SKI Report 00:41

Deep Repository for Long-lived Low- and Intermediate-level Waste in Sweden (SFL 3-5):

An International Peer Review of SKB's Preliminary Safety Assessment

Neil Chapman
Michael Apted
Fred Glasser
John Kessler
Clifford Voss

October 2000

ISSN 1104-1374
ISRN SKI-R–00/41–SE

SKI Report 00:41

Deep Repository for Long-lived Low- and Intermediate-level Waste in Sweden (SFL 3-5):

An International Peer Review of SKB's Preliminary Safety Assessment

Neil Chapman[1]
Michael Apted[2]
Fred Glasser[3]
John Kessler[4]
Clifford Voss[5]

[1]QuantiSci Ltd, 47 Burton Street
Melton Mowbray, Leicestershire LE13 1AF, UK

[2]Monitor Scientific, 3900 S. Wadsworth Blvd., Suite 555
Denver, Colorado 80235 USA

[3]University of Aberdeen, Department of Chemistry
Old Aberdeen AB24 3UE, Scotland

[4]EPRI, Inc., 3412 Hillview Avenue
Palo Alto CA, USA

[5]United States Geological Survey, 12201 Sunrise Valley Dr.
431 National Center, Reston VA 20192 USA

October 2000

SKI Project Number 00092, 00094

Preface

The Swedish Nuclear Fuel and Waste Management Company (SKB) has completed a preliminary safety report of the planned deep repository for long-lived low- and intermediate level waste (SKB TR-99-28). This repository must be regarded as an important part of the Swedish system for final storage of spent nuclear fuel and nuclear waste. It should according to present plans contain reactor core components, decommissioning waste from the planned encapsulation plant and CLAB, and also waste from research and development activities at the Studsvik facility.

The background of the safety report is that SKB was requested to produce an up-to-date safety assessment for the proposed disposal concept in government decision from 1996. SKB has now produced one for the planned deep repository for long-lived low- and intermediate level waste (SFL 3-5), and one for the planned repository for spent nuclear fuel (SFL 2). These safety reports are not part of a license application but have the purpose of evaluating SKB's concepts before starting site investigations, which is the next phase in SKB's long term plan.

The Swedish Nuclear Power Inspectorate (SKI), in consultation with the Swedish Radiation Protection Institute (SSI) has requested an independent expert review of the safety assessment for SFL 3-5. This report summarises the findings of an international expert group, appointed by SKI and SSI. The outcome of their work will be an important basis in the authorities own review. The context and conditions for this international review are described in more detail in SKI-PM 99:64 (available from the Swedish Nuclear Power Inspectorate).

The readers of this review should consider that safety report for SFL 3-5 is at a more preliminary stage compared to the corresponding one for the planned spent fuel repository (SFL 2). According to recent plans the SFL 3-5 repository will to be constructed much later stage than the SFL 2 repository, which means that there is more time available to refine the concept and evalute the long-term safety.

Stockholm, October 09 2000

Bo Strömberg

Contents

1 Introduction

The Swedish Nuclear Fuel and Waste Management Company (SKB) has completed a preliminary safety assessment of the planned deep repository for long-lived low- and intermediate level waste (SLF3-5). The Swedish Nuclear Power Inspectorate (SKI), in consultation with the Swedish Radiation Protection Institute (SSI), has requested an independent expert review of this assessment.[1] The outcome of this expert review will be an important basis for SKI's and SSI's own review.

The review was carried out by the following international team of experts:

Dr Michael Apted	Monitor Scientific, USA	EBS, Gc[2]
Prof Neil Chapman (Chairman)	QuantiSci Ltd, UK	PA, SA
Prof Fred Glasser	University of Aberdeen, UK	CS, Gc
Dr John Kessler	EPRI, Inc., USA	Bi, EBS, PA
Dr Clifford Voss	United States Geological Survey	Geo, Hyd

Each member of the team independently reviewed the principal documentation provided by SKB and provided an initial list of comments and questions for clarification. The review team then met with SKB staff in March 2000 to clarify the questions, following which the present joint review report was produced.

The following five key SKB documents were reviewed, with supporting documents also being made available where required:

- Deep repository for long-lived low- and intermediate-level waste: preliminary safety assessment. SKB Report TR 99-28. November 1999.
- Compilation of data for the analysis of radionuclide migration from SFL 3-5. Skagius et al. SKB Report R 99-13. December 1999.
- Analysis of radionuclide migration from SFL 3-5. Pettersson et al. SKB Report R 99-14. December 1999.
- Evolution of geochemical conditions in SFL 3-5. Karlsson et al. SKB Report R 99-15. December 1999.
- Gas generation in SFL 3-5 and effects on radionuclide release. Skagius et al. SKB Report R 99-16. December 1999.

This document describes the results of the review, which was carried out over the period February to May 2000. The views expressed in this report reflect the personal opinions of the reviewers listed above and do not necessarily reflect the views of their organisations.

---

[1] A separate review of SKB's proposed repository concept for the disposal of spent fuel, SFL 2, is being conducted by the OECD/NEA.

[2] Each member of the review team has extensive experience of geological disposal safety assessments. In addition, individuals were assigned principal responsibilities for evaluating the following areas: PA = performance assessment, SA = systems analysis, Geo = geology, Gc = geochemistry, Hyd = hydrogeology, CS = cementitious systems, EBS = engineered barrier systems, Bi = biosphere.

1.1 Background

Swedish law states that the producers of nuclear waste have full responsibility for the safe handling and final disposal of spent nuclear fuel and nuclear waste that is produced. This includes the responsibility to carry out the necessary research and development (R&D) activities in support of these obligations, and to present a comprehensive R&D programme every third year. The owners of the Swedish nuclear power plants have jointly set up the Swedish Nuclear Fuel and Waste Management Company (SKB) for this purpose. The Swedish Nuclear Power Inspectorate (SKI) and the Swedish Radiation Protection Institute (SSI) are responsible for the supervision of nuclear (waste) safety and radiation protection, respectively.

The Swedish Government has accepted geological disposal of spent fuel and other nuclear wastes as the fundamental basis of SKB's research and development work. According to the current concept, spent fuel will be emplaced in copper/iron canisters, surrounded by bentonite clay, at a depth of about 500 m in stable Swedish crystalline bedrock (in a repository referred to as SFL 2). Other long-lived nuclear wastes will be placed in a system of rock caverns at about 300 to 500 m depth (in a repository currently referred to as SFL 3-5). The caverns that are intended for the waste with the highest radionuclide content will have internal concrete vaults, which will act as a barrier limiting release of radionuclides. Before sealing, the vaults and the caverns will be back-filled by porous concrete and sand/crushed rock, in various configurations for each of the three cavern concepts (SFL 3, 4 and 5).

In a Government decision in 1996, SKB was requested to produce an up-to-date safety assessment for each of the proposed disposal concepts. SKB has now completed a safety assessment (called SR 97) for the planned repository for spent fuel, and an additional, separate, assessment for the other wastes in SFL 3-5. Both of these reports illustrate the application of SKB's disposal concepts to the conditions representative of three different sites in Sweden. The importance of evaluating the overall SKB concept at this point in time is related to the decision points in the site selection processes that are now being approached.

SKB is currently performing feasibility studies (desk studies) for the actual construction and operation of the SFL 2 and SFL 3-5 repositories in six municipalities. The next step involves selection of at least two municipalities for more detailed site investigations from the surface, including drilling of deep boreholes. These early steps of the decision process do not involve any formal licensing. However, the municipalities participating in SKB's siting programme have indicated that they need a renewed endorsement of SKB's disposal methods by both the authorities and the Government, before consenting to any site investigations.

An important basis for SKI's and SSI's evaluation of SKB's safety assessments will be the outcome of independent reviews by international experts. The OECD-NEA has reviewed the SR 97 assessment for spent fuel, while the review team for SFL 3-5 was set-up by the authorities themselves. Both review groups worked independently of the authorities.

1.2 SFL 3-5

According to the proposed disposal concept, the deep repository for other long-lived (non-fuel) nuclear wastes will be constructed in three components (caverns, plus or minus internal concrete vaults):

- SFL 3 (cavern with vault) will be used for waste from Studsvik, where, for instance, waste from early Swedish activities in the nuclear sector is currently stored. Operational waste from the central interim storage for spent fuel (CLAB)[3] and the not-yet-built encapsulation plant will also be placed in SFL 3;

- SFL 4 (cavern) will be used for decommissioning waste from CLAB and the encapsulation plant, as well as transport casks, transport containers and fuel storage canisters;

- SFL 5 (cavern with vault) will be used for decommissioned reactor core components and internal reactor parts with high activity.

Although this study represents the first full analysis of this type of repository by SKB (following a pre-study in 1995), there are some precedent studies of broadly equivalent deep geological disposal concepts for similar low and intermediate level wastes (L/ILW). In Switzerland, Nagra has carried out safety studies for the proposed Wellenberg geological repository for L/ILW. Exact waste-type attributions to the Swiss HLW-TRU and the proposed Wellenberg repositories have yet to be made precise, but much of the latter allocations would comprise nuclear facility decommissioning wastes. In the UK, Nirex carried out safety assessments for a deep geological repository for L/ILW (mainly reprocessing wastes, with limited decommissioning wastes) which included the first attempt at a comprehensive study of gas generation within a repository and its impacts. Both of these studies are also preliminary in nature, but do provide relevant documentation available to the Swedish waste disposal programme. Finally, The SFL 3-5 concept can be seen to be based in part on actual experience at the SFR shallow geological repository for generally short-lived low and intermediate level wastes at Forsmark. The SFL 3 and SFL 5 cavern and vault designs can be seen to be derived from the BMA cavern-vault region of this facility.

1.3 Location of SFL 3-5 and Context of the Safety Assessment

For many years, SKB reports have shown the SFL 3-5 repository located at the same site as the spent fuel repository (SFL 2), but with a sufficiently large distance between them that they would not interact significantly, chemically, hydraulically or thermally. However, at present, SKB does not rule out the possibility that SFL 3-5 will be placed at an entirely different location.

In discussion on planning issues with SKB, as part of the review process, it emerged that SKB would favour uncoupling SFL 3-5 from the present work on the spent fuel repository. This is because much of the waste for disposal in SFL 3-5 is yet to be produced and most would not arise for several decades. Consequently, the requirement for the repository lies many years into the future. SKB suggests that nuclear power plant decommissioning may take place over a period of thirty years, with reactor core components likely to be placed in

---

[3] The spent fuel itself is intended for disposal in the SFL 2 repository.

interim storage for about 40 years prior to disposal. CLAB decommissioning wastes are unlikely to arise before 2050. Neither waste group is thus likely to be routed for disposal before this time, and the planned operational date for SFL 3-5 is around 2040. In addition, the waste inventory eventually routed to SFL 3-5 will depend to some extent on more immediate decisions on the future of the existing SFR repository, which disposes of reactor operational and other generally LLW. If the capacity of this repository is extended, some of the shorter-lived or lower activity inventory currently assumed for SFL 3-5 would already have been disposed of in SFR.

In its recent response to SKB's RD&D programme for 1998 (FUD-program 98), the Government noted that (with respect to site investigations):

> In FUD-program 98, SKB AB has not touched upon any questions concerning the final storage of long-lived nuclear waste other than spent fuel. The Government expects that the company will address appropriate questions in association with the programme for site characterisation.

This is an important issue from the point of view of the present review. If the SFL 3-5 project is to be uncoupled from SFL 2, then there is clearly much time to refine the analysis presented in the documents assessed by the review team. If it is to remain linked to the SFL 2 project, then its results have more immediate importance, particularly with respect to the siting and site characterisation studies currently underway. Consequently, the point at which SFL 3-5 lies within the SKB programme affects the 'assessment context' within which the safety assessment approach, its degree of comprehensiveness and how the results of SKB’s current performance assessment (PA) of SFL 3-5 should be viewed.

SKB points out that the present safety assessment is preliminary in nature. An earlier 'pre-study' analysis had been carried out in 1995 (Wiborgh, SKB Report TR 95-03) which covered some of the design and safety issues. The preliminary nature of the report is based on the apparent belief by SKB that there will be many years over which to refine the analysis and the design. This present assessment might thus be taken to have a similar context to the KBS 3 or SR 91 assessments for spent fuel, which advanced an overall concept and showed how that particular repository concept would relate to site-specific geoscientific data.

Given this uncertainty about the programmatic context of both the SFL 3-5 repository project and the safety assessment, it is important to note a significant aspect of the safety assessment results at the outset of the review. The results indicate that SFL 3-5 would produce potentially perceptible radionuclide releases to the environment, with consequent doses from water wells that are close to regulatory comparison levels, on a timescale of hundreds to thousands of years. This is in contrast to the SR 97 assessment for the SFL 2 spent fuel repository, whose base scenario predicts no releases over a million year timescale. Regardless of any considerations of the degree of conservatism in the SFL 3-5 assessment, it is clear that, for co-located facilities, it is *the SFL 3-5 repository* that has the potential for real impacts in the more immediate future. That this would be the case can have been no surprise to SKB, based on the near-field releases predicted five years earlier in their pre-study, and on the results of, for example, the 1995 and 1997 Nirex assessments of the proposed Sellafield repository, in the UK. This raises the level of expectation of what SKB might have wished to achieve with the present analysis.

