An International Peer Review

of

Safety Report 97:

Post-closure Safety of a Deep Repository for Nuclear Spent Fuel in Sweden

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

FOREWORD

A major activity of the Nuclear Energy Agency (NEA) in the field of radioactive waste management is the organisation of independent, international peer reviews of national studies and projects. The NEA peer reviews help national programmes to assess their achievements. The review reports also provide reference information to be shared with others on what is desirable and what is feasible.

This report presents the common views of the International Review Team (IRT) established by the NEA Secretariat on behalf of the Swedish Nuclear Power Inspectorate (SKI) to perform a peer review of a post-closure safety study of a deep repository for spent nuclear fuel in Sweden, Safety Report 97, produced by the Swedish Spent Fuel and Waste Management Company (SKB). The review is based on the main reports of the project and supporting documents, on information exchanged with SKB staff both through the intermediary of SKI and in direct interaction at a week-long workshop in Sweden, on a visit of the SKB's Äspö Hard Rock Laboratory and Canister Laboratory, as well as on internal discussions within the IRT.

In keeping with NEA procedures for independent reviews, neither SKI nor SKB have checked this report. The IRT has made its best effort to ensure that all information is accurate and takes responsibility for any factual inaccuracies.

ACKNOWLEDGEMENTS

All members of the International Review Team would like to thank the SKI, SSI and SKB staff for their hospitality during our brief visits to Sweden. Both visits were productive, thanks largely to the care in planning and preparation taken by SKI, SSI and SKB. We also thank the staff at SKB for their efforts in supplying us with additional information during the review, as well as at the Workshop. Finally, we appreciated the opportunity to visit the Äspö Hard Rock Laboratory and the Canister Laboratory at Oskarshamn.

Although the IRT is responsible for the contents of this report, we acknowledge the helpful input supplied by our colleagues, notably those at the Center for Nuclear Waste Regulatory Analysis (CNWRA) in the United States and the Consejo de Seguridad Nuclear (CSN) in Spain.

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SUMMARY STATEMENT OF THE REVIEW

The Swedish Nuclear Fuel Waste Management Company (SKB) recently completed Safety Report 97 (SR 97), a safety assessment of the KBS-3 concept for the disposal of Sweden's spent nuclear fuel. This document describes a peer review of SR 97 organised by the OECD Nuclear Energy Agency and conducted by an International Review Team (IRT). The review was requested by the Swedish Nuclear Power Inspectorate (SKI) with the agreement of the Swedish Radiation Protection Institute (SSI).

The review was carried out between December 1999 and May 2000. In these six months, the IRT reviewed the SR 97 main report and its three chief supporting references, and exchanged information with SKB staff both through the intermediary of SKI and in direct interaction at a workshop in Sweden. The review was guided by two important considerations:

- SR 97 is primarily a study of a conceptual phase of a repository development, so that any question of judging regulatory compliance is still some years away; and
- SR 97 and its various reviews form only part of the decision basis for the future direction of the Swedish spent fuel management programme.

The SKB disposal concept and programme

The KBS-3 disposal concept has the essential elements of a sound concept for the disposal of spent nuclear fuel in a geologic repository. It provides defence in depth through a set of passive barriers with multiple safety functions. The concept is based on well-established science and a firm technological foundation. It is well defined, and appears to be implementable.

SR 97 provides a sensible illustration of the potential safety of the KBS-3 concept that takes account of the conditions in Swedish bedrock, based on data from three sites. The documentation is generally well written and the arguments well presented, but there is room for improvement in completeness of argument, traceability and transparency.

Given the current state of advancement of the SKB geoscience and engineering programmes and the favourable indications from SR 97, SKB's desire to move to a site-selection phase is well founded. This is reinforced by the observation that the performance of the geosphere barrier is site-specific. Data from potential sites are needed to develop, better focus and test the assessment methodology.

No issues have been identified that need to be resolved prior to proceeding to the investigation of potential sites. Several observations and recommendations are made that SKB and the safety authorities may wish to consider in the future development of the Swedish spent fuel disposal programme.

Observations and recommendations on SR 97

The terms of reference for the review included a number of specific questions. The IRT's main observations and recommendations related to these questions are as follows.

1. To assess the overall strategy for demonstrating safety

SKB has developed a robust multiple-barrier concept that involves a long-lived canister emplaced in a low-permeability bentonite buffer located in a geologic setting favourable for long-lived engineered barriers and isolation of the waste. In order to evaluate and reduce uncertainty, and to demonstrate safety, SKB is conducting rigorous engineering and scientific investigations, both generic and site-specific. SKB is also developing a capability to evaluate quantitatively the performance and ultimate safety of the facility. SKB's strategy is sufficiently flexible to incorporate improvements in the concept resulting from advances in science and engineering as the programme proceeds.

The SKB strategy to achieve and demonstrate safety is well founded, but it has not been sufficiently well presented in SR 97. A high-level document should be prepared describing the safety strategy. This document should be updated as the strategy develops (*e.g.*, in response to increased information, and in connection with periodic safety assessments). The document would identify the critical items on which safety rests, outline how the concept has evolved in time, tie together major components of the programme, describe the scientific and engineering knowledge that have led to changes in the strategy, and describe how confidence in the achievability of safe disposal has developed. Overall, the strategy document will promote a common understanding of programme objectives and status within SKB, will facilitate dialogue between SKB and safety authorities, and will provide a coherent explanation of the SKB strategy to wider audiences.

SR 97 represents SKB's first full safety assessment in over a decade. More frequent, iterative safety assessments would facilitate the timely evaluation of the significance of new scientific and engineering information and enhance the role of safety assessment as a means to integrate the programme. More frequent safety assessments would also develop and ensure the continuity of staff experience and skills required to conduct such assessments.

2. To assess the methodology and determine whether the suggested concepts and tools may adequately assess:

2.1 The scientific basis for representation of processes and barrier functions.

The scientific basis is advanced for the step in the programme that SKB wishes to take. No issue has been identified that would undermine the overall conclusions of the safety report. On the other hand, future improvements in some identified areas would enhance the robustness of the safety analysis. For example, a requirement of the current KBS-3 concept is the re-establishment and long-term stability of a reducing groundwater environment at repository depth. There is a need to better document the evaluation of all processes that could challenge this condition. This and other issues can be investigated in parallel with other work, and need not impede progress in the Swedish programme.

