are typically ‘problem’ radionuclides in this respect, and there is an added sensitivity in terms of the ratio of organic to inorganic carbon present. Whilst not stating that the values cited are underestimates, it would be worth looking in more detail at these radionuclides, especially as C-14 is critical to performance. This would be preferable to an arbitrary treatment whose degree of conservativeness is difficult to judge.

A further exception is the treatment of well probability. First, it has to be pointed out that there seems to be little justification for applying probabilistic methods so partially. If they can be used in the biosphere to evaluate well drilling likelihood, they could have been used to assess the impact of uncertainty in near field flow and other parameters. As noted above, several areas of uncertainty are simply set aside (in Final Safety Report Section 5), when a probabilistic approach may have been useful to scope impacts. The specific issue of the well receptor is discussed more in Section 7.4.

7.4 Assessment Methodology

The question addressed here is:

Are the safety assessment methodology and the scope of the analyses appropriate?

Generally, it is felt that the SAFE approach is thorough, up-to-date and has been well executed, with some caveats. Here, a number of separate issues have been raised by the review:

Time scale of the assessment: the 10 000 year cut-off chosen by SKB is not unreasonable, and both SAFE and the exploratory SKI calculations show stable or diminishing levels of dose rate in the 6000 – 10 000 year period. However, it cannot be justified by reference to the regulations, which simply state that the assessment shall extend up to at least 10 000 years. As the repository contains actinides and other long-lived radionuclides, it would have been useful if SAFE had looked beyond 10 000 years, perhaps using a 'fate-of-repository' scenario, such as presented in the exploratory PA calculations.

Step (discontinuous) changes in system properties: the exploratory PA calculations investigated the importance of time-dependent changes. Whilst this did not identify any factors that may have been misinterpreted by the SAFE stepped approach, it is difficult to be certain, owing to other differences in the two modelling methods that would have to be deconvoluted. The independent PA analysis showed that simple time-stepping approach is capable of producing physically unrealistic estimates of transport. An example of where it may make a difference is that the SAFE Base Scenario (Final Safety Report Section 5.7.3) had to assume arbitrary biosphere compartment distributions and transfers of radionuclides with changing surface environment, which could be avoided by a time dependent approach. Sensitivity to time dependence warrants further study

Well-receptor model: we do not agree with the probabilistic model used to assess the likelihood of a well being present in the future. The data are used to assert that there is a 10% probability of a well being present at any given time and hence to reduce risks by a factor of ten. In fact, this means that for 10% of the future a well is assumed to be present, so the doses that have been calculated will be valid at those times and the risks at the particular time will not be reduced. Consequently, it could equally well be argued that a probability of unity should be attached to these doses. Also, presenting the well as an 'alternative biosphere' is misleading: it is a probable feature of the biosphere that will exist after 8000 AD. The broader issue of scenario probabilities is discussed later. In the light of the high doses from a well receptor (Final Safety Report Section 5.7.5) it seems reasonable to question the wisdom of not accounting for geosphere attenuation in the SAFE modelling, as this may mitigate these impacts. (although this conservative approach is also used by SKB to justify their lack of a specific treatment of colloid transport).

Scenario definition and treatment: generally, the scenarios derived appear to be a useful set to illustrate performance. The lack of a 'fate-of-repository' calculation was commented on earlier. The screening of human action FEPs based on SR 97 experience seems doubtful for a shallow repository such as SFR 1 and it could be argued that a wider range of potential human activities at the surface and in shallow groundwater should have been considered, particularly if any could disturb the important chemical containment factor. The issue of roof-fall has not apparently been carried forward into a scenario, and SKB simply state that they 'assume' BMA will be top-filled to prevent connections being formed between vaults: another reason for a better look at future management and closure options now.

Treatment of some of the scenarios raises problems. The permafrost scenario appears sensibly conservative until the impacts are calculated using an impossible marine receptor, on the very weak argument of being asked to compare with releases today. We note that although SSI's generic regulations suggest some comparisons with doses as they might be received in today's biosphere, in the SFR 1 case (where releases occur over a short period during which the biosphere changes rapidly) this is entirely unhelpful, owing to the massive and unrealistic dilution involved. Figure 5-39 of the Final Safety Report amply illustrates this point and does nothing to aid understanding of safety

The degraded barriers scenarios do not look at the possibility that the bentonite as well as the concrete may degrade, causing higher fluxes through the Silo, nor that degradation might be widespread, rather than being localised to a small region of the vaults. The level of presentation of this rather critical scenario could be improved (not enough information is presented in diagrams). The tectonic scenario is lost when it is assigned to fall within a base case variant and is not subsequently discussed.

Scenario probabilities: as noted previously, we do not believe that there is any justification for attributing a probability of < 1 to the well receptor after about 4000 – 5000 AD: it should be a component of the 'reasonable biosphere'. For the separate 'intrusion well' scenario, a potability argument would be more compelling than estimates of well frequency, as would application of ICRP 81 suggestions on appropriate dose measures against which to judge intrusion significance. The probability figures shown for each of the 'Other Scenarios' are generally arbitrary and a case could be made for higher or lower values for each, or for combinations of conditions that have not been analysed. We do not believe it enhances the credibility of either SKB or the regulators to embark on these rather sterile arguments. Instead, the values of dose calculated should be taken at face value as 'what if' illustrations of behaviour, and due recognition should be taken of the fact that these behaviours are considered less likely.

7.5 Issues Raised Previously

The question addressed here is:

Have previous concerns been addressed in the new study?

The previous regulatory review identified three topics (Issues R-1 to 3 in Section 3) that would require further work: land uplift and the well receptor, uncertainties in data on complex formation, and scenario combinations. The first two have been dealt with in the new study: a thorough groundwater flow study of the impact of a well has been carried out and SKB has stated that complexant concentrations will remain below critical values as a result of sorption onto concrete, with radionuclide sorption in any case adopting conservative values. Many uncertainties in these areas arise principally as a matter of alternative ways of interpreting the results of the analyses (see discussion above on wells), rather than from the data used. However, the review team retains some reservations about both of these issues, in particular about the conservativeness of the flow model used for the well scenario and of the sorption values appropriate for regions of the repository with high organic content.

The third, scenario combination, issue has not been addressed adequately. In discussion, SKB simply asserted that there are no 'interesting' combinations. In any case, sufficient information is available from those studied to allow empirical combinations to be made; with the conclusion that circumstances could be envisaged where relatively high doses could arise. This is discussed in Section 7.6.

7.6 Repository Performance

The question addressed here is:

Has the safety assessment demonstrated robust performance for the repository?

The conclusion of the regulatory authorities at the last review was that doses up to 1 mSv y^{-1} (and, 'improbably', up to 10 mSv y^{-1}) could be envisaged if uncertainties were taken into account, and that such doses correspond to risks currently accepted by society. The SAFE project and the exploratory PA studies continue to present a similar picture. Although SKB has gone to some lengths to show that risks are generally below the new regulatory target of 10^{-6} y^{-1}, the arguments are not convincing and a more transparent conclusion would be similar to that drawn in 1994: the uncertainties involved indicate that, under certain circumstances, doses (and risks) to some individuals could potentially be of the same order as those posed by natural background radioactivity.

The safety of the SFR 1 depends to a large extent on the maintenance of favourable chemical conditions for sorption of radionuclides on the engineered barrier materials. The calculated releases of all radionuclides are sensitive to the parameters that represent radionuclide sorption in the exploratory PA calculations. Consequently, the estimated low impacts depend on these values being realistic or conservative. This is generally believed to be the case, but this level of dependence on one aspect of system properties means that the safety performance of the system cannot be said to be robust. Nevertheless, any short-term adverse behaviour of either the engineered system or the geosphere will be strongly counteracted by the dilution capacity of the marine receptor in the next thousand years or so.

Beyond that period, both SAFE and our own calculations indicate that a convincing safety case can be made for retention and/or decay of almost all radionuclides in the repository until their final dispersal in some tens or hundreds of thousands of years. Even this eventual total degradation of the repository appears unlikely to give rise to consequences that are greater than those from earlier releases to a lake or well (although 'pond' situations can be envisaged where environmental concentrations may locally exceed the variability in natural levels of radiotoxicity, depending on how erosion proceeds). In this context it would be useful for SKB to present environmental concentrations in addition to dose rates to humans.

However, the exception to this generally positive picture is C-14, the principal contributor to dose at early times. The potential for uncertainties in inventory and chemical behaviour seem to persist, although SKB insists that both are treated conservatively. In Section 5.8 of the Final Safety Report, SKB presents a number of areas where C-14 behaviour could be treated more realistically, giving some potential for improved performance. We believe it would be useful to follow these up, together with the inventory aspects mentioned above, in order to achieve a more realistic appraisal of the fate of C-14.

Chemical retardation in the repository will itself be sensitive to water flow through the vaults, in so far as this may influence rates of microbial activity and gas production. Unlike all other parameter choices made in the PA, no attempt appears to have been made to treat this factor conservatively in SAFE, which takes a central rather than a pessimistic value. Our exploratory assessment does suggest that flows would need to be increased by around a factor of ten to make a significant difference to calculated dose rates. However, this needs to be investigated further.

7.7 Future Evaluations

The question addressed here is:

What could be done (by either SKB or the regulatory authorities) to enhance future evaluations or further improve understanding of SFR 1?

Seven areas have been identified where further work would improve understanding:

1. evaluation of uncertainties associated with the C-14 inventory, speciation and behaviour in the wastes and the engineered barriers;
2. refinement of the estimates of uncertainty of water flow through the vaults, using better calibrated data and closer analysis of the impact of heterogeneity;
3. presentation of a realistic calculation case representing the best estimate of performance, as well as a compliance-oriented conservative case;
4. a proper sensitivity analysis of performance based on best estimate parameter values and realistic ranges;
5. a closer look at aspects of performance that might be affected by the use of a fully time-dependent calculation approach;
6. consideration of alternative methods for completion, closure and sealing of the repository and how such options may affect performance; and
7. future assessments would benefit from a clearer audit trail that allowed the derivation and justification of calculation cases to be followed from inception to results.

In addition, attention is drawn again to Tables 5.2 and 5.3, which identify a number of more specific aspects of the SFR 1 system. SKI should keep these under consideration in its own review process.

8 Conclusions

Project SAFE is a very considerable advance on the previous evaluation of safety for SFR 1 and SKB have deployed their latest techniques of PA to carry out a comprehensive systems evaluation. In general, they have addressed the key issues that have been identified in earlier reviews and produced a much more rigorous analysis of the repository.

Notwithstanding this increase in rigour and complexity, neither SKB's improved techniques nor the exploratory PA studies carried out for this review on behalf of SKI have identified any new factors or interpretations that indicate safety is other than was envisaged at the time SFR 1 was originally licensed.

Our interpretation of the results of both sets of PA calculations is that the projected radiological impacts of SFR 1 are broadly similar to those indicated in previous studies. In particular, when uncertainties are taken into account in describing the future evolution of the disposal system, it is possible to derive estimates of individual exposure for members of the hypothetical critical group via a well that lie in the range of natural background exposures. Although SKB has tried to show that SFR 1 could meet current risk standards, the uncertainties in the likelihood that such exposures (in the region of 1 mSv y^{-1}) could occur are sufficiently large that we believe such an argument cannot easily be sustained on the basis of PA approach adopted by SKB. However, there are in-built reserves of performance that have not been deployed in the safety assessment and which could be investigated more closely in future.

As a result of this review, the key issues that the regulatory authorities will need to address when reviewing SKB's safety case for SFR 1 have been identified as:

1. There is no clear statement of SKB's overall safety concept for SFR 1 in the documents that have been reviewed. It is therefore difficult to judge the results of the PA against general expectations for how the disposal system has been designed to function, or with respect to the intended roles of individual system components in providing safety assurance. Our interpretation is that long-term safety performance is largely dependent on containment by immobilisation of longer-lived radionuclides as a result of chemical sorption within the two highest-inventory vaults, the Silo and the BMA. By comparison, long-term (> 300 year) physical containment plays a subordinate role, provided that groundwater movement through the waste materials is within reasonably expected limits.

2. One aspect of system description that needs to be treated in more depth is the way in which final closure of the repository will be achieved. SKB states that technical solutions have not been finalised and imply that the details of closure are not critical to the evaluation of safety performance. It is indeed important not to finalise closure plans too soon, in order to retain a measure of flexibility in future operations. However, it is not too early to begin to consider, as part of the ongoing development of the safety case, the possible implications of alternative management, backfilling and sealing options.

3. The projected evolution of the SFR 1 system and its environment has been examined in detail within Project SAFE, and the uncertainties associated with developing such a description are discussed. However, it is difficult to identify which variant of those investigated in relation to the Base Scenario is considered by SKB to represent the expected evolution. Linked to a well-defined safety concept, an explanation of expected evolution ('design basis') is a clear way to explain and understand system performance and associated uncertainties. Our interpretation of the supporting documentation is that the Main Case (Intact Barriers) variant of the Base Scenario is regarded as 'expected evolution'; however, our review results suggest that the Degraded Barriers variant of the Base Scenario may in fact be a more appropriate reference position.

4. There are a number of different timescales and rates relevant to processes operating within the SFR 1 system that can affect the magnitude of radiological impacts. These include: repository resaturation and gas evolution timescales; the rate at which changes in local sea level take place; the rates of engineered barrier degradation; and groundwater transport times through the geosphere. Therefore, it is not always possible clearly to identify which choices of parameter values can be regarded as 'conservative', and any such assertions by SKB need to be treated cautiously.

5. One exception to SKB's intended use of conservative parameter values is the specification of water flow rates through the vaults, where it is argued that values assumed as a basis for the PA calculations are realistic. However, even though we understand that SKB is aware of calibration problems involved in deriving the flow data, which could mean that flow rates have been underestimated, the SAFE assessment does not investigate the implications of higher values. Independent PA calculations carried out in support of this review have illustrated the sensitivity of calculated impacts to this parameter. In addition, higher water flow rates could lead to increased microbial activity and rates of corrosion, more rapid gas production and accelerated physical

degradation of reinforced concrete. In practice, this means that SKB has given more emphasis to evolution of the chemical properties of engineered barriers than processes that could lead to their physical degradation.

6. No systematic approach has been taken to the incorporation of sensitivity or uncertainty calculations within the PA, and some of the claims for pessimistic parameter choices would appear to be difficult to sustain. The use of probabilistic calculations to address uncertainties in the biosphere but not in the rest of the disposal system reflects an incoherent approach to the quantitative treatment of uncertainty in the PA as a whole.

7. The probability figures that have been assigned to scenarios and scenario variants are generally arbitrary. Indeed, a case could be made for higher or lower probabilities in each case, or for the evaluation of combinations of situations that have not been addressed in the SAFE assessment. In particular, the use of a probability of less than one for the 'well' scenario is questionable. We do not believe it enhances the credibility of either SKB or the regulators to embark on somewhat sterile arguments regarding the likelihood of future human actions, expressed in probabilistic terms, as a basis for quantitative estimates of 'risk'. Instead, we suggest that the values of dose calculated in the assessment should be taken at face value as 'what if?' illustrations of the implications of different actions or types of behaviour, and recognition should then be given to implications of these results (including the size of the corresponding hypothetical critical group) in the light of judgments that certain behaviours are considered less likely than others.

8. SKB has undertaken calculations for a 10 000 year period after repository closure. Independent PA calculations suggest that overall risks posed by the repository will be highest within this period, even though peak impacts associated with some scenarios may not be achieved until after this time, and that radiological impacts are therefore unlikely to have been underestimated as a result of the time cut-off used in the SAFE assessment. Nevertheless, consideration of longer timescales, particularly for the expected 'normal' evolution of the system, would have been helpful in illustrating the long-term safety implications of waste disposal in SFR 1, as well as demonstrating SKB's understanding of the processes that are expected to determine the eventual fate of the repository.

9. The nature of the software tools used by SKB has meant that the some continuous processes (such as the degradation of engineered barriers) have been represented in a discontinuous step-wise manner. Independent PA calculations have therefore been undertaken to investigate the possible

importance of being able to represent continuous changes more explicitly. Whilst these calculations did not identify any factors that may have been misinterpreted in the SAFE assessment's stepped approach, nor suggest significantly different radiological impacts, they do illustrate that step-wise calculations can lead to physically unrealistic estimates of radionuclide transport.

10. Long-lived actinide radionuclides may be retained by sorption processes (particularly in the Silo) on very long timescales. If this is the case, peak impacts are likely to be dominated by long-lived fission and activation products (beta-gamma emitting radionuclides) such as Mo-93, Nb-93m, Ni-59, Cl-36, Se-79, Cs-135 and C-14. Having identified which are likely to be the most significant radionuclides in terms of potential impacts in the wider environment, it is important that assumptions made in relation to their behaviour are scrutinised to ensure that possible discrepancies or in-built biases are identified. Inventory issues were not addressed in this review, as this is being assessed separately by the regulatory authorities. For many of the PA calculations, C-14 (in organic form) appears to be the dominant radionuclide; hence, in the review of the SKB inventory by the regulatory authorities, particular attention needs to be given to assumptions about the magnitude of the C-14 inventory, as well as to assumptions about its chemical speciation, both in the wastes and upon mobilisation from the wastes into the engineered barrier system and groundwaters. In particular, the basis for the assumption that 10% of C-14 is in organic form needs to be checked. This topic appears to merit a definitive study.

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Appendix: Reviews of Supporting Documents

This Appendix gives the full text of the document reviews summarised in Section 5 of the main text. The reviews are presented in the order shown in Table 5.1.

Note that most of these reviews were carried out on draft versions of the reports concerned, and all of them before the SKB Final Safety Report was available to put them into context. Consequently, a few of the detailed points raised by the reviewers have been superseded by later information. So far as possible, such points have been eliminated from the summary material brought forward into the main body of this report and not taken into account in the overall review conclusions. However, for traceability and consistency, these Appendices have not been post-edited by the compilers of this report.

A1 Modelling of Future Hydrogeological Conditions

Report Number: R-01-02

Authors: J. Holmén and M. Stigsson

Reviewer: Joel Geier, Clearwater Hardrock Consulting

A1.1 Summary

This report presents a modelling study in which a finite-difference model of saturated, uniform-density groundwater flow in a 3-D continuum is used to predict flow around and through the SFR facility for a period of 6000 years into the future.

The model was used to estimate magnitudes of groundwater flow through the SFR tunnels including through the waste/encapsulation domains, as well as flow path lengths, discharge locations, and advective transport times (breakthrough times for flow) for water that travels from the storage tunnels to the ground surface.

The model includes regional and local-scale fracture zones, which are represented as homogeneous, tabular zones of elevated hydraulic conductivity relative to the intervening rock mass. The rock mass is modelled as a continuum of uniform hydraulic conductivity. The boundary conditions at the top of the model account for a situation of decreasing relative sea level, with specified-head conditions for the portions that are below the sea level at a given time, and a maximum potential recharge condition for the portions that are above sea level.

Separate calculation grids are established for the regional (approx. 13 km x 16 km x 1 km) and local (2.3 km x 1.7 x 0.5 km) scales, with the regional grid being used to predict time-dependent boundary conditions for the local-scale grid. An intermediate-scale ("semilocal") grid and a detailed-scale grid are also used for specific calculations.

Since the high density of fracture zones in the local-scale domain is considered to be a consequence of more intensive site characterization near the SFR, the calculated equivalent hydraulic conductivity of the local-scale grid (for a uniform applied hydraulic gradient) is used as a representative estimate for similar-sized blocks in the regional grid. Variational cases are used to evaluate the consequences of regional-scale, uncorrelated heterogeneity, outside of the local domain.

Access tunnels, storage caverns, and barriers are represented in the model by grid cells of equivalent hydraulic conductivity, matching the layout as closely as possible within the constraints of a rectilinear calculation grid.

Special calculations were performed to predict the origin of water entering the tunnels, the process of resaturation of the repository in the post-closure period, the dilution to hypothetical water wells, and the influence of sedimentation on the evolution of flow paths from the repository. The report also includes calculations for several scenarios that involve failure of various engineered components and a proposed extension of the SFR tunnel system.

A1.2 Commentary

This study uses a complex numerical model to predict general and detailed aspects of groundwater flow around the repository for a period that extends 6000 years into the future. The major weaknesses are that:

1. the model omits significant heterogeneity which is manifested on the local scale,
2. the model has been calibrated with respect to a very limited amount of data for a single hydrologic situation that is significantly dissimilar to the situation for which predictions are sought, and
3. no convincing demonstration is given that the model is able to predict hydrologic measurements from situations other than the case that has been used to calibrate the model.

A1.3 Treatment of Heterogeneity

Each of the hydrogeological units in the conceptual model (fracture zone or rock mass) has been modelled as having uniform properties throughout the local-scale domain, despite data that indicate the presence of significant heterogeneity.