This important issue of assessment context and its implications is returned to in the conclusions of this review.

1.4 Initial impressions

Within the declared preliminary scope of the assessment, SKB and its contractors have carried out a competent job of developing and presenting an analysis of a basic conceptual model of system behaviour. The review team was impressed with the quality of presentation, the reasonable (although somewhat patchy) level of traceability and the openness of the assessment. In particular, the waste inventory, which was developed specifically for this work, is an excellent and essential starting point for future studies.

Despite this overall positive evaluation, the team has many comments that raise questions about the robustness of the analysis and the usefulness of the study at the present juncture of the Swedish radioactive waste management programme, given the contextual discussion in the previous Section. These are covered in the following sections.

2 Waste Inventory and Disposal Concept

This section examines the inventory of wastes considered by the assessment and the disposal concept, together with the repository design that has been developed to contain the wastes.

2.1 Waste and Radionuclide Inventory

The SFL 3-5 repository is expected to contain a wide variety of waste materials that have already arisen over several decades, and that will arise over several decades into the future. The first requirement for the assessment was thus to construct an inventory of the anticipated waste arisings, covering their physical and chemical nature, their radionuclide content and their existing or future conditioning and packaging systems. An excellent start was made (on what will inevitably have to be a continually refined and upgraded inventory) by Lindgren et al. (1998).

Inevitably, the current inventory contains numerous uncertainties about both past and future waste streams. These lie in various areas, including:

1. the nature and activity of some historical wastes from Studsvik;
2. future arisings and how they will be conditioned and allocated to SFL 3-5 or elsewhere;
3. radionuclide contents of each waste stream estimated using correlation factors;
4. radionuclide contents of reactor core components estimated using activation models.

The first issue can only be resolved by further exploration of the level of information available in the 'corporate memory' of the waste producers and by further characterisation of waste packages in store and if/when they are reconditioned or repackaged. Currently, the radionuclide inventory must be estimated based on the limited analyses conducted prior to conditioning. The second issue can be tracked as the future Swedish waste management and decommissioning programme evolves. This again requires a significant degree of extrapolation to derive estimated inventories.

2.1.1 Correlation factors

Resorting to the application of correlation factors for the estimation of radionuclide inventory (the third issue above) is understandable, and some of the uncertainties in their application are outlined by Lindgren et al. A correlation factor is the measured ratio of activities between a readily measured index radionuclide, such as gamma-emitting Cs-137 or Co-60, and another, less easily measured radionuclide. By measuring correlation ratios for a certain type of waste, the expectation is that the inventory of subsequent wastes of the same type can be assessed by measurement of Cs-137, Co-60 or some other index radionuclide, followed by application of the correlation factors. The acceptability of this approach in a preliminary assessment depends on the total fraction of the inventory which could be in serious error: as the magnitude of the uncertainty in the actual inventory increases, the acceptability of using correlation factors must decrease.

Lindgren et al (1998) provide the primary source of information regarding specific correlation factors applied by SKB to SFL 3-5 wastes. It is a well-documented report, containing references to many correlation factor studies in Sweden and abroad. Where multiple values for correlation factors have been derived for similar types of wastes, these values are cited and graphed to show the range of values. The text also indicates that expert judgement is then used to identify a single preferred value for the correlation factor for each radionuclide.

With respect to this approach, the review team felt that a number of issues would benefit from greater clarity. In particular, there is a need for a more formal acknowledgement and assessment of the reliability and uncertainties in the correlation factors and, hence, the derived radionuclide inventories for SFL 3-5 wastes. The following points need to be considered in future work:

- A list of key radionuclides for which inventories are derived by correlation factors should be identified. A key radionuclide is one that has been found to be a potentially significant contributor to dose in safety assessment calculations. With respect to the issue of correlation factors, however, only those key radionuclides that are non-solubility limited and non-sorbing are of relevance (e.g., C-14, Cl-36, Mo-93, I-129), and the dose or release rates of such radionuclides will roughly scale with changes in their waste inventories.

- There is a need for a detailed, critical review of the studies cited. Uncertainties in the measured activities, hence in the calculated correlation factors, are not reported. If such data are absent, it might be prudent for an estimate of such uncertainties to be made on the basis of analytical detection limits. In addition, the potential impact of environmental factors (e.g., differential effects of volatility between radionuclides, redistribution by moisture, etc.) that might introduce added uncertainty should be considered.

- The way in which expert judgement was used to select final preferred correlation factors should be documented. In several cases, reported correlation factors used to derive nuclide inventories span a range of several orders of magnitude. Lindgren et al. (1998) generally adopt intermediate values within these ranges as their preferred values. It is not clear, however, if a consistent log-mean value or arithmetic-mean value or some other formal selection technique was applied. Furthermore, without a critical review of the cited data and associated but unreported uncertainties, it is difficult for SKB to defend any particular correlation factor value that has been selected by expert judgement.

- It could be useful to SKB to pursue consensus on correlation factors in conjunction with other international waste management programmes that are confronted with similar future wastes, such as reactor operational and decommissioning wastes. In this regard, the Lindgren et al. report is an excellent starting point because of its extensive use of both Swedish and non-Swedish sources of information.

2.1.2 Other inventory issues

The fourth issue identified at the beginning of Section 2.1 concerns the estimation of radionuclide inventories in reactor core components. It is known that both alpha and beta/gamma activities in materials inside the reactor pressure vessel and those containing neutron poisons may be underestimated using the ORIGEN-2 code. Outside the fuel region the neutron flux is underestimated, as U is infinitely dilute such that fluxes are not subject to U self-shielding. At the higher than estimated fluxes, U/Th impurities in steel (e.g. 3 to 10 ppm) might give rise to errors of one to two orders of magnitude in Pu, Am and Cm activities, depending on fluxes and irradiation times. There may thus be more alpha activity in SFL 5 than assumed. The sensitivity of the PA results to increased alpha (and some beta/gamma) concentrations in SFL 5 wastes may need to be considered further.

Finally, several calculations are made of the inventory in SFL 4 where much of the activity is in the form of surface activity. The total is given as $7 \cdot 10^{13}$ Bq: however, if washed, this is said to decrease to $1 \cdot 10^{11}$ Bq at time zero. The difference between these two activities is unaccounted for: if it goes into SFL 3 or SFL 5, these inventories will accordingly need an upward adjustment. While this would result in a relatively small incremental adjustment upward, the resulting adjustment is not noted.

2.2 Design Basis and Safety Concept for the SFL 3-5 Repository

The SFL 3-5 disposal concept (TR 99-28) envisages encapsulation of the higher activity L/ILW in containers of steel and concrete. These containers, in turn, are emplaced in a "concrete waste structure" surrounded by a crushed rock gravel between the waste structure and the excavated crystalline host rock. Two such concrete waste structures are envisaged, SFL 3 and SFL 5. For less active L/ILW, waste packages will be emplaced directly in tunnels with only a crushed rock backfill (i.e. no concrete waste structure). This lower activity L/ILW, designated SFL 4, is to be emplaced in perimeter tunnels around the SFL 3 and SFL 5 caverns (Figure 1, TR 99-28). The depth for the SFL 3-5 repository is projected to be between 300 and 500 meters below the ground surface, with about a 1 km separation distance from a possibly co-located SFL 2 spent fuel repository.

Underlying this design, there is, however, lack of a clear statement of the basic *safety concept* and justifications of barrier function and other design parameters (e.g., depth and distance from the SFL 2 repository). This is particularly relevant because the design presented in TR 99-28 is significantly altered from the previous SFL 3-5 repository design concept (Wiborgh, 1995, TR 95-03). The Executive Summary of TR 99-29 notes that:

> *"The proposed design is largely based on experience from construction and operation of the BMA rock vault in SFR 1" (page iii)*
>
> *"In the long time perspective it is the permeability of the near-field barriers..... and the composition of the water in the repository that will be important for the liberation and release of both radionuclides and toxic pollutants from the near-field." (page vi)*

Beyond these generalities there is no central, comprehensive description and justification of the current SFL 3-5 design concept presented in TR 99-28. Chapter 3 on "Repository design and layout" identifies engineered barriers and design geometry, but does not specify the functional basis or relevant properties of these barriers. Of particular concern to SKB, as noted above, are the permeabilities of barriers and their capacity for chemical buffering (especially pH) of near-field groundwater. However, the relevant information on these performance factors is scattered throughout this report or presented only in cited references.

Repository depth (300 m or deeper) and distance from a possible co-located SFL 2 repository (about 1 km) are presented without justification. Consideration of factors such as isolation from human and climatic impacts and constructability has led to selection of a 500 m depth for the SFL 2 repository concept (SR 97). It is not evident why SKB would deem a shallower depth suitable for the SFL 3-5 repository, given that similar far-fields were assumed in both the SFL 3-5 analysis and the SFL 2 study. Likewise, the 1 km separation may be related to the extent of postulated hydrogeological, thermal or chemical perturbations, or it might be arbitrary: there is no stated basis for this value.

This is more than a matter of style of presentation; there is a need for single report that provides a clear, integrated and technically defensible basis for assessment of the SFL 3-5 repository concept by all stakeholders. What is required are:

- reasons for the choice of the various vault designs and dimensions (why this size, shape, thickness, depth, etc)
- statement of the design principles with respect to the safety concept: how each component is expected to contribute to safety and the safety principles themselves (e.g., slow releases, dilution, hydraulic cage, diffusive control)
- qualitative explanation of the degree of flexibility the safety concept will allow in design and site properties before it would need to be modified or changed to a different concept.

2.3 Physical and chemical containment strategy

A key aspect of the design basis and safety concept is the physical and chemical containment strategy adopted to ensure that radionuclide releases into the far-field and biosphere are at acceptable levels. The SFL 3-5 design has two principal characteristics in this respect: the deployment of a hydraulic cage system to control groundwater flow and radionuclide transport in the near-field, and the use of cement-based engineered barriers.

2.3.1 The Hydraulic Cage Concept

One of the key concepts of the SKB design is the provision of a “hydraulic cage” around the concrete waste structures. Conceptually, water flowing through the near-field rock reaches the crushed rock backfill surrounding the concrete waste structures. It is anticipated that flow will occur preferentially through the crushed rock: penetration of the lower permeability concrete will be reduced, relative to a scenario in which all man-made barriers and backfills have permeability similar to that of the concrete.

Chapters 6 and 7 of TR 99-28 briefly identify the contrast in permeabilities between the gravel backfill and host rock (i.e., hydraulic cage) as key to the SFL 3-5 isolation concept. This conclusion is based on extensive computer simulations reported by Holmén (TR 97-10). These results indicate that flow through the waste-bearing concrete structure will be extremely slow, ensuring that the release of dissolved radionuclides from this structure into the gravel backfill will be controlled by diffusion.

Chapter 8 outlines the conceptual model for near-field transport of radionuclides for this hydraulic cage design based on sensitivity calculations conducted in Pettersson et al. (1999, R 99-14). Chapter 10 presents some additional insights from the same study, noting, for example, that the contrast in permeability of the waste-containing concrete structure relative to the host rock can also have a marked effect on radionuclide release from the concrete structure, if the backfill has a low permeability. Indeed, the difficulty of ensuring that the waste-bearing concrete structure will retain a lower permeability than the host rock may be a key justification in SKB’s decision to change from the 1995 pre-study, low-permeability, bentonite-based backfill concept for the SFL 3-5 repository (Wiborgh, 1995) to the current hydraulic cage concept.

The formation of a hydraulic cage influences the way in which other barriers perform and degrade. The preliminary assessment should have been an opportunity to ask: given plans artificially to control flow patterns in the vicinity of the waste, which aspects of previous research are still relevant? Also, could previous work be modified so as to be relevant to the new situation? However, the opportunity was not taken to relate previous work to the new scenario. Thus, the reviewer is presented with a mass of factual data, little of which is well-related to, and focused on, post-closure performance in the current scenario. The functioning of the hydraulic cage is discussed further in Section 4.4.

2.3.2 Cementitious Barriers

Many of the waste streams will be cement-conditioned for storage, transport and emplacement. In addition, large quantities of a cementitious grout will be used as well as cement, mortar and concrete used in the course of construction and operation and, during closure, in the form of plugs. Credit is apparently only taken for the grout, which is estimated to contain 13,000 t of cement, based on discussions between the review team and SKB. Several processes are said to contribute to deterioration of the cementitious barriers. These include the leaching action of groundwater as well as a number of processes involving reaction between different parts of the man-made barriers: for example, between steel and concrete as well as between concrete and degradation products of the wastes (gas, liquid, and solid). It is however concluded that the barriers will give robust performance for $>10^5$ years.

The key performance features of the cement rely on its physical and chemical properties. An interpretation of the role of its physical properties is complicated by the application of two types of cementitious materials, one having very low permeability, which is used for containers, the other having high permeability, used to fill space and consolidate containers. Both cement formulations are envisaged as having similar chemical properties. These include a sorptive contribution and a chemical contribution which, in certain situations, effectively limits the solubility of some radionuclides.

A key performance consideration with respect to any repository containing cement-based wastes is the potential for development of a high-pH plume that might migrate into the host rock. Such a high-pH plume could affect the performance of the host rock or even the performance of any co-located, non-cement-based repository, by (for example) focussing groundwater flow along 'unblocked' fractures or partially destabilising a bentonite buffer.