2.2 The performance of engineered and natural barriers for relevant scenarios and time periods.

SR 97 has evaluated a set of scenarios that illuminates relevant aspects of the performance of the engineered and natural barriers and illustrates the long-term safety. A formal justification for the choice of scenarios is lacking, however, and SR 97 does not adequately discuss the representativeness and purpose of the different scenarios. For instance, SR 97 lacks a discussion of the strategy for moving from the set of selected scenarios to an integrated evaluation of safety where all relevant features, events and processes are considered. The "base case" is a suitable starting point to investigate the isolation properties of the system and additional scenarios build on this to illustrate different aspects of performance. The eventual demonstration of regulatory compliance will likely require a more complete and integrated treatment of features, events and processes. This should include specifying the range of conditions and treatment of uncertainties within each scenario.

The THMC diagrams are a valuable contribution to organise the presentation of information about features, events, and processes, but the connection between the THMC diagrams and the scenario selection methodology should be developed.

2.3 *Data and model uncertainties and their impact on the assessment results.*

SR 97 illustrates that SKB has an appropriate selection of models and computational tools that can be used and developed flexibly. The concept of the Process Report is a valid and commendable one. It provides a good information base. Documentation of the models is lacking, however, and this is necessary in order to show how the process information is incorporated into the analysis. An integrated approach to uncertainty and sensitivity analysis that covers a fuller range of parameter and model uncertainties and evaluates multi-parameter sensitivities should be developed. This would provide a better understanding of the influence of the various uncertainties within a system context.

Improved traceability is needed in the selection of parameter values defined as “realistic” or “pessimistic”. SKB is also advised to reconsider methods to construct probability distributions from limited amounts of data.

2.4 *Risk and impact of individuals on the natural environment.*

SKB calculates a bounding estimate of risk according to their own independent interpretation of regulations, which have been issued only recently (SSI) in Sweden or are in the process of being issued (SKI). The result is of uncertain meaning both statistically and from the point of view of regulatory compliance. SKB would benefit from additional guidance from the safety authorities on the definition of risk and on the authorities’ expectations, and a discussion on the practical methods that might be employed to calculate risk while preserving statistical veracity. Discussion is also required with SSI regarding their expectations for assessing impacts to the natural environment and how requirements might be met. The experience gained in SR 97 and the illustrations it provides are useful background to these discussions.

2.5 *To assess whether the methodology may sufficiently describe the performance of the repository and consequences to the environment.*

The SR 97 methodology implements a bounding analysis approach that is geared towards demonstrating safety rather than investigating detailed aspects of performance. The methodology allows a sufficient description of performance in respect of safety. In future safety assessments, consideration should be given to incorporating more realistic descriptions of the performance of the facility. The adaptation and completeness of the present scenarios to the conditions of specific sites should also be considered.

3. To comment on the feasibility of the technical implementation, specifically including whether SKB adequately has identified the site-specific data that are needed for the safety assessment.

The review has identified no issues that would prevent the technical implementation of the KBS-3 concept. A pertinent concern at this stage is the lack of a discernible link, within SR 97, between the results of safety assessments and the development of site investigations and siting criteria. SKB is in the process of documenting, separately from SR 97, which site-specific data it considers to be most significant and potentially to be obtained during the site characterisation programme. Incorporation of more comprehensive sensitivity and uncertainty analyses into the assessment methodology could help to support this effort in future studies.

1. INTRODUCTION

1.1 Background to SR 97

The Swedish Nuclear Fuel Waste Management Company (SKB) is responsible for developing a nuclear waste disposal programme for Sweden. For spent nuclear fuel, SKB has developed a disposal method known as the KBS-3 concept. This concept has been developed and refined over 20 years, including undergoing extensive reviews. It involves the final disposal of spent nuclear fuel in sealed copper canisters, emplacement of the canisters surrounded by bentonite clay in boreholes drilled into the floor of disposal galleries, and the location of these galleries at a depth of about 500 m in Swedish crystalline bedrock with an underground water composition favourable to the long-term stability of bentonite-clay and copper canisters. Research and development on the KBS-3 concept is documented in tri-yearly reports issued by SKB and formally monitored and evaluated by the Swedish safety authorities and other stakeholders. The two main Swedish safety authorities (the "authorities", hereafter) are the Swedish Nuclear Power Inspectorate (SKI) and the Swedish Radiation Protection Institute (SSI).

SKB is currently completing feasibility studies for underground disposal in six municipalities. A forthcoming, planned step is the selection of at least two municipalities for detailed site investigations from the surface, including drilling of deep boreholes. Sweden is thus approaching an important decision point in its programme for the management of spent fuel.

The authorities and the Swedish government concluded that an up-to-date safety assessment of the KBS-3 concept should be prepared and then reviewed and evaluated by the authorities and other stakeholders. The affected municipalities have also expressed a desire that the authorities and the government should provide a renewed endorsement of the concept of nuclear fuel disposal at this time. As part of the decision basis for this step, SKB initiated, in December 1996, an assessment of the long-term safety of a deep repository for spent nuclear fuel which is now published in Safety Report 97 (SR 97). It was prepared by SKB to meet the Swedish government's request:

[…] to demonstrate that the KBS-3 method has good prospects of being able to meet the safety and radiation protection requirements which SKI and SSI have specified in recent years (SKB 1999, p. 13).

SR 97 describes three hypothetical implementations of the KBS-3 disposal concept, based on geological and surface environmental conditions at three sites in Sweden identified generically as Aberg, Beberg, and Ceberg.

The Swedish government has also requested information on topics that include the available geological data base, the evaluation of feasibility studies in the participating municipalities, the criteria for the selection of sites to be investigated further, the site investigation programme and the interaction of SKB with affected municipalities and other interest groups. SR 97 is expected to contribute to some of these reports, from results and observations as well as from the experience gained in developing the safety report.