Heterogeneity within the defined hydrologic units is a demonstrated property of the site. Results of hydrologic tests in boreholes (as given by Carlsson et al., 1986, Appendix 4) show that the hydraulic conductivity of the "rock mass" (i.e. the rock outside of the identified fracture zones) can locally exceed the value that was used for the rock mass in the model, by as much as three orders of magnitude.

Borehole tests shows that the local transmissivity of individual fracture zones can vary by up to three orders of magnitude from point to point (Carlsson et al., Section 6.4). Interference test data demonstrate the existence of groundwater flow paths, within fracture zones, that are significantly more transmissive than the geometric mean of single-borehole transmissivity estimates.

These observed properties of the site cannot be reproduced by a hydrogeologic model that uses homogeneous properties within each major hydrologic unit. The significance of this simplification is not adequately addressed by the sensitivity analysis. This is a major shortcoming of the modeling study.

Evidence of significantly higher permeability in the shallow portions of the bedrock has been disregarded.

Prior analyses indicate a significantly higher permeability in at least the upper 40 m of the rock mass (Carlsson et al., 1986; Axelsson and Hansen, 1997). The present report dismisses this evidence based upon an analysis of "different sites in Sweden" by Walker et al. (1997). However for the Finnsjön site, which was the closest of the three sites analyzed by Walker et al., Table 6-7 in the main report for SR 97 (SKB, 1999) shows a contrast in mean hydraulic conductivity of more than an order of magnitude, between the shallow bedrock and the bedrock that lies deeper than 100 m.

The calibration as performed is not sensitive to this evident property of the site. Neglecting this property in the model may have led to (1) underestimation of actual recharge and (2) exaggeration of the effects of surface topography on the flow system at depth, e.g. in relation to regional flow systems. The net impact of this simplification in terms of safety is difficult to judge without calculations based on a more realistic model.

Structured heterogeneity on a regional scale has not been considered.

The analysis of regional-scale heterogeneity by use of an uncorrelated "stochastic" continuum does not consider the possibility of structured heterogeneity, particularly in the vertical dimension where a very coarse mesh is used for the lower part of the model. The analysis has not considered alternative scenarios to account for uncertainty in the structural models, e.g. the possibility of an undetected, subhorizontal, regional-scale fracture zone similar to H2 but at greater depth, which could potentially convey elevated heads to the base of the model. Given experience at other sites in Sweden, such a zone could reasonably be hypothesized as an alternative explanation of the excess heads that have been observed at the SFR.

A1.4 Model Calibration

The calibration of the model is based almost entirely on a single, highly perturbed hydrologic situation which is very dissimilar to the principal situation for which predictions are sought.

The calibration case is one of quasi-steady, strongly radial flow to air-filled tunnels. In terms of the direction and magnitude of hydraulic gradients, this situation is very dissimilar to the principal situation for which predictions are sought, i.e. the post-closure period after the SFR is resaturated, when flow will be through rather than into the repository. The equivalent hydraulic conductivities within the various hydrologic units, for this situation, are not necessarily the same as the equivalent hydraulic conductivities for flow in response to natural hydraulic gradients, in the post-closure period. The parameters controlling transient behavior of the model are not significantly constrained by the calibration.

Complicating effects exist which are not represented in the model, but which could have decrease the measured inflow values that were relied on for calibration by as much as an order of magnitude.

Inflow to the air-filled tunnels is strongly influenced by near-tunnel "skin" effects which are not well represented in the model, including (1) reduced relative permeability due to unsaturated flow effects in rock-mass fractures that intersect the tunnels, (2) permeability changes due to rock stress concentrations around tunnel openings, and (3) grouting effects. Previous analyses have estimated skin factors as low as 0.1 (Carlsson et al., 1986). The present model includes skin factors as fitting parameters for three of the fracture zones, but does not consider skin effects for the rock mass. The likely result is an underestimate of equivalent rock mass conductivity for the local-scale domain.

The calibration dataset is of very coarse resolution in relation to the number of hydrologic parameters that are being deduced. Hence the parameter estimates are poorly constrained.

The amount of data used directly in the calibration is small in relation to the number of parameters that were considered to be adjustable. In essence, a model with 10 adjustable parameters (fracture zone and rock mass conductivities, plus three fracture-zone skin factors) was used to obtain an approximate match to 4 data points (the total inflow rates to the major SFR components), subject to a constraint that 5 of the parameters (the fracture zone transmissivities) should "diverge as little as possible" from their initial estimates (the geometric means of single-hole transmissivity measurements, which as noted above showed a high degree of variability).

Most of the fracture zones do not directly intersect the SFR components, or only intersect components that are also intersected by other fracture zones plus the rock mass. Hence the calibration problem as posed is unlikely to have a unique solution. There does not appear to have been a systematic effort to identify and evaluate the consequences of different combinations of parameters for fracture zones and rock mass which would yield essentially the same total inflows to the four parts of the SFR.

As one example of a case of concern, based on the calibration Fracture Zone 9 was assigned a hydraulic conductivity that is practically indistinguishable from the rock mass, and a transmissivity that is an order of magnitude less than estimates from interference tests. This zone is characterized as a discrete (i.e., low-porosity) conductor that features moisture, dripping, and running water (Axelsson and Hansen, 1997), and thus could represent a potential path for relatively rapid transport of radionuclides to the surface environment. The possibility that this zone has much higher transmissivity than in the calibrated model should have been considered.

The effective porosity estimates are poorly constrained.

Values of effective flow porosity were estimated for two of the fracture zones based on interpreted or assumed seawater breakthrough times for sampling intervals in two relatively shallow boreholes. For the other zones and the rock mass, values were simply chosen.

Little evidence is presented that the calibrated model is capable of predicting actual hydrologic measurements that were not used as part of the calibration dataset.

For a hydrological model that will be used to predict future behavior under situations very different from the hydrological circumstances that are represented by the calibration dataset, it is advisable to show that the model is capable of matching system behavior in response to a variety of perturbations, including data that were not used directly in the calibration.

The only such prediction that is made in the present study is a prediction of excess heads, but none of the model variants produced excess heads equal to more than half of the maximum excess heads that were measured at the site.

Very little use has been made of the 48 hydraulic interference tests that were performed in fracture zones at the site, although these form a dataset that is relevant to the transient behavior of the model, and which is free from some of the complicating effects that are present around tunnels. For confidence in the transient predictions of the resaturation process, it would be useful to demonstrate that the model gives a reasonable match to the interference tests, to the time-dependent evolution of inflows that were observed during the repository construction period, and/or to the time-dependent drawdowns in nearby boreholes.

A1.5 Miscellaneous Issues

The verification status of the GEOAN code used for these calculations is not clear. The few comparisons with simpler models and checks of internal self-consistency that are presented in this report are not sufficient to give a high level of confidence in the results. A description of the scope of verification that has been done for the version of GEOAN that was used for these predictions could help to alleviate this concern.

The locations of groundwater "divides" could be radically shifted in a model that took account of the observed high degree of heterogeneity of the rock mass. The conclusions in Section 18.11 regarding the unimportance of the tunnel plugs and the Singö fracture zone should not be relied upon in the safety case, as these are largely functions of the decision to disregard heterogeneity.

The flow path analysis, including the analysis of "interactions" between tunnels, is highly contingent upon the omission of rock mass heterogeneity. A structured, heterogeneous rock mass would allow more rapid groundwater movement through a small fraction of the rock mass. Whether or not tunnels interact will depend primarily on whether or not they are intersected by the same high-permeability domains. Experience from the Stripa Project and elsewhere shows that flow paths around excavations in heterogeneous fractured bedrock can be very complex.

The analysis of flow to a well located in the rock mass is strongly influenced by the use of a homogeneous rock mass. The two "rock mass" wells (B and C, in Section 12.5.4) could not achieve the designated capacity for a small farm. A realistic analysis would consider that a farm needing a well would persevere until a borehole intersected either a major fracture zone, or one of the relatively high-permeability domains that are evident in the rock mass. The risk of radionuclide intake via a well may have been underestimated by considering wells in an unrealistic, homogeneous model of the rock mass.

The modeling of the influence of sedimentation on effective boundary conditions at the surface is potentially of interest as a scoping study of the potential for sedimentation to affect groundwater flow through a repository located near a receding shoreline. However, as the authors note, the model of the sediment accumulation process is quite speculative and highly generalized. Hence it would be unwarranted to rely upon the predicted effects (e.g. longer discharge path lengths) as an integral component of the repository safety case.

A1.6 Relevance to Safety Case for SFR

The conclusions of this study are dependent on a numerical model for which only a very limited dataset representing a single, highly perturbed groundwater flow situation has been used for calibration, and for which no convincing demonstration has been given of an ability to predict datasets that were not used in the calibration.

Sensitivity studies have not addressed significant uncertainty that remains regarding model parameters that could affect the predictions. Alternative distributions of conductivity among fracture zones and the rock mass have not been ruled out; this affects estimates of flow through the tunnels. Alternative hypotheses for the configuration of large-scale structures have not been considered.

The predictions of long-term flowrates through the storage tunnels are likely underestimated due to the exclusive use of tunnel inflow data for calibration, since these data are subject to tunnel skin effects which are in part temporary, and which are not adequately accounted for in the model. The authors' assertion that the uncertainty in predicted tunnel flows is low, because the calibration was made with respect to tunnel inflows, applies only for the circumstances of the calibration (i.e. in which the tunnels are kept air-filled and at atmospheric pressure).

The lack of calculation cases that incorporate heterogeneity in the rock mass or fracture zones is a major shortcoming of this modelling study, and casts doubt on the conclusions that relate to detailed-scale behavior. The risk of radionuclide uptake via a well may have been underestimated by considering wells in an unrealistic, homogeneous model of the rock mass.

Alternative values of porosity, a very poorly constrained parameter, have not been considered; this affects estimates of breakthrough times and groundwater velocities. This will affect the evolution of near-field chemical conditions and degradation of engineered barriers so far as these are impacted by infiltration times for meteoric water. Transport times for non-sorbing radionuclides are also directly affected.

For sorbing nuclides, the lack of small-scale heterogeneity in the model may lead to overestimates of the ratio of wetted surface area to transit times, depending on how these quantities were calculated from the output of this model. This ratio is of major significance for repository safety.

Conclusions regarding the unimportance of tunnel plugs and the Singö fracture zone are strongly predicated on the disregard of heterogeneity, and should not be relied upon for the safety case. The flow path analysis, including the analysis of "interactions" between tunnels, is also highly contingent upon the assumption of a homogeneous rock mass.

The modeling of the influence of sedimentation on effective boundary conditions at the surface is potentially of interest as a scoping study for the effects of this process, but the sedimentation process model is too speculative for the conclusions to be relied upon as an integral component of the repository safety case.

Given the weakness of the calibration, the omission of important aspects of heterogeneity, and the lack of a convincing validation by comparison of predicted vs. observed system behavior, the uncertainty in the predictions must be assessed as high. The residual uncertainty will be very difficult to assess without analyses of additional model variants that are aimed at the key assumptions that the model makes regarding these issues.

A1.7 References

Holmén, J.G. and Stigsson, M.,"Modelling of future hydrogeological conditions at SFR, Forsmark," SKB Report R-01-02, January, 2001.

Carlsson, L., Winberg, A., and Arnefors, J., "Hydraulic Modeling of the final repository for reactor waste (SFR): Compilation and conceptualization of available geological and hydrogeological data," SKB Progress Report SFR 86-03, October, 1986.

Axelsson, C-L. and Hansen, L. M., "Update of structural models at SFR nuclear waste repository, Forsmark, Sweden," SKB Rapport R-98-05, December 1997.

A2 Details of Predicted Flow in Deposition Tunnels

Report Number: R-01-21

Authors: J. Holmén and M. Stigsson.

Reviewer: Joel Geier, Clearwater Hardrock Consulting.

A2.1 Summary

This report presents predictions of future groundwater flow in and around waste-storage tunnels and the SILO cavern at the SFR facility. The predictions are based on the groundwater flow model described by Holmén and Stigsson (2001), which is a finite-difference model based on assumptions of saturated, uniform-density groundwater flow through a 3-D continuum representation of the rock.

The report presents calculated flows for segments of the BMA, BTF, and BLA tunnels as well as the SILO cavern. These results are provided as input to the near-field transport modelling, for the SFR safety assessment. Each segment is represented in the model by a number of grid cells which represent the waste and enclosing barriers.

Tables list the calculated volumetric net flows (1) for each external face of the group of grid cells that represent the waste within each tunnel segment, and (2) for each external face of the enclosing barriers (giving results separately for floor, roof, and side-wall sections). Additional tables list calculated vector values of "specific flow" (the volumetric flow per unit area, *i.e.* the Darcy flux) averaged over domains in the rock just outside the tunnel sections. These results are given for 1000-year increments over a period of 5000 years.

Results are presented for a base case and for two "sensitivity cases" that are intended to represent (1) a failure of the encapsulation in a section of the BMA tunnel, and (2) a failure of the barriers in the SILO. For the base case, results are given in terms of net flows and specific fluxes for segments of each of the tunnels and the SILO cavern. For the BMA and SILO sensitivity cases, results are given for the tunnel/cavern in which these failures occur, but not for the other tunnels/caverns in the SFR.

The BMA sensitivity case considers a breached section adjacent to a particular fracture zone (Zone 6) by assigning a single, increased value of hydraulic conductivity to all grid cells representing the waste and encapsulation within that tunnel section. The

SILO sensitivity case considers a general failure of the SILO encapsulation, by assigning a single, increased value of hydraulic conductivity to all grid cells representing the SILO and encapsulation.

A2.2 Commentary

As stated by the authors, the present report can be viewed as an appendix of the previous report (Holmén and Stigsson, 2001), since the aim is simply to give detailed results from the same model that was described in the previous report. These detailed results are obtained by apparently straightforward calculations from the model that was previously described. Hence the major technical issues hinge largely upon the assumptions and calibration of the original model, as described in the previous report.

This review addresses first the technical issues that relate directly to this report, and afterwards discusses key issues in interpreting the results, the most significant of which arise primarily from concerns about the original model.

A2.3 Technical issues arising directly from the present report

Insufficient justification for hydraulic conductivity values that were chosen for the two sensitivity cases.

In presenting the sensitivity cases, no indication is given of how hydraulic conductivity values were chosen to represent the failed BMA section or the failed SILO barriers. In the corresponding sections of the prior report (Sections 14.3 and 14.4, Holmén and Stigsson, 2001) these are referred to as "assumed properties," which implies that these are simply *ad hoc* values rather than values that were developed e.g. by expert elicitation, scoping calculations, or experimental data on the properties of failed barrier materials.

The discussion of the hydraulic conductivity value chosen for a failed SILO (Section 7.2, paragraph 3, specifically the statement that "much of the bentonite will remain in the barriers .... and there will be both cracked and intact concrete containers") seems to imply that the assumed value of hydraulic conductivity is to be regarded as conservative. However, the report does not explicitly state that this value is to be regarded as conservative, and the arguments given are not sufficient to establish that the assumed value of 10^{-5} m/s is a conservative value.

For the BMA sensitivity case, the present report states that 10^{-5} m/s is an assumed value of the encapsulation for the base case. Comparing with Section 10.6.8.3 of the previous report this is apparently the assumed value of hydraulic conductivity for the backfill in the base case, although that report states on p. 93 that "it is very likely that the material that will be used as backfill when the repository is closed will be a coarse material having a larger conductivity than that of the base case [1×10^{-5}m/s]." From this it might reasonably be asked why an even higher value, such as the value 1×10^{-4} m/s which was used in the second alternative layout (p. 83 of the previous report), might not be considered as within the range of realistic values.

Either in this report or at a higher level in the safety assessment, a more clear and thorough justification ought to be given for these "assumed" properties and whether they can be regarded as conservative or even realistic for the designated scenarios.

BMA sensitivity case geometry not entirely conservative.

The BMA sensitivity case described in Section 3.2 is intended to represent a case of a "large fracture intersecting the concrete walls of the encapsulation or a local collapse of the concrete walls." A reasonable scenario that could give rise to the former case would be reactivation along a fracture zone such as Zone 6, which represents a zone of mechanical weakness in the rock.

If displacement occurred along Zone 6, one would expect damage all along the intersection between this fracture zone and the BMA tunnel. However, the "breached" section in the BMA sensitivity case covers only about half of this intersection, as shown in Figure 3-1. A through-going breach would be expected to produce higher flows through the waste than a partial breach. Such a breach would produce increased area of direct coupling between the fracture zone and the high-permeability failed encapsulation for flow in the vertical direction, and less resistance to flow in the horizontal direction along Zone 6 (since otherwise the unfailed section still acts as a low-permeability inclusion in the high-K zone).

Examination of the net flows through this tunnel section for the base case show that, over the 5000 year period of the predictions, the model always predicts flow through this section to be dominantly vertical (*i.e.*, the K-1 and K+1 faces carry higher flows than the I-1 and I+1 faces). Hence the restriction of flow in the horizontal direction, due to the assumption of an incomplete breach along Zone 6, is likely to be of secondary significance. The restriction in the vertical direction can be bounded by simple geometrical considerations to have less than a factor-of-two impact, with the maximum effect realized only in the limiting case where the hydraulic conductivity of the failed waste section far exceeds that of the hydraulic cage material and Zone 6.

Thus, if we assume that the underlying hydrologic model is correct, the net effect of assuming an incomplete rather than a complete breach along Zone 6 is arguably no worse than a factor-of-two underestimation of the flows predicted from this scenario. Most likely this issue is of less significance than the uncertainty in the properties of the failed waste encapsulation, as discussed above.

Insufficient documentation of the specific formulae that were used to convert from basic model output to the presented results.

The verbal explanations of net flow and specific flow given on p. 7-8 should be clarified by giving the (presumably) simple mathematical formulae that were used to calculate these quantities from the basic output of the model. The present report does not state what type of averaging is used to calculate the "average specific flow" values that are presented. On p. 81 of the previous report, the authors state that the average specific flow is "a volume[-]weighted average value," but the present report states that this is "often given as an average value." While it is not difficult to guess what formulae should have been used, a clear statement of the formulae would allow a reviewer to confirm that formulae based on appropriate assumptions and physical understanding have in fact been used.

A2.4 Technical issues stemming from assumptions in the previous report

A review of the previous report pointed out the following main weaknesses in the underlying model that forms the basis for these detailed predictions:

1. the model omits significant heterogeneity which is manifested on the local scale,
2. the model has been calibrated with respect to a very limited amount of data for a single hydrologic situation that is significantly dissimilar to the situation for which predictions are sought, and
3. no convincing demonstration is given that the model is able to predict hydrologic measurements from situations other than the case that has been used to calibrate the model.

For the purposes of discussing the present report, points (2) and (3) can be lumped together as a single issue pertaining to the residual uncertainty in the model following calibration. These weaknesses give rise to the following concerns in interpreting the detailed flow predictions:

A2.5 Effects of ignoring local-scale heterogeneity in the rock mass and fracture zones

The model treats the rock mass and fracture zones as homogeneous domains, although site data indicate the presence of at least three orders of magnitude variation in "point" measurements of hydraulic conductivity within both rock mass and fracture zones (as discussed further in a review of the previous report).

Concerning the predictions in the present report, it is almost certain that the variability of flows to tunnel sections has been underestimated by a model that assumes homogeneous properties within each structural unit. The extent to which the variability in flows has been underestimated depends on to what extent the small-scale heterogeneity of the rock averages out over the lengths of the sections of the tunnels that are considered.

The presence of this heterogeneity, and the fact that it is not represented in the model, signify that no meaning can be attached to predictions that any specific tunnel section will have greater flows than another specific tunnel section. At best, these detailed predictions can be viewed as illustrative of which tunnel sections are most likely to experience greater flows than others, due to unfavorable positions relative to the boundaries and the main fracture zones.

The presence of heterogeneity also introduces uncertainty into the assessment of the sensitivity cases. For instance, coincidence of a failed tunnel segment with a relatively high-conductivity portion of Zone 6 would result in higher flows than have been predicted for the homogeneous model. The potential magnitude of this error would depend on the spatial scale over which heterogeneity in the fracture zone tends to average out, in comparison with the length of the tunnel segment.

A2.6 Effects of residual uncertainty in the calibrations

As discussed in the previous review, there is reason to believe that the calibrated parameters of the model are subject to significant residual uncertainty stemming from, *e.g.*, nonuniqueness of the calibration with respect to the available data, and neglect of skin effects in the rock mass which result from, e.g, unsaturated conditions in air-filled tunnels.

To the extent that the calibration is in error, this will affect the detailed predictions of flows to tunnel segments. Calibration errors could affect both the total predicted flow through tunnel segments, and the distribution of flow among different tunnel segments. Thus both the average value and the variability of the predicted flows could be affected.

A2.7 Relevance to safety case for SFR

The following are the main issues of relevance for the safety case for the SFR, as identified in this review:

1. Omission of heterogeneity from the underlying hydrologic model very likely results in an underestimate of the variability of flows to tunnel segments. Correlations between flows and transport distances to the biosphere could also have been misestimated, if these were evaluated from the flows and transport distances for particular tunnel sections.