Chapter 6 of TR 99-28, citing equilibrium, mass-balance calculations in R 99-15, states that the expectation is that high-pH solutions arising from dissolution of alkali hydroxides and portlandite in concrete will be neutralised within the SFL 3-5 backfill. This is assumed to be achieved by reaction of hydroxyl ions with quartz and alumino-silicate minerals of the crushed host rock that composes the backfill. There are questions regarding appropriate kinetics in pH neutralisation reactions, the relative rates of supply and consumption of hydroxyl ions (including limitations on the transverse dispersion of a high pH plume that prevent 100% contact of the plume with the available backfill), the absence of equilibrium or kinetic data at elevated pressure and the possibility of reduction in rates due to coverage of primary minerals by reaction products. These questions raise potentially significant uncertainties regarding the equilibrium, mass-balance analyses of TR 99-28, requiring further studies, as recognised by SKB (R 99-15).

The calculated doses for the SFL 3-5 repository are dominated by long-lived, non-solubility limited, non-sorbing radionuclides (e.g., C-14, Cl-36, Mo-93, I-129). The peak dose release rates for these species are noted by SKB to be rather insensitive to any changes in near-field or far-field barrier performance. However, SKB presented additional dose calculations to the review team on the sensitivity to sorption of Cl, Mo and I by cement. If the extremely small, but non-zero, sorption coefficients assumed for Cl, Mo and I on cement (TR 99-28, Table 8-3) were assumed to be zero, the predicted release dose rates would be increased by 1-2 orders of magnitude. Conversely, greater sorption by cement (than the values cited) could be expected to lead to lower peak does rates.

SKB currently speculates that these low values may be related to ionic exchange of sulphate phases in the cement. This large effect on such key radionuclides for such small values indicates that further study of this factor is warranted. In particular, an uncertainty analysis of any measurement of extremely small sorption coefficients is needed. Also, it should be established whether 'aged' as well as fresh cement produce the same sorption behaviour.

3 Approach to Safety Assessment

3.1 Systems Analysis and Scenarios

Recent performance assessments by both SKB and SKI have placed much emphasis on being comprehensive in their analysis of the system being considered. Demonstrating that this is the case is normally done by carrying out a formal systems study based on the identification of all the FEPs (features, events and processes) that could affect system performance. This approach is now becoming widespread internationally. Although it does not imply that all aspects of system behaviour would be analysed in detail, it does show that all issues that could be important have been identified and the critical ones isolated, for thorough study, often in the form of a scenario analysis.

It is thus surprising that the SFL 3-5 assessment has not adopted this approach in a more organised and self-evident fashion. The 1995 pre-study tested the methodology on SFL 3-5 (although the results are less readily available internationally, being in the SKB 'AR' report series) but its comprehensive application to the present evaluation is not documented at all (it is merely noted that some analysis was done to support the development of the Reference Scenario). Significant design changes have taken place since 1995. Also, the present study would have been the first opportunity to carry out a proper scenario analysis for alternative evolutions of the facility. Neither of these matters has been addressed comprehensively.

What is, in fact, presented is a deterministic analysis of a single conceptual model of system behaviour, with some parameter variants to evaluate (partially) the impacts of parameter uncertainty and variability. Uncertainties in the system description would normally be addressed by looking at alternative conceptual models of aspects of system behaviour. As will be discussed later, this seems to the reviewers to be especially important in describing the different ways in which the waste and engineered barrier system might evolve. Uncertainties and variability in parameter values would normally be addressed by carrying out a formal, systematic sensitivity analysis. Again, as presented later, the sensitivity study appears to be partial, and not entirely representative of potential variability and uncertainty in the parameters (and ranges of values) chosen.

In some cases, for example the water well receptor, estimated peak dose rates are at or near the comparison level. Without adequate descriptions of the many assumptions (stating whether they are 'best estimate', conservative, or potentially non-conservative) used to obtain the estimated peaks, readers of the report may be left with a false impression about the potential hazard involved with the disposal of SFL 3-5 wastes. Thus, it would be beneficial for SKB to compile a list of the assumptions used, identifying those considered conservative or non-conservative. For each assumption, a quantitative, or at least semi-quantitative comparison of the impact of the assumption on the results (compared to a potentially more 'best estimate' assumption) would provide a great deal of necessary perspective.

Finally, a proper scenario analysis would explore uncertainties in the future evolution of the repository, its environment and the impacts of people. This requires quantitative analysis of how different scenarios might affect 'reference' performance. This has not been carried out in the current study, which, instead, has provided only limited qualitative and, at times, debateable discussion and assertions with respect to alternatives to the Reference Scenario. In particular, the review team was surprised to find that the impacts of glacial and periglacial environments, over the next 100,000 years or so, was barely treated at all.

The principal criticisms of the overall approach to the assessment can thus be summarised as follows:

- no record of a comprehensive systems analysis approach or its findings;
- unsystematic and incomplete sensitivity analysis;
- lack of consideration of alternative conceptual models of near and far-field behaviour;
- incomplete and qualitative description of alternative scenarios and their impacts.

3.2 Use of Site Data and Other Issues

A number of other issues arise with respect to the overall approach to the assessment. The first of these concerns the use of site-specific data to evaluate near-field groundwater fluxes, far-field radionuclide transport and biosphere properties. Each of these aspects is dealt with in more detail later in the review. At present only one matter is raised, related to repository location.

The geological and hydrogeological data used in the assessment were taken from the three sites used in the SR 97 study, where actual field investigations have developed rather detailed models for volumes of rock in which an SFL 2 repository might be located. In keeping with their original plans, SKB have assumed that SFL 3-5 could be sited about 1000 m away from these locations. SKB justifies the lack of treatment of issues such as variability of rock-groundwater system properties and their choice of a limited range of parameter values by saying that, in these locations, there is only sparse site-specific data, as they are away from the central areas evaluated for the SFL 2 repository.

This argument is extraordinary. Given that there is no intention of actually siting the SFL 3-5 repository within the present study, and that one of the chief objectives was to explore the effects of different rock and groundwater properties, it would have been more transparent and defensible for SKB simply to have 'located' the SFL 3-5 repository where they had most geosphere data: i.e. at the same spots used to evaluate the performance of SFR 2 in SR 97. As discussed further, in Section 5, this appears to have resulted in the use of inadequate ranges of flow parameter variability. This relegation of valuable information from real sites appears to be a significant lost opportunity on the part of SKB.

A second point concerns an apparent isolation of the SFL 3-5 assessment from the other international studies that might be relevant and from earlier safety studies of the conceptually connected SFR repository. None of this work is referred to in any depth in the reports. This seems to be a particular omission in terms of the gas analysis, where an earlier study by Nirex (the 'Nirex 97' assessment) addressed almost the same issues, but more comprehensively, and provided valuable results that go beyond those presented in the SFL 3-5 assessment.

Finally, SKB also needs to choose an analysis methodology that is self-consistent with respect to its use of probabilities. While some parameters were obtained using a probabilistic approach (e.g., the EDFs), the overall assessment did not employ probability information. Instead, a series of deterministic calculations was used, without reference to the likelihood that the particular combination of assumptions, conceptual models, and parameter values represents reasonable future conditions and processes.

3.3 Fitness for Purpose

Overall, these criticisms of the general form and content of the assessment raise the question as to whether the SKB TR 99-28 report could provide the appropriate underpinning for important programmatic decisions that may need to be taken in the next few years. The answer to this question hinges on the matter of assessment context, raised in Section 1.4 and considered further in Section 6. Because it is preliminary, and clearly not comprehensive, there may be important issues that have not been explored, and significant uncertainties about the quantitative nature of the results. As will be discussed further in the conclusions, this means that the present report may not be an adequate basis for decisions, with respect to siting in particular, should such decisions be required in the near, rather than far future.

4 Vault Evolution

4.1 Groundwater flow in and around the vaults

The only site-specific aspects of the near-field analysis were the regional ground-water flow value selected for each site and some aspects of the water chemistry for each site. Only one value of regional ground-water flow was selected for each site and converted to a near-field flux via an analysis by Holmén (TR 97-10). This type of generic analysis is clearly only appropriate for a conceptual level evaluation, particularly as uncertainties in site-specific factors affecting flux are not considered. SKB informed the review team that, at the present juncture, such a limited PA approach is being used simply to generate an initial quantitative safety analysis of the hydraulic cage design concept. Even at this level of analysis, a number of issues arise that bring into question the safety margin provided by such a design concept.

A generic study of the hydraulic cage concept has been made by Holmén (TR 97-10) supplemented by a study made by Pettersson and others (R 99-14). These studies present analyses indicating that, if the backfill conductivity is sufficiently high compared to that of the vaults themselves, the hydraulic cage design should, theoretically, reduce flow through the concrete vault such that transport of solutes would occur primarily by diffusion rather than by advective transport through the concrete. This result seems to be robust, irrespective of the heterogeneity and flow direction in the surrounding rock, at least for relatively low regional ground-water fluxes. However, other SKB results show that the cage does not reduce dose significantly, relative to a design without the cage, and that low conductivity backfill may reduce dose more than the conductive backfill. Doses determined for SFL 3-5 are already only a little below the comparison level in some cases. Thus SKB needs to explain in more depth why the low conductivity backfill of earlier designs for SFL 3-5 was discarded, and why the cage is a better barrier to ensure long-term safety. The issue of presenting a sound design basis was raised earlier, in Section 2.2.

Further, the hydraulic cage concept of the SFL 3-5 repository, and particularly the focussing of groundwater flow through the outer SFL 4 region of the repository, depend in part on the assumed long-term functioning of the seals emplaced at the ends of the SFL-3 and SFL-5 emplacement tunnels. SKB (TR 99-28) does not present an analysis or scenario treatment for potential failure of this particular barrier.

The review team considers that the hydraulic cage concept, whilst attractive in theory, raises a number of practical questions. With this type of repository design, the drift acts as a conductive drain that attracts much of the ground-water flow in the vicinity, with 20 to 100 times higher water flux being brought into immediate contact with the vault than in the case where concrete fills the drift entirely. Degradation of the concrete could be accelerated by the focussed flow through the cage, increasing its hydraulic conductivity relatively early in the post-closure phase. SKB must deal with the question of whether the risk that the concrete vault and backfill conductivities will remain constant for around 100,000 years is worth the isolation that the concept provides in the early period of vault evolution. The long-term functioning of the cage is discussed in more detail in terms of how it affects near-field releases, in Section 4.4.

4.2 The early period of vault evolution

During the 40-50 years of repository operations, the open tunnels excavated in the rock permit an exchange between the ventilated tunnel atmosphere and the groundwater in the adjoining rock. Depressurisation can permit precipitation of calcite, while the introduction of oxygen can lead to the precipitation of insoluble iron oxyhydroxides. Other atmospheric gases may dissolve into the groundwater and other dissolved volatiles (e.g., methane, carbon dioxide) may exsolve from the groundwater. A drip-shield roof, if installed during the operational period, would presumably be removed prior to repository closure. Shotcrete, and other engineering countermeasures used to assure tunnel stability are more likely to be left *in situ*, although SKB says that their removal may be considered It is not clear what the long-term effects of such materials might be on the adjoining rock-water system.

After emplacement of wastes and closure of the emplacement tunnels, the near-field is expected to resaturate relatively quickly (tens to hundreds of years), depending on the hydraulic properties of the surrounding rock. Radiogenic heating by SFL 3-5 wastes, as well as evolved heat from curing of cement and corrosion of metal components, are sufficient to raise local temperature by only a few degrees centigrade at most. The mechanical stability of the voids left between the gravel backfill and host rock at the top of the emplacement tunnels has not been addressed specifically in this report.

The chemical composition of water across the repository after resaturation is a more difficult problem to resolve confidently. R 99-15 presents an analysis based largely on assumed thermodynamic equilibrium and mass-balance constraints to outline the general time-evolution of geochemical conditions in the near-field. The reaction of intruding groundwater with the cement-based materials of the waste vault will result in a temporary change in groundwater composition. Specifically, pH will increase locally to about 12.5, with possible depletion of calcium, magnesium and bicarbonate due to high-pH reactions, and a return to reducing conditions promoted in part by corrosion of metallic components. With time, the cement phases will dissolve and form alteration phases in response to external chemical buffering by the host rock.

As noted in Section 2, of key concern is the rate of chemical buffering, especially pH and Eh, and, related to this, the potential migration of a strongly altered groundwater plume out from the repository into the host rock. SKB’s current assumption (R 99-15) is that the pH front is entirely neutralised within the confines of the gravel backfill, based on equilibrium and mass-balance constraints. However, factors such as sluggish kinetics, and formation of metastable phases, may confound this expectation. Given the potential for affecting the isolation performance of the far-field rock if such a pH plume were to migrate into it, a more comprehensive analysis (including evaluation of uncertainties), supported by field and laboratory studies, seems warranted.