1.2 Terms of reference and conduct of the review

Following the Swedish government review of SKB's latest RD&D programme (1998), SKI concluded that SR 97 should be subjected to an international peer review. The results of the international review would provide a broad perspective for consideration by the authorities during their own examinations of SR 97. Accordingly, after consultation with the SSI, the SKI contacted the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development with a request to organise such a review.

The NEA set up an international review team (IRT) of experts with wide experience of deep geological disposal projects. The members of the IRT were chosen from implementing, regulatory and independent organisations in several countries, so as to present a balanced viewpoint. The qualifications and some brief information on the IRT members are provided in the Appendix.

The SKI developed the terms of reference for the review of SR 97 and finalised them in discussion with the NEA. Three main objectives were identified.

The review should address the potential of SKB's methodology to make a credible safety case, having in view the main requirements in relevant Swedish regulations. This includes:

1. *Assessing the overall strategy for demonstrating safety, such as the relative weights of the safety functions of the different barriers at different times after closure.*

2. *Assessing the methodology that has been developed for the analysis and its application and determining whether the suggested concepts and tools may adequately assess:*
   - *the scientific basis for representation of processes and barrier functions,*
   - *the performance of engineered and natural barriers for relevant scenarios and time periods,*
   - *data and model uncertainties and their impact on the assessment results,*
   - *risk and impact of individuals on the natural environment, and*

   whether the methodology may sufficiently describe, in general terms, the performance of the repository and consequences to the environment from a hypothetical release occurring at any time after closure.

3. *"[…] Assess the feasibility of the technical implementation of the KBS-3 disposal concept in Swedish bedrock […] to identify any major unresolved issues concerning the technical basis for the construction of the engineered barriers and for carrying out future site investigations"*, and specifically determining *"whether SKB adequately has identified the site-specific data that are needed for the safety assessment"*.

The decision to endorse SR 97 lies with the Swedish authorities, and it was agreed within the IRT that the present review would be concerned only with judgements, conclusions and opinions on technical matters. In particular, the present review would not:

- be concerned with judgement of safety, regulations and site acceptability, nor would it be an evaluation of compliance;
- comment specifically on whether SR 97 is consistent with the regulations nor whether it meets their criteria; and
- consider aspects of community involvement, other social factors or the Swedish decision making process.

The input documentation for the review is listed in Box 1, while the conduct of the review is summarised in Box 2.

Box 1. Input documents

The primary input to the review was the SR 97 report set consisting of the "Main Report Summary" and "Main Report", as well as three chief supporting reports called the "Design Report", the "Processes Report" and the "Data Report".

1. Deep repository for spent nuclear fuel: SR 97 – Post-closure safety. Main Report Summary, and Vols I and II. SKB Technical Report TR-99-06, Nov. 1999. (Review Edition).
2. SR-97 – Waste, repository design and sites. SKB Technical Report TR-99-08, Oct. 1999 (Review Edition).
3. SR-97 – Processes in the repository evolution. SKB Technical Report TR-99-07, Nov. 1999.
4. SR-97 – Data and data uncertainties. SKB Technical Report TR-99-09, Oct. 1999.

SKB also provided the IRT with copies of their 1998 RD&D report and other SKB reports as requested by individual team members. The SKI and SSI provided copies of reports describing their regulations, proposed regulations and related material. The review also drew on information gained from SKB's responses to questions prepared by the IRT and extensive discussions with SKB staff (see Box 2).

Box 2. Conduct of the review

The IRT met for the first time in Stockholm on 9 and 10 December 1999. During these two days, SKB staff presented an overview of SR 97 at a seminar also attended by SKI and SSI staff and technical representatives of one of the affected municipalities. In addition, staff from SSI and SKI outlined the regulatory framework in Sweden. The IRT also discussed the terms of reference for the review and the division of review work.

During the ensuing weeks, each member of the IRT examined the main and supporting documents, focusing on those sections of the report closest to his or her professional expertise. The partitioning of the detailed evaluation was such that each major element of SR 97 was examined by two or more team members. At the end of January 2000, the IRT sent a set of more than 200 questions to SKB for clarification. Another three sets of questions were forwarded in February. SKB responded to these questions in writing or orally during the subsequent workshop.

The IRT met a second time during a workshop with SKB, held from 29 February to 2 March in Stockholm. There were presentations by SKB staff who had played a role in the preparation of SR 97 and by a consultant to SKB. SKB focused the presentations to cover issues requiring clarification as revealed by the written questions. The presentations covered an overview of the programmatic framework surrounding SR 97, the general assessment methodology and confidence issues, near field modelling, site characterisation, siting and design criteria, biosphere modelling, representation of climate change and the earthquake scenario. The format of the workshop encouraged in-depth questioning and discussion. The IRT also visited the Äspö Hard Rock Laboratory and the Canister Laboratory at Oskarshamn and were able to question key staff at both facilities. SKI and SSI observers were present throughout the workshop and laboratory visits.

At the close of the workshop on 3 March 2000, the IRT Chairperson, Margaret Federline, presented the initial collective opinion of the IRT to staff from SKB, SKI, SSI and community representatives. Later, each IRT member prepared written views and comments that were compiled into a draft report. This was reviewed by team members, and iteratively discussed and refined to the present report, which presents the consensus views of the IRT.

In formulating and documenting its review, the IRT kept the following points in mind:

- SR 97 is primarily a study of a conceptual phase of a repository development, although it draws on information from *in situ* studies of sites (using data collected at different times and at different levels of detail and quality) and the experience of fabrication of prototype canisters and other elements of the engineered barriers. Any question of judging regulatory compliance is still some years away.
- SR 97, the international peer review, and the review by the authorities constitute only a part of the decision basis required to determine the continuation of SKB's waste management programme into the start of surface-based site investigations at potential disposal sites.

1.3 Organisation of this report

A Summary Statement of the Review is given at the front of this document. It summarises the main observations and recommendations from the review and is designed to "stand alone", if necessary.

The main text of the report presents the main body of the observations and recommendations from the review. The text presumes that the reader is generally familiar with the aims and content of the SR 97 study, but not necessarily with the details of its documentation. It is directed to SKI, SSI and SKB, and other interested organisations in Sweden and abroad.