2. Weaknesses of the calibration of the underlying model will carry over as uncertainty in the predicted flows to individual sections. In the previous review of the report that described the underlying model, it was noted that long-term flowrates through the storage tunnels are likely underestimated. If that is the case, the detailed flow predictions would also be systematically biased toward lower flowrates than should actually be expected.

3. Other issues stemming from this review are not likely to be as significant for the safety case for the SFR, as are the two issues noted above. One exception could be if the BMA drift or SILO failure scenarios are critical to the safety case. In that case, further attention should be given to the parameter values that were assumed for these scenarios. These parameter values appear to be *ad hoc* choices, and should be better justified to establish that they are conservative or at least realistic.

A2.8 References

Holmén, J. and Stigsson, M., "Modelling of future hydrogeological conditions at SFR, Forsmark", SKB Report R-01-02, January 2001.

A3 Characterisation of Bituminised Waste

Report Number: R-01-26

Authors: Michael Pettersson and Mark Elert

Reviewer: W. Miller, EnvirosQuantiSci Ltd

A3.1 Summary

This report summarises the current state of knowledge of degradation processes that can affect bitumen and draws conclusions as to their significance for the degradation of bituminised wastes in the SFR repository. A number of quantitative calculations of radiolysis, water uptake and radionuclide transport through the bitumen are performed.

The report provides a description of the SFR and the types of wastes to be bituminised, including their volumes, activities and planned emplacement geometries in the repository. The bituminised waste emplaced in the SFR contains mainly ion exchange resins and relatively small amounts of evaporator concentrate. The total volume of bituminised wastes planned to be emplaced in the SFR is 6800 m^3 to be distributed between the Silo, the BMA and the BLA, although the majority of the radionuclide inventory for the SFR as a whole will not be solidified in bitumen. The highest activity wastes are placed in the Silo and the lowest activity wastes in the BLA.

The type of bitumen used for waste immobilization is manufactured by distillation of petroleum (known as 'straight run' bitumen). The composition of the bitumen product is dependent, in part, on the origin of the petroleum and the distillation process. In general, this bitumen is considered to have chemical and physical properties which are favourable for radionuclide immobilization. The report considers five processes which may affect the long-term behaviour of bituminised wastes: radiolysis, biodegradation, ageing, water uptake and leaching.

Radiolysis of bitumen (from embedded radionuclides) can cause generation of radiolysis gases which, if generated at a high rate, may cause swelling and mechanical disruption to the bitumen mass. Various laboratory results are quoted which suggest that the mechanical effects are dependent on bitumen type, size and surface-to-volume ratio of the bitumen mass. Most important, however, is the dose rate, although alpha radiation is two to ten times more efficient than gamma radiation at causing radiolysis. It is concluded that at dose rates below 0.1 MGy, the radiolysis effects are negligible, at

rates between 0.1 and 2 MGy the generation of radiolysis gases must be considered, and at rates greater than 2 MGy, substantial swelling may occur.

Biodegradation can be observed in laboratory experiments on bitumen surfaces but the rate of degradation is very slow. It is concluded that this processes is of minor importance.

Ageing is the term used to describe the slow changes (hardening) to bitumen that occurs due to the loss of volatile components from the solid and the solid-state redistribution of large hydrocarbon molecules. It is most rapid in oxidizing conditions in the presence of light. Ageing results in embrittlement and cracking of the bitumen, increasing water penetration. The authors conclude, however, that the significance of ageing on the long-term performance of a bitumen barrier is unknown.

Water uptake (diffusion of water vapour into the bitumen mass) occurs in aqueous conditions and in humid air. In pure bitumen, the processes is deemed to be negligible. When bitumen is used to immobilize ion exchange resins, however, the diffusion process may transport water through the bitumen to the resin, which absorbs it, causing swelling and potential mechanical disruption to the bitumen mass, thus increasing water penetration. Various laboratory results are quoted which suggest that the mechanical effects are dependent on waste material type, temperature, and bitumen-to-waste ratio. The effect is greatest for a dehydrated resin wastes which may swell by 200% unless otherwise treated with Na_2SO_4 which reduces swelling capacity. The theoretical maximum volume increase due to water uptake of ion exchange resins was calculated for different waste packages. The greatest swelling was calculated to occur for a F.17 waste package in the BMA which swells by 0.58 m^3 and a F.18 waste package in the Silo which swells by 0.43 m^3. These volume increases are larger than the void space in the packages suggesting that, if maximum swelling did occur, mechanical disruption to these packages could take place.

Leaching refers to the release of radioactive components embedded in the bitumen. In an undisturbed state, diffusion of radionuclides through the bitumen is deemed to be negligible. If, however, mechanical disruption to the bitumen occurs due to radiolysis or water uptake, then a porosity can be established through which water can penetrate to leach radionuclides. The rate of leaching of readily soluble radionuclides is controlled by the rate at which a porosity is formed. The rate of leaching of sparingly soluble radionuclides is controlled by the nuclide dissolution rate. Various laboratory results are quoted which suggest that the overall release rates are dependent on type of bitumen, type of waste, temperature and bitumen-to-waste ratio. It is concluded that all the radionuclides in a 200 l drum could be leached in 1000 years, based on extrapolations from short-term laboratory experiments.

Overall, it is concluded that bitumen controls the release rate from the near-field only for those radionuclides which are mostly embedded in the bitumen. Generally, most radionuclides are immobilised in cement and, thus, the long-term performance of the bitumen barrier is not critical to the safety of the SFR. The radionuclide most controlled by bitumen is ^{14}C because the entire inventory of this nuclide in the BMA and a large proportion in the Silo is bituminised. It is concluded that the bitumen reduces the release of ^{14}C by a factor of 2 for the BMA inventory and a factor of 1.5 for the Silo inventory.

A3.2 Commentary

The report provides a comprehensive overview of bitumen degradation processes, as investigated in laboratory experiments. The report does cover all of the relevant degradation processes (radiolysis, biodegradation, ageing, water uptake and leaching), although each is treated separately to a large extent and no detailed consideration is given to coupling between these processes. For example, whether radiolytically damaged bitumen is more susceptible to microbial degradation. Nonetheless, given the conclusion that overall bitumen degradation does not significantly affect repository performance, information on coupling between the degradation processes would be of little more than academic interest.

The information presented in the review is poorly focussed on the specific conditions expected in the SFR. It would have been desirable if Chapter 3, which describes the bituminised waste, was more detailed and discussed the expected dose rates in the bitumen at known waste loadings, expected groundwater chemistry in the near-field in terms of pH, Eh, salinity and temperature. Without knowledge of these parameters it is difficult to distinguish in the review those laboratory data that are relevant from those that are not. In fact, may of the laboratory results that are presented are from environments which are grossly dissimilar to the SFR near-field, meaning that they are of only tangential interest.

An example of information presented that has minimal relevance comes from in Section 4.5 (leaching). In this section, the results of leaching experiments are presented that were derived from studies in which bitumen samples were left exposed to the atmosphere (in daylight, oxidising, mildly acidic conditions) or buried in soils (oxidising, mildly acidic conditions). In neither case do these environments replicate SFR near-field conditions which would be dark, hyperalkaline, chemically reducing and saline (at least in the period before land uplift raises the repository from the Baltic Sea). As such, these test results have very little significance and the measured leach rates derived from them cannot be applied directly to a safety case for an SFR nor can they be extrapolated to SFR conditions.

It would be a useful exercise to extract and tabulate those data derived from experiments which do have relevance. Overall, perhaps less than one third of the laboratory results presented in the review would be suitable. Even then, most replicate only one or two parameters at a time and very few replicate the actual waste loadings, hyperalkaline conditions or saline groundwaters.

The report notes that the majority of the laboratory studies are short-term and that there is some uncertainty regarding the extrapolation of these data to repository time scales. In this regard, a significant omission of the report is the suite of information that has been derived from studies of natural analogues. There are a number of natural analogue studies which have been performed on naturally-occurring bitumens from environments with relevance to the SFR. For reviews of the subject, see Heckers et al. (2000); Miller et al. (2000); Alexander and Miller (1994). For a discussion of naturally-occurring bitumens, see Mossman and Nagy (1996). These natural analogue studies provide mostly qualitative or semi-quantitative information. They are, nonetheless, an important adjunct to the laboratory data and frequently can be used to support the validity of relevant laboratory-derived numbers or to provide bounding limits to expected long-term process rates.

The quantitative calculations presented in the Appendices for the estimation of absorbed energy caused by radiolytic decay, swelling due to water uptake and radionuclide transport in the BMA, all are based on a number of conservative assumptions but appear to be valid approaches for deriving approximate, conservative estimates of these processes, although no estimation of the degree of conservatism was presented.

The report concludes that ‘bitumen is an effective barrier against release of radionuclides’ and that ‘bitumen will act as an effective barrier for radionuclide releases during a time span of several hundred to thousand years’. The reviewer concurs with this conclusion.

Section 1.1 (Background) criticised an earlier assessment for using unnecessarily conservative modelling assumptions and recommended consideration of a new model coupling radionuclide release from bitumen with water uptake. It is a surprising omission, therefore, that the report authors do not then make any recommendations for how to account for the bitumen barrier in a safety case (or even if it should be accounted for) given the findings of their work.

A3.3 Relevance to the Safety Case for the SFR

The report concludes that the bitumen barrier used to immobilise certain waste materials has only a limited effect on the overall safety of the SFR. The releases of only a few specific radionuclides (notably ^{14}C) are reduced by long-term immobilisation in bitumen: this is because the largest proportions of most radionuclide inventories are immobilised in cement rather than bitumen. As such, calculated repository performance is not sensitive to uncertainties concerning the long-term behaviour of bitumen.

It follows that the report's conclusions are interesting but are not critical to the development of a safety case for the SFR. Disregarding the bitumen barrier or assuming a simple, conservative leaching rate of radionuclides would be defensible modelling approaches in the safety case calculations (although could be criticised as being overly conservative and unrealistic).

Neither the report's content nor conclusions highlight any significant implications for groundwater flow or chemical conditions in the near-field. There is, however, the potential for enhanced groundwater penetration into the bitumen mass as a consequence of mechanical disruption to the wasteform due to swelling and cracking. The consequences of this are, however, minimal for safety for the reasons outlined above. Likewise, there is the potential for bitumen radiolysis and biodegradation products to affect near-field chemistry by providing a source of organic complexants. Again, however, the consequences of this are minimal because the effect will be masked by the much larger source of complexants generated by degradation of cellulosic wastes.

There is some potential for changes to the near-field physical properties as a consequence of bitumen swelling. The report indicates that for a few waste packages (F.17 in the BMA and F.18 in the Silo), the maximum potential volume expansion due to water uptake is greater than the available void spaces. In the case of the Silo, these waste packages are grouped together in the centre region and, therefore, the potential swelling of these packages combined may have some physical effects, although this was not quantified in the report. This is, perhaps, an issue which could be investigated further to ensure that there is no likelihood of stresses building on the reinforced concrete structures of the Silo itself.

As a consequences of the above, there will be minor time dependent changes to the repository system. The leach rate from the bitumen may increase in the first few hundred years as water uptake and radiolysis causes mechanical disruption to the wasteform, enhancing groundwater penetration. Likewise, water flow through the Silo and BMA may be locally modified if waste packages swell (as a consequence of water uptake) into void spaces. Neither of these processes are considered significant and do not require explicit inclusion in the assessment models.

A3.4 References

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A4 Complexing Agents

Report Number: R-01-04

Authors: Fanger et al.

Reviewer: Michael J. Stenhouse, Monitor Scientific LLC

A4.1 Summary

The report by Fanger et al. (2001) on the presence and impact of complexants in the SFR repository has examined in detail what complexants are present, or likely to be present (i.e. by degradation) within the waste itself, as well as from waste package containers and structural concrete. The work is based on a detailed examination of sources and quantities of complexants, calculations of potential concentrations of complexing agents (including degradation products), and an examination of the literature on the impacts of complexants on the sorption and solubility of radionuclides on cement/concrete. In the analysis, this work has also taken into account the location of the complexants within the different sections of the repository (i.e. Silo, BTF, BLA, BMA).

In the literature review, advantage is taken of the relevant results and conclusions presented in recent publications from Swedish researchers (Pavasars, 1999; Pedersen, 2001) as well as relatively recent accounts of work done principally in Switzerland, at the Paul Scherrer Institut (PSI).

Cellulose is recognised as the main source of degradation products (predominantly isosaccharinic acid, or ISA) which may significantly affect radionuclide behaviour. Degradation products of bitumen and ion exchange resins are covered, as well as other complexing agents directly present in wastes; notably, citric acid, oxalic acid, nitrilo-triacetic acid (NTA), ethylene diamine tetra-acetic acid (EDTA) and Na-gluconate. Calculations are carried out of potential concentrations of these latter complexing agents in the repository. Similarly, cement additives were addressed, the main additives (e.g. cellulosic additives such as lignine, lignosulphates) being included in subsequent calculations to determine their likely concentrations in the repository.

The key conclusions of the report concerning the effects of ISA on radionuclide sorption are that the balance of available evidence indicates a 'significant' effect of ISA on the sorption of:

- tri-(3+: Am, Cm and Eu) and tetra-(4+: actinides, Tc, Zr, Nb) valent elements; at ISA concentrations > 10^{-4} M;
- bi-(2+)valent elements (Ni, Co, Fe, Be, Pb); for ISA concentrations > 10^{-2}M.

Fanger et al. (2001) also conclude that (i) EDTA will affect the sorption of Ni and Mn, at complexant concentrations ≥ 10^{-3}M, and Pb ≥ 10^{-2}M; (ii) NTA will only affect the sorption of Ni, Mn and Pb, at (complexant) concentrations ≥ 10^{-1}M; and (iii) citric acid will affect only Mn, at (complexant) concentrations ≥ 10^{-1}M.

A4.2 Commentary

Key Issues

- The degradation process for cellulose, the source of the most important complexant, isosaccharinic acid (ISA), is (rightly) discussed in detail, including degradation rates and other possible degradation products apart from ISA. ISA is, however, expected to be the predominant degradation product, although it may itself degrade (to constituent carboxylic acids), especially under microbial attack. This latter possibility is not discussed in this report.
- With regard to the effects of ISA on radionuclide sorption, Fanger et al. (2001) conclude that the available experimental evidence indicates a 'significant' effect of ISA on the sorption of:
- tri-($^{3+}$: Am, Cm and Eu) and tetra-($^{4+}$: actinides, Tc, Zr, Nb) valent elements; at ISA concentrations > 10^{-4} M;
- bi-($^{2+}$)valent elements (Ni, Co, Fe, Be, Pb); for ISA concentrations >10^{-2} M.
- In the literature review which provides the basis for the above conclusions, there are some *conflicting results* around ISA concentrations of ~10^{-4} M, mainly for Th(IV) and Eu(III). For example, Bradbury and van Loon (1997) found no influence on Th sorption for equilibrium ISA levels of ≤ 10^{-4} M, but reduction of sorption by a factor of at least x40 at ISA levels in the range > 10^{-4} to 10^{-2} M. Wieland et al. (1998) found a significant effect for ISA levels in the range 10^{-5} to 10^{-2} M. For Eu(III), Weiland et al. (1998) observed negligible effects in the ISA concentration range 10^{-5} to 10^{-2} M, whereas Van Loon and Glaus (1998) observed an effect on sorption at an ISA concentration of 10^{-4} M. Sorption on cement of a radionuclide-ISA complex may explain these discrepancies. On balance, the conclusions of Fanger et al. (2001) are conservative.

- Bitumen and ion exchange resins and their degradation products are discussed, but were considered (with justification, based on the experimental evidence) to have a negligible impact on radionuclide behaviour.
- The sorption onto cement of complexing agents themselves, as well as radionuclide complexes, has been examined and the strong experimental evidence for the sorption of ISA as well as radionuclide-ISA complexes is recognised.
- Other complexing agents present in wastes and addressed by Fangers et al. (2001) are: notably, citric acid, oxalic acid, nitrilo-triacetic acid (NTA), ethylene diamine tetraacetic acid (EDTA) and Na-gluconate. Complexation by Ca^{2+} present in alkaline porewaters is an important way of reducing the formation of complexes with radionuclides and is rightly acknowledged. (This conclusion was also confirmed in an independent modelling study carried out for ANDRA by Stenhouse, Savage and Duro (1998).) Consequently, of these complexing agents, only EDTA at concentrations > 10^{-2} M is expected to have a significant effect (by a factor ≥ 10) on the sorption of certain elements, with Ni and Mn the elements affected. [Bradbury and Van Loon (1997) subsequently identified Ni as the only safety-relevant radioelement affected].
- As acknowledged in various parts of the text, conservatism has been incorporated in the calculations reported:
    - Degradation of ISA was not considered in calculations, therefore the maximum concentration of ISA is assumed to be available for complexing.
    - Removal of ISA, e.g. by diffusion, from the waste package regions, is ignored.
    - All cellulose is assumed to be available for degradation and to degrade to ISA – whereas experiments indicate that certain chemical reactions can occur which can block degradation, and in addition, small amounts of degradation products other than ISA are formed.
    - No sorption is considered for EDTA, citric acid and similar complexants –such sorption would have the effect of (i) reducing complexant levels in solution available for complexing, and (ii) the retardation of radionuclide complexes.
    - No degradation is considered for complexing agents such as EDTA, citric acid etc., similar to that of ISA.

- Certain fatty acids are assumed to degrade to ISA, thereby adding to the ISA 'inventory' – whereas, there is no evidence for such degradation.
- No sorption of Na-gluconate was taken into account – yet experimental evidence indicates substantial sorption of this complexant.

A4.3 Scope for Improved Treatment

- Fanger et al. (2001) note, but do not expand on, the conclusion of Pavasars (1999) and others (last sentence, p. 14) that
  "in a long-term perspective, the effects of cellulose degradation products on radionuclide sorption will probably be negligible".
- This conclusion is *presumably* based on a likely reduction in ISA concentration due to (i) dilution of alkaline porewaters (and leached radionuclides) as they move away from the waste packages, and (ii) sorption of the complexant (ISA) itself, or of the radionuclide-ISA complex on cement phases. Given the importance of this conclusion, it merits some supporting explanation or expansion.
- The treatment of whether or not to allow for sorption of complexing agents on cement/concrete is inconsistent. Reduction of Na-gluconate concentrations by sorption on cement phases was acknowledged (rightly) as a significant mechanism for reducing levels of this complexant in solution, in the same way as for ISA. Yet sorption was taken into account for ISA but ignored (albeit conservatively) in the treatment of Na-gluconate. The role of sorption in reducing ISA concentrations below critical levels (where they affect sorption significantly) is shown in this report to be important. While this same role is acknowledged for Na-gluconate, it is used only as an argument for limiting the significance of the results presented in Tables 3.2.4 to 3.2.6 [p. 37].
- Strictly, the basis for the reduction factors presented in Table 2.3.2 are (theoretical) speciation calculations carried out by Hummel (1993) and not Bradbury and Sarott (1995) as reported.
- With regard to the effect of EDTA on the sorption of certain elements, there is an inconsistency concerning whether an EDTA concentration of 10^{-4} M will affect the sorption of Ni and Mn (cf. text at bottom of p. 15, and Table 2.3.2).
- The basis for the ISA yield of 0.1 mole/kg (Skagius et al., 1999), representing the degradation of cellulose after a few years, is not discussed in this report; yet this value is used in the calculations on subsequent ISA concentrations

presented in Tables 3.2.1, 3.2.2, and 3.2.3. [p. 27 "*Concentration of ISA based on 2% degraded cellulose (0.1 mole/kg) is a more likely estimation.*"] Although other degradation yields are included in Appendix B of the report, the value of 0.1 (mole/kg) forms the basis of identifying critical levels of ISA (see comment below). There is no argument about the nature of this conclusion, only the level of supporting detail provided.

- Section 3.4 is confusing since it does not contain clear conclusions about the impacts of organic complexants in different waste types. The section contains more a series of arguments for why levels of complexants should be considered less than those calculated. It would be better here to simply list all the reasons why calculations of complexant concentrations should be considered conservative.

A4.4 Gaps/Weaknesses in Use of Data

- Many of the reports cited in the literature review section appear to provide qualitative results (e.g. "significant" reduction in sorption), which makes it difficult to draw good comparisons or quantitative conclusions.
- A clear statement in Section 2 or early in Section 3 of what are described as "critical ISA levels" would be helpful. The concept is mentioned within the text, but not described explicitly in terms of critical concentrations until Section 3.4.1, i.e. concentrations (of different complexants) above which a reduction in sorption (and solubility?!) must be taken into account. Similarly, critical levels for two other complexing agents are included in the caption to Table 3.4.1, but not linked to specific complexants.
- A clear statement is needed that the yield of 0.1 mole/kg, as opposed to degradation equation 2.1, is the one favoured and, hence, adopted in terms of calculations carried out to determine what concentrations of ISA exceed the critical level.
- The treatment of solubility is superficial at best, with less than half a page (p. 19) devoted to it. Section 3.4 contains "solubility" in its title, but solubility is not discussed at all. Although solubility issues are likely to be secondary in importance to sorption in the SFR and even negligible in the case of most radioelements, there needs to be some quantitative argument (e.g. predicted radiolement concentrations) for neglecting the effect of organic complexants on increased solubilities of certain elements, particularly Pu.