4.2.1 Gas Formation

The Reference Scenario (Chapter 6 of TR 99-28) describes a set of assumptions regarding the formation, transport and rapid dissipation of two-phase conditions (water plus gases such as hydrogen and methane) in the SFL 3-5 repository. In general, the rates and quantities of gas generation are assumed to be high from the diverse sources considered, including cellulose degradation, anaerobic corrosion of structural steel, waste steel and waste aluminium, and radiolytic decomposition of water. It is assumed that a few cracks, forming from either volume expansion of corroding metals or curing cracks in the concrete, will be sufficient to allow the rapid escape of the gases formed. The low capillary forces in the gravel backfill will allow rapid, buoyant transport of the gas upward to the void at the crown between the backfill and host rock. This is expected to allow the gas to spread over the entire crown of the emplacement tunnel, enabling rapid escape of the gas into fractures within the rock. Taken together, the assumed rapid formation, transport and escape of the gas enable SKB to neglect any direct effects of gas in the SFL 3-5 safety assessment. However, the review team considers that variants to this Reference Scenario for gas should also be considered in future analyses:

- The assumption of rapid gas formation ought to be supplemented with consideration of cases in which one or more of the gas-forming reactions are considerably slower than the rates currently envisaged by SKB. A more reasonable rate of gas generation may lead to a more extended release of C-14 and other radionuclides that are mobilised over a longer timescale.
- The possibility of episodic gas generation, rather than continuous generation, ought to be considered. Such gas "burps" might arise from localised formation of two-phase conditions or impediments to the access of water to the surface of corroding metals.
- The rapid escape of gas into rock fractures may be impeded by blockage or sealing of such fractures during repository construction and operations.
- High overpressures, significantly greater than can be sustained by concrete, are predicted to occur in the post-closure phase (R 99-16). As a consequence, concrete will crack. TR 99-28 correctly cites relevant background literature but implies that when failure occurs by cracking, the critical crack for gas escape need only be 0.1 mm, and that 0.1 mm cracks will have little or no effect on hydraulic properties. As a theoretical exercise, this may be correct but it neglects the stored elastic energy which may build up prior to failure. The consequences of this stored energy, especially in restrained systems, e.g., reinforced concrete systems, could be much more disruptive than envisaged.
- The cracking from expansion of corrosion products may be localised rather than uniformly distributed as assumed by SKB. The implications of such localised cracking on gas escape ought to be examined.
- Related to the last point, while fracturing of the cement is assumed to promote an increase in gas permeability, the possibility of more extensive cracking leading to formation of preferential flow paths should also be passed to variant cases or scenarios for water flow and radionuclide transport. Larger cracks, if they exist, could call into question SKB's assumption that radionuclide release from the vaults is primarily diffusive rather than advective.
- An assessment should be made of the flammability hazard that might be presented if there are concentrated and spatially focussed releases of hydrogen in the early years after closure. Such releases might be envisaged to occur up a dominant fracture zone into the basement structures of buildings constructed on the surface many years after the repository has been built. This was evaluated in 1997 by Nirex in the UK, but the results are not referred to in this study.
- The full range of volatiles that could be formed by degradation of the wastes and containers and which could incorporate C-14 or H-3 and migrate from the repository has not been evaluated in the present study.
- The formation of a two-phase condition in the near-field that migrates into the far-field may strip other volatiles from the host rock near the surface, including radon. Nirex found that this could give rise to significant doses under certain assumptions, but the present work has not considered these findings.

4.3 The Long-Term: Waste and Cement Degradation

The evolution of knowledge about long-term repository performance and near-field chemistry, as applied to the SFL 3-5 repository, has occurred slowly and over a considerable period of time: approximately 15 years, as evidenced by literature citations. SKB has supported an extensive programme of research on the impact of cement barriers. The results of these projects are described in TR 99-28, which is fully referenced. It has not been possible in the time available to trace every assertion and conclusion to source. However, the review team finds that the key conclusions correctly represent the underlying literature citations. Both SKB reports and international literature are cited: the latter being selected from peer-reviewed sources. Tasks relating to post closure performance have been sub-divided amongst researchers and research groups, as is common in multi-disciplinary programmes. Individual reports are often of high standard but overall, the reports on cement barriers are of uneven quality and perpetuate a number of misconceptions. There are gaps - often serious gaps - which are identified below.

The following paragraphs are devoted to analysis of specific performance-related post-closure features of the cement and concrete vaults presented in TR 99-28 and in the underlying literature. They are presented in terms of general, physical aspects of vault behaviour, and chemical degradation processes, specifically in the cement/concrete structures.

4.3.1 Physical aspects of vault performance

Quantity of backfill materials

The nature of gravel backfill materials used in the near-field is explicit, but their performance, especially resistance to change in the course of performing their function, depends in part on chemical buffering and maintenance of sorption. For this purpose, it is important to identify the total quantity of the various materials present. The inventory values cited in TR 99-28 are for various products made with cement: grout, concrete, canisters, etc. The chemically most active component is Portland cement. Yet it is difficult to establish the cement content and hence the total mass of cement. The review team has concerns that overall, too little cement is being used. In the course of discussions with SKB, the quantity of cement was stated to be 13,000 tonnes. This value is basic to assessment of the future chemical conditioning action and needs to be explicitly presented.

Some materials, notably organics, e.g. sulfonated melamine formaldehyde, may be added to cement to improve its properties. Quite large masses of organics may thus be introduced, up to 3% by weight of cement. Given the known sensitivity of repository performance to the organic content (as a result of reduced sorption on cement and enhanced solubility of some radionuclides), as evidenced by construction of a separate inventory of organics, it may be a significant oversight that the organics in cement have not been included. The organics in the cement dominate the total organic inventory, such that the true content of potentially relevant organics appears to be seriously underestimated.

Gravel, 4-32 mm in nominal diameter, will also be used as a backfill to construct a hydraulic cage around the inner part of the repository. It is said (3.4.2, pages 3-11) that the gravel will “contribute…..to pH and Eh buffering reactions, for example consumption of hydroxide from concrete leaching and consumption of oxygen trapped at closure”. Compelling evidence in support of these statements is lacking.

Repository Location with Respect to Groundwater Chemistry

Section 4 of TR 99-28 outlines hydrogeology, geology and geochemistry at three potential sites. The description raises several issues which require comment. A particular concern is illustrated by the Beberg site, where large local variations in groundwater chemistry occur: for example, Beberg 1 and 2 analyses, Table 4.4, page 4.9. The impression is given that barrier performance is essentially independent of groundwater composition but no detailed analysis, other than for pure water, appears to have been done in support of this supposition.

Backfill Settlement

The development of a hydraulic cage, involving an envelope of 4 to 32 mm gravel, may have consequences in terms of settlement. This is acknowledged in TR 99-28: *"Settlements may occur in the gravel fill… already during the water saturation phase but also in a longer term perspective"*. The nature of these settlements is a potential source of weakness to the performance of physical barriers if, as planned, foundations, side walls and cross-walls are founded directly upon gravel. Settlement and associated cracking in the load-bearing portions will, of course, be detrimental to their physical isolation performance. This requires further analysis and explanation.

Concrete cracking

The Reference Scenario of SKB (TR 99-28) assumes that the available volume of the concrete surrounding corroding metal is sufficient to accommodate the expansion of corrosion products of aluminium and steel. The issue of cracking in concrete and details of crack spacing and crack size are complex. During resaturation, TR 99-28 predicts that compression of boxes may cause early failure. It is important to determine whether this will occur or not. However, if cracking occurs early, during re-saturation, relief of subsequent gas over-pressures will not be a problem. 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. The sensitivity studies conducted by Holmen (TR 97-10) and the analyses by Pettersson et al. (R 99-14) all seem to be based on a uniform hydraulic conductivity for the waste-containing concrete structure. An exploration of the release behaviour of extensive localised cracking in this concrete structure ought to be pursued, to establish the robustness of the hydraulic cage concept.

The SFL 3-5 pre-study design, based on a low-permeability, bentonite-based backfill (Wiborgh, 1995), is briefly mentioned as an alternative. However, concerns with respect to potential elevated pressure of hydrogen gas in the near-field and chemical incompatibility of bentonite with high-pH solutions seems to have led to a de-emphasis of this design concept by SKB. SKB has not made it clear, however, if these were the reasons that the previous design was abandoned.

4.3.2 Cement & Concrete Deterioration Mechanisms

The different cementitious formulations intended for use in the vaults have been described in varying detail in the TR 99-28 report. This is generally permissible in a preliminary assessment, although it does need to be established that materials exist which have the desired properties. The plugs specified for SFR 3-5 are a case in point: it needs to be established that large-diameter seals can be formed having the requisite properties. However, the central issue in the performance of the repository is the long-term evolution of the cement-based barriers. A number of deterioration mechanisms which affect barrier performance in the post-closure phase are discussed in TR 99-28, and supported by trial calculations. The review team has the following comments on these mechanisms:

- Cement may react, with loss of pH, with other materials in the repository. Because of short diffusion paths, the most reactive of the non-cement materials are likely to be (a) pumice or other pozzolanic fillers (b) sand in mortars and concretes and (c) aggregate ("ballast") in concrete, decreasing in approximately that order. Other, physically remote materials such as crushed rock backfills are less reactive. It is therefore perplexing to find so much attention devoted to reactions of cement with crushed rock backfills without also undertaking calculations on the more reactive components of the system. A rethink of priorities is needed. If reaction with siliceous materials is a problem, it may be useful to consider alternatives.

- Some causes of concrete deterioration are well-described in underlying literature but are not dealt with in TR 99-28. An example is AAR (alkali-aggregate reaction). Having raised the problem and concluded that it may be a cause of deterioration, it needs to be included in the overall assessment. Perhaps it is now thought to be of diminished importance: if so this should be stated and evidence cited.

- TR 99-28 does describe fully other causes of deterioration of cement/loss of high pH. However, the impacts of various factors are treated piecemeal. This approach is particularly unsatisfactory for saline water where (a) civil engineering experience shows that attack of saline water on cement is cumulative and (b) attack does not occur uniformly; physical and mineralogical zonation occurs, as a consequence of which, calculations based on bulk changes to specific volumes of solids - and hence the potential for expansion - are unrealistic.

- The underlying literature cited in TR 98-28 significantly underestimates the amount of portlandite produced by cement. Perhaps this is conservative but if so, it is unrealistically conservative. What is not conservative is the increase in porosity, and hence in permeability, attending dissolution of portlandite. The review team believes that the resulting increase in permeability will be significant. In discussion with SKB it was stated that the calculation was based on concrete (which would undergo an increase in porosity of ~1%), not cement (which would be higher). Even if this is correct, it does not adequately resolve this issue. The rock component is inert with respect to dissolution: Ca(OH)2 dissolution can only occur from the cement matrix, where the impact on its permeability is substantial. The dissolution calculations are apparently based on fresh water and need to be repeated with appropriate input data for saline water.

- Many calculations are based on the assumption that the performance of cement will be roughly the same in fresh and saline waters: certainly no calculations related to brines are presented. Yet from civil engineering, it is known that deterioration rates of cement and concrete, as well as mechanisms of deterioration, are very sensitive to groundwater chemistry. Indeed, this may potentially influence site selection. These issues are not adequately addressed in TR 99-28.

- The nature of interactions between cement barriers and groundwater is not well related to flow regimes. Since the hydraulic cage is a relatively novel concept, much more detail is required to determine the relationship between advective and diffusive-driven transport processes. The presence of a weak thermal halo in the vicinity of the repository and of its potential influence on transport processes seems not to have been considered.

4.3.3 Radionuclide interactions with cement

The radiochemical immobilisation potential of cement is addressed and defined by two approaches: the K_d approach, and a solubility-limited approach. During discussion, it was apparent that some thought had gone into which approach should be applied to key nuclides. If so, this decision-making process is not adequately justified in TR 99-28, in which the choice of approach seems to be quite arbitrary.

Sources and application of K_d values (Table 8.3) are unclear. For example, it is not clear whether the values labelled “concrete” are for cement, or whether aggregate is also believed to play a part. Similarly, for rock/gravel, it is not clear whether the pH is assumed to be ~8 as it is for groundwaters, or whether the action of cement, which raises pH, is allowed for in the numerical values of K_d. Data sources and pH range of applicability are not sufficiently well quantified. The impact, or potential impact, of an alkali plume on sorption in or on rock is not addressed except in a qualitative manner.

The extent to which solubility limitations, where known, are applied in preference to, or in conjunction with, K_d values is uncertain. The literature records many more solubility-limited values than are given in Table 8-4, although these are not used. If concentrations lie below the threshold for precipitation, this needs to be stated and supported by data. Only a few solubility-limited values are shown in Table 8-4 and they are not compared with those in the literature.

4.4 Near-field transport

Near-field transport in this context involves those processes concerned with transporting radionuclides out of the concrete structures into the surrounding backfill and then into the surrounding rock. This Section assumes that the radionuclides are in either aqueous or colloidal form such that transport is via the groundwater pathway. Gaseous transport has been considered earlier in Section 4.