Introductory material on the background, terms of reference and conduct of the review has been given in the preceding part of this section. The remainder of the main text is structured into four parts. Sections 2 to 4 consider the three objectives given to the IRT. Namely, to assess:

2. The strategy for achieving and demonstrating safety;
3. The methodology and its application;
4. The feasibility of technical implementation.

Brief conclusions of the review are presented in Section 5.

The Summary Statement and main text represent the consensus views of the IRT.

2. THE STRATEGY FOR ACHIEVING AND DEMONSTRATING SAFETY

The SKB strategy for achieving and demonstrating safety consists of three connected elements.

1. **Facility design and siting**. SKB has developed a robust, multiple barrier design that includes a durable, long-lived canister surrounded by a low-permeability layer of bentonite clay. The repository itself is located in a geological setting that has favourable isolation properties and provides a stable physiochemical environment that promotes the longevity of the canister and other engineered barriers. These barriers have multiple safety functions: for example, the bentonite buffer provides mechanical protection and restricts water access to the canister and would also retard the movement of contaminants away from the canister in the event of it being breached. Some functions are supplied by more than one barrier: for instance, radionuclide migration can be delayed by sorption effects both in the bentonite buffer and in the surrounding rock.

2. **Underlying engineering and scientific support**. SKB has organised and conducts a rigorous programme of engineering and scientific investigation, including generic and specific studies. These provide the information necessary to design and evaluate the performance of the disposal system for expected conditions and also in the event of less favourable circumstances. These studies will lead to the more general confidence in scientific understanding necessary to support a safety case. SKB has two dedicated research facilities: the Äspö Hard Rock Laboratory, which was constructed between 1990 and 1995, and the Canister Laboratory at Oskarshamn, which opened in 1998. Important experiments to prove feasibility and to improve the understanding necessary to demonstrate safety are taking place at both facilities. SKB has demonstrated openness and leadership in opening these facilities to international co-operation as well as in other international collaborative projects, such as the Stripa Project (NEA 1993).

3. **Evaluation of safety**. SKB has developed tools to carry out an analytical evaluation of performance and safety of geologic repositories. SR 97 is the most recent example of an implementation of these tools in a

safety assessment. It describes three hypothetical implementations of the current KBS-3 concept, integrating site-specific and generic understanding of engineered and natural barriers. SR 97 is also directed at regulations recently released in Sweden concerning the disposal of nuclear waste. The study explores the potential safety of the KBS-3 concept for a number of scenarios and discusses how the various natural and engineered barriers contribute to safety.

The IRT is satisfied with this overall strategy. It is well founded and provides logical connections between concept, understanding and evaluation of safety. The IRT also believes the strategy is well implemented, in that SKB has adopted a disciplined, step-by-step approach that is geared to provide the required information with the level of confidence needed to support a stepwise decision-making process. Moreover, SKB's strategy is sufficiently flexible to incorporate improvements in the concept resulting from advances in science and engineering as the programme proceeds.

The IRT makes two recommendations to assist SKB in improving their overall strategic approach: one relates to preparation of a strategy document and the other to exercising and refining their safety assessment capabilities.

Safety strategy document

The SKB strategy to achieve and demonstrate safety is well founded, but it has not been sufficiently well presented in SR 97. For example, the IRT did not immediately appreciate the significance and impact of a change in the KBS-3 concept, whereby cast iron replaces lead as the insert to the copper canister. This modification delays any penetration of water to the fuel, even for a defective canister and, thus, provides greater assurance of long times before any radionuclide release can occur from the engineered barriers. One way to make such improvements more transparent would be to develop a high-level "strategy" document. This document should be updated as the strategy develops (*e.g.,* in response to increased information, and in connection with periodic safety assessments). The strategy document would:

- Identify the critical items on which safety rests (*e.g.,* the re-establishment of reducing groundwater conditions);
- Outline how the concept has evolved and also expectations for ongoing assessment and research work;
- Tie together major components of the programme;

- Describe the scientific and engineering knowledge that have led to changes in the strategy;
- Describe how additional knowledge has affected the confidence in the performance of different barriers and the allocation of safety in different aspects of the safety case; and thus
- Describe how confidence in the achievability of safe disposal has developed.

The strategy document would discuss not only the engineered barriers, but also the natural barriers and the biosphere, and the effects of improving knowledge and representation therein. For instance, the document could acknowledge that much more is known about the Swedish geosphere, today, than was known during safety studies conducted in the early 1980s.

The strategy document should emphasise that SR 97 and succeeding safety studies are not stand-alone analyses but, rather, that they represent a large and growing volume of accumulated scientific and engineering knowledge and safety studies. It would show how safety assessment is supported by the scientific and technical information base and how the understanding of safety has developed with time.

The strategy document should elucidate SKB's view on the role of safety assessment. Safety assessment is not only a tool to explore the projected behaviour of the disposal system and to demonstrate safety, but can also contribute to decision making. For instance, safety assessment can help to focus research studies and to identify the geological factors that are most important to consider during site selection.

Overall, the document will promote a common understanding of programme objectives and status within SKB, facilitate dialogue between SKB and the safety authorities, and provide a coherent explanation of the SKB strategy to wider audiences.

Exercise of assessment capability

SKB's strategy would benefit from more frequent, iterative safety assessments. In particular, the periodic exercise and review of safety assessment capability could benefit SKB's assessment capability in the same way that other components of their programme have benefited from presentation and review in the triennial RD&D reports.

Assessment documents related to the KBS-3 concept issued by SKB[1] in recent years include: the SKB91 assessment (SKB 1992), which had only a limited objective related to the contribution of the geology to safety; a safety assessment document template (SKB 1995); and a higher-level perspective on the potential danger from spent fuel (Hedin 1997). These documents are valuable but none are comprehensive in scope. Thus, SR 97 represents SKB's most complete safety assessment of the KBS-3 concept since the first evaluation (SKBF/KBS 1983) over a decade ago.