In the case of ISA, for example, in Section 2.3.2, the first sentence states:

"The presence of ISA will affect the solubility of trivalent and tetravalent elements."

and again…..

"The solubility of Pu increases significantly at ISA concentrations above $0.1 \cdot 10^{-3}$ M." [10^{-4} M?]

yet ISA concentrations > 10^{-4} M are calculated for some waste types.

Despite the statement:

"In the coming radionuclide transport calculations, higher solubility constraints may be applied for some radionuclides."

no guidance is given on how to treat possible impacts on solubility. If outside the scope of the study, this should have been stated upfront. It is not sufficient to state:

"International safety assessments have shown that the enhancement of radionuclide solubility by organic degradation products is in general not of concern in low- and intermediate-level waste repositories."

A4.5 Important Uncertainties

- There is no discussion of what cement phases are involved in the sorption of radionuclides as well as complexing agents, and the possible effects of aging on these cement phases.
- Some research regarding the effects of Na-gluconate on the sorption of key radionuclides other than Eu is to be recommended.
- The idea of possible saturation of sorption sites by complexing agents (or even alpha-emitting radioelements which exist beyond trace levels) should be explored further, taking into account all the complexing agents. This concept was addressed in terms of its effect on ISA levels, but considering all complexants together would be important, if only to eliminate the suggestion that there might not be sufficient sites on cement phases to sorb radionuclides. Even one or two sentences providing an estimate of total number of sorption sites (moles/kg and moles) would help. This could be done in the conclusions section where it could be emphasised that concentrations of complexing agents

will only be high locally, and that further away (within the repository), concentrations will be reduced significantly.

A4.6 Relevance to Safety Case for the SFR Repository

- The presence of certain complexants, predominantly ISA, a degradation product of cellulose, at sufficiently high concentrations in porewaters, can adversely affect the solubility and sorption properties of some radionuclides, in particular actinides. Based on the calculations performed in the study, sufficiently high concentrations of ISA in some waste streams (F.17, F.23/steel and S.21 in BMA and S.22 in the Silo) are expected to affect the sorption of bi-, tri- and tetra-valent elements.
- Despite the careful review and calculations carried out in this report, there is no clear guidance on what information/data should be carried through to performance assessment (PA) calculations, e.g. whether there should be a specific reduction in Kd value, or specific increase in solubility, of certain elements such as Pu. Thus, the feeling at the end of this report is that the reader is the one who must make up his/her mind concerning the significance of possible concentrations of complexing agents in solution.
- The concept of "sorption recovery" (demonstrated experimentally for EDTA) is an interesting and important one, whereby an initial reduction in sorption has been observed but normal (unperturbed) sorption has subsequently been restored. The latter is attributed to the sorption of EDTA itself (as well as EDTA-radionuclide complexes) on cement. If this phenomenon applies 'across the board' (i.e. to all radionuclides), the adverse impacts of complexing agents on radionuclide retardation will be dramatically reduced.
- Based on the arguments presented in the report, the concept of surrounding certain (unconditioned) waste packages in the BMA section with cement, to promote sorption of ISA, thereby decreasing the concentration of ISA in porewaters, appears worthwhile.
- Although probably outside the scope of the review, it would be useful to see implications of enhanced concentrations of complexing agents carried through to dose calculations, to determine the significance of the findings. This would help direct any future research effort focussing on this issue.

A4.7 References

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Van Loon, L.R. and Glaus, M.A. (1998) Experimental and theoretical studies on alkaline degradation of cellulose and its impact on the sorption of radionuclides. P*SI Bericht* **Nr. 98-07**. Paul Scherrer Institute, Würenlingen and Villigen, Switzerland.

Wieland, E. Tits, J., Spieler P., Dobler J.P. (1998). Interaction of Eu(III) and Th(IV) with sulphate-resistant Portland cement. In *Scientific Basis for Nuclear Waste Management* **XXI**, *Mat. Res. Soc. Symp.* **506**.

A5 Microbial Features, Events and Processes

Report Number: R-01-05

Author: K Pedersen

Reviewer: J M West, British Geological Survey

A5.1 Summary

This 55 page report is written by a microbiologist who has undertaken subsurface microbiological work for SKB for a number of years. The report comprises an abstract, summary and 4 chapters:

- Microbes and microbial processes – general principles applicable to the SFR
- The prospect for microbial life in the SFR repository – environmental considerations
- Evaluation of the prospects of microbially induced processes in the repository
- Microbial processes in the SFR interaction matrix.

In addition there is a reference list (40 references) and one appendix. The cited aim of the report is 'to evaluate whether there exist microbial processes that may threaten the integrity of the SFR' (Chapter 1, last sentence of first paragraph, p13).

The report starts with a broad explanation of basic microbiological processes and requirements for life in the context of the SFR environment. It then describes the waste types and, briefly, the microbial environment within the SFR repository. Transport processes within the repository are then described in the context of microbial activity (diffusion, advection and microbial mobility). Microbial processes within the waste canisters are then discussed followed by a description of processes during and following containment breakdown. A mostly qualitative evaluation of microbially induced processes within the SFR examines direct effects (bitumen, concrete, cellulose degradation, metal corrosion, clogging of flow paths, gas consumption and generation) and indirect effects (formation of complexing agents, effects on radionuclide dissolution and mobility, bio-geochemical effects on groundwater composition). Some quantitative assessments are given for steel corrosion and gas production. The report concludes with comments on a list of 'Environmental effects on the microbial state' and a list on the 'Effects of the microbes on the state of the repository'.

The report fulfils its stated aim although it is a mostly qualitative assessment of microbial FEPs and, as such, cannot be used directly in the safety case for SFR.

A5.2 Commentary

The report is a qualitative assessment of microbial processes that may influence the integrity of the SFR. Taking each chapter in turn:

Ch 1. Microbes and microbial processes – general principles applicable to the SFR

This chapter is a broad introduction to microbiological processes, some of the text could be placed in an appendix, as it is not directly relevant to the report (eg discussion of the 3 major domains of life). In contrast, the section dealing with microbial growth requirements (Section 1.4) is brief with few specific examples and references.

The comparisons between batch culture systems and SFR containers, and continuous culture systems with the near-field/far-field interface are interesting and could be very useful for determining, in the first instance, the relevance of microbiological effects to the safety case. However, the approach is simplistic and could encourage examination of only fluid phases and disregard surface rock/water/microbe reactions that will occur. Disregarding surface reactions would have implications for the geochemical component of the safety case. Increasingly the literature shows the importance of the effects of microbial activity at the small scale within biofilms (eg work by Beveridge and colleagues on biogenic mineral formation).

On a minor detail – hard rock aquifer? Correct terminology?

Ch 2. The prospect for microbial life in the SFR repository – environmental considerations

This chapter worries me. It starts with a summary of the waste types (Tables 2.1 and Tables 2.2.a-d) and briefly examines the SFR repository in terms of microbial environments. The author says ‘ it is obvious that the SFR would become a huge bioreactor unless microbial activity is restricted in various ways’ (Section 2.1.2 p 24). However, there is no tabulation or assessment of the energy/nutrient inventories of the various waste packages which would help to define the capacity for microbial life in the SFR environment and hence their effects. There then follows a primarily qualitative assessment of transport processes affecting microbial activity in the repository. Diffusion is disregarded (probably correctly - but no supporting data are given here) and emphasis placed on advective flow based on biofilm productivity in a marine system (a better analogy may be the biofilm development work undertaken at the

Canadian URL by Brown and co-workers). No attempt is made to evaluate the extent of possible biofilm development up-gradient of the SFR, within the SFR or down-gradient of it. A brief assessment of microbial mobility is made with limited data (no references cited) and with no discussion of the controls on mobility such as pore size (which will change in different parts of the repository and in the host rock). Information on the movement of microbial tracers in groundwaters and pathogens in the subsurface would assist here (eg World Health Organisation documentation).

Qualitative descriptions are then given of microbial processes independent of transport and transport-dependent processes. Processes in the 'closed system' after waste emplacement (especially containers in BTF, BLA and BMA caverns) will probably be controlled, at least initially, by the availability of water (as cited in the text). If the system is intact and stagnant then the situation given in Figure 2-3 is a fair qualitative assessment. However, this assessment will change when water is present. This being the case, then the key matter to calibrate the 'closed system' is to establish the amount of water present in the containers on emplacement that would be available for microbial use (simple worst case scoping calculations could be undertaken using nutrient and energy inventories for the waste packages). Similarly, transport dependent processes described in section 2.2.5 and in Figures 2-5 and 2-6 could be calibrated in time and space using simple calculations based on waste package and groundwater compositions. This approach has been taken by in Canada (Stroes-Gascoyne and co-workers), Switzerland (McKinley and co-workers) and the UK (West and co-workers). Although such calculations will, inevitably, make assumptions they do provide worst case predictions which can be used in performance assessments and that can, if necessary, be constrained by actual observations.

Ch 3 Evaluation of the prospects of microbially induced processes in the repository

Chapter 3 examines microbial processes within the SFR and is, again, mostly qualitative and, as such, is not useful for the safety case. Bitumen degradation in the SFR is said to be unlikely in the 'closed system' and 'slow' in the longer term. This is based on low water availability (unquantified) and 'very low' porosity (Table 3-1). A similar qualitative approach is made with regard to concrete degradation, cellulose degradation, gas consumption, formation of complexing agents and radionuclide mobilisation and transport. Whilst there is a lack of specific background data for many of these areas, it is possible to perform scoping calculations to constrain the issue which could be used in performance assessment for the SFR. Examples of this approach can be seen in the work of Humphreys and co-workers at Drigg, UK.

There has been an attempt to quantify both gas production (based on the Nirex work with GAMMON model) and metal corrosion. Gas production is likely to be a major problem (as correctly assessed using Nirex data) but again requires putting into the SFR context. Calculations made in the report on metal corrosion are useful but need to be put into the context of the SFR safety case.

Ch 4 Microbial processes in the SFR interaction matrix

This brief discussion of the possible interactions between microbes and other elements within the SFR interaction matrix demonstrates:

1. The recognition of environmental controls on microbial life within the SFR;
2. The recognition of the effects of microbial activity on the repository;
3. The importance of water on microbial activity (although water present in the waste packages on emplacement is not mentioned).

In summary, the report:

- Identifies the broad key issues (environmental controls on microbial life particularly the supply of water, nutrients and energy sources; and the direct and indirect effects of microbial processes on waste containment in the near- and far-fields). It identifies gas production as a particular issue.
- Does not draw on information from other workers in the field. For example, the approach to establishing the relevance of microbial processes in repositories used in Switzerland could have been very useful to this document (eg McKinley, I.G. & Grogan, H. A. (1991) Consideration of microbiology in modelling the near-field of a L/ILW repository. Experientia 47, 573-577; McKinley, I.G., Hagenlocher, I., Alexander. W. R. & Schwyn, B. (1997). Microbiology in nuclear waste disposal: interfaces and reaction fronts. FEMS Microbiology Reviews 20, 545-556).
- Presents limited data as it is mostly qualitative in its approach. No calibration is possible except in qualitative terms eg gas production is of particular concern.

A5.3 Relevance to SFR Safety Case

The report correctly identifies the environmental controls on microbial life in the SFR. It also identifies all the likely microbial processes that could affect the integrity of the repository and that are directly relevant to the safety case. However, as it is a qualitative document none of the information can be used directly in the overall safety case for the SFR. Performing simple scoping calculations to give worst case predictions can rectify this. Workers in Canada, Switzerland and the UK have adopted a similar approach and it has proven a useful first step for assessing microbial effects within a safety case. Assumptions made during the calculations can then be constrained, as necessary, by using targeted, experiments and field observations. These calculations can then be used to define:

1. Biomass in the waste containers – changes with water availability and with time and space; implications for gas production and consumption; geochemical effects; biodeterioration of the waste package; mobilisation of radionuclides.
2. Biomass in the far-field – indigenous populations and changes in population with time (within the repository and down-gradient); generation of biofilms and implications for rock/water interactions; mobility of radionuclides; effects of microbial processes on geochemical environments (up-gradient, within the repository and down-gradient).

A6 Gas Related Processes

Report Number: R-01-11

Author: Moreno, Skagius, Södergren & Wiborgh

Reviewer: Peter Robinson, Quintessa Limited, Henley-on-Thames, UK

A6.1 Summary

The report is a collection of discussions relating to gas processes in the SFR. In consists of ten chapters and three appendices.

After a very brief introduction, chapter 2 describes the structure and inventory for each component of SFR (Silo, BMA, 1BTF, 2BTF and BLA).

Chapter 3 summarises the gas-generation processes (metal corrosion, microbial degradation and radiolysis) and presents estimates for the gas generation rates in each component for each process. This chapter also presents a brief discussion of heat generation due to corrosion and radiolysis.

Chapter 4 presents a conceptual model of gas escape and effects. This starts from an assumption of a resaturated system and discusses gas transport through the concrete structures. The effects of opening gas pathways are discussed for each part of SFR, particularly focussing on the potential for water to be expelled. No mathematical model is presented.

Chapter 5 presents data on capillary pressures, bound water, hydrological parameters, and physical and chemical properties. The basic radionuclide inventory is also reproduced.

Chapter 6 discusses the calculation cases (these are sometimes referred to as scenarios) that have been considered. Calculations are described for the Silo, BMA and 1BTF. The impact of gas generation in 2BTF and BLA was deduced to be insignificant in Chapter 4. For the Silo, four situations are considered covering different scenarios for gas escape involving the vents in the lid and fractures in the concrete base. For the BMA, four situations are again considered, including a design option filling the space between containers with porous concrete. For 1BTF, two situations are considered – with or without a fracture across the modelled region.

Chapters 7, 8 and 9 present results for the calculations for the Silo, BMA and 1BTF respectively. The results are presented in terms of the amount of water expelled and the radionuclide content of that water.

Chapter 10 presents a discussion and draws some conclusions. The main conclusions are that the impact of contaminated water expelled by gas is small if the gas escapes as designed. If the Silo vent or the gaps around the BMA lid do not function correctly then large quantities of contaminated water can be expelled. The use of concrete backfill in the BMA is also said to be very important.

Three appendices are included in the report.

Appendix A summarises the relevant data.

Appendix B is a short note on recent advances in gas generation and migration reported in the general and radioactive waste literature (since 1986). This is referred to in Chapter 3.

Appendix C is a review of experiments on gas movement in porous concrete. This summarises some reports that are otherwise only available in Swedish.

A6.2 Commentary

The report presents various conceptual models, data and calculation case results but lacks a clear overall thread. It is unclear why the only gas effect that is considered is the expulsion of contaminated water (the potential impact of the gas itself and the potential for gas pressure to damage the repository structures are ignored). The origin of the scenarios (or calculation cases) appears to be ad hoc – no reference is made to the overall scenario report. In general, the report appears to be a collection of potentially relevant items rather than a coherent exploration of the topic. The primary assumption throughout the report is that gas generation starts after the repository is resaturated. This is clearly untrue (as the timescales given for corrosion of aluminium indicate) and it may distract attention form the real processes that occur.

These points are expanded in the following discussion of the report chapter by chapter.

1. Introduction

The focus is immediately placed on expelled water without any discussion of why other effects are not of interest.

The final paragraph of 1.1 appears to contradict itself (maybe a translation problem) in stating "No nuclide-specific calculations were performed, but the release was determined for a set of radionuclides".

2. Repository description and waste inventory

This chapter is basically a statement of the design and can only be taken to be correct.

In 2.1.1, the phrase "according to present plans" appears while discussing sealing the Silo. This seems to suggest that various other options exist but these are neither discussed nor analysed. Given the eventual conclusions about the importance of the gas escape vents, it needs to be clear that the current study is for a particular design and would need to be updated if this design is changed.

Figure 2.1 fails to show the location of the gas vents. A similar figure in SFR 85-09 shows them penetrating the concrete lid into a thin layer of sand (as implied by the text in 2.1.1 here).

In 2.2, two options for closure of the BMA are presented. The gaps between waste package will either be left open or filled with concrete grout. No reference is made to any overall design document so it is not clear whether these options are carried through the overall assessment or have been introduced in this gas work because of concerns about the amount of free water that might be expelled.

3. Gas generation

Some of the discussion in this chapter pre-empts the conceptual model discussed in the next. The chapter assumes the gas generation occurs in a (re-)saturated repository.

There is no discussion on the potential for radioactive gases to be created. This should be discussed even if it can be shown to have little impact.

The initial gas generation rates for aluminium, with timescales of just a few years bring the resaturation assumption into question. What really happens in the first few years after closure, or in the years prior to closure? Is the resaturated assumption conservative? Could gas pathways, formed as the initial air content of the repository escapes, be kept open? What would the consequence of this be? Could some regions stay unsaturated for an extending period? Would this change the corrosion rates?

The total gas generated from steel corrosion in the Silo is substantially higher than previous estimates. 2.1×10^6 Nm^3 is predicted (Tables 3-3 and 3-11) from 3649 tonnes of Fe (Table A2-3). In SFR 85-09 the total amount of FE was just 1510 tonnes. Why has this changed so significantly?

4. Conceptual model …

The conceptual model seems to be that all the air is driven out by water in a few years, then gas is generated and has to drive some of the water out. This seems too simplistic – in reality the resaturation and gas generation processes are linked. There is little discussion of where the gas goes once it has escaped (e.g. can it escape to a localised spot on the surface).

No reference is made to any systematic analysis of relevant FEPs.

In 4.3 it is stated that a steady-state will be reached. This does not seem to be self-evident in a non-linear system. Perhaps the gas pressure builds up until a path can be forced and then falls back quickly so the path is closed. Can such pulsing occur?

In 4.4.2, it is claimed that the volume of water expelled into the Silo walls must exceed the sorption capacity before any contaminated water enters the bentonite or sand-bentonite. This appears to assume an irreversible sorption mechanism which is inconsistent with the view taken elsewhere.

The conceptual models consist of a history of water flows in response to gas generation. The transport of radionuclides is linked into the story. A diagram or cartoon for each location would have greatly eased the task of understanding the conceptual models.

The mathematical models implied in the conceptual descriptions are never made explicit. There should be a short section on these models, including the parameters that are used.

5. Data

This chapter discusses various data but without a description of the mathematical model it is difficult to judge whether the values are appropriate.

6. Calculation cases

This chapter describes the cases considered but fails to place these into any overall context (such as a system level scenario and uncertainty analysis). Thus, the purpose of the calculations appears to be rather ad hoc.

7. Results for the Silo

Tables of results are presented presumably calculated by some computer code implementing the undescribed mathematical model. Somewhere there must be a document described the mathematical model and how it has been implemented, which should at least be referenced here (and preferably summarised). If no such reference exists then the description should be in this document (as another Appendix say).

The results for tritium, on which gas generation is said to have a significant impact, lead to questions about the potential for release in gaseous form. These need to be addressed.

Plotting results down to 1e-21 per year does not seem very helpful – the models clearly cannot accurately predict release at the level of a few atoms a day! The main effect is to make the graphs hard to read for the higher values.

Various of the figures and commentary refer to release calculations without the gas generation. Were these calculated with the same code? Are they from the main PA calculations?

The summary of results in 7.6 refers to dose calculations although none were presented in the rest of the chapter. The absolute impact of gas generation (in terms of doses) is surely more important than the 5 orders of magnitude increase in tritium release from almost nothing to no quite nothing.

8. Results for the BMA vault

The same comments apply as for chapter 7.

Figure 8.1 present rates over 28 orders of magnitude. A sensible lower cut-off is needed (even 1e-15 would still be very small).

9. Results for the 1BTF vault

The same comments apply as for chapter 7.

10. Discussion and conclusions

The discussion section here is actually a recap of the conceptual models, and is quite useful in this regard.

The conclusions section ends with strong statements about the importance of the adequate functioning of evacuation pipes in the Silo, the gaps between lid and wall in the BMA and the use of backfill in the BMA. These should be carried forward to the overall safety report and it should be shown that there is reasonable confidence in the correct functioning.

Appendix A

This data collection contains a lot of detailed information and it is unclear whether this is actually used in the main report.

Reference is made to report R-01-14 (the SFR data report). It is surprising to find that this reference in turn refers to earlier documentation on radionuclide transport calculations to provide physical dimensions of the repository. There should be a design document that states this information directly. As an example, we find that R-01-14 (Table 4-1) gives two values for the bentonite thickness (1.0 or 1.2 m). The gas report uses 1.2 m. The difference is small, but why is this information in any doubt at all? R-01-14 gives the total concrete volume for the Silo as 9500 m^3, whereas the gas report uses 9134 m^3. Why the small differences?