As discussed in Section 2.3.1, a unique and central aspect of the SFL 3-5 repository design is the concept of the ‘hydraulic cage’. By designing the surrounding backfill to have orders of magnitude larger hydraulic conductivity than the concrete vaults containing the majority of the radionuclides, a very low hydraulic gradient across the concrete vaults can be obtained. By ‘designing’ in such a very low hydraulic gradient, the SKB analyses show that advective flow of radionuclides out of the concrete vaults is negligible. Thus, SKB models invoke only diffusive release of radionuclides from the concrete vaults, accounting for sorption in the cement mass further to slow the release of those radionuclides with a non-zero sorption coefficient. The hydraulic cage concept depends, therefore, on maintenance of the following conditions for the entire period of importance:

- the hydraulic conductivity of the backfill must remain significantly (at least one or two orders of magnitude) larger than both the surrounding rock and the concrete vault;
- no 'significant' preferential flow pathways must exist through the concrete vault such that advection – even on a local scale – could become important.

Thus, near-field transport behaviour, as modelled by SKB, seems quite dependent on the assumption that the near-field system is fairly homogeneous. Significant heterogeneity in, or other combinations of, the conductivity values chosen for concrete and near-field rock might nullify the beneficial effects of the hydraulic cage. The importance of the above assumptions has been partially highlighted by the analyses provided in Chapter 11 of R 99-14. The 'base case' conductivity of the concrete vault and the backfill material was assumed to be 10^{-8} and 10^{-4} m/s, respectively. The base case effective diffusivity of radionuclides that do not sorb onto cement was assumed to be $3x10^{-11}$ m^2/s - roughly 1 to 1.5 orders of magnitude lower than bulk diffusivity values of most ions in water.

Analyses provided in Chapter 11 of R 99-14 show that the hydraulic cage concept is effective in providing an upper bound on the release rate of radionuclides from the concrete vaults in the sense that increases in the groundwater flow rate in the surrounding rock eventually cause only negligible increases in the release rate of radionuclides from the vaults. At very low groundwater flow rates (~1 m^3/yr for the 'base case' assumptions) release rates become proportional to flow rates. The actual flow rate at which the release rate becomes proportional to the flow rate would be somewhat lower if diffusion into the surrounding rock had also been considered in the model.

Table 11-1 and Figure 11-4 of R 99-14 provide a summary of the sensitivity studies on releases from the near-field as a function of different hydraulic conductivity values of the backfill and concrete (rock conductivity was fixed in all models at 10^{-9} m/s). The results show that the relative amount of specific groundwater flow through the concrete structures can be reduced to as low as 1% of that in the surrounding rock if the hydraulic conductivity of the backfill can be maintained at 10,000 times the concrete value (consistent with the base case assumption). However, the relative amount of specific flow in the concrete increases with decreasing backfill conductivity.[4]

What matters, however, is the effect of various combinations of conductivity values on the *absolute* release rate. Results provided in Figure 11-4 do show that the relative contributions to release from diffusion (represented in Figure 11-4 by relative releases from the backfill) and advection (represented by releases from the concrete structure) change dramatically as the assumed backfill conductivity is decreased. However, the absolute value of release is shown to increase by only a factor of two as backfill conductivity is changed over six orders of magnitude. Thus, it seems to make very little difference to total release whether or not the backfill conductivity is kept high relative to the rock or concrete. It is difficult to understand, therefore, why SKB is stressing the value of the hydraulic cage concept when the 'benefit' of the hydraulic cage concept seems to be

---

[4] Presumably the same would be true if the concrete conductivity were increased, although sensitivity studies for various values of concrete conductivity were not presented.

limited to only a factor of roughly two for the release rate. It would have been enlightening if the sensitivity studies as shown in Figure 11-4 had been extended for backfills with conductivities significantly lower than that of the surrounding rock – as may be the case, for example, with a bentonite-based backfill. The trend toward even lower absolute release rates with successively lower backfill conductivity values just begins to show in the existing Figure 11-4.

From presentations by and discussions with SKB staff, the reviewers understand that the hydraulic cage concept was developed due to difficulties with a previous design that employed a bentonite backfill. SKB also believes that it will be useful in dissipating gases generated in the vaults. Since the existing design probably indicates theoretically higher water-borne radionuclide release rates than for the previous bentonite backfill design (assuming the bentonite performs as was originally intended), it would be useful for SKB to discuss the reasons why the previous bentonite-based backfill design has been abandoned and why the existing design is better even though it may appear to have higher release rates than the old design. For example, since the release rate in the current design seems only slightly sensitive to the actual backfill conductivity it could be said that the present design is ‘robust’ in this respect. In more general terms, and in line with the review team's earlier comments on the lack of a clearly defined design basis, it would be useful if SKB were to explain more clearly the benefits and consequences of adopting the hydraulic cage model.

One concern with the hydraulic cage concept as presented in the existing analyses is the assumption that the concrete conductivity does not change with time. Previous discussion in this review has highlighted our concern that SKB may be somewhat optimistic in its assumption about the long-term integrity of the concrete structures. Further discussion and/or analyses by SKB should be included to address the bases upon which SKB makes the assumption of long-term concrete integrity; alternatively, SKB should provide analyses that consider the effects of short- or long-term concrete degradation on repository performance. In the specific case of the hydraulic cage concept, if SKB feels it cannot fully support the assumption of long-term concrete integrity, then SKB should reassess the assumption of both homogeneous and constant concrete properties. The reviewers are concerned that short- or long-term degradation mechanisms in the concrete could introduce cracks that penetrate the entire depth of the concrete vault walls that could violate SKB’s assumption of homogeneous concrete properties. For example, if the cracks are large enough, advection may become important on the local scale. Advection through cracks may lead to preferential leaching of the $Ca(OH)_2$ from along the cracks with subsequent changes to both local concrete permeability and sorption properties. Large-scale leaching of concrete may lead to increases in conductivity, although the cursory SKB analyses presented suggest that the conductivity increases are likely to be small, because bulk (or global) porosity is only projected to increase by 1%. The basis for this statement needs to be documented, but, in any event, it is the consequential localised changes to permeability that need to be assessed.

In their written documentation, SKB provided no analyses for the potential implication of concrete cracks on their assumption about homogeneous properties and diffusion-dominated radionuclide release. The constructability of crack-free barriers needs to be demonstrated. During discussion between SKB contractors and the reviewers, an SKB contractor did provide some convincing analysis to suggest that small cracks penetrating the concrete vault walls will not be significant enough to violate the above assumptions. This analysis should be documented. Furthermore, SKB should consider whether much larger cracks that would violate the homogeneity and diffusion-dominated release assumptions could reasonably occur. If so, SKB should provide appropriate consequence analyses.

Radionuclide release from the concrete structures will be in the presence of high pH conditions due to the simultaneous dissolution of $Ca(OH)_2$ from the cement. The current conceptual model provided by SKB assumes that there is sufficient buffering capacity in the backfill effectively to neutralise the pH, and that the pH-reducing reactions are relatively fast. The SKB estimates of buffering capacity appear to be based on the assumption that *all* of the backfill is available to buffer the high pH plume. Such an assumption would imply efficient mixing of the high pH plume with the groundwater passing through the backfill. Efficient mixing would require either turbulent flow conditions or, in the case of laminar flow, a sufficiently large transverse dispersion.[5] Turbulent flow conditions are not supported by the relatively low assumed flow rates through the backfill. Thus, SKB needs to provide evidence of sufficiently large transverse dispersion with respect to the assumed kinetic rate terms, to support the mass balance assumption, leading to equilibrium reaction between the high pH plume and the gravel. Otherwise, SKB ought to adjust, as appropriate, their estimates of available buffering capacity provided by the backfill.

Furthermore, SKB does not consider the effects on the backfill properties due to reaction with the high pH plume. It may be that reaction products could significantly alter the porosity, conductivity, and sorption properties of the backfill. Colloids containing radionuclides may also be generated in the pH-reducing reactions. At the least, SKB should provide analyses to suggest these reaction product effects are negligible. The mass balance calculations discussed above would provide the basis for some of this argument.

The current conceptual model for near-field release assumes the source term is homogeneous. That is, it does not consider heterogeneities in the material placed in SFL 3-5. Given the diverse nature of the material to be disposed of in the proposed SFL 3-5 repository it is likely that some degree of heterogeneity in the source term from one section of the repository to the next could be expected. Some of the waste may also be released in more of a ‘pulse’ than in the steady manner assumed in the current conceptual model. The current assumption that the groundwater flow direction is parallel to the SFL 3 and 5 drifts, acts further to homogenise (but also to concentrate) the source term. If a reasonable amount of heterogeneity in the emplaced material were considered along with flow more perpendicular to the SFL 3 and 5 drift direction it may be that a significantly heterogeneous plume would occur to warrant separate analysis. It would be useful for SKB to provide arguments why both spatial and temporal heterogeneity in the source term can be neglected.

---

[5] Pure diffusion is likely to be too slow to be of value for the groundwater velocities in the backfill assumed by SKB.

5 Far-field Flow and Radionuclide Transport

The primary factor that controls rate of degradation of engineered barriers and ultimate transport of radionuclides to the biosphere is the flow of ground water. The quantity of ground-water flow through each site was estimated by SKB on the basis of hydrogeological structural modelling and hydrologic numerical modelling for SFL 3-5. However, none of this analysis was specifically done for SFL 3-5 and it is rather a by-product of work carried out for SR 97.

There are several problems with the SFL 3-5 analyses of ground-water flow that may call into question the conservativeness of the SFL 3-5 PA. This is important, because the report has demonstrated that ground-water flux is one of the key factors affecting dose. Specifically, it is the opinion of the review team that the assessment has not considered high enough flow rates at each site, nor has it considered the significant range of uncertainty possible in this factor. This doubt is elaborated on a site-by-site basis in Section 5.1 below.

As noted in Section 3, for each site, the SFL 3-5 repository was 'placed' *outside* the most investigated areas, where practically no local site information was available. The review team believes that a more realistic analysis could have been accomplished by placing the repository in the same location as SFL 2 in the SR 97 analysis. Since no interaction of repositories is considered in either analysis, independent location of each at exactly the same place would have been feasible for SKB’s exercise.

The analysis employed an uneven and unconvincing use of data and hydrogeological models considering all three sites together, and thus has not been able to show the extent to which differences in site characteristics yield differences in repository safety. Two different numerical ground-water flow codes were used for the three sites. Even where the same code was used (Beberg and Ceberg) the code was applied to each in a significantly different way, especially in terms of meshing and parameterisation. Thus, none of the ground-water model results may be directly compared for the sites. It may be quite possible, for example, that using Aberg’s code to model Ceberg or Beberg would give different results, and vice versa.

A further flaw in the PA is that only one regional flow value was selected for each site at the arbitrary location of SFL 3-5 for the purposes of near-field calculations. This approach ignores the most striking characteristic of ground-water flow in fractured rock: its variability. Although, when taken together, the flow values selected for the three sites range over 3 orders of magnitude, this does not necessarily imply, as SKB suggests, that it may be considered that the flow rate was properly varied for each site or for the PA as a whole. SKB must first demonstrate that applying all three flow rates at each site would not have different effects on dose at each due to real differences in structure, geometry, chemistry and other site-specific factors. The review team is concerned that this may not be found to be true.

5.1 Ground-water flow at the three type sites

Aberg was the most recently and most intensely studied of the three sites. Thus, the local hydrogeological characterisation has the highest resolution of the three. Despite this effort, there are still significant uncertainties and unknowns inherent in the hydrogeological structural model of the site. For this analysis, the SFL 3-5 repository was located outside the main investigation area, and knowledge of the hydrogeological structures there is even more limited compared with the investigated area. Somehow, and possibly inadvertently, the SFL 3-5 repository was placed within a major regional fracture zone at this site, which may provide serendipitous conservatism to the determined flow rate, although the effect was not quantified.

The numerical code used for analysis was PHOENICS, which solves general forms of the Navier Stokes equations for fluids. The code was adapted for application to random porous media with fracture zones and for variable-density fluid. The model considers a porous medium with flow parameters distributed randomly in space for the rock matrix, but without spatial correlation. The lack of spatial correlation is questionable, as it results in low spatial connectivity of modelled transmissive features in the rock, and may underestimate total percolation. Except for a few local structures that intersect the Äspö Hard Rock Laboratory, only regional fracture zones were included in the model used to determine flow near SFL 3-5. These were included implicitly, by a method that modifies the random permeability field in the vicinity of the zones. This approach to representing transmissive zones may reduce their connectivity and thus may impede through flow, thus reducing calculated fluxes.

Except for the placement of the repository in a fracture zone, a number of other factors in the analysis of Aberg tend to underestimate the ground-water flow. The analysis has not considered the possible range of ground-water flow rates that may occur in the PA for this site, because only one conceptual model representation of the site was used for determination of flow near SFL 3-5.

Beberg was investigated in the mid to late 1980s, and most effort was directed at understanding the hydrogeology associated with, and the flow through and around, a single highly conductive fracture zone (Zone 2), of limited lateral extent. In the vicinity of Zone 2, and to the depth of Zone 2, the site characterisation gave relatively high resolution of hydrogeological features. Outside this immediate area, resolution was much lower. The SFL 3-5 repository was located outside this main investigation area, resulting in an obvious reduction in the number of hydrogeological features in the repository’s vicinity. This may reduce the modelled through flow near the repository.

The finite-element code NAMMU was used for the hydrogeological analysis. This code solves well-accepted ground-water flow and transport equations for variable-density fluids in porous media. Fracture zones were modelled using an implicit method (different from Aberg’s method) that modifies permeabilities of finite elements in the model mesh. Again, this may decrease spatial variability and may spread conductive flow paths, decreasing fluid velocities in parts of the modelled domain. The mesh, however, follows along fracture zones, making the numerical representation of fracture zones more accurate using this approach than for Ceberg (discussed below).