A programme of more frequent, iterative safety assessments would:

- facilitate the timely evaluation of the significance of new scientific and engineering information,
- enhance the role of safety assessment as a means to integrate the programme, and
- develop and ensure the continuity of staff experience and skills required to conduct such assessments.

New iterations could focus on selected areas of the methodology or system performance. Each iteration would also provide the opportunity to refine and test components of the safety assessment methodology, to practice the integration process and identify any gaps or weaknesses, and to explore and develop additional lines of evidence that support and strengthen the case for safety.

[1] Safety assessments of the KBS-3 concept have also been conducted by SKI, mainly to test assessment methodologies and to develop in-house experience. These are documented in the Project-90 and SITE-94 reports (SKI 1991 and 1996).

3. THE METHODOLOGY AND ITS APPLICATION

The safety assessment methodology employed in SR 97 conforms to the internationally accepted approach that can be considered to consist of the following general stages (*e.g.,* see NEA 1991, 1995 & 1999).

- Collation and evaluation of the available scientific understanding, site specific and other data necessary to the representation and quantification of the various elements of the disposal system and their performance.
- Selection of cases – scenarios – that describe the possible future evolution of disposal system and can be the basis for illuminating aspects of performance of the various repository barriers and evaluating overall performance and safety.
- Representation of the disposal system by mathematical models and data, and taking systematic account of the various uncertainties either within alternative model formulations or by the selection of data.
- Calculation of endpoints appropriate to illustrate the performance or safety of the system, including those endpoints required by regulations.
- Consideration of all factors not included within the quantitative analysis and assessment of the level of confidence in the calculated results considering both uncertainties due to omission and simplification, and alternative, more qualitative, lines of argument that support the results. Thus, assess whether a sufficient description of the system and assurance of safety has been achieved at the current stage.

The performance of SR 97 against each of these items, which also correspond to the questions posed by sub-points from the terms of reference (see Section 2), is discussed in the following subsections.

Safety assessment also plays a role towards determining the feasibility of implementation. This is considered in Section 4.

3.1 The scientific basis for representation of processes and barrier functions

The scientific basis is advanced for the step in the programme that SKB wishes to take. No issue has been identified that would undermine the overall conclusions of the safety report. On the other hand, future improvements in some identified areas would enhance the robustness of the safety analysis. For example, a requirement of the current KBS-3 concept is the re-establishment and long-term stability of a reducing groundwater environment at repository depth. There is a need to better document the evaluation of all processes that could challenge this condition. This and other issues can be investigated in parallel with other work, and need not impede progress in the Swedish programme.

Engineered barriers

The design of the engineered barrier system (EBS), including the high integrity canister and the use of a bentonite clay buffer, constitutes a well-developed and robust design, similar to designs for nuclear waste disposal in crystalline rocks being considered in Canada, Finland and other countries. In general, there is a substantial database of international information to draw from concerning the behaviour of the EBS.

- SKB, in co-operative efforts with other national programmes, has studied questions related to fuel inventory and radionuclide release from spent fuel in a number of experimental studies for almost 20 years. A good mechanistic understanding of fuel corrosion is now available, but additional progress and more data are expected in future.
- For almost two decades, SKB has relied on copper as the reference canister material because of its excellent corrosion properties in air and in reducing groundwater. In fact, the use of copper canisters is a fundamental characteristic of the KBS-3 concept. SKB has developed a sound and convincing scientific foundation to describe the long-term behaviour of the copper shell of the canister under expected conditions and also when accounting for perturbations such as the effects of sulphides and pH variation. In addition, more information is being generated in laboratory and underground studies. More experimental work is still needed in respect of some processes *(e.g., c*orrosion in the presence of oxygen and conditions for localised corrosion). This will augment the depth and scope of the treatment as presented in SR 97.
- The bentonite buffer provides a diffusive barrier between the waste and potentially mobile groundwater in the host rock; bentonite is also an important component of the gallery backfill. The use of bentonite is

common to many programmes for the disposal of high-level radioactive waste, and its characteristics and performance are well established under a wide range of conditions over experimental time scales. There is greater uncertainty when extrapolating to very long-term performance and, therefore, evidence for stability should continue to be accumulated from natural analogues, long-term field tests and modelling studies. Some specific uncertainties, such as performance in contact with highly saline groundwater, are also under investigation by SKB.

An important requirement for the long-term integrity of the EBS, in the KBS-3 concept, is the re-establishment and preservation of a reducing groundwater environment around the disposal galleries. Therefore, a clear identification and evaluation of *all* events, conditions and processes that could challenge the reducing state of the repository or its buffering capability is required. The IRT identified the possible presence and effect of oxygenated glacial melt water penetrating to repository depth as a possible threat that deserved fuller consideration. Discussions revealed that SKB have confidence in reducing conditions at depth based on a range of arguments but these are not fully articulated in SR 97.

Similarly, in view of the importance of canister performance to the safety case, a comprehensive treatment is needed for uncertainties and representation of degradation processes that may shorten the canister life. Two examples are, firstly, better quantification of the time taken to establish reducing conditions at the canister surface following emplacement and, secondly, examination of the copper corrosion processes that may occur before the canister is emplaced and during the time after emplacement, but before reducing conditions are established.

In SR 97, SKB introduces the cast iron insert, replacing the lead filler considered in prior studies. SKB has also provided analyses that take credit for the combined effect of the copper and its insert in the event that groundwater enters the canister through a small defect in the shell. The processes described in SR 97 involve general corrosion of the iron, generating hydrogen gas and creating a magnetite layer near the defect site. The large mass of iron ensures a long-lasting reducing environment in the canister because the hydrogen gas prohibits radiolytic effects and maintains a favourable environment with regards to UO_2 dissolution. The consequence is that most radionuclides cannot leave the canister for several hundred thousand years in the "realistic" case. This mechanistic understanding is used primarily in the "canister defect" scenario and is based on information that has been generated over the past few years. It is to be noted that the knowledge base for this particular design feature is not yet as mature as it is the case for copper corrosion. Questions remain that require further study. These pertain to the mechanical stability offered by the cast iron insert, the characteristics (notably size and frequency) of the presumed defects, the corrosion mechanism and kinetics of the cast iron insert, and the risk of hydrogen embrittlement of the iron insert. The new canister design incorporating the cast iron insert is promising and SKB is encouraged to further develop the technical basis for its use.