Appendix B

This is a useful survey. Its final conclusion that some tools that could be used for a calculation of resaturation and gas effects has presumably not been carried forward.

Appendix C

This is a useful summary of some experimental work. The anomalous relative permeability data rather undermine confidence in the other results quoted.

A6.3 Relevance to Safety Case

Although not particularly well presented, the results indicate that the effect of gas generation is essentially a short-term issue. With the sub-sea location of the SFR, doses in the short-term are low in any case. The direct impact on flows beyond the first few years in not important.

Of more interest to the longer-term safety case would be the potential damage to physical integrity of the flow barriers. This is not discussed, except in the context of a potential escape route for gas, where a few small cracks are enough to allow all the gas to escape. Thus, the report does not provide useful input to the physical degradation of barriers. In addition to cracking caused by large-scale over-pressurisation, the effect of corrosion of reinforcement on the integrity of barriers should have been considered.

There is no discussion on whether the gas release has a chemical effect on the system although this seems to be unlikely.

Although not impacting directly on the overall safety case as such, the lack of any formal FEP analysis or systematic approach to looking at uncertainties here might be indicative of a wider issue in the assessment work that has been undertaken.

A7 Modelling of Long-term Concrete Degradation Processes

Report Number: R-01-08

Author: L. O. Höglund

Reviewer: David Savage, Quintessa Limited, Nottingham, UK

A7.1 Summary

The report deals with the modelling of long-term physicochemical evolution of concrete at SFR due to interaction with groundwater.

Chapters 2-4 summarise input data for the chemical compositions of groundwater in the SFR region, cement compositions and the compositions of bentonite and sand-bentonite mixes. Proportions of cement and ballast in 'construction concrete', 'silo grout' and 'conditioning cement' are presented. It is noted that cement additives are present in construction concrete and silo grout, but not conditioning cement.

Chapter 5 presents evidence for concrete hydration and degradation processes. 'Capillary', 'gel' and 'contraction' porosities in concrete are calculated. The total porosities thus calculated are: 0.099 (construction concrete); 0.309 (silo grout); 0.256 (conditioning cement). Concrete dissolution considers an ion exchange process for the release of alkali hydroxides and a more sophisticated model for CSH gel than considered previously by SKB. The amounts of calculated free portlandite are higher and the amounts of CSH gel are lower as a result.

Chapter 6 presents a conceptual model of the interaction of concrete with groundwater and bentonite. The model incorporates ion exchange, dissolution of portlandite and CSH gel from the concrete, the equilibration of gypsum, calcite, brucite and Friedel's Salt. No dissolution of silicates in the bentonite is included. Reaction-transport calculations were carried out using PHREEQC2.

Chapter 7 is a compilation of relevant thermodynamic data.

Chapter 8 presents the results of the calculations and forms the bulk of the report. For a notional 1m thickness of construction concrete, data for 3 calculational cases are presented:

1 Diffusion with constant composition of groundwater (concrete only).

2 Advective flow of groundwater through a fractured concrete barrier.

3 Diffusion through a sand-bentonite layer with constant groundwater composition.

An SFR-specific geometry was not considered. Porosity changes due to the interactions were calculated. Results for case (1) showed that leaching was slow, such that after 10 000 years, CSH in the concrete remained intact at depths greater than 10 cms. The porosity of the concrete reached a maximum of 11% (10% initially). Results for case (2) showed depletion of CSH to a depth 30-40 cms into the concrete after 10 000 years and significant solid phase changes occurred throughout the slab considered. pH of interstitial fluid was 10.5 and porosity reached a maximum of 17%. In case (3), leaching was very slow and after 10 000 years, CSH remains intact at all depths.

Höglund concludes that alkaline conditions will be maintained in concrete at SFR for 10 000 years or more and even for the most degraded concrete, pH will not drop below 10. For PA calculations, the porosity of concrete has been assumed to be 15%, which is conservatively greater than calculated in this report. Degraded concrete also has a porosity < 15%, except for the most extreme example. Höglund calculates that diffusivity could increase by a factor of 30 in the most exposed portions of the concrete.

A7.2 Commentary

This report is analogous to that written for SKI by Savage et al. (2000) [SKI 00:49]. The key issue which is raised by the report is that of time dependent conditions of pore fluid composition and physical properties of the concrete barriers at SFR. Geochemical calculations carried out by the author suggest pore fluid pH greater than 10 for 10 000 years and porosity less than 15% for the same time period. SKB has carried out PA calculations assuming a porosity of concrete of 15%, which would seem to be conservative.

Areas which are technically weak or could be considered as omissions in the report concern:

- Silicate mineral dissolution-precipitation processes are omitted from simulation of interactions of cement with bentonite. Ion exchange and dissolution-precipitation of gypsum, calcite and brucite are the only processes considered in the report. The completeness of the conceptual model is therefore questionable.

- SFR is treated as a homogeneous entity, whereas some portions will have much less cement and concrete than others. The conclusions of the report may thus not be applicable to all portions of the SFR repository.
- Groundwater compositions used as input to the modelling were selected to be typical of the 'salt water period' at SFR and were assumed to be the most aggressive. However, this need not necessarily be the case, so calculations with fresh water are warranted to demonstrate this.
- Understandably, since there are no natural systems of this type, and also since results of laboratory experimental systems are not directly comparable, it is difficult to validate the results of these modelling studies. Not surprisingly, extrapolation of these results to the timescales of relevance to safety assessment are therefore questionable and involve considerable uncertainty.

A7.3 Relevance to safety case for SFR

The implications of the results of this report are that:

- Repository pore fluids at SFR are likely to have pH > 10 for timescales of the order of 10 000 years, thus justifying the use of sorption and solubility data for radionuclides under hyperalkaline conditions.
- The porosities of the concretes concerned at SFR are unlikely to increase above 15%, the value which SKB has conservatively chosen for its safety assessment work.
- Concrete alteration is unlikely to proceed deeper than 10 cms beneath exposed surfaces.
- It is calculated that diffusivities could increase by a factor of 30 due to changes in pore geometries.

The study does not address potential alteration of bentonite by cement pore fluids. Other published studies suggest that as much as 50% of a 1 m thick layer of bentonite could be converted to a mixture of CSH, zeolites and sheet silicates over a 1000 year time period.

A7.4 References

Savage D, Stenhouse M J and Benbow S J. Evolution of Near-Field Physico-Chemical Characteristics of the SFR Repository. SKI Report 00:49.

A8 The Biosphere Today and Tomorrow in the SFR Area

Report Number: R-01-27 (Final Draft)

Authors: Jones C & Södergren S (edited by Kautsky U)

Reviewer: Mike Egan, Quintessa Limited, Henley-on-Thames, UK

A8.1 Summary

This report summarises several pieces of work that have been undertaken on behalf of SKB to characterise the biosphere and its evolution as a basis for assessment modelling. The report identifies three main study areas, reflecting the different spatial scales on which it has been deemed relevant to describe change and to evaluate the dispersion of radionuclides released from SFR – (a) the local area adjacent to the facility within which releases to the surface environment are expected to occur; (b) Öregrundsgrepen, the strait between the mainland and the islands of Gräsö and Örskär in which the facility is situated; and (c) the Baltic Sea. The main focus of the descriptive work is on the identification and characterisation of local biosphere systems within contaminant concentrations arising from possible releases are likely to be the highest; however, this involves giving consideration to the implications of changes taking place on a regional scale and beyond.

Characterisation of the present-day biosphere and its projected future development covers the following topics:

- Climate, including long-term change associated with glacial-interglacial cycling;
- Shoreline displacement and its effect on water depth;
- Bed sediment accretion and erosion (and soil formation);
- Water turnover
- Salinity
- Coastal ecosystems
- Local terrestrial and lake ecosystems

- Human communities and resource exploitation practices, including agriculture and wells

The report concludes with a synthesis of projected landscape evolution and its implications for the definition of assessment biospheres over a period of approximately 10 000 years from the present-day. This description provides the foundation for assumptions adopted in the development and implementation of radionuclide distribution and exposure models used in the SAFE assessment.

A8.2 Commentary

This report is an important component of the audit trail for the biosphere component of the SAFE assessment, drawing together a comprehensive, scientifically-justified basis for the identification and description of biosphere systems relevant to evaluation of long-term radiological impacts of SFR. It provides a summary of the results of a substantial number of research and environmental characterisation reports that have been produced for SKB within the BIOSAFE project. It is recognised that some of the questions and comments reported in the current review may be answered by information from these more detailed reports.

The two main inputs to the overall assessment provided by the biosphere description are:

- Identification of the spatial domain of the biosphere that is relevant to the performance assessment;
- Characterisation of that region of the biosphere, now and in the future, in terms of key components and phenomena relevant to radiological assessment.

When considering the first of these, it is relevant to note that the biosphere is more than simply the receptor in which the radiological impacts of future releases will be expressed. Features of the biosphere, and processes occurring within the biosphere, also serve to establish boundary conditions for groundwater flow and may therefore be important in determining the magnitude of release of, and pathways followed by, radionuclides from the disposal facility itself. This fact is recognised in the “Biosphere Matrix”, outlined in Section 2, where the first column of the matrix relates to the interactions between the biosphere and geosphere systems.

There is relatively limited evidence in the report that the analysis has focused on the possible implications of biosphere system change for the repository itself; as a general rule, the emphasis is on those parts of the biosphere that represent potential discharge areas or regions where a significant fraction of any potential release may migrate and accumulate in radiologically-significant concentrations. Hence, for example, in Section 4 (Study Areas), the description of the local model area, Öregrundsgrepen and the Baltic Sea are geared towards features of the surface environment that are 'downstream' of potential release locations, with no apparent importance attached to factors that might influence the migration of those locations with time. Likewise, the synthesis, presented in Section 13, is primarily a description of projected changes in the characteristics of potential biosphere 'receptors' (e.g. turnover of surface waters, salinity, plant and animal communities, etc.). There is some recognition of migration of the geosphere-biosphere interface, in so far as displacement of the shoreline is expected to "affect the size of the discharge zones" and subsequent accumulation of organic materials in fens and bogs may cause a rise in groundwater level, with the implication that discharge zones will "shift towards the shoreline". However, there is no clear link from the detailed analysis of biosphere change presented in this report to the development of time-dependent descriptions of the groundwater flow system as a whole. It may be that the systematic consideration in other documents is given to changes on the geosphere side of the interface, but the existence of a link to the work described here is not apparent in this report.

Characterisation of the important components of the biosphere as a function of time (the second of the steps identified above) involves two main considerations: first, it is necessary to identify the main drivers of change; then the implications of projected changes need to be propagated through the system. The "Biosphere Matrix" (Section 2) indicates a systematic way of undertaking this analysis; specifically, it incorporates a conceptual representation of the influence of the external surface environment (and changes to the external environment) on the dynamics associated with interactions between biosphere system state variables. In identifying and, to some extent, describing the potential role of such a systematic methodology, SKB are leading the development of state-of-the-art methods for the biosphere component of scenario development. However, as the report currently stands, the role played by the Biosphere Matrix in the remainder of the analysis is not very clear; there is no discussion in Section 2 of the way in which the matrix has been used, and subsequent sections of the report are, in the main, a series of largely unconnected discussions of specific issues with no clear narrative thread. The implication is that a systematic approach to describing projected changes within the biosphere has been partially developed, but is not yet at the stage where it can be fully implemented for the SAFE analysis.

The main 'external' drivers of change considered by SKB are climate and shore-level displacement. These two aspects of change are, of course, connected: for example, the current rate of apparent sea level change in the east of Sweden is attributed to isostatic rebound following ice melt at the end of the last glaciation. At the same time, global warming (both following the last glaciation and into the future) is a cause of global sea level rise, linked to the melting of continental ice sheets and mountain glaciers, as well as thermal expansion of water in the seas and oceans.

The report draws the following conclusions regarding the implications of these drivers of change:

- The impact of global climate change on regional climate in the vicinity of SFR is believed to fall within the range of natural variations in mean annual temperature and precipitation, for a substantial fraction of the period of interest. It is not projected that there will be significant change in regional climate until the onset of the next ice age, with a reduction in precipitation and the development of periglacial conditions.
- It is calculated that there will be an effective reduction in the local sea level at Forsmark, as a result of the continuing effects of glacio-isostatic rebound, by some 20m over the next 4000 years. The shoreline is projected to be above the repository within 1000 years, and the connection of local waters to the open sea in the vicinity of SFR cut off within a further 2000 years. This has a major influence on the type and characteristics of the biosphere into which possible releases of radionuclides may occur.

These primary controls on environmental change set the frame of reference for subsequent discussions of change within the report. Responses to change within the biosphere are the described in terms of local processes, such as water turnover, the filling of lakes by sediment and the invasion of vegetation.

There is limited discussion of the uncertainties associated with these projections of change. For example, it is not evident from the report to what extent the underlying research documents address the sources, or implications, of uncertainty associated with either the main drivers of change, or the implications of such change that become propagated through the biosphere system. However, it is slightly surprising to find references being made to the “next ice age”, starting as a cold climate in about 5000 years, when long-term climate projections of the effects of global warming are now indicating delays of the next ice age by 50 000 years or more.

Sources of uncertainty that might be relevant to consider include, inter alia:

- Possible implications of global warming over the next thousand years on eustatic sea level (e.g. substantial loss of valley glaciers in the northern hemisphere, stability of the Greenland ice sheet) and hence on the effective rate of shore-level displacement at Forsmark;

- Possible effects of a super-interglacial warming episode on regional climate, including implications of possible changes to the north Atlantic circulation;
- Possible long-term effects of global warming on the glacial-interglacial cycle over the next 100 000 years.

It is perhaps worth noting that uncertainties associated with the impact of global warming (sea level rise, local climate) on a timescale of 1000 years (10% of the overall timescale represented in the assessment) could be rather larger than is implied by the simple statement that "*uncertainties will increase dramatically with time in the future*" (Chapter 9). Whatever simplifications have been adopted in undertaking the assessment, and for whatever reason, it is important that potentially relevant uncertainties are identified so that can be properly taken into account in interpreting the significance and implications of the modelling results.

Set against uncertainties associated with global warming and other aspects of change, some of the descriptions of projected changes within the biosphere (e.g. in discussion of coastal ecosystems and vegetation successions) could be seen as inappropriately detailed. Although the overall synthesis (Chapter 13) is presented at a much simpler level, such considerations highlight the importance of presenting this kind of analysis in a systematic fashion, so that assumptions, approximations and simplifications are highlighted and justified according to the context of the assessment, and set against the development of a clear narrative thread.

A8.3 Relevance to Safety Case

Swedish radiation protection regulations (SSI FS 1998:1) identify the following timescales for the presentation of radiological impacts as part of the overall safety case:

- 1000 years, corresponding the period for which "quantitative analyses of the impact on human health and the environment" are expected to be made.
- 10 000 years, corresponding to the period of integration for the evaluation of collective impacts, based on projections of discharges from the disposal system in the first 1000 years after closure.
- The period beyond 1000 years after closure, for which it is appropriate to consider "various possible sequences for the development of the repository's properties, its environment and the biosphere".

However, the same regulations also highlight the importance of the present-day system state because the overall safety case is expected to include (*inter alia*) an assessment "*based on the assumption that the biospheric conditions which exist at the time when a* *licence application … is submitted will not change*". The approach summarised in this report, which sets a context for the biosphere and human exposure modelling undertaken in the SAFE assessment, demonstrates the extent to which SKB has recognised the potential importance of system evolution in the definition of suitable assessment biospheres. Indeed, if present-day biosphere conditions (including the depth of coastal waters and location of the coastline at Forsmark) were assumed as a basis for the performance assessment, the radiological implications of potential releases over the next 10 000 years (and, particularly, beyond 1000 years after present) would most likely be substantially lower than those derived from the projections described in this report.

It is interesting to note, however, that the synthesis reported in Section 13 of the report emphasises a particular sequence of change (up to approximately 10 000 years), rather than considering the implications of uncertainty via a range of possible sequences of change. It may prove to be the case that the synthesis of projected biosphere change for the Forsmark area described in the report does indeed represent a sufficiently pessimistic basis for the SAFE radiological assessment, in so far as it tends to the shortest possible timescale on which groundwater flow pathways from SFR being to emerge into the terrestrial environment, rather than the waters of Öregrundsgrepen. On the other hand, depending on the rate at which radionuclide releases to the environment from SFR are projected to occur, the peak impacts may not occur until much later than this. If data used in the biosphere models for periods beyond 5000 years into the future are chosen to reflect substantially lower productivity than today (as a result of the assumed onset of the next ice age), it could be that potential exposures will be underestimated by comparison with those that might occur in an enhanced-warmed global climate with local conditions broadly similar to (or even warmer than) those prevailing at present. Care therefore needs to be taken to ensure that interpretation of the biosphere change within the assessment (and in discussion of the results) reflects all potentially relevant uncertainties.

The focus in this report is on identifying a range of possible biosphere 'receptors' at the geosphere-biosphere interface, according to the environment changes resulting from land rise and coastline displacement. Comparatively little emphasis is given, by contrast, to the implications on the geosphere side of the interface, such as factors that might cause the location (or rate) of contaminated groundwater discharge to change with time. Assumptions made in relation to the location of, and dilution at, the geosphere-biosphere interface are potentially a very significant part of the overall radiological assessment and it is not evident from the report how (or even if) the implications of biosphere change on the groundwater flow system have been into account in developing the groundwater flow and transport component of assessment calculations.

One important geosphere-biosphere interface that arises from consideration of change, and is discussed within the report in the context of changes to local human communities, is the possibility that wells might be drilled in the vicinity of SFR. Because the shoreline is projected to migrate beyond the repository, the possibility arises that a drinking water well might intersect a contaminated groundwater flow path, or even the repository itself, beyond 1000 years or so. The way in which wells are taken into account in the assessment (e.g. the representation of dilution in the near-surface hydrological system) is not directly relevant to the scope of the this report – however, the fact that they have been identified in this way highlights the importance of the analysis of change that SKB has undertaken.

A9 Models for Dose Assessments

Report Number: TR-01-14

Authors: S Karlsson, U Bergström and M Meilli

Reviewer: Mike Egan, Quintessa Ltd

A9.1 Summary

This report describes the development and testing of a biosphere modelling system for the SAFE project. The model system is designed to encompass key components of the biosphere from the perspective of assessing the potential radiological impacts of releases from SFR. The models evaluate the transport and distribution of radionuclides in a broad range of ecosystem types, representative of the potentially contaminated environment under present-day conditions as well as those anticipated as a result of landform evolution over the next 10 000 years. Discussion is also provided of the methods used to evaluate radiation dose rates to individual members of hypothetical critical groups, as indicators of the most exposed individuals from communities that could inhabit the contaminated surface environment in the vicinity of SFR at some time in the future.

The report begins with a short description of the region represented in the models (Section 2) and brief overview of the model system (Section 3). The description highlights the role of shore level displacement (isostatic rebound from the last glaciation) in modifying the biosphere in the vicinity of SFR as land emerges from the present-day brackish waters between the Swedish mainland and the island of Gräsö. Over the period of time covered by the assessment, pathways associated with groundwater transport from SFR to the surface environment could terminate in a broad range of ecosystem types, including coastal waters, lakes, marshland ("mire") and agricultural land.

The models are described as dynamic, since they compute the distribution of radionuclides between physical components of the system as time-dependent solutions to coupled first-order differential equations representing the identified transport processes, including sorption/desorption kinetics. However, the model system is not itself time-dependent, which is to say that the physical characteristics of individual model components and the rate constants representing transfers between them do not

change with time. Evolution of the biosphere system is therefore represented by a sequence of distinct, time-invariant models for the individual ecosystem types. No attempt was made in the SAFE study to construct networks of different ecosystem types – at any stage in the sequence of change, only one model was used.

The structures of the individual ecosystem models are described in turn (Chapters 3 to 8). In addition to the possibility of natural releases to different ecosystem types, consideration is given to situations where the release to the biosphere could occur as a result of human intervention – for example as a result of the use of wells and/or contaminated irrigation water. For each model, radionuclide concentrations in environmental media and foodstuffs are determined assuming that they are in equilibrium with the calculated radioactivity content in corresponding physical components of the system; these concentrations then form the basis for evaluating radiation doses associated with multiple pathways of exposure. The system is configured for probabilistic analysis of the implications of parametric uncertainty, based on the specification (and, in some cases, correlation) of statistical distributions of parameter values, including assumptions about human habits and diet.

Models for calculating doses from a range of exposure pathways, summarised in Chapter 9, are based on standard techniques. Estimates of potential ingestion dose are based on average diet, but are maximised by assuming that all relevant contributions to diet are produced in the local contaminated area.