The effect of Zone 2 stands out in all model results, apparently indicating the importance of this one structure as a control on ground-water flow and movement of salt water. While a superficial examination may consider that this is the only such structure in the entire Beberg area, the reviewers take the view that this is unlikely. Rather, the modelling shows how careful field characterisation in the vicinity of Zone 2 has demonstrated an under-characterisation in the rest of the area. Other conductive fracture zones and segments are possible. In the PA for Beberg, SKB should have considered the potential impact on performance should similar conductive structures at various depths and locations exist throughout the area.

The lack of conductive structures near SFL 3-5 in the model and the relatively coarse discretisation of features may lead to the low ground-water flows predicted for the PA. SKB has not weighed the impact of other possibly undiscovered structures and connectivities on the flow through the repository.

Ceberg is the earliest investigated site of the three. It is unusual among SKB's study sites, in the sense that it is difficult to distinguish the transmissivity of the rock mass and fracture zones at the site. Fracture zones seem not much more permeable than the rock mass, as fracture zone and rock mass conductivity have similarly large variation. However, this judgement is based on an early field characterisation programme; investigations took place there nearly 20 years ago. While there are some geological arguments for uniformity of transmissivity at Ceberg, it is possible that a return investigation of the site with a larger number of boreholes and current investigative approaches would resolve fracture zones that are significantly more conductive than the rock mass. The old data may indicate simply that the site was not sufficiently characterised to resolve structures. SKB did not consider this possibility when reinterpreting old site data for the SR 97 and SFL 3-5 analyses.

SFL 3-5 is located at the outside edge of an area in which a few local fracture zones were found. Other zones considered in the analysis are only regional. Between SFL 3-5 and most potential discharge points for flows moving through the repository, there is only intact rock mass. This hydrogeological description of the site would tend to underestimate flow near the repository, in comparison with an alternative description that includes more local fracture zones.

For the hydrogeological analysis, the finite-element code, NAMMU, was also used. In this case, the implicit method used to represent fracture zones may have a strong impact on decreasing spatial variability because the mesh is not aligned with the structures. This may further decrease fluid velocity in parts of the modelled domain.

5.2 Radionuclide transport

To calculate far-field radionuclide transport from SFL 3-5, SKB used the code FAR31, which considers radionuclide chain decay and migration along a one-dimensional flow path with advection, dispersion, matrix diffusion, and linear sorption. Use of such one-dimensional transport codes to bound far-field migration of radionuclides has become almost a standard in radioactive waste repository assessment internationally.

Appropriate and defensible application of such a code determines the range of transport behaviours possible, considering the spatial and temporal variability of factors and parameters at a site to the extent known, as well as uncertainties in the understanding of a site. The key to sound application lies in the choice of parameter values for the code, both in terms of selecting a range for individual parameters, as well as in selecting a variety of diagnostic combinations of values of different parameters. Ranges must be selected that include the possible minimum, maximum and 'normal' values for each parameter for a site. Diagnostic combinations of parameter values are those that cause extreme transport behaviours, as well as those that are most likely to occur together because of physical or chemical conditions at the site.

For SFL 3-5, SKB selected only a *single* set of parameter values for each site. Thus, determination of the possible range of transport behaviours was not accomplished, and neither uncertainties nor variability were evaluated. Values of parameters were borrowed from the parallel SR 97 study, with little additional effort expended for SFL 3-5. Obviously, this makes it impossible to prove the robustness of the SFL 3-5 design with respect to the range of parameter values that might be found at a real site, and this lack is considered to be a major shortcoming of the assessment.

5.2.1 Far-field transport parameters

Parameter values derived from the far-field numerical ground-water modelling were path length and travel time, ground-water velocity and discharge points, and flow-wetted surface area. Path length and discharge points, as determined by particle tracking in each site’s model, may be questioned inasmuch as the coarseness of numerical meshes used and the poor resolution of the underlying structural geological model near SFL 3-5 at each site may have a strong impact on the results. The sensitivity of the results to variation in meshing and structural model was not tested in the report, so the usefulness of these results is unclear. Similarly, sensitivity to repository depth should be investigated: SFL 3-5 is shallower than SFL 2 and it is not explained why despite the finding that long paths to the biosphere may be beneficial to safety. Travel time depends in part on effective porosity, a parameter that was also not varied in the analyses. For far-field flow modelling, the sensitivity of path length and discharge point to a variety of boundary conditions was also not tested. Conditions applied at lateral, top and bottom boundaries in the models, and the locations of lateral and bottom boundaries, may strongly impact discharge points and path length. No sensitivity analysis of these factors was carried out.

As mentioned in Section 3, a particularly unrealistic aspect of the PA is the use of present climatological conditions for assessing flow-related parameters over the next 100,000 years and longer. It is accepted by SKB that periglacial and glacial conditions will occur at some time during the period of concern for SFL 3-5 repository safety, but the effects of these colder climates on performance are dismissed in the PA. Permafrost, cold- and warm-based glaciers, even at some distance from each site, would cause significant changes in hydrogeological boundary conditions and water chemistry, with powerful effects on discharge points, fluid velocity, and path length. On the other hand, SKB takes credit for glaciation when it ‘scrapes away biospheres in which radionuclides and chemotoxic species are accumulated’. This is an uneven handling of the same stress on the system. Effects of climate must be considered thoroughly in both positive and negative senses for repository safety, and must be considered together with other parameter variations.

One of the key controls on far-field radionuclide transport is the ‘F’ parameter that influences retardation, allowing radionuclides to decay to varying extents before exiting the subsurface. ‘F’ depends on path length (derived from the far-field numerical flow model for each site) and flow-wetted surface. Again, only a single value of ‘F’ was selected for each site, and the value selected may not be representative of the lowest values possible, given uncertainties in rock structure. Flow-wetted surface depends directly upon the geometries of flow paths within fractured rock, and these are not known for any of the sites. Selection of higher ‘F’ values for a PA decreases maximum and total doses.

‘F’ site values for SFL 3-5 were drawn from values used in SR 97. The Aberg value, 2.4×10^{11} s/m, is two orders of magnitude higher than a minimum reasonable value for the site as determined by Dverstorp and others (SKI Report 96:14, 1996). In the face of a lack of field data directly measuring ‘F’, an ‘F’ range was determined by these authors based on simple geometric reasoning. The lower end of their range has a value of 10^9 s/m, which may occur in case of some degree of flow channelling in fractures, or in highly conductive fracture zones; both of these types of structures are likely to exist at Aberg. The report does not refer to this previously published work, nor is such geometric reasoning attempted. Similar geometric arguments concerning flow channel geometry are possible for Beberg and Ceberg, but were not considered by SKB, and the values of ‘F’ used by SKB for these sites may be relatively high and thus optimistic for PA.

The penetration depth for matrix diffusion, another key parameter affecting far-field transport, impacts primarily the retardation of non-sorbing nuclides. SKB has selected the maximum possible theoretical value of this parameter for each site, half the distance between fractures, 2m to 20m. Research in other countries shows that matrix diffusion is limited to a narrow band of rock (on the order of centimetres thick) adjoining flowing fractures. Other PA studies of fractured rocks consequently use limited penetration depths for matrix diffusion. Lower values tend to increase releases from the far-field and cause them to occur earlier. Thus, SKB’s selection of values of this parameter for PA is not conservative, though it affects only a few of the radionuclides important to dose.

K_d is the linear sorption coefficient that has different values for each radionuclide and that takes on different values depending on both water chemistry and rock composition (i.e. which minerals coat fractures). SKB considered only minor variation of this parameter based on whether water types would be fresh or saline. However, the SFL 3-5 repository and discharge paths at each site may encounter waters that are fresh (rainfall or glacial meltwater), seawater, or shield brine. Migration of subsurface water bodies of these types during climate change was not considered by SKB, and the variations of K_d are thus incomplete. Furthermore, K_d depends on rock type and on the coatings in flowing fractures. K_d variation based on these factors was not considered at all in the PA. It is not clear what effect such variations would have on releases.

Effective diffusivity is an important factor controlling the retardation of radionuclides in the far-field . Values for each radionuclide were not related to the three sites for SFL 3-5. The values were determined based on a limited number of laboratory diffusion experiments using small rock segments and an interpretative method to apply these results for the determination of other radionuclides. There is some uncertainty concerning diffusivity values determined in the laboratory due to insufficient sampling of heterogeneous pore distributions in the rock when using only a few samples, and due to the unloading of the rock during testing. Both of these factors may tend to over-estimate the diffusivity, which is non-conservative for the PA. Future *in-situ* measurements may be able to verify these values, but these must be treated with caution at present. To accommodate this uncertainty, SKB should have employed a range of diffusivity values for each radionuclide in the SFL 3-5 PA.

Taken together, this lack of consideration of uncertainty and variability in far-field transport parameters indicates incompleteness in the safety assessment, with several indications that releases calculated for each SFL 3-5 site may not be conservative. The result of the single parameter set for each site already comes close to the comparison levels used for individual doses. Because a sensitivity analysis of the whole system performance has not been presented it is difficult to say how a more conservative approach to the far-field analysis might weight the overall results. Nevertheless, there are grounds in the discussion above for believing that conclusions drawn on appropriateness of design concept may not be sufficiently robust. This issue is returned to in Section 7.

6 The Biosphere and Exposure Groups

The biosphere was modelled in order to derive a set of "Ecosystem Dose Factors" (EDFs) to convert radionuclide concentrations entering the biosphere from the geosphere into an annual individual dose to a member of the 'critical group'. Individual EDFs were generated for the full suite of radionuclides considered in the SFL 3-5 exercise for several different assumed biospheres.

6.1 Choice of biospheres

The biospheres selected by SKB were:

- **Lake** (release of radionuclides from the geosphere directly into lake waters: i.e., by-passing lake sediments) with use of lake waters for drinking, and irrigation of crops and livestock;
- **Running water** (radionuclides are assumed to be homogeneously distributed in the water without sedimentation) with exposure due to drinking water, fish, crustaceans, and milk and meat from cattle that have consumed water and aquatic plants or have grazed on land irrigated with the contaminated running water;
- **Archipelago** or **'coastal area'** (release of radionuclides into waters near, but not directly into the Baltic Sea) with use of archipelago waters for eating plants and animals (e.g., fish, crustaceans);
- **Agricultural** (upwelling of radionuclides into agricultural soils with use of the soils for agriculture) with exposure pathways that include consumption of cereals, leafy vegetables and root crops, plus milk and meat from animals fed with feed produced on contaminated land, inhalation of dust, and external exposure from contaminated soil;
- **Peat** (upwelling of radionuclides into peat land with subsequent use of peat land for agriculture or heating) with similar exposure pathways as that for agriculture plus inhalation of gases from burning peat;
- **Well/irrigation** (extraction of groundwater directly from the geosphere via a well for use in small garden irrigation, watering livestock; and drinking);

Although forest ecosystems dominate all three of the study sites, peat land was substituted for forest land since a biosphere model for forest ecosystems has not yet been developed.

The above conceptual models involve a large number of assumptions in the development of the biotope. With further research (which the review team understands is currently underway by SKB), it may be that current assumptions about biosphere features (such as sediment sorption and the rate and method of conversion of lakes into wetlands, bogs, and then agricultural land) will unearth some fundamental improvement in conceptual model understanding as it relates to the transfer or buildup of radionuclides in various parts of the biosphere. SKB is encouraged to continue these studies. However, it is also recognised that additional model complexity is not necessarily the goal of these studies. SKB noted that one of the conclusions from previous model inter-comparison exercises in which SKB participated was that more complex models are not necessarily 'better' than less complex ones (TR 99-40, Section 6.2).

The terrestrial biospheres were stylised into 250 m x 250 m squares with homogeneous biosphere properties within each square. For most of the scenarios it is assumed that radionuclides entering each square are uniformly distributed; radionuclide flux and the assumed biosphere processes are assumed invariant over a period of 10,000 years to achieve steady state flux of radionuclides through the biosphere system.

6.2 Approach to biosphere model development and EDF calculations

When assessing the appropriateness of the biosphere modelling approach used by SKB, it is most important to remember that the details of the future biosphere systems as they affect, and are affected by humans, remains largely speculative. While it may be possible to have a reasonable amount of confidence that future *natural* biosphere systems (i.e., systems unaffected by humans) are understood, future human behaviour is largely unknown. Thus, detailed modelling of biosphere systems related to specific human exposure pathways are probably inappropriate.[6] Because of the unknown nature of future human behaviour, many regulators and other international guidance groups recommend that biosphere assessments assume future human behaviour and future biospheres in which those humans will live should resemble those in the present (or, sometimes, in the past) (see, for example, IAEA BIOMASS Theme 1, Working Document 3, 1999, for a discussion of this issue and a review of relevant guidance and regulations).