Geological barrier

SR 97 notes that the geological barrier provides physical isolation of the waste from humans and the human environment, helps to maintain a stable physical and chemical environment that supports the performance of the EBS and can retard the migration of key radionuclide species in groundwater. The depth of knowledge concerning Swedish bedrock derives from a number of studies carried out over more than 20 years. More recently, the knowledge gained at the Äspö Hard Rock Laboratory has allowed SKB to explore the geological system at the spatial scale of interest for performance assessment.

The description in SR 97 of the past, present and future of the geology in Sweden is comprehensive. SKB has generally built a good understanding of the performance of the geosphere and demonstrated a capability that allows the measurement of key data needed to predict that performance. The study of natural analogues that may add information in the time scale of interest for performance assessment could have also been more extensive and more thoroughly described in the SR 97 Processes Report.

There are no urgent issues that must be solved, although there are some that warrant effort to enhance understanding, and that could be included in future safety studies. One such is the understanding of the origin and evolution of groundwater (including rock pore water) and solutes. This information could help in the testing of groundwater flow models, discriminate between alternative models and contribute to studies on possible geochemical interactions that might affect the performance of the bentonite buffer. Another issue is the measurement and interpretation of the “flow-wetted surface” parameter. This is one of the most important parameters in SKB’s radionuclide-migration modelling of the geosphere, but its interpretation from field data is problematic. A fuller understanding is required concerning the adequacy of the measurement techniques and reliability of the data.

The biosphere

Even if the disposal system is well designed and properly managed, there remains a potential for small releases of radioactivity to the surface environment, especially in the far future. ICRP Publication 81, *Radiation Protection Recommendations as Applied to the Disposal of Long-lived Solid Radioactive Waste* (ICRP 2000), indicates that radiological assessment of a disposal system for solid radioactive waste needs to consider the possibilities for human exposure, even at long times. Thus, the processes by which the released radioactivity can be distributed in the biosphere and that could lead to human exposures have to be considered, and models built to calculate potential doses and/or radiological risk to hypothetical individuals assumed to be present at the location in the future. ICRP 81 indicates that a critical group and biosphere should be defined either using a site-specific approach based on currently available site or using regional information or a stylised approach based on more general habits and conditions. It is important to acknowledge that these estimates of dose will have growing uncertainties as a function of time due to incomplete knowledge of the repository system including conditions in the biosphere and human habits and characteristics. Doses and risks, as measures of health detriment, cannot be forecast with any certainty for periods beyond several hundred years. Estimates of dose or risk for longer time periods can be made, however, and compared to appropriate criteria in a test to give an indication of whether the repository is acceptable given current understanding of the disposal system.

SKB have developed a flexible approach to modelling the biosphere that is in advance of methods used in most other safety assessments to date, in that it represents the spatial variation of different ecosystems over the possible surface area over which radionuclides may emerge and be distributed.

This more “realistic” representation of present day conditions at a site gives a better representation of the spatial distribution of contaminants However, it has not been shown whether this representation leads to different estimates of exposure to man than would be achieved by the simpler biosphere models used before *(e.g.,* SKB 91). The additional degrees of freedom that the modelling approach provides may help SKB to respond to requirements that SSI may place in respect of assessing impacts to the environment. It may also help to build representations of the biosphere that are recognisable, and thus more convincing, to local communities. On the other hand, it must be weighed that the site specific and general scientific information requirements are greater, and data are currently lacking, for example, to calculate ecosystem dose factors for natural and semi-natural environments such as the forest ecosystem. More fundamentally, ecosystem changes at any site are largely unpredictable, especially considering the influence of man on land use and ecosystems. This leads to a question about the role of biosphere modelling in long-term safety assessment that is not yet resolved *(e.g.,* NEA PAAG 1998).

The IRT appreciates that SKB are taking an innovative line in the area of biosphere modelling and consider that this a worthwhile contribution to international experience. SKB should set down their expectation and requirements of biosphere modelling, and its role in safety assessment within their safety strategy and in connection to Swedish regulatory requirements. In particular, the question of the extent to which a present-day biosphere should distinguish between sites at which no surface contamination is expected until many thousands of years in the future should be considered. It could also be informative to compare results from the spatially-distributed model and more conventional biosphere models.

3.2 The performance of engineered and natural barriers for relevant scenarios and time periods

SR 97 has evaluated a set of scenarios that illuminates relevant aspects of the performance of the engineered and natural barriers and illustrates the long-term safety. A formal justification for the choice of scenarios is lacking, however, and SR 97 does not adequately discuss the representativeness and purpose of the different scenarios. For instance, SR 97 lacks a discussion of the strategy for moving from the set of selected scenarios to an integrated evaluation of safety where all relevant features, events and processes are considered. The "base case" is a suitable starting point to investigate the isolation properties of the system and additional scenarios build on this to illustrate different aspects of performance. The eventual demonstration of regulatory compliance will likely require a more complete and integrated treatment of features, events and processes. This should include specifying the range of conditions and treatment of uncertainties within each scenario.

The THMC diagrams are a valuable contribution to organise the presentation of information about features, events, and processes, but the connection between the THMC diagrams and the scenario selection methodology should be developed.

Completeness and organisation of FEPs

A first step in scenario development is the construction of a comprehensive catalogue of features, events and processes (FEP) that could be relevant to the long-term performance of the disposal system. Thereafter, these FEPs should be evaluated and, by some method, scenarios constructed that include the more important FEPs in logical combinations to produce relevant illustrations of repository performance. It is not possible to prove that either all relevant FEPs or all relevant scenarios have been identified, and alternative methods exist to synthesise and arrange the information. Therefore, key tests of the adequacy of a scenario development are that the process followed is systematic, thorough and well-documented.