The simulations described in the report correspond to a set of studies undertaken to investigate the rate at which contaminants migrate through the different (time-invariant) model ecosystems under varying assumptions about sorption properties. These indicate the potential importance (for more strongly-sorbed species) of residual contamination from earlier stages in the sequence of landscape evolution (e.g. sea bed and lake sediments), which might become a secondary source in the new, altered ecosystem as land rise takes place. However, no detailed consideration is given to how such transitions would be simulated in practice within the PA. Ecosystem-specific dose conversion factors (EDFs) (i.e. individual dose rate per unit release of radioactivity) are directly relevant to PA calculations, but are reported (Appendix B) for the coastal model only.

A9.2 Commentary

Similar modelling approaches have been used in the past by SKB (both for the original SFR assessment and the more recent SR 97 study of the Äspö site), so there is a good track record of developing biosphere models for determining radiological impacts of possible releases to present-day coastal environments. Features that have been given particular attention in the models described this report include a more detailed characterisation of the present-day surface environment than was undertaken for the original assessment, alongside predictions of its anticipated evolution based on techniques developed for SR 97.

Key considerations associated with each element of the modelling system are: (a) the characterisation and configuration of components of the dynamic transport model, (b) the specification of dynamic transfer coefficients, and (c) the choice of parameters used to represent equilibrium distribution and accumulation of radionuclides within the environmental media and foodstuffs associated with each model component. However, the extent to which dose calculations undertaken using the models, for the purposes of comparison with regulatory criteria, can be viewed as appropriate also depends on how far the modelling approach (and its specific implementation within the PA, not described in this report) matches the regulatory expectations.

Chapter 1 – Introduction. The Swedish regulatory system recognises the uncertainties inherent in biosphere modelling over long time periods, but nevertheless requires dose assessments to be undertaken. In the absence of an agreed approach to the use of 'reference biospheres', indicators of radiological impact need to be derived from the characterisation of suitable assessment biosphere systems, taking account of the local environment today and in the future. This chapter provides a brief summary of the site characterisation information that has been used as input to the identification of representative biosphere system states, addressing a range of different ecosystem types. However, because the focus of the report is on development and analysis of individual models for the selected states, and not their implementation as part of the PA, there is no discussion here of the uncertainties inherent in the description of sequences of change (e.g. as a result of uncertainties in the rate of global climate change and the interaction between eustatic sea level and land rise) or the possible implications of the dynamics of change from one system state to another.

Chapter 2 – General characteristics of the model system. A compartment modelling approach to the representation of the biosphere, based on time-invariant system properties, is generally consistent with international practice. However, because substantial attention has been focused elsewhere in the SAFE assessment (e.g. SKB R-01-27) on the question of biosphere change, it is natural to ask how such a modelling system can be practically deployed within the PA to reflect the key considerations associated with the analysis of change. Consideration is given in the report (notably in Chapter 10) to the rate at which contaminants with different chemical properties move through the model system, highlighting the potential implications of the dynamics of contaminant transport within an evolving, rather than static, system. But it is not clear from this analysis (although it may be present in other reports, not seen by this reviewer) how an overall understanding of biosphere change and its potential importance in generating indicators of radiological impact has been deployed in practice within the PA.

The model system provides the capability to undertake a probabilistic analysis of parametric uncertainty. This is reasonably straightforward to implement, but care needs to be taken in the way such a capability is used and the results interpreted, particularly in relation to biosphere models. On the one hand, uncertainties in the basic process models that relate to radionuclide behaviour may be reasonably well represented using such an approach, particularly if due consideration is given to possible changes in the range of parametric uncertainty under different assumptions about climate conditions etc. relevant to each ecosystem model and there is sufficient information to be able to make adequate correlations between factors such as soil/sediment type, sorption and bioaccumulation factors. On the other hand, it should be recognised that important aspects of the surface environment (e.g. vegetation, drainage pathways, animal populations etc.) are influenced by factors (particularly future human actions) that are inherently unpredictable. Uncertainties in the conceptualisation of the biosphere system (components, features, characteristics and mass transfers) do not therefore necessarily derive from the interpretation of what, in principle, ought to be verifiable information, based on system characterisation; rather, they reflect the adoption of a range of assumptions and hypotheses (albeit constrained by the site-specific factors) that are geared towards providing suitable indicators of radiological impact. In these circumstances, substantial emphasis is placed on the arguments deployed to justify the particular assumptions adopted in defining the conceptual models; to address 'uncertainty' simply by using probability distributions of parameters is not necessarily an appropriate strategy.

Chapter 3 – Coastal model. The inventory/concentration in 'local' waters, adjacent to SFR, is the most important physical component from the perspective of evaluating individual doses associated with a release to the marine environment. Water turnover in the present-day local coastal environment is rapid and is the critical factor in determining the contamination for radionuclides released directly into the water column. It is also reasonably straightforward to characterise (as an annual rate) with some confidence. Sorption to suspended sediments, which then accumulate on the sea bed, is catered for in the model and recognised as potentially important as a secondary source of contamination, becoming exposed at later times as a result of land rise.

There is an explicit representation of sorption/desorption kinetics in the model for transfer between solution and suspended material, but no obvious attention has been given to the potential importance of this aspect of the model. Data given in the report indicate that the rate constant is assigned a (radionuclide-independent) range of variability of four orders of magnitude, with a mid-value roughly equivalent to the turnover rate for 'local' waters. This suggests that, for the majority of simulations, it is likely to have an influence on the estimated local accumulation of contamination in bed sediments (though not necessarily on the evaluation of individual doses). Some discussion of the importance of this modelling assumption, and its potential relationship to the choice of Kd values, is therefore merited. In practice, sorption processes will often exhibit (at least) two characteristic times; a quasi-instantaneous phase associated with surface processes and a longer period, linked to diffusion into the body of the particle; if a single time constant is assumed, short-term sorption may be significantly underestimated – leading to an overestimate of the loss of contamination from the model system. Moreover, the kinetics of sorption and de-sorption may have different characteristic times and will vary between different radionuclides; hence, it may be inappropriate to assume a single value, uncorrelated with contaminant (or water/sediment) chemistry. Further, it is relevant to note that many of the equilibrium Kd values reported in the literature for suspended marine sediments have been measured in situ, so kinetic processes are implicit in the measured values, depending on the sampling regime and its location relative to the source of contamination.

A further modelling uncertainty relates to the exchange of contamination between the sea bed and the overlying water column. Again, this is not particularly important for evaluating individual doses associated with the marine environment, but its characterisation is particularly relevant for determining the long-term accumulation of contamination in bed sediment and the rate at which contamination may subsequently be remobilised. The model incorporates a particulate remobilisation flux, resulting from bed stresses, calculated as the difference between gross and net accumulation of sediment. Data given in the report indicate that the net accumulation is assumed to vary between zero and 44% of the total mass flux from the settling of fine particles, representing a potentially significant range of uncertainty in terms of influence on the estimated rate at which contamination is accumulated on the sea bed. If attention is to be given in the assessment to the long-term implications of such accumulation, and particularly if proper account is to be taken of long-term changes in sea level leading to the eventual exposure of such contamination, then further testing of the modelling approach and associated data is merited. In particular, it may be relevant to consider the role of sediment turnover and mixing in the near-bed boundary layer, rather than representing the exchange of contamination solely on the basis of gross sediment flux averaged over the depth of the water column.

Sea/sea bed interactions, and the specification of compartment depths for model components representing the bed sediment, would be much more critical to the dose calculation if the model allowed for the possibility of release radionuclide via the sea bed (rather than directly into the water column). There is no discussion of this important assessment assumption (and potentially significant source of uncertainty) in the report.

One potential source of secondary contamination associated with discharges to the marine environment (sea spray transfer to land) is not represented in the model system, because the biosphere assessment for the SAFE study does not account for networks of different ecosystem models. However, it is pessimistically assumed that livestock graze on coastal aquatic plants, which provides a secondary route for exposure arising from the consumption of food products (milk and meat) derived from those animals.

Chapter 4 – Lake model. The basic structure of the lake model is similar to that of the local compartment of the coastal waters model. It includes many of the same features, including the use of similar process models for kinetic sorption, particle deposition and remobilisation. Key data differences include the specification of parameters relating to physical properties of the system (turnover rate, suspended sediment load etc.), as well as radionuclide-dependent data (e.g. Kd values), reflecting differences in water chemistry. One important difference in implementation of the lake model is that it provides a capability for considering contamination to enter the system not only in water (as in the coastal model), but also via suspended matter or sediment.

Data given in the report indicate that the net accumulation of bed sediment within the lake is assumed to vary between zero and 100% of the total mass flux from the settling of fine particles, with a best estimate of 20%. Given the possibility of considering radionuclide release to the biosphere via lake sediments, the wide range of uncertainty in effective rates of remobilisation is potentially a very significant parameter, and some indication of potential sensitivity would be merited. However, evaluation of the lake model in Chapter 10 appears to be restricted to consideration of sensitivity to variation in Kd values. This is potentially important, because the decision was taken – without apparent consideration of the importance of the remobilisation component of the model – not to represent lake bed sediments as a potential source of radionuclides in the SAFE study.

The specification of physical parameters for the lake system is an example of a situation where care needs to be taken in the use of a probabilistic approach to the treatment of uncertainty. The area, depth and turnover rate of the lake are based on rough estimates, reflecting the difficulty of making precise predictions of future surface hydrological conditions in a dynamically-changing environment. However, these parameters are presented as distributions, implying an intention to consider the implications of such uncertainty as part of the overall probabilistic analysis, rather than seeking to justify a particular set (or sets) of assessment assumptions as providing suitable indicators of radiological impact.

It is interesting, in passing, to note that correlation coefficients for some of the parameters specified as probability distributions within the lake model are specified with a precision of two significant figures. Given the probabilistic approach that has been taken in addressing biosphere model uncertainties, it would be interesting to consider the extent to which model results are sensitive to the precise values of such correlations.

Chapter 5 – Agricultural land model. The basic structure of this model is a simple top soil/deep soil system, with an underlying saturated zone. Additional complexity is unlikely to be merited; however, care needs to be taken to ensure that the characteristic length scales and transfer rates represented in the model are consistent with best judgments regarding the conditions under which contamination could occur. Within the model, it is assumed that the water table is maintained approximately 1 m below the ground surface, if necessary by artificial drainage systems, thereby providing a suitable substrate for agriculture. Groundwater in this region may be contaminated directly, or the soils (assumed to be former sea bed and/or lake sediments) may be assumed to include residual contamination resulting from releases in previous system states.

Loss of contamination from the model system is assumed to arise from one of two processes: top soil erosion and 'horizontal' flow of dissolved radionuclides within the saturated zone. The specification of these parameters is a critical consideration in determining overall coherence in implementation of the model. The possibility of considering contributions to losses from the system as a result of the cropping of vegetation is not discussed; as a general rule the rate would be low, but the potential significance of this pathway is increased in situations (as illustrated in Chapter 10) where the time-constants for other loss processes are slow.

Rates of topsoil erosion are uncertain (being assigned a variability of one order of magnitude in the model), but are considered to be slow, corresponding to loss rates of topsoil in the region of 0.0015% per year. Even so, if the model configuration is to remain valid over a long period of time, this mass flux needs to be compensated for by the addition of 'new' topsoil. If it is assumed that this is generated by the weathering of underlying soils, the contaminant transport model should include an equivalent upward migration term from deep soil. Alternatively, it might be assumed that erosion losses are addressed by the addition of new, uncontaminated topsoil from outside the spatial domain represented in the model. However, the potential role of migration as an effective transport parameter merits some consideration, especially given the very long characteristic timescales for accumulation of contamination illustrated in the model results shown in Chapter 10.

The approach used in this study includes an ‘aquifer’ as part of the assessment biosphere, with contamination assumed to enter (from the geosphere) in solution. However, outflow from the ‘aquifer’ is determined solely by meteoric water infiltrating from above – with no apparent contribution from sub-horizontal interflow associated with adjacent parts of the catchment, or regional discharge of the aquifer system. This begs questions of mass conservation and consistency with assumptions about the nature of the geosphere/biosphere interface, since it implies that the effective throughput of water in the both the unsaturated and saturated zones is the same. Given the long characteristic timescales associated with the agricultural land model (Chapter 10), the turnover of water within the saturated zone is a clearly critical parameter of the model, especially when it is configured to evaluate the radiological impacts of groundwater contamination.

Chapter 6 – Mire model. This is a very simple model of the physical domain of a marshland region, with consideration being given to the dynamics of exchange between model compartments representing the soluble and solid/organic phases. The overall status of long-term radiological assessment modelling for such ecosystems is in its infancy, so simple relatively conceptual approaches are probably most appropriate at the present time. In the light of this, however, the incorporation of a variety of conceptual uncertainties into an over-arching probabilistic parametric analysis (as has been done in the report) is probably not the best way of presenting this particular model.

It is interesting to note that, although consideration of this system state was introduced as a result of an evaluation of potential landform change, the possibility that residual contamination may be present as a result of accumulation in former lake and seabed sediments has not been considered in the SAFE-study. The importance of the model stems from the fact that it is considered a potentially relevant biosphere receptor for an extensive period of time, from 2000 to 10 000 years post closure.

Some key parameters of this relatively simple model have a broad range of uncertainty. For example, it incorporates an explicit representation of sorption/desorption kinetics in the model for transfer between the soluble and solid/organic phases. Data given in the report indicate that the rate constant has been assigned a (radionuclide-independent) range of variability of four orders of magnitude. The possible significance of this parameter for the dose calculation, given that the half-time associated with the assumed outflow rate of water from the mire is approximately 5 years, is not clear. However, there are clearly a number of uncertainties associated with representing this process, similar to those highlighted above in discussion of the same component of the coastal model.

Chapter 7 – Well model. The well model is a simple dilution model, in which it is assumed that the release of contaminants is diluted in an annual water volume extracted from the well. A relatively small volume is specified, on the assumption that such a well might be used by a family group, living on a small farm. The most important consideration in using the model is the representation of the interface between the well and the geosphere – in effect, how is the release of contaminants into the well determined?

Although a well model for the biosphere seems very simple, and probably should be an important consideration in any situation where such a mechanism for release is possible, the question of the geosphere-biosphere interface associated with a 'point' discharge raises a number of fundamental questions. In practice, the best approach may well be for the concentration in well water to be determined from a concentration boundary condition (Bq/m^3), established by a geosphere transport model on the basis of an explicit consideration of the hydrogeological formation from which it is assumed that the well water will be drawn. Responsibility for the well 'model' then largely becomes a geosphere/near-surface hydrology problem, rather than something to be addressed explicitly as part of the biosphere system models. The alternative approach, used in this report, requires the definition of an assumed release rate – effectively, that within the volume of water withdrawn each year via the well somehow captures all (or a well-defined fraction) of the activity in the groundwater plume at a particular location downstream from the disposal facility. Discussion of the validity and implication of such a conceptual approach in the specific context of the SAFE study has not been provided in this report.

Chapter 8 – Sub-model irrigation. This model is used to evaluate the potential implications of using contaminated lake water or well water to irrigate a garden plot. The possibility that the same water resources might be used for watering animals is directly taken into account in the lake model and well model. Pasture irrigation has not been considered in the SAFE study.

Irrigation is an episodic procedure, and the amount of irrigation required depends on the weather in any given year, particularly during critical points in the growing season. It is standard practice to adopt fairly pessimistic assumptions about the amount of irrigation as a 'first cut' in order to investigate the radiological importance of such pathways, and to then refine the assumptions to more realistic values if required as part of a sensitivity analysis. However, the approach taken in the SAFE project is to define distributions of key parameters (number of irrigation events, total irrigation area, etc.) as part of an overall probabilistic uncertainty analysis.

The irrigation model is presented as being 'coupled' to the freshwater component of the corresponding lake or well models; irrigation is therefore apparently treated as the dynamic transfer of contaminants, rather than being based on a calculated 'equilibrium concentration' value. The advantage of such an approach is that it allows for the possibility that contaminated run-off from the irrigated soil and plants can be returned to the source, ensuring that there is no loss of contamination from the system. However, it also introduces the necessity to consider the extent to which the withdrawal of irrigation water may be a significant fraction of the total volume flow rate through the system and, therefore, whether the act of irrigation itself might influence the calculated concentration of radionuclides in the lake or well water. The explicit representation of transfer pathways to and from such water bodies, and the need to ensure coherence of assumptions regarding volumetric fluxes of water across different system sub-models, is not described in the report, which leaves a question mark regarding the actual approach that was followed in the study. In practice, provided that it can be confirmed the total irrigation volume does not significantly affect volume flows in the lake or well, and given all the other uncertainties inherent in the biosphere models, it would be much more straightforward (and would require fewer arbitrary parameters, such as irrigated area, to be represented by probability distributions) if the irrigation model were simply based on the equilibrium concentration in the respective sources.

Interception and retention of irrigation water on plant surfaces is considered as part of the calculation of radionuclide contamination of foodstuffs. This introduces a measure of double counting, however, because the retained water volume (and contamination) on plants is not subtracted from the total amount of irrigation water in determining the rate constant for transfer to topsoil. No analysis has been made of the possible significance of capture by the plant canopy on the overall mass balance represented in the model.

It is interesting to note that expression for calculating downward migration of contamination from topsoil to deep soil includes a 'runoff' parameter (precipitation – evapotranspiration), which is set at the same rate as that defined for the agricultural land model. However, whereas the agricultural land model is geared towards evaluating the effect of migration in soil averaged over a year, with a continuous input of contamination, the contamination arising from irrigation is associated with specific events, for which an annual average 'runoff' may not necessarily provide the most appropriate measure of the downward infiltration of contamination. Uncertainties associated with the conceptualisation of downward migration of irrigation water merit some consideration in order to ensure that the model is not excessively over-predicting or under-predicting the implication for radiation exposure.

Chapter 9 – Methods for calculation of doses to humans. The approach uses standard models for determining radiation exposure from external and internal pathways, so there are no major technical issues to highlight. However, there are one or two questions relating to consistency and overall approach.

The expression used to evaluate intake of radioactivity by grazing animals includes a component representing consumption of grass from irrigated pasture. Indeed, an assumed 'shore grazing period' is specified in the list of data used to calculate radionuclide intake by cattle. However, in the description of the irrigation model (Chapter 8) it is stated that pasture irrigation has not been considered in the SAFE study. This (and any other places where the models described do not appear to correspond to what was actually done in the assessment) ought to be clarified.

In some of the expressions used to describe the calculation of activity content in crops, reference is made to concentrations in soil and water derived 'from the dispersion model'. It is not always clear which dispersion model is being alluded to at each stage, and there seems to be potential for conflict with the descriptions given in the previous chapters. In addition, the model used to evaluate contamination of vegetables at harvest from the surface retention of irrigation water is quite complex and it would be useful to have presented (or referenced) a more detailed analysis of the implications of the time integral and sensitivity to choice parameter values, as well as other uncertainties in, or omissions from, the model (e.g. loss from plant surfaces between harvest and consumption). A similar type of model was used to describe the effects of surface contamination following irrigation in one of the recent BIOMASS Example Reference Biospheres (ERB2A), and it would be useful to compare the two approaches.

The data for human consumption rates of different foodstuffs, as well as inhalation rates and external exposure times, are presented as probability distribution functions. The danger of folding such parameters into an overall probabilistic assessment is that no distinction is then drawn between the basic assumptions that underlie the definition of 'indicators' of radiological impact (such as human behaviour) and more specific uncertainties relating to the parameterisation of migration and accumulation processes (such a radionuclide dependent parameters). Without a better understanding of how the dose calculations are presented in the SAFE assessment (there are no dose calculations at all in this particular report – except for those alluded to below for Chapter 11) it is not possible to make a definitive commentary on this issue. However, the concern is that a deeper understanding of which are the most important premises underlying the biosphere assessment, as well as the identification of critical model components and transport/exposure pathways, will be obscured in a presentation of the calculated 'probability distribution' of individual dose.

Chapter 10 – Effects of different sorption properties and contamination pathways. This is an interesting and informative analysis of some of the dynamics of contaminant transport within particular sub-models. However, as noted elsewhere, it begs several questions regarding the influence of, and sensitivity to, other elements of the system models (i.e. other than the choice of Kd) on the model results. Several conclusions appear to have been drawn regarding the value of representing residual contamination as a result of system evolution from one ecosystem to another, but these appear to be based solely on consideration of different sorption properties. In particular, no account appears to have been taken of the implications of assuming that the geosphere-biosphere interface (for the coastal and lake models) might be situated within the sediment, rather than emerging directly into the water column.

Chapter 11 – Summary and discussion. The final part of the discussion (Comparison with other studies) makes reference to the evaluation of 'ecosystem specific dose conversion factors' (EDFs) determined for the coastal model and presented in Appendix B. It is not clear whether these represent the results of best estimate calculations, or if they are based on the expectation value (or some percentile) of the calculated probability distribution of annual dose. If the former approach has been used (and particularly if it has been applied in the SAFE assessment itself) then it would be useful to clarify this point. Alternatively, if the EDFs have been derived from probabilistic calculations, more substance is required in the discussion of the results, how they were derived and what their implications might be.