6.2.1 Range of biosphere systems

Where specific biosphere systems are likely to change over time, or are unknown, the use of a variety of biospheres is useful to get some idea of the range in possible biosphere effects, such as for site selection. It seems that a reasonably wide range in possible biosphere dose conversion factors have been captured in the present SFL 3-5 analyses, with the following exceptions: SKB should provide future evidence (as it becomes available) that forest biotope results would also fall in the range of the present results; conservatisms in the ‘coastal area’ biosphere, if removed, would provide even lower EDFs; other conservatisms, if removed would tend to lower all the EDFs (the exact amount of lowering is unknown). This is discussed in more detail later.

Post glaciation rebound will have the most dramatic effect on the validity of constant biosphere assumptions for coastal sites like Aberg, although uplift will also affect Beberg and Ceberg. SKB does recognise continued uplift will cause a shift of discharge to more terrestrial and less marine areas. Furthermore, they also recognise there is uncertainty in the exact discharge points into each of the existing areas. Finally, it must be remembered that none of the three sites are the actual disposal site. In general, SKB has dealt with these issues by assuming that at some point during the history of radionuclide release from each site, radionuclide release will occur into each of the terrestrial biospheres (with Aberg also having the archipelago biosphere). This seems like an appropriate approach given the present level of knowledge and the fact that the final disposal site has not yet been chosen.

The reviewers agree with SKB that the biosphere assumptions are an important component in the total repository system model. This is because the individual dose conversion factors for many of the most important radionuclides are orders of magnitude different for different biosphere assumptions and postulated pathways. This causes the dominant radionuclides to shift for one biosphere versus another. Thus, SKB should carefully justify the biosphere assumptions made - particularly the use of each exposure pathway. Impacts of biosphere assumptions on site selection and engineering design should be considered

---

[6] This also has implications related to the appropriate level of detail when modelling geosphere and engineered systems.

explicitly so SKB understands whether certain assumptions have a strong influence. While the reviewers recognise that the present biosphere analysis includes many of the components required to make such an assessment[7], SKB has not gone the final step of evaluating their own analyses in this respect. For example, both the relative magnitude of total dose and the dominant radionuclides contributing to that dose for the Aberg site are different from that for Beberg or Ceberg for the 'normal' scenario. This is partially due to the point of release (marine versus terrestrial for Beberg and Ceberg), and partly due to the short transport time. It could be very useful for site selection to understand whether doses are most affected by geosphere (short transport times) or biosphere (terrestrial vs. aquatic; relative dilution and radionuclide buildup in various parts of the biosphere) considerations.

SKB indicates that peat land was substituted for cases where there was forest, due to lack of data for modelling forests. This is likely to be a particularly conservative assumption since the majority of the biosphere in some places is actually forest. SKB indicated to the review team in a written response to questions, that ongoing work, such as that in the IAEA BIOMASS programme, suggests that EDFs from a forest ecosystem are likely to be significantly smaller for most radionuclides of importance than that for the peat ecosystem. However, the forest ecosystem will likely have EDFs that are larger than for the archipelago ecosystem. If this is true, then including a forest ecosystem will not widen the range of possible future EDFs for at least the Aberg site, although it may extend downward the reasonable range of possible EDFs for sites similar to Beberg and Ceberg. The development of a forest ecosystem model will add perspective to the other ecosystem models, in the sense that the forest ecosystem, at least for inland sites, would be the most likely ecosystem into which radionuclides would be released if releases were to occur today. Thus, adding a forest ecosystem model will be valuable for discussions with the public, if perhaps less valuable in the actual licensing process where the regulator may require compliance with dose limits for all of the biotopes deemed possible at the site – no matter how rare each biotope may be.

6.2.2 Approach to critical groups and non-human biota

SKB assumes that essentially 100% of the nutritional needs of the critical group are supplied from contaminated foodstuffs. This is potentially a very conservative assumption that some recommend against making (e.g., IAEA's BIOMASS Theme 1, Working Document 3, 1999). SKB needs to consider the implication of the SSI regulation allowing a factor of 100 range in doses to individual members of the critical group in this light. That is, it may not be necessary to assume that *all* of the critical group members have 100% of their nutritional needs met from contaminated sources. Perhaps only the upper range of critical group members would have such characteristics. The review team is not familiar enough with the details of the new SSI regulation to know if SSI/SKI would allow consideration of a more reasonable set of assumptions about the amount of locally produced foodstuffs consumed by the critical group.

SKB is aware that their EDF estimates are actually for the 'most exposed individual' rather than for the mean of the critical group, as they discuss very briefly in TR 99-14, Section 3.1.2. In this section they seem to imply that their 'most exposed individual' dose estimates can be assumed to represent ten times the mean of the critical group dose. Thus, SKB seems to be assuming that the 'most exposed individual' dose limit can be ten times higher than the regulatory limit for the mean of the critical group. SKB should verify that SSI/SKI interpret 'most exposed individual' dose estimates the same way.

---

[7] For example, the tables in Chapter 4 of report TR 99-14 are particularly useful in providing insight into the most important radionuclides and biosphere pathways.

None of the analyses presented in the SFL 3-5 report (TR 99-28) provides any estimates of impacts on non-human biota. Yet SKB recognises that the SSI regulation requires them to do so (TR 99-40, page 12). It is recognised that the science of estimating non-human biota radiological impacts are less well developed than that for human radiological impacts. However, it would have been useful for SKB to have at least provided a summary of their future plans for addressing the non-human biota impacts part of the SSI regulation. There is, at present, considerable controversy over the need for, usefulness and practicality of addressing non-human biota impacts when human impacts are already being calculated. Since Sweden is one of the few countries that does have such a regulation SKB may have to take the lead in developing such an approach.

6.2.3 Ranking of sites and use of site data

Table 5-1 in TR 98-20 provides a relative ranking of the Aberg, Beberg, and Ceberg sites based exclusively on biosphere considerations. It is always dangerous to develop subsystem performance evaluations like this for the purposes of site selection. Rather, some better measure should be used for site selection, such as dose rates from *total* system performance (not just the biosphere). For example, the dose estimates provided in TR 99-28 suggest that Aberg should have been ranked first. Furthermore, the ranking system used in this table seems to be poorly thought out. What really matters could be: geosphere/biosphere interface; land use (which SKB has considered, but depends on exposure pathways); population (which may be appropriate to include *if* population dose considerations form part of the site selection criteria); and specific exposure pathways (that SKB has considered, but are actually part of land use). SKB is discouraged from using this table in isolation for decision making. Rather, decision making should be based on *total* system performance considerations, not just on biosphere considerations.

The SKB report TR 98-20 provides a wide variety of data and other more general information about the biospheres in the Aberg, Beberg, and Ceberg areas. In general, it is difficult to understand if and how SKB has incorporated this information in their biosphere model development work. It seems that the majority of the information provided in this report was not specifically used in the models. The decision making process that SKB used to exclude some of the information from the models has not been fully documented. For the purpose of improving the transparency and traceability of the biosphere models it would be useful to more properly document the use of the information contained in this report.

6.3 Details of the biosphere models and parameters

6.3.1 Biosphere spatial discretisation

Justification for discretising the biosphere into 250 m x 250 m squares does not seem particularly strong. In discussions with SKB, it was learned that this size was selected based on practical reasons. While remaining practical is, of course, not to be discouraged, it would have been useful for SKB to provide some sensitivity studies evaluating the sensitivity of the calculated EDFs to square size. Of particular importance is the relationship between the size of the contaminant plume in the geosphere to the size of the biosphere area, and the amount of land required to provide the range of exposure pathways assumed in each biosphere model. While a smaller square size may allow more spatial homogeneity in the radionuclide release from the geosphere into the biosphere (thereby providing the ability to maximise – if desired), it may become too small practically to support the variety of foodstuffs the model assumes is produced on the land.[8] Conversely, a larger square size may be able to better support the range of exposure pathways assumed in each model, but will have a more spatially diverse radionuclide release into it such that more averaging is required. Spatial averaging has been employed by SKB which may or may not be appropriate. SKB should explicitly consider whether some degree of spatial averaging in this latter case is acceptable. It is likely to be acceptable if the larger amount of land is required to support the full range of exposure pathways. Averaging may also be acceptable given the recent SSI regulation allowing a factor of 100 range in doses to individual members of the critical group. That is, it may be unreasonably conservative to assume that a very small amount of land into which the highest radionuclide flux is entering is large enough to support the diversity of exposure pathways assumed in the models. Since SKB has not explicitly considered these issues with respect to their choice of 250 m x 250 m sub-areas it is not possible to assess the potential level of conservatism in the approach.

In fact, it is not entirely clear how a 250 m x 250 m plot size affects the biosphere models or how this assumption has been used by SKB to evaluate biosphere impacts of the repository. It may be better for SKB to simply point out that the plot size needs to be of sufficient size to support the suite of human activities and exposure pathways assumed for that particular biotope. SKB also assumes that the entire 250 m x 250 m square is assumed to be composed of entirely the ‘predominant ecosystem’. It may be that one of the smaller ecosystems has orders of magnitude larger EDFs than the predominant ecosystem. SKB needs to provide better justification for the exclusive use of the ‘predominant ecosystem’.

6.3.2 Water wells

SKB makes reference to the well capacities of those wells existing at some of the sites to develop well capacity assumptions of 300, 1000, and 500 litre/hr for Aberg, Beberg, and Ceberg, respectively. SKB then shows that EDFs for the ‘well’ biosphere are approximately inversely proportional to the well capacity. This is consistent with the equation for radionuclide transfer found in Section 3.2.1 of TR 99-14. Presumably, the ‘VW’ term in this section is proportional to the well capacity numbers above times some annual irrigation time in hours. This equation must be based on a conceptual model for radionuclide transfer that assumes the entire annual amount of radionuclides released from the repository into the water body of interest is homogeneously distributed into a volume, VW, of water. Thus, the ‘well capacity’ should be related to the estimated flux of water (groundwater or surface water) carrying the radionuclide plume rather than any actual well withdrawal rate. If the above well withdrawal rates were related to the total contaminant plume size the total plume flux in the groundwater would be between (300 litre/h x 8766 h/a x 1 m^3/1000 litre) = 2600 m^3/yr and (1000 x 8766 x 1/1000) = 8800 m^3/yr. It is unclear if this is SKB’s meaning for ‘well capacity’ since this is not the normal meaning. For ‘well capacity’ and the plume flux to be the same SKB must be assuming that the wells exactly capture the entire plume – no more, no less. This is unlikely. If the plume flux is much larger than the amount of water extracted from the well, then not all of the radionuclides will be extracted by the well, so the EDFs would be overestimated by assuming the well

---

[8] Some individual agricultural plots of land in Sweden can be much smaller than 250m x 250 m. In reality, such small plots are almost always devoted to a single agricultural activity (e.g., grassland for cattle grazing) rather than a larger suite of activities assumed in the SKB model. While this observation is not necessarily a criticism of the SKB approach to biosphere modelling, it would be well for SKB to more fully explain to the reader that the 250 m x 250 m plot sizes are arbitrary, and, if true after further assessment, do not affect the calculated EDFs.

extracts all the radionuclides. The converse may or may not be true if the plume flux were smaller than the well extraction rate. That is, it may be quite reasonable to assume dilution during extraction.

6.3.3 Soil consumption

The value of soil consumption used (10g/a) seems low for the SKB assumption that no radionuclides have been removed during food cleaning.

6.3.4 Agricultural land

For the agriculture biosphere it is assumed that radionuclides enter the agricultural land by moving upward from an aquifer (in the geosphere) 20 meters below the land surface. SKB does not specify the mechanism by which the radionuclides manage to travel this last 20 meters into the biosphere from the geosphere. Instead, they conservatively assume that the migration is instantaneous. The relative conservatism is unknown, but will depend on the mechanisms that promote or retard radionuclide movement through this zone. Radionuclide retardation is likely for sorbing radionuclides. The exact amount of retardation will depend on the magnitude of the sorption coefficient for the solids occupying the upper 20 meters. For radionuclides with very long half lives, the assumption of instantaneous transport may not be unreasonable given the current SKB approach: while the time of arrival of the radionuclides into the biosphere may be early, the magnitude of the flux may not be very different than if instantaneous transport had occurred. For shorter-lived radionuclides, specifying the transport mechanism through this last 20 meters may be very important. SKB should evaluate the necessity of improving their biosphere model to specifically include this 20 meter layer with these considerations in mind.

6.3.5 BIOPATH model

The BIOPATH model was not investigated in any detail by the review team. However, it is recognised that BIOPATH has been used in BIOMOVS II work that tested various codes to solve essentially the same biosphere problem. The specifics of the problem in the Complementary Studies exercise within BIOMOVS II was similar to the well and agriculture biospheres SKB used in SFL 3-5 and SR 97 analyses. The BIOPATH model results for this exercise fell within the range of the other models, although the range spanned several orders of magnitude in some cases. As will be discussed below, it may be useful for SKB to consider the use of an alternative model and modelling group to provide some understanding of the robustness of the model upon which the current EDFs are based.