SKB has developed a method to promote completeness of consideration of the processes that could occur within the various engineered and geologic barriers based on "THMC" (thermal, hydrological, mechanical and chemical) diagrams[2], and have organised the presentation of information on relevant processes around these diagrams. These diagrams are interesting from a presentation point of view, but the IRT found difficulty when trying to understand the diagrams in detail and trace connections between diagrams. The diagrams probably help in organising information and discussion but should be regarded as rather approximate illustrations of the processes relevant to each barrier including many hidden subjective judgements. This is, however, a criticism that could also be aimed equivalent techniques (*e.g.,* matrix and influence diagrams) used in other safety assessment projects.

Screening and scenario selection

Several alternative strategies have been used world wide to develop or select scenarios for repository safety assessment. Generally the use of scenarios is associated with dealing with "future" uncertainties. This requires a set of scenarios to be selected that, together, cover the possible future evolution of the disposal system and allow the consequent influences on performance and safety to be investigated. In this case, a "reference" scenario is defined that usually explores the "expected" evolution while alternative scenarios are defined to investigate less likely circumstances or events. An alternative approach is to define a "base" scenario that is a starting point for the analysis of the performance of the repository system. It may include a limited set of features and processes, and the objective is to gain a first level understanding of the performance. Additional features, events and processes may then be added, building up complexity and learning more about the performance and, specifically, the importance of the added FEPs. Whatever strategy is adopted, this needs to be explained and a reasoned selection of scenarios made.

A significant criticism of SR 97 is that there is no formal consideration and screening of the various FEPs that should be considered as potentially scenario-generating nor a justification of the scenarios selected for quantitative analysis. These are selected "*based on the system description and previous experience from previous safety assessments*". Nonetheless, the IRT concludes

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2 These diagrams also include radiation and radionuclide migration processes and it might be more useful to consider a more generic name.

that SR 97 has taken into consideration a large collection of important FEPs and subsequently examined a set of scenarios that reasonably illustrates the performance of the disposal system. This conclusion arises in part because the IRT is aware of SKB's prior efforts in scenario analysis. In fact, SKB has made many useful contributions to the development of the subject, such as their joint work with SKI and later work on interaction matrices and THMC diagrams.

Strategy and balance of presentation

In future safety assessments, SKB should set out a strategy[3] for scenario selection and apply a more formal scenario selection procedure. The strategy and procedure should be documented making clear the function of the selected scenarios within the analysis. The presentation of the analysis of each scenario should then be balanced accordingly.

For example, if the canister defect scenario is to be discussed from a safety aspect, more attention should be given to the estimation of the likelihood and characteristics of canister defects and measures that could be taken to prevent defective canisters being fabricated or emplaced. On the other hand, the analysis of the canister defect scenario in SR 97 provides a convenient and credible test of the performance of the other barriers of the KBS-3 system. The analysis thus illustrates the multi-barrier nature of the KBS-3 concept, and is valuable for this reason.

Another example is the analysis of the earthquake scenario. The presentation in SR 97 focuses on the calculation of the possible number of canister failures due to displacement on fractures due to ground movement from randomly occurring earthquakes. The value of the analysis, however, is that it can be used to estimate constraints on the location of a repository relative to nearby potentially active fault zones that might be a source of future earthquakes. If the repository is sited at a sufficient distance from any such zones, the probability of earthquake-induced failures will be negligible.

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3 Different strategies to scenario development can be envisaged. In some programmes, the aim is to compile a set of scenarios that accurately represent the possible range of future evolutions at a site. In other programmes, the aim is to define a set of scenarios that illustrate and test the different safety functions for a range of perturbations. For example, in SR 97, the base scenario examines the isolating capacity of the EBS and geosphere, while the canister-defect scenario examines the retarding effect of the EBS and geosphere.

Comments on specific scenarios

- An alternative name for the "base" scenario might be the "design" scenario, to signify that the ensuing discussion describes what would happen if the repository evolves according to the engineering design. The discussion of performance is convincing. A more thorough description of the hydrogeological and geochemical aspects relevant to isolation and more quantitative analyses would improve the balance with the detailed analysis of the geosphere presented in the canister defect scenario. For example, hydraulic evolution processes are discussed in detail in the canister-defect scenario, but given much less attention in the base scenario. This is surprising because these processes might, presumably, have important influences on the long-term evolution of groundwater composition and redox conditions that affect the chemical evolution of the buffer/backfill and the corrosion of the copper canister described in the base scenario. The changes in hydraulic and geochemical evolution induced by climate change also deserve detailed attention.

- The evaluation of performance of a defective canister is judged to be adequate – a convincing analysis of the evolution of processes in the event that a defect exists. A key uncertainty that deserves fuller discussion is the likelihood and nature of significant defects, if any. A discussion of other possible EBS "defects" *(e.g.*, poor buffer emplacement), and why these are not analysed would be valuable.

- The climate change scenario provides convincing discussion and predictions of the possible sequence of hydrogeological and biosphere conditions at sites in southern coastal Sweden. The analysis does not capture all possible conditions and is limited to a qualitative discussion of consequences and uncertainties. A more detailed discussion on the potential for oxygenated glacial meltwater to intrude to the repository depth, and the features and processes that make such an occurrence unlikely would be valuable.

- The mechanical modelling of the earthquake scenario is interesting, innovative and useful. The IRT was surprised, however, that the scenario was given such important weight given the reputedly stable character of the Swedish basement rock. On the other hand, if an earthquake scenario is to be presented, it should include consideration of the hydrogeological transient effects and any potential for longer term effects (*e.g.*, on groundwater chemistry).

- The method for considering coupling between scenarios and use of alternate models needs to be better developed. For instance, the potential magnitude and frequency of earthquakes will vary during climate change cycles due to glacial loading and unloading effects. Site specific influences also need to be considered.

- For the human intrusion scenario, the analysis in SR 97 is well thought out and is typical of the current level of development in other national programmes that have attempted to deal with this topic. A significant benefit of the analysis in SR 97 might be to help focus dialogue with the SSI and SKI on the treatment and regulatory requirements for this scenario.