A9.3 Relevance to Safety Case for SFR

The conceptualisation of the transport and distribution of contaminants in the coastal and marine ecosystem, described in this report, is based on characterisation of the present-day biosphere in the vicinity of SFR, which is assumed to be valid over the next 1000 years or so. This time period is specifically identified in Swedish regulations (SSI FS 1998:1) as requiring an assessment based on "quantitative analyses of the impact on human health and the environment". The same regulations highlight the importance of the present-day system state because the overall safety case is expected to include (inter alia) an assessment "based on the assumption that the biospheric conditions which exist at the time when a licence application … is submitted will not change".

The coastal/marine ecosystem is also particularly relevant from the perspective of evaluating collective dose, for which an estimate (integrated to 10 000 years, based on expected discharges over the first 1000 years after closure) is required as part of the overall safety case, according to the 1998 regulations. There is no reference in the report to the potential use of the any of the models in addressing collective doses. However, it may be that SKB has decided to restrict the scope of the SAFE study to consider only potential individual doses.

In addition to the present day biosphere system, a safety case developed in accordance with the same regulations also needs to include consideration of "various possible sequences for the development of the repository's properties, its environment and the biosphere" in the period after the first 1000 years following repository closure. Hence the approach to biosphere modelling in the SAFE assessment has recognised the potential importance of system evolution to the definition of suitable assessment biospheres.

Very few published performance assessments have adopted a fully time-dependent approach to representation of the biosphere system, allowing the physical characteristics of individual model components and the rate constants representing transfers between them to change continuously with time. Indeed, such a strategy presents particular problems from the perspective of biosphere modelling, because of the difficulties in representing moving boundaries, the identification of potentially relevant processes associated with changing environment, and the fact that the models need to be integrated with assumptions about human communities and their exploitation of the environment. Representation of the evolution of the biosphere system within the SAFE assessment is achieved through the definition of a sequence of distinct, time-invariant models for the individual ecosystem types. The report provides some useful justification for the configuration of the selected biosphere models, although there are questions regarding the detailed approach that has been taken in defining the physical dimensions of some compartments and the transfer coefficients representing the transport of radionuclides through the system.

It would be useful to provide a tighter link between the assessment modelling strategy described in this report (including definition of the geosphere/biosphere interface) and the detailed scientific analysis that SKB has conducted to study the projected evolution of the biosphere (summarised in SKB R-01-27). Even though the use of a set of time-invariant system states may be warranted for the SAFE assessment, it would be useful if the following considerations could be more explicitly addressed somewhere in the biosphere analysis:

- If individual system states are considered in isolation as separate assessment biospheres, what is the most appropriate strategy for dealing with conceptual uncertainties linked to definition of the basic configuration of system components (and the description of human behaviour)? Is it more appropriate to try to capture all such uncertainties as part of a general probabilistic uncertainty analysis based on parameter sampling or to justify specific parameter choices?

- Are there any situations where consideration of the sequence of system states might be merited as part of the discussion of system performance – even if not explicitly simulated in the PA? Could any particular radiological concerns (e.g. release of accumulated contamination) be linked to the transitional phase?
- How are such arguments modified if explicit consideration is given in the coastal and lake models to the possibility of groundwater release taking place via underlying sediments? How would such an assumption about the geosphere/biosphere interface affect confidence in the suitability of models for sediment/water column interactions?
- How is possible migration of the region of contaminated groundwater discharge with time taken into account in making decisions about the nature and location of the geosphere/biosphere interface and the appropriateness of attempting to simulate explicitly the sequence of system evolution?
- If residual contamination is ignored in defining the sequence of system states, does it make sense to run the independent, time-invariant models to (or close to) equilibrium, however unrealistic that might be?
- What additional biosphere model simulations and sensitivity analyses could be undertaken in order to identify the most important parameters and assumptions governing the relative radiological significance of different ecosystem types, and thereby to guide understanding of what is being presented in, and concluded from, the biosphere component of the PA?

Finally, although identified as a 'final draft', there are a number of places in the report where editing remains to be completed. In particular, cross-references to Tables and between sections of the report are often incorrect, which can make it difficult to trace some of the arguments and data flows presented in the document.

A10 A Transport and Fate Model of C-14

Report Number: TR-01-15 (Final Draft)

Author: L Kumblad

Reviewer: Mike Egan, Quintessa Limited, Henley-on-Thames, UK.

A10.1 Summary

This report describes work carried out on behalf of SKB to develop and ecosystem-based model of C-14 behaviour in aquatic environments. The model has been applied to simulate two main system states:

- present-day conditions in the part of Öregrundsgrepen local to SFR; and
- postulated future conditions in two thousand years (i.e. at 4000AD), by which time it is projected that the coastal waters in the vicinity of SFR will have been reduced in size to a low salinity enclosed archipelago, with a single channel outlet to the sea.

Models for each system state are based on a compartmental representation of mass and energy transfer within the foodweb and associated physical environment. This is then used to develop a dynamic representation of the behaviour of C-14. For the purposes of the simulations, it is assumed that C-14 enters the biosphere via groundwater in inorganic form (e.g. CO_2 or HCO_3^-), where it becomes available to autotrophic organisms. A constant rate (5.13×10^7 Bq per year) is assumed over a period of 1000 years. Calculations of C-14 distribution are used to evaluate exposures (Gy) and effective bioaccumulation factors (Bq/kg wet weight per Bq/l in water) for different organisms, as well as ecosystem-specific dose conversion factors (EDFs) for humans (Sv y^{-1}/Bq y^{-1} after 1000 years of continuous release).

The modelling results indicate water turnover within the model region is sufficiently fast (as a consequence of circulatory and wind-driven currents) for most of the released C-14 (99.8% under present-day conditions, 98.4% at 4000AD) to be dispersed rapidly to the wider marine environment. The remainder is available to be assimilated by primary producers within the model region, enabling the transfer of C-14 to higher trophic levels and, eventually, to man. Sensitivity studies have been undertaken to evaluate the importance of differing assumptions regarding initial uptake of C-14 within the system (whether uniformly available to all plants via dissolved inorganic

carbon, or directly accumulated by benthic plants on entry to the system, or a combination of the two), as well as the implications of reduced water exchange rates in the present-day system. The total radioactivity accumulated in the system increases with reduced water exchange (also at 4000AD relative to the present day, for the same reason) or when benthic accumulation is assumed.

Because the average depth of sea water in the model region is fairly shallow (approximately 10m at present, 3m at 4000AD), light penetration to the bed means that the benthophyte community represents the highest fraction of the total carbon within the system, both for the present day (just under 50%) and at 4000AD (more than 80%). The model therefore indicates that, apart from the fraction of C-14 that is lost by water exchange or remains in the system in dissolved inorganic form, benthophytes tend to be associated with the highest fraction of the total C-14 within the system at equilibrium, whatever the assumed route of entry.

Ecological half-lives for C-14 predicted by the model tend to be in the region of 200 to 350 days, implying total system equilibration times in the region of 10 years or less. Effective bioconcentration factors vary by up to two orders of magnitude between different organisms (benthophytes, grazers and plankton being highest, zooplankton, benthos and water fowl being lowest), and factors of up to 400 for a given organism depending on assumptions about the route of entry into the system and, to a lesser extent, water exchange rate.

The model results have been partially validated by:

1. Comparing the predicted carbon budgets from the mass and energy transfer model with observations for similar regions, which indicates (among other things) the implications of using annually-averaged primary production and respiration rates.
2. Comparing predicted bioconcentration factors for C-14 with observations in the vicinity of Sellafield, which appear to demonstrate the role played by higher water exchange rates in the eastern Irish Sea compared with SFR model area.

The equilibrium EDF derived for the ‘present-day’ ecosystem is calculated to be approximately 5 times lower than that determined using the generalised coastal model used for other radionuclides (SKB TR-01-04).

A10.2 Commentary

Special consideration of the ecosystem pathways associated with C-14 were deemed appropriate by SKB because initial calculations for SFR had indicated that it is one of the most important radionuclides contributing to total individual dose. The modelling exercise reported here provides an initial indication of the potential value to be gained from adopting a more complex simulation approach compared with that adopted in the standard models for dose assessment. However, the report is essentially the result of an R&D project, and its focus is therefore understandably on evaluation of the performance of the model itself, rather than the conclusions that can be drawn regarding its role in the overall safety assessment.

Any ecosystem model used as a basis for radiological assessment has to strike an appropriate balance between the uncertainties inherent in developing descriptions of the system (particularly for projections at future times) and the precision with which the system is represented. Simpler models – developed with the primary aim of evaluating individual doses to man – are typically based on the use of equilibrium parameters (bioaccumulation factors and Kds) that are derived from concentration ratios for trace substances measured in the field. However, such approaches are much less appropriate where the focus is on determining the distribution of contamination within the food web, such as would be required in determining potential doses to organisms other than man. Because they do not represent the dynamic processes responsible for contaminant transfer between organisms, such models may also be less suitable for investigating the impacts of radionuclides (such as C-14) that exhibit environmental behaviour that is not realistically represented via simple equilibrium ratios.

In the present case, a more complex model serves to provide a more 'realistic' appraisal of the distribution of C-14 through trophic levels of the food web and is therefore better able to support the investigation of specific factors, such as the dynamics of accumulation and elimination, as well as the implications of different assumptions about the initial route of entry into the system. However, such complexity is achieved at a price; the large quantity of information required to support the underlying process models inevitably means that the results are dependent on various theoretical assumptions regarding system characteristics and properties, as well as basic input data.

Assumptions adopted for the modelling study reported here include the following:

- Total biomass for different types of organisms are derived as annual-averaged values;

- Simplified conversion factors (based on seasonally adjusted light-days and degree-days) have been used to evaluate primary production, respiration and consumption rates required by the dynamic carbon flow models;
- Carbon flow models for 4000AD are determined assuming that water visibility, organism groups at different depths, abundance, ecosystem function and incoming solar radiation are all the same as at the present day;
- C-14 losses from the system include a contribution from the exchange of biomass (for phytoplankton and zooplankton only) with the surrounding coastal waters, at a rate equivalent to the water turnover rate.

Some general remarks are given in the report regarding the potential influence of these basic inputs to the model, particularly in the discussion of the extent to which the models are validated by field data (Section 7.1) and the implied carbon self-sufficiency of the system at 4000AD (Section 8.1). However, the report does not provide a quantitative evaluation of the potential implications of such modelling assumptions on the radiological endpoints of the C-14 calculations. Hence, although the results reported in the study are informative and provide a useful insight into the potential value to be obtained from an ecosystem model (particularly for endpoints, such as exposures of a range of non-human organisms, which are not accessible to simpler models), it is not easy to draw definitive conclusions regarding the uncertainties associated with deploying such a modelling approach. For example, it is noted elsewhere (e.g. in discussion of the projected evolution of the biosphere in the vicinity of SFR – SKB R-01-27) that the salinity of the bay area at 4000AD would be expected to be somewhat lower than that of the present day, which could have a marked effect on ecosystem structure. As noted in the conclusions (Section 8.2) the results obtained using the 4000AD model therefore need to be treated with considerable caution.

It is instructive to make a more explicit comparison between results for the present-day coastal area obtained using the ecosystem model and those derived from more simple models based on empirical concentration factors (reported in SKB TR-01-04). The 'retention time' of coastal waters in the present-day coastal area represented by both models (2.11×10^{-3} years, or 18.5 hours), is much shorter than the calculated ecological half-life of C-14 in the various components of the ecosystem model (approximately 200 to 350 days). Even if the water exchange rate were reduced by a factor of 10, physical turnover can still be expected to dominate the distribution of C-14 within the model system. In this respect, it is worth noting that the 1000 year simulation time used in the study is not apparently necessary, since the reported ecological half-times for C-14 transfer are less than a year. The fairly rapid rate at which equilibrium seems to be achieved within the system is potentially important in view of the overall dynamics of environmental change in the region, linked to land rise.

Given the above data, both the simple and more complex models can therefore be expected to yield similar values for the total amount of C-14 that is present in the water column. This is evident from the following sets of figures, derived for a uniform release rate of 5.13×10^{7} Bq per year. For the simple model, most of the inventory is assumed to be in solution, owing to the combination of low suspended matter load (5×10^{-3} m^3 kg^{-1}) within the model region and small distribution coefficient for carbon (1×10^{-3} m^3 kg^{-1}). Within the more complex model, the C-14 inventory in the water column is calculated as the sum of the contributions from DIC (dissolved inorganic carbon) and POC (particulate organic carbon). The results are illustrated in Table A.1 below.

Table A.1 *Calculation of C-14 Inventory in Water*

Model	Route of C-14	Water Turnover	C-14 Inventory in
Simple		2.11×10^{-3} years	1.56×10^{5} Bq
Ecosystem	via water column	2.11×10^{-3} years	1.40×10^{5} Bq (>99% inorganic)
Ecosystem	via benthic plants	2.11×10^{-3} years	1.40×10^{5} Bq (<6% inorganic)
Simple		2.11×10^{-2} years	1.56×10^{6} Bq
Ecosystem	via water column	2.11×10^{-2} years	1.40×10^{6} Bq (>98% inorganic)
Simple		2.11×10^{-1} years	1.56×10^{7} Bq
Ecosystem	via water column	2.11×10^{-1} years	1.40×10^{7} Bq (>88% inorganic)

Part of the explanation for the small difference between the models is that the water volume associated with the simpler model (0.1064 km^3) is slightly smaller than that associated with the ecosystem model (0.11 km^3). In addition, a fraction of the total C-14 inventory within the ecosystem model is linked to living components of the ecosystem, particularly benthic organisms.

It is also instructive to attempt to compare the effective bioaccumulation in fish (consumption of which is assumed to be the primary pathway of exposure of man) derived using the simple model with that obtained from the ecosystem model.

The bioaccumulation factor for C-14 used in the simple model (SKB TR-01-04) is based on the ratio of the measured carbon content in fresh fish compared with that in sea water, working out at 2×10^{3} Bq kg^{-1} per Bq l^{-1} (with the acknowledgement that the value for Baltic Sea fish is actually some 20% higher). This can be compared with the value of 2×10^{4} Bq kg^{-1} per Bq l^{-1} (with a range from 2×10^{3} to 2×10^{5} Bq kg^{-1} per Bq l^{-1}) for marine fish reported in the international literature (IAEA Technical Reports Series No.247 – *Sediment K_ds and concentration factors for radionuclides in the marine environment*).

These figures can, in turn, be compared with the equivalent factor derived using the ecosystem model, which varies according to the whether the C-14 is assumed to enter the system in dissolved inorganic form via the water column (and therefore homogeneously available to all plants) or via benthic plants and, to a lesser extent, according to the assumed water turnover rate. For the "present-day" ecosystem, assuming a water turnover rate equivalent to that used in the simple coastal model, the equilibrium C-14 concentration in water is given by the total inventory (DIC+POC) divided by the total water volume (0.11 km^{3}), which is 1.27×10^{-6} Bq l^{-1}. The C-14 concentration in fish can be derived from the results reported in Appendix III of the report (given as Bq per gC and assuming 10.2 g fresh weight per gC in fish – as in Table 6), which indicates values of between 8.7×10^{-4} and 6.9×10^{-1} Bq kg^{-1} fresh weight depending on the assumed route of entry of C-14 into the system.

The effective bioaccumulation factor for fish may then be calculated as the ratio of the calculated C-14 concentration in fish to the concentration in the water column, yielding values in a range from 6.9×10^{2} to 5.4×10^{5} Bq kg^{-1} per Bq l^{-1}. These values span (and indeed exceed) the range of reported values from the literature, suggesting that the route via which C-14 is assumed to enter the system can have a major influence on the endpoints of a dose calculation.

It is worth pointing out in relation to the above comparison that the detailed figures reported in the document are somewhat confusing. Section 6.8 of the report summarises bioconcentration factors for various organism groups based on the results of the model, but these are significantly lower than those derived above. Indeed, the basis on which the effective bioconcentration factors has been calculated is not at all clear, and does not appear to bear a direct relationship to the calculated C-14 concentrations in water. This complicates any attempt to make a detailed comparison of the reported results of the ecosystem model with the simpler models.

Likewise, it is difficult to understand how the ecosystem-specific dose conversion factors (EDFs) have been derived from the more complex model. It is stated (Section 6.9) that the basis for the calculation is an assumption that the 2.3% of the total available fish population is taken for human consumption. However, the standing biomass of fish associated with the model for the present day is reported (Appendix II) as 8.3×10^6 gC, which equates to some 8.5×10^4 kg total fresh weight. The consumption of 2.3% of this amount amounts to a dietary intake of almost 2000 kg of fish per year. This may by an appropriate figure for determining annual collective doses based on total fish catch from the region, but it is hardly suitable for evaluating individual dose (as required for the determination of the EDF). For comparison, the annual individual consumption rate assumed in the simple biosphere model (TR-01-04) is reported as 30 kg per year. This discrepancy needs to be resolved if direct use is to be made of the results of the ecosystem model within the SAFE assessment. It should also be pointed out that other results suggest that EDF values derived using the ecosystem model would be almost three orders of magnitude higher than those reported in Section 6.9 if it was assumed that the C-14 release was accumulated first by benthic plants rather being homogeneously available in the water column as dissolved inorganic carbon.

Overall, the ecosystem model should provide a useful basis for investigating some important sources of uncertainty in the evaluation of radiological impacts of C-14, which cannot be readily studied using a simpler modelling approach. In addition, the ecosystem model provides a valuable route for investigating the potential radiological implications for the ecosystem itself. However, in its current form, the report does not appear to provide a robust basis for dose calculation in support of the SAFE performance assessment. Moreover, given the importance that has been attached to environmental change as a basis for the biosphere assessment, it is notable that the focus of the report is on potential releases of C-14 to brackish marine ecosystems, rather than terrestrial systems that are projected for time periods after 4000AD.

A final observation on the report is that caution is required in interpreting the graphs provided in Chapter 6, for which the y-axis has been inverted. This is acknowledged in the Figure captions, but nevertheless is potential confusing to the reader.

A10.3 Relevance to Safety Case

Initial calculations in support of the SAFE assessment identified C-14 as a potentially significant contributor to total individual dose. The ecosystem model presented in this report provides a basis for investigating some of the contributions to uncertainty associated with the determination of radiological impact from possible future C-14 releases. The intention is that this should be achieved via a more mechanistic analysis of the processes of mass and energy transfer than is possible using simpler assessment approaches based on the use of empirical equilibrium parameters to represent the effects of environmental processes on contaminant transport. However, because of its complexity, the model is necessarily founded on a range of assumptions that do not appear to have been fully tested. Indeed, the requirement for detailed model testing and validation is stronger where the evaluation of contaminant transport and accumulation is based on a dynamic process model rather than empirical equilibrium relationships.

These limitations, together with some questions concerning the way in which the radiological impact analysis has been undertaken using the model, casts doubt on its potential role in providing a direct input to the safety case.

A further consideration in the context of the SAFE assessment is that the treatment of environmental change is somewhat limited, with the analysis covering two possible 'marine release' scenarios that are relevant to the period up to 2500 years from the present. The development – and validation – of mechanistic ecosystem models for future conditions is a challenging task and the author of the current report admits that the assumptions underlying the results even for the 4000AD model mean that it needs to be treated with considerable caution.

Nevertheless, against this background, it is worth noting that Swedish radiation protection regulations (SSI FS 1998:1) explicitly identify the 1000 year timescale as one for which "*quantitative analyses of the impact on human health and the environment*" are expected to be made. The regulations also highlight the importance of the present-day system state because the overall safety case is expected to include (*inter alia*) an assessment "*based on the assumption that the biospheric conditions which exist at the time when a licence application … is submitted will not change*".

Highlighting this early timescale as one requiring particular attention in the development and use of quantitative models for impact assessment provides a strong justification for the application of more complex tools such as that described in the report, provided that they can be suitably validated. A further motivation for emphasis on this type of modelling arises from the regulatory requirement to address impacts on the environment through consideration of the "biological effects of ionising radiation in habitats and ecosystems". Whereas it may be that case that a robust safety case for environmental protection can be developed on the basis of more generalised evaluation of such effects, an ecosystem model such as that reviewed here can potentially provide valuable support in demonstrating that consideration has been given in the performance assessment to exposures of different organisms in the specific environmental context of the SFR facility.

A11 Scenario and System Analysis

Report Number: R-01-13

Authors: J. Andersson and K. Skagius

Reviewer: N. A. Chapman, Quintessa Associate Consultant

A11.1 Summary

The report describes the systematic approach to describing the SFR system that is used to evaluate processes and their interactions. This, in turn allows issues to be identified that will need to be incorporated into PA calculations and scenarios to be constructed on which to base the structure of the PA. The key to the methodology is the use of expert judgement and comprehensive documentation of decisions taken.