6.3.6 Conservatism and uncertainties in the modelling

The biosphere model assumes a radionuclide build-up time of 10,000 years. Since it is unlikely that any of the biosphere systems SKB considers will remain ‘stable’ (i.e., at approximately steady state) for that long, the EDFs SKB calculates will be conservative. The analysis SKB provides in Table 4-2 of TR 99-14 provides an excellent summary of the degree of conservatism of this assumption on the calculated EDFs.[9] This analysis shows

---

[9] It would be very helpful if SKB could provide similar studies of the quantitative impacts on the other assumptions it makes in the biosphere model. For example, much more could be done to provide some perspective on the degree of conservatism of the critical group assumptions, as discussed elsewhere in this review.

that for the most important radionuclides contributing to total dose estimates (H-3, C-14, Cl-36, Ni-59, Mo-93, I-129), the time to reach 50% of the 10,000-year EDF is no longer than 600 years (Ni-59). Thus, it seems that the 10,000-year build-up assumption is not hugely conservative; rather it seems reasonably conservative. If, on the other hand, some of the more highly sorbing actinides were to contribute largely to the total dose, then the 10,000-year assumption would be much more conservative – perhaps inappropriately so.

Section 5 of TR 99-14 provides a useful discussion of parameter uncertainties, although a clear discussion of the decision making involved in determining the exact uncertainty ranges/distributions based on the considerations in Section 5 remains largely lacking. Furthermore, the uncertainty ranges for the parameters used in the biosphere uncertainty analyses seem to be, in general, rather small. For example, only a 10% variation in consumption used rates were considered. Actual consumption ranges are much larger that are more like a factor of three.[10] The overall uncertainty range around the mean EDFs used in the overall analyses was usually limited to one order of magnitude or less for the most important set of radionuclides listed in the previous paragraph (e.g., Table 4-1 and others in TR 99-14). This uncertainty range is lower than that reported by others (see, e.g., EPRI's report on the Yucca Mountain biosphere: EPRI TR 107190, December 1996 for one example of many). However, the review team recognises that SKB has conducted extensive research on these three biospheres such that comparison of the uncertainty range SKB uses with those of others looking at other biospheres may not be entirely appropriate.

In addition, the uncertainty analyses SKB provided was only for parameter uncertainty. The more important uncertainties, conceptual model and numerical model uncertainties have not been explored by SKB. Yet SKB recognises that these two uncertainties can lead to very large uncertainties in the resulting EDFs in their discussion of the results of the BIOMOVS I and BIOMOVS II exercises in which SKB participated (TR 99-40, Section 6.2). In SKB's conclusions in TR 99-40, they note, "One major conclusion from the (BIOMOVS) studies was that model development is a multidisciplinary exercise… . It was also pointed out that important assessments should be performed by at least two groups. (Existing) studies have however mostly been addressing the uncertainties coupled to parameter values while there is still a need to investigate the uncertainties coupled to conceptual parts of the models." SKB should take heed of its own conclusions and more carefully look at the uncertainties introduced due to use interpretation and conceptual model uncertainties.

In TR 99-14, it is stated that fruits and berries were not considered 'due to lack of data for most radionuclides'. Yet some assessments (e.g., EPRI TR 107190, December 1996) found that the fruit pathway was more important than other consumption pathways for some of the major radionuclides. It may be that SKB has data for fruits and berries for a *subset* of the radionuclides that includes the likely important ones. Also, other assessments include other consumption items. For example, beef liver has been separated from beef muscle since the liver accumulates some radionuclides much more strongly than muscle. Again, SKB could undertake a *limited* investigation of the potential importance of this item to provide further confidence in the appropriateness of the current SKB approach. For both fruits/berries and liver, it is likely SKB can make some relatively simple screening arguments to explain why they could be excluded or perhaps should be included.

---

[10] However, it may not be even necessary to bother investigating uncertainties in human food/water consumption rates if, as SKB suggests, it is only attempting to model the 'most exposed individual' behaviour. Uncertainties for consumption should then consider the range for the critical group rather than for the most exposed individual.

Continued post-glacial rebound of the Fennoscandian Shield may require a change in the assumptions SKB makes about erosion rates and EDFs based on 10,000 years of radionuclide build-up. On the other hand, in TR 99-14 Table 3-2, last row (*soil removal*), a mean soil removal of 0.4 kg m^{-2} a^{-1} was chosen. SKB should assess whether this is small enough that the assumption of 10,000 years of build-up in the soil is possible.

7 Conclusions

The SKB safety assessment of the SFL 3-5 repository can be read in two contexts:

- as a preliminary evaluation of the performance and design options for a repository that will not be required for perhaps forty years, and that might be sited at any suitable location some decades into the future;

- as an evaluation of a repository that might need to be sited together with the SFL 2 spent fuel repository, and whose nature and performance might thus need to be understood to a level that can be used to make wider programmatic decisions during the next five years.

These two 'assessment contexts' are quite different, and an overarching issue is the fact that it was not clear to the review team which view to take. Apparently, SKB would tend towards the first context. In this respect, the reviewers expectations would be limited to seeing a 'first cut' and largely generic assessment. Indeed, the assessment is a competent piece of work at this level, for the most part well-presented and clear in structure and content, although somewhat deficient in traceability and systematic identification of uncertainties. However, it is not at all apparent to the reviewers why the second context should not be the predominant driver in the near future.

The review team notes that the SFL 3-5 repository, as modelled by SKB, gives rise to potentially perceptible radionuclide releases to the environment on a timescale of hundreds of years after closure. Consequent doses from the use of water wells are close to regulatory comparison levels. This is in contrast to the SR 97 assessment for the SFL 2 spent fuel repository, whose base scenario predicts no releases over a million year timescale. The review team was specifically asked by the regulatory authorities not to consider the overall safety of the SFL 3-5 repository in their evaluation. However, the need to establish SKB's expectations of this project (in other words, why SKB has carried out the SFL 3-5 safety analysis in the way that it has, at the present time: assessment context) means that the relative radiological impacts of the two repositories does need to concern the reviewers. Regardless of any considerations of the degree of conservatism in the SFL 3-5 assessment, it is clear that according to SKB’s SR97 and SFL3-5 analyses, for co-located facilities, it is *this* repository that has the potential for real radiological impacts in the immediate future. As noted in the Introduction, that this is the case should be no surprise to SKB, based on the near-field releases predicted five years earlier in their own pre-study, and on the results of other national studies, for example, the 1995 and 1997 Nirex assessments of Sellafield in the UK.

In the review team's opinion, this latter 'context' raises the level of expectation of what SKB might have wished to achieve with the present analysis. **An initial recommendation from the review, which would significantly affect any future studies, is that SKB and the regulatory authorities consider together which context is appropriate to the current status of the Swedish repository programme.** This is considered important, because an overall impression of the reviewers, in respect of the second context, is that the analysis would not be 'fit for purpose' if it were needed to assist with decision-making by SKB or the regulatory agencies. There are too many unanswered questions, and the overall impression of the safety concept is one of some fragility. Because there is no real design basis presented, no thorough systems analysis and sensitivity study, it is difficult to dispel this impression, which may, indeed, be much too pessimistic.

However, despite the fact that many of the review team's findings relate to this context, they should be read not only in this light, but also as recommendations for improvements in the inevitable next phase of SFL 3-5 safety studies, *whenever* they might be set under way. The review group believes that this may need to be soon, if the SFL 3-5 repository is indeed to be on the critical path for siting the spent fuel repository, whether this was ever intended by SKB or not.

The following points summarise some of the main findings of the review:

- The systematic basis of the study is rather weak. To address safety relevant issues comprehensively, a future study needs to look at a full 'systems approach' to evaluating relevant FEPs and constructing appropriate scenarios. In particular, the potential impacts of climate change, including scenarios involving permafrost and glaciation, have not been considered seriously. Climate evolution driven changes in mechanical, chemical and flow conditions may have powerful effects upon the repository and upon radionuclide migration. Alternative conceptual models of the central processes (specifically vault evolution) need to be evaluated. The degree of conservatism (or otherwise) of present assumptions needs to be identified on a factor-by-factor basis. A proper sensitivity study is needed.

- The radionuclide inventory developed for this study is an excellent first step and has been presented extremely well. It needs to be kept under review and improved regularly, with the intention of identifying and reducing uncertainties, particularly with respect to actinides and other radionuclides central to the safety case. The physical and chemical compositions and properties of waste streams are also important. The review team note the necessary use of correlation factors to estimate radionuclide inventories, and several suggestions have been made for clarifying or reducing the uncertainties surrounding their application. In addition, it is suggested that SKB reviews (separately) its approach to estimating radionuclide activities in reactor core components.

- SKB should consider how best to present the *design basis* and *safety concept* for SFL 3-5. At present, the report gives the impression of the design having evolved on a rather *ad hoc* basis, as no comprehensive explanation is provided of why the pre-study design was judged to be less adequate, what the design options are (were) and how decisions have been reached on which route to adopt. Although SKB makes no claims to the effect, it is doubtful that this constitutes the optimised design for isolating these wastes in this type of geological environment, and this cannot be judged confidently from the present analysis.

- A central facet of the safety study is the hydraulic cage concept. The team felt that this is a good theoretical construct, although not being entirely convinced of the superiority of its quantitative benefits. The concept needs significantly more work on its sensitivity to various factors, carried out via a proper scenario analysis. Factors that need to be considered are:

  - impacts of a heterogeneous flow field in the rock on vault evolution and radionuclide migration;
  - possible modes of vault degradation (cement cracking, permeability development, switch from diffusive to advective transport, etc);
  - full comparison with the performance of other concepts (low conductivity barrier, or a combination of high and low conductivity barriers) that do not focus flow close to the vaults;

  - factors that could cause inhomogeneity in the near-field source term (the degree of mixing of the high pH plume during its interaction with the gravel backfill, localised cracking in the vault, perhaps combined with artefacts from the waste emplacement strategy).

- The lack of use of available site-specific geological data constitutes an inexplicably lost opportunity. It has resulted in a weak and seemingly non-conservative analysis of the impacts of spatial variability and uncertainty in structure and groundwater flow.

- Ground-water modelling should be done consistently for all sites that are considered in a PA. The reviewers believe that a uniform hydrogeological approach would allow more meaningful inter-comparison of flow and flowpath variability among different sites and within any given site. Alternative structural hydrogeological models as well as alternative mathematical representations of these (e.g. deterministic, stochastic) need to be included in the analysis, fully to determine possible variability and uncertainty in key hydrogeological controls on dose. Model discretisation needs to be tested for each model, to prove that velocity distributions are not narrowed by numerical, spatial or temporal averaging, making the PA too optimistic. In order to reduce primary uncertainties in a future PA, the most valuable new hydrogeological field measurements would be those that determine: location of a repository within a ground-water flow regime (recharge vs. discharge area), potential flow paths from the repository, and the “F” parameter at appropriate spatial scales. Overall, the ranges of values for fluxes of water, “F” values, and penetration depth values applied to matrix diffusion, were not considered by the review team to be conservative.

- It is acknowledged that the site data were used to illustrate the impact of rock properties and biosphere variations, not to compare the actual sites from which data were abstracted. Nevertheless, different safety margins were found at each site. Ceberg performs better because the ground-water flux is lower and the path length to discharge points from the repository are longer than at the other sites, and the rock appears to be more homogeneous (possibly due to non-current site characterisation methods applied there). At Aberg and Beberg, the repository is located in or very near ground-water discharge areas, giving shorter path lengths, and there are more structures near the repository. SKB has concluded that the two main factors controlling doses are groundwater flow and the biosphere. They must also attempt to draw other equally pertinent conclusions from the results presented. For example, all other factors being equal (e.g., socio-economic considerations), it would be preferable for the site to have relatively long potential discharge path length lengths (i.e. location in ground-water recharge area, not in a discharge area), and have relatively homogeneous transport properties.

- The analysis of gas generation and its impacts is incomplete, and the review team has made a range of suggestions as to how this could be improved. These include examination of slower rates of gas production, impacts of gas-induced cracking on concrete permeability, the potential hazards associated with hydrogen gas flammability, and the production of additional radioactive volatile and gaseous species to those considered by SKB.

- Several issues concerning the chemical evolution of the vault are thought to need more study. These include:

  - the extent and rate of migration of the alkaline cement plume into the backfill and rock;
  - the effects of inhomogeneous disposition of waste in the vaults when similar assumptions are made on localised cracking or spatial variations in flow in the rock;
  - variant scenarios regarding the generation, transport and dissipation of repository gases;
  - the impacts of large (dominant) quantities of organic additives in the cement on sorption on the cement;
  - the mass balance of cement to waste in terms of its chemical conditioning capacity;
  - the high sensitivity of certain safety-related radionuclide release rates to the somewhat uncertain (and small) sorption values on cement;
  - the behaviour and stability of cement barriers in saline groundwaters.

- The development of EDFs for a variety of different biotopes provided significant insight into the potential behaviour of radionuclides in each biotope. The review team agrees with SKB that the biosphere assumptions are an important component in the total repository system model. This is because the individual dose conversion factors for many of the most important radionuclides are orders of magnitude different for different biosphere assumptions and postulated pathways. This causes the radionuclides that contribute the most to the total EDF to shift for one biosphere versus another. Thus, SKB should carefully justify the biosphere assumptions made - particularly the use of each exposure pathway. Impacts of biosphere assumptions on site selection and engineering design should be considered explicitly so that SKB understands whether certain assumptions have a strong influence – especially in cases where the detailed assumptions about future human behaviour are critical to the calculated dose. In addition, the reviewers believe that there are several issues that SKB ought to discuss with the regulatory agencies, such as the definition of exposed individuals.