Chapter 2 describes how the systems approach has been applied. It is based on earlier SKB experience with interaction matrices of sub-systems of the repository and its environment that are constructed by groups of experts. The matrices contain parameters that affect system behaviour, and interactions between parameters. Both parameters and interactions can be directly compared with and audited against lists and descriptions of FEPs that are widely available.

Chapter 3 describes how the FEP audit allowed the identification of FEPs not included in the SFR sub-system interaction matrices (EFEPs) and how these were managed so as to produce a reasonable set of scenarios of possible evolution of the repository on which to base the PA calculations. 'Scenario generating' EFEPs were identified and combined to produce a 'Base Scenario' (reasonably expected evolution of the system) and others, under the headings of 'Initial Defects in Technical barriers', 'Climate Change' and 'Human Actions'. Means of analysing the scenarios are suggested.

Chapter 4 describes the system, as structured into the interaction matrices. The diagonal elements (or parameters) are introduced. A brief description of the interactions identified as being potentially important is provided: others are assigned to an appendix.

The Conclusions state that most scenario-generating events and conditions can be analysed within the Base Scenario, or within parameter variants of it.

Six Appendices provide names of experts, FEP list information, EFEP management, unimportant matrix interactions and the matrices themselves.

A11.2 Commentary

The methodology applied has been developed and tested before by SKB, so now has a reasonable track record of providing a comprehensive approach to evaluating system structure and what controls system behaviour. There is also an extensive international database of FEPs on which to base such an approach. The approach adopted is thus judged to be sound, and appropriate for the SFR safety study.

A vital aspect of the approach is that SKB documents the decision-making that underpins the approach and the information basis used to support these decisions. Section 2.1.5 describes how this has been done (mentioning an Interaction Matrix Database). It would be useful if SKI were able to examine this documentation to confirm the depth and comprehensiveness of the process. This is important, as the report makes numerous assertions about what is, or is not, worth evaluating and it would be useful to check the basis of some of these decisions. Presumably, some of these are based on a 'Safety Concept' (e.g. being conservative by not accounting for solubilities, or sorption on corrosion products), but this concept is nowhere described. Perhaps it is in the missing ‘Overview’ Report?

Section 3.1.1 (p 18) notes that the recent SKI-SSI review of SR 97 asked for more discussion on combinations of scenario initiators within the same methodology as used here for SFR. The present report (and the associated 'calculation' report) do not appear to have looked at this matter comprehensively.

An underlying problem with reviewing this document is that the preparation seems to have been hurried. Although the 'Final Draft', it has clearly not been proof-read. There are statements that raise questions about the attitude taken to the study, such as:

These potentially important scenario initiators need at least be qualitatively discussed before they can be discarded for further analysis (p27)

The key problem is that the conclusions regarding what should be analysed in the PA, and how, are neither clearly summarised nor defined in sufficient depth and detail. Consequently, it is not possible readily to check whether the suggestions for what needs to be evaluated have actually been followed (in related Report R-01-18). In places, it almost appears as though the systems and scenarios report was prepared after the PA calculations had been structured and it is providing a *post hoc* justification for earlier decisions, taken outside the structured 'system approach' outlined here. For example:

The impact of dissolved salt on water composition and degradation of surrounding concrete barriers is not specifically addressed within SAFE (p 47).

Within SAFE sorption on bentonite…..is considered ….while the potential sorption capacity of other materials is neglected (p 58)

This report should be passing on recommendations to PA, which then acts upon them. The impression is given that most of the decisions had already been taken, before the system evaluation had looked at possible importance.

This impression is reinforced by several statements about interactions that have been considered important enough to be retained but have been omitted from evaluation within the PA. This is apparently because not enough is known about them (e.g. see statement on methylation at end of p 58 and over page), which seems not a very good reason, or for reasons that seem to have more to do with the will to study the issue (e.g. final para on p 25 on unsealed boreholes). The discussion on cave-in rejects the need for any analysis on the vague basis of 'appropriate engineering action' (p 100) without saying what this is. It is not at all clear that cave-in would not cause more than just local connection of vaults (? e.g. connection to the ground surface?). This scenario might warrant further study (although the reviewer has not seen Fredriksson, 2000).

Thus, the main criticism of the report is a lack of clarity in the suggestions made to the PA and a consequent significant problem with traceability.

In more detail, the Base Scenario appears to be a sensible and feasible basis for the PA work and for exploring system behaviour. However, the (other) Scenarios that are distilled out of what purports to be a major systematic effort are not described in any kind of detail. There are confusing statements about scenarios that are said to need to be developed, which are then discarded later on (Chapter 3).

Some points about particular scenarios:

- Barrier defects: it is not apparent that the statement about the worst position for a crack in the silo being in its base (p 24) is agreed by the PA group or carried through into a proper analysis in 01-18.
- The permafrost scenario selected is complete freezing. It is not clear why discontinuous permafrost (with possibilities for focussed flow) is less important, or why it is 'well covered by assumptions made in the Base Scenario' (p 29). What are these? Some discussion of what kinds of parameter variants are motivated is essential, but is absent.

- Tectonics: It does not follow that a probability of 0.2 in 100 000 years reduces to 0.02 in the next 10 000 years, without some discussion of mechanisms that control frequency. It is not clear that the suggested analysis of a magnitude 7 earthquake at 7000 years has been 'at least qualitatively assessed' (p 29) in the PA report. If some relevant calculation case has been done, it is not described as such in 01-18. Or is there actually an 'earthquake scenario' in SAFE, as indicated on page D:7? Poor traceability again.
- Well intrusion: the analysis is stated to require evaluation of effects on both water flow and transport. It is not clear that the former comprises part of the 01-18 analysis.
- Direct intrusion: this is not analysed. SKI and SSI need to be content with this position. One interpretation of ICRP 81 is that direct consequences of intrusion can only usefully contribute to decision-making if they are analysed at the time of repository siting and used to compare alternatives. An analysis at the moment serves no useful purpose, but SKB should justify their position properly. (See also comments under the review of 01-18).
- Inventory deviations: discarded because a 'conservative method' is to be used to estimate the inventory (p 32). This is not an adequate description or justification. What does it mean and how do we know that it is conservative?

A side-issue arises, in that the report can say little about the evolution (and impacts of evolution) of plugs and seals, as no decision has been taken about them. This is a topic in which SKI perhaps ought to be taken a more active interest, as confidence that the repository can be adequately plugged is something that should not be left until a late stage.

More discussion of scenario initiation conditions and their likelihood is needed. It would perhaps be easier if the scenarios were properly described. The reason for doing it is to follow recent ICRP suggestions for providing decision-makers with disaggregated 'dose plus likelihood' data, as an alternative to risk figures. Providing more information about how and when scenarios might occur and combining it with information about impacts at different times, allows some consideration of how resilient the repository system is. Perhaps this type of discussion will be found in the 'Overview' report?

A11.3 Relevance to Safety Case

The key point that needs to be checked in the safety case made in SAFE is that the scenarios are properly analysed, either individually or as clearly delineated variants of

Base Scenario parameters. This will be difficult to judge, as the link between both the scenario development and the system description, and the development of calculation cases, is hard to trace.

The report does motivate a sensible set of scenarios for analysis, but does not give much guidance on how to do it. However, it is not apparent that the set is comprehensive, since, despite going through a complex and, presumably, time-consuming process of setting up the system description, some rather weakly justified jumps have then been made in deciding what to analyse.

Two additional scenarios can be suggested for possible analysis:

- the roof fall scenario in BLA, discussed above;
- an 'end point' scenario when the wastes might be exposed at the surface, for example in the aftermath of the next major glaciation, in say 120 000 years time. Erosion by ice could, by that time, have unroofed the caverns and silo. After land uplift, this might leave water-filled depressions in the land surface with wastes in direct contact with water and sediments. The residual activity of longer-lived (e.g. uranium series) radionuclides that had not leached out of the vaults could then cause exposures.
- The last type of scenario is thought to be a useful presentation in many types of safety case, as it illustrates the final 'fate' of the repository and the wastes. Clearly, it is of more interest for shallow repositories such as SFR, which will be destroyed in relatively short periods of time.

A12 Compilation of Data for Radionuclide Transport and Analysis

Report Number: R-01-14 (Preliminary Draft)

Authors: Anon.

Reviewer: Philip Maul, Quintessa Ltd, Henley-on-Thames, UK

A12.1 Summary

This report compiles the data used by SKB in the radionuclide transport calculations in the SAFE project. Because the document is a preliminary draft, some of the text has not been completed. The report includes a good summary of the scenarios and models used, and this is followed by a description of the data used in the following areas:

- Repository description, including inventory information
- Groundwater flow through the repositories
- Physical and Chemical data for the engineered barriers
- Radionuclide transport in the geosphere
- Biosphere modelling.

A12.2 Commentary

The report provides a generally very good audit trail for the data that has been used in the SAFE assessment. Key areas where it is felt that there are significant shortcomings are as follows:

Section 5 does not actually give any data for the water flows through the repositories. Instead reference is made to Holmén and Stigsson [2001]. The reason given is that a very large number of flow values were used in the radionuclide transport calculations. Although it would not be appropriate to reproduce all the data given in that reference, the lack of any summary and discussion of the data is a major shortcoming of this document. This is particularly the case because the overall safety case relies heavily on the calculated flow rates that are very much smaller than those used in the original safety case assessment for SFR. The lack of data supplied here can be compared with the very detailed information given in Section 8 on the very large number of parameters used in biosphere modelling. The discussion of the data uncertainties (Section 5.4) is completely inadequate for such important parameters.

In the discussion of near-field sorption values in Section 6.2, Kd values have been taken that are representative of high pH and alkaline conditions. These coefficients will be lower than those for non-saline water (which will be applicable after the Baltic has retreated from the region of SFR). It is not necessarily the case that lower Kd values will be conservative in the overall assessment (as implied in the present document); this will depend on the important timescales for system evolution. There is a similar implicit assumption in Section 7 (geosphere migration data) that rapid transport through the geosphere is necessarily conservative- this will generally be the case, but not always.

The near field data assume a single 'regime' on the basis that high pH conditions are likely to last for the entire 10 000 years of interest. The reasoning behind this assumption is well documented, but reflects the restriction of SKB's assessment calculations to this 10 000 year period. If it is necessary to consider possible impacts on longer timescales, then the data choices could be open to question.

In the discussion of data sources for information on the transport of radionuclides through the geosphere in Section 7.1.2 it is stated that there are no site specific data for the flow wetted area per unit volume of rock, and 'generic' data have therefore been used. It is surprising that this data is not available for SFR, and would appear to reflect the relatively low emphasis given by SKB to the contribution of the geosphere to the overall safety case.

In addition to the above, a number of more minor points have been noted:

1. In Table 6.1 solubility limits are given for concrete pore water in the absence of complexing agents. It would have been useful to give some indication of the size of the change in these parameters that are possible in the presence of complexing agents.
2. Text to justify the data choices on porosity and diffusivity in Section 6.4 are missing from this preliminary draft.
3. Text to justify the data choices on sorption and diffusion in the rock matrix in Section 7.2 are missing from this preliminary draft.

A12.3 Relevance to the Safety Case for SFR

By definition, the data choices for the SAFE calculations are fundamental to the safety case for SFR. Some of the key issues noted above coincide with points raised by reviewers of other supporting SKB documents. These can be summarized as follows:

1. There is an over-reliance on the preciseness of the calculated groundwater flows through the repositories, with insufficient information being provided on the uncertainties associated with these calculations.
2. Parameter choices are sometimes based on arguments of conservatism. In a complex system like SFR it is not always possible to ascertain in advance what assumptions are actually conservative.
3. The SKB calculations are based on calculations over a 10 000 year period. Some of the assumptions made will not be valid if it proves necessary to consider impacts on longer timescales.
4. The lack of some site specific data for SFR reflects the low importance placed on the geosphere in the overall safety case.

A13 Radionuclide Release and Dose

Report Number: R-01-18

Authors: M Lindgren, M. Pettersson, S. Karlsson & L. Moreno

Reviewer: Neil Chapman, Quintessa Associate Consultant

A13.1 Summary

This draft report describes the PA calculations made for radionuclide releases from SFR by the groundwater pathway. It provides a summary of results but does not discuss them in a safety or performance context.

Chapter 2 describes the calculation cases selected for the Base Scenario, on which most of the study is focussed, and for the other scenarios identified in draft report 01-13. Chapter 3 provides a brief description of the computer codes used in the analysis. Chapter 4 covers basic assumptions and presents the key data used in the calculations.

The results are presented as release and dose versus time curves for a selected group of individual radionuclides in Chapters 5 and 6. Appendices give more information on the selection of the 'indicator' radionuclides, the models and some sample input files for the calculations.

A13.2 Commentary

There is not a clear connection between this report and the one that would have preceded it, if the systematic SKB approach were being followed (01-13: systems and scenarios). Section 2.1, for example, states that 01-13 gives the 'expected evolution of the repository system' and the 'selection of calculation cases', which it does not. The 01-13 report is considerably vaguer than implied here.

Figure 2.1 (p 3) suggests that the scenarios only affect the near-field. This cannot be the case for either the well scenario (impact on flow) or the permafrost scenario (impact on flow and on biosphere).

It would have been useful to have a table summarising all the calculation cases undertaken and the situations (base case variants, uncertainties, scenarios) that they were intended to represent. It would show, for example, where and how the

'Earthquake scenario' (and others) referred to in places in 01-13 had been translated into calculation cases for the Base Scenario.

Section 2.2.1 seems to imply (p 5) that large fractures in the barriers are an admissible part of the Base Scenario (hence acceptable closure condition?), provided they do not intersect. This section provides the description of repository evolution that is missing from 01-13.

There is a concern that the mechanisms for concrete cracking described in Section 2.2.2 do not account for physical degradation processes. This issue was encountered earlier, in SKI's independent panel review of SFL 3-5, from which these words are taken;

The general experience with steel-reinforced concrete is that such material experiences severe localised cracking soon after immersion in water. While this cracking may provide rapid pathways for the escape of gases generated by anaerobic corrosion, cracking could also lead to a much higher hydraulic conductivity for this material. Large cracks, in turn, might invalidate some of the assumptions regarding the relative contrast in permeabilities among the concrete structure, the gravel backfill, and host rock, and the assumption that aqueous radionuclide release from the concrete vaults is diffusion-dominated.

This is a significant issue, since it implies that barriers could degrade earlier than the 1000-year post-closure initiation time used in the SAFE study. It should certainly have been explored in SAFE as a variation case. Similarly, the issue of roof-fall in the unfilled vaults and its potential impact on release paths ought to have been included at this point.

The water consumption figure assumed from the well is precise (2.37 cubic metres a day). Where does this figure come from and how representative is it? The associated individual consumption figure of 600 litres per year (Section 6.4) seems low – and it is arguably a sensitive factor. Again, where does it come from? Would a larger well (presumably feasible in the large void space in some vaults), for a larger group, affect either flow or release (and dose)? There is no indication of how sensitive these factors are. Section 2.5.3 is not consistent with page 11 on the date for sinking a well (3000 or 4000 years hence).

Section 2.5.1 ought presumably to look at 'several large fractures' in the silo, as well as the vaults. Why this omission?

The parallel review of 01-13 suggests that the potential for focussed flow in the more likely scenario of discontinuous permafrost might be more significant that the continuous case covered by Section 2.5.2.

The model for BMA (Section 3.2.2) suggests that there is a large void space filled with water inside the concrete structure, which would presumably lead to more rapid diffusional mixing of mobilised radionuclides across each cell. This is not discussed.

Given the uncertainties on flow through the vault expressed in the parallel review of 01-21, the increased flows through the various parts of the system shown in Table 4.6 appear insignificantly different from the base values in Table 4.5. SKB report 01-21 itself concludes by suggesting that the flows under undegraded conditions might be underestimated by 100% or overestimated by 50%. Flow rate has a marked effect on barrier degradation and biological activity as well as transport. The uncertainties should be included in the PA.

If an uncertainty analysis had been carried out, it would be expected that it should look at varying the assumed proportions of organic and inorganic carbon, as ^{14}C is the critical radionuclide in the dose calculations. At present, an assumption of 10% organic carbon is made. Inorganic carbon is assumed to sorb significantly in the cementitious vault materials and slightly in the sand/bentonite, whereas organic carbon does not sorb in either. It is difficult to tell from the inventory report exactly where all the ^{14}C resides in the wastes, although it would appear that the bulk is in ion exchange resins. Some of the carbon may be present in activated metals (but it is not clear whether the scrap metals in the inventory are activated or surface contaminated). There is evidence (not cited in the SKB study) that carbide in metals may leach as organic species into water, but this may have little impact for the wastes in SFR as the proportions of these materials may be very small.

The opening paragraph of Section 5 betrays the lack of consistency and connection between this report and the scenario and systems study. Here, 'uncertainty in sorption data' is presented as a 'scenario'. This raises again the associated question as to why there is not a proper uncertainty, variability and sensitivity analysis in the Base Scenario – in particular for groundwater flow.

Some figures are missing or uncaptioned (5.25 and 5.26).

It would have been expected that Section 5.3.2 would have presented radionuclide migration calculations for the Degraded barriers in 1BTF, particularly as the well recipient would appear likely to present dose $>10^{-4}$ Sv. The text does not explain why it was decided to omit this information.

Again inconsistently, Section 6.1 chooses to omit from analysis a case suggested to be important by the 01-13 report (Section 3.3.1): fractured silo base. This is on the basis stated here (but not in the scenario report) that even if it were fractured, the bentonite would continue to limit flow. This statement needs to be checked against the SKI review of silo bentonite degradation mechanisms, as it is potentially the most problematic scenario.

The 'initially degraded barriers' scenario discussed in Section 6.1 is unaccountably not accompanied by dose calculations. This would be instructive information to have available.

The permafrost scenario uses the present day biosphere and then incorporates 'significant dilution' (p 90) in a body of water that will not be present at 12 000 AD. This is not justified, or conservative.

A number of observations can be made on the results, although they are not discussed here, but will be raised in the final Safety Report that brings together the results of the whole review process:

- the results for the 'downstream well' presented in this Chapter are in many cases close to, or exceed, SSI's currently proposed 10^{-5} Sv individual dose criterion for a repository (if this were to be applied to SFR);
- BLA and BTF seem to dominate the well doses from the whole repository;
- partial combination of scenarios (e.g. chemical and degraded barriers in BMA), gives doses approaching 1 mSv for the well recipient.
- the 'intrusion well' doses (which are not explored for sensitivity to well size and consumption) are several tens of mSv.

Should SKB evaluate acute doses to intruders and how should the results of the prolonged exposures from well-intrusion be viewed? For the moment, the recent ICRP guidance is noted for further discussion in our overview:

- ICRP 81 notes that their previous recommendation of a dose constraint of 0.3 mSv/a for members of the public for the optimisation of protection is not applicable in evaluating the significance of human intrusion. They point out that any protective actions required should be considered during the development of the disposal system. If intrusion could lead to doses sufficiently high to lead to deterministic effects following an acute exposure, or an unacceptable risk of stochastic effects following prolonged exposure, reasonable efforts should be made to reduce the likelihood of intrusion; for example, by increased depth of disposal.
- For acute exposures (e.g. to an intruder), ICRP notes that doses less than 0.5 Sv are unlikely to result in serious deterministic effects. For prolonged

exposures, if doses are calculated to be less than about 10 mSv/a, intrusion will not require further attention. From 10 to 100 mSv/a, the possibility of reducing likelihood of intrusion will have to be evaluated, considering the magnitude of doses, costs and feasibility.

A13.3 Relevance to Safety Case

All of the points made in the commentary are considered to be relevant to the safety case. A key concern is that analysis does not provide a discussion of the impacts of uncertainty and variability in some key parameters (inventory, water flow rates), yet the results indicate, by other repository standards, some relatively high doses at short times into the future for scenarios that appear quite likely. The SKI modelling study should explore some of these omissions.

A14 The SAFE Document Review Team

See Table 5.1 for documents reviewed by each team member.

Reviewer	Organisation	Principal disciplines	Years experience in radioactive waste management
Prof Neil Chapman	Quintessa Associate	Geology Safety assessment	25
Dr Mike Egan	Quintessa Ltd	Biosphere Radiological protection	20
Dr Joel Geier	Hardrock Consulting Inc	Hydrogeology Rock mechanics	15
Dr Philip Maul	Quintessa Ltd	Physics Safety assessment	22
Dr Bill Miller	QuantiSci Ltd	Geology Geochemistry	12
Dr David Savage	Quintessa Ltd	Geochemistry	23
Dr Mike Stenhouse	Monitor Scientific Inc	Radiochemistry	25
Dr Peter Robinson	Quintessa Ltd	Physics Modelling	22
Dr Julie West	British Geological Survey	Microbiology	20