3.3 Data and model uncertainties and their impact on the assessment results

SR 97 illustrates that SKB has an appropriate selection of models and computational tools that can be used and developed flexibly. The concept of the Process Report is a valid and commendable one. It provides a good information base. Documentation of the models is lacking, however, and this is necessary in order to show how the process information is incorporated into the analysis. An integrated approach to uncertainty and sensitivity analysis that covers a full range of parameter and model uncertainties and evaluates multi-parameter sensitivities should be developed. This would provide a better understanding of the influence of the various uncertainties within a system context.

Improved traceability is needed in the selection of parameter values defined as "realistic" or "pessimistic". SKB is also advised to reconsider methods to construct probability distributions from limited amounts of data.

Parameter value uncertainty

SR 97 uses probabilistic ranges only for a few, albeit important, parameters, for which there is significant statistical database *(e.g.,* host rock permeability). For most parameters in the radionuclide migration model chain, SR 97 adopts "best estimate" and "pessimistic" values. This is based on a methodological argument, also favoured in some other assessment programmes, that states that the derivation of parameter distributions is not warranted for parameters for which there is only a sparse or incomplete measurement base. On the other hand, some other assessment programmes argue that the use of parameter distributions is even more necessary in such circumstances, and parameter distributions better reflect the large uncertainty that must be present. SR 97 does not sufficiently discuss the data selection strategy, neither its relation to the level of available information nor its relation to stage of programmatic decision-making and regulatory requirements.

The discussion and evaluation of parameter uncertainty in SR 97 is extensive but not uniform. Most of the effort is focused on the engineered barriers and on the hydraulic evolution of the geosphere. Other aspects of the geosphere and most of the biosphere have received less effort. In addition, almost all consideration of uncertainty is limited to the analysis of the canister defect scenario. A more consistent and balanced approach would provide the same type and degree of treatment for all important uncertainties, for all components of the disposal system and for all scenarios. The deterministic and probabilistic analyses provide useful insights into the expected radionuclide migration behaviour for the canister defect scenario. A similar level of quantitative analysis for the base, earthquake and climate evolution scenarios could similarly illuminate factors of importance in these scenarios, and whether the climate- and earthquake-induced perturbations substantially affect the functioning of the isolation and radionuclide migration functions of the disposal system.

Although the assignment of realistic and pessimistic values for most parameters is explained to some extent in SR 97, this process should be made more transparent and reproducible. Guidelines should be formulated to encourage more consistent and systematic assignment of realistic and pessimistic values. At present, the rationale supporting these decisions is not transparent. For instance, the Data Report appears be arbitrary in applying multiplicative factors of 10 to arrive at "pessimistic" values for parameters like the flow-wetted surface and diffusivities. More formal statements are required on how experts in the different disciplines contributed to the data abstraction process. SKB has, in the past, considered methods that permit the construction of probability distributions from limited amounts of data (*e.g.,* Bergström *et al.* 1990), and it may be timely to revisit this topic.

Probabilistic analysis

The "bounding" approach to probabilistic analysis in SR 97 was adopted late in the assessment in response to a new regulatory requirement, and SKB has yet to evaluate the method. The IRT believes that the limitations caused by assigning only two data values for most parameters result in an incomplete analysis with an unknown level of bias. As a consequence, the results have no well-defined statistical meaning and it is not clear that, as SKB assert, the analysis leads to an overestimate of mean dose. For example, it is assumed (without proof) that there is a monotonic response from values intermediate between the "realistic" and "pessimistic" values, whereas there may be non-monotonic and complex multi-parameter dependencies that can only be covered by fuller sampling of the parameter ranges. Similarly, the probabilistic uncertainty and sensitivity analyses, are incomplete and biased in the sense that they do not examine all feasible values of the parameters.

On the other hand, SKB do have the capability to perform a fuller probabilistic analysis given sufficient time and resources to define appropriate input data distributions. The modelling of the location of defective canisters and also the generation of distributions of groundwater fluxes are appropriate uses of stochastic modelling techniques.

The IRT believes that SKB should examine methods that would enhance their future analytical capabilities, notably in the areas of probabilistic uncertainty and sensitivity analysis. Approaches that examine one parameter at a time are useful, but more general methods would contribute to the robustness of the arguments. These should explore the full range of parameter uncertainties and deal with multi-parameter sensitivities. The application of such methods will aid in decision-making and add to the robustness of the safety case for a specific site and repository. For instance, sensitivity analyses can quantify how much an uncertain parameter influences estimates of dose and risk, and thereby shed light on which parameters might be important from the viewpoint of collecting site-specific data.

Model capability

In general, model uncertainty is not as extensively discussed and documented as parameter uncertainty in SR 97. The IRT highly regards the effort made in SR 97 to build realistic groundwater flow models and to explore different variants and different modelling approaches. The results obtained from the Alternative Models Project are particularly interesting and important. Similar studies might contribute to more confidence (and less uncertainty) in the near field model, for example. The quantitative analyses performed in the base scenario to assess the isolation function of the repository may also benefit from this type of analysis.

The role and rank in the modelling strategy of the different models used in the quantitative analyses performed in the sections on the radiation-related, thermal, hydraulic, mechanical and chemical evolution are not clearly identified. This is more evident for scenarios other than the canister defect where the chain of models used for radionuclide transport is clearly defined. Other details important to the assessment of the use of these models, such as the version and data bases used in the case of the geochemical models are not always given.

Overall, although SKB appears to have a set of models that are sufficiently extensive and reliable for SR 97, more conclusive support and more transparent and traceable documentation would be valuable. SKB should consider producing reports on the computer models used in SR 97. These reports would specify the mathematical formulations, consolidate the available arguments that support the use of these models and could provide up-to-date references and support to the Process Report. The first purpose would improve transparency and traceability. The second purpose would better uncover the role and use of each model within the assessment.

3.4 The risk to individuals and impact on the natural environment

SKB calculates a bounding estimate of risk according to their own, independent interpretation of regulations, which have been issued only recently (SSI) in Sweden or are in the process of being issued (SKI). The result is of uncertain meaning both statistically and from the point of view of regulatory compliance. SKB would benefit from additional guidance from the safety authorities on the definition of risk and on the authorities' expectations, and a discussion on the practical methods that might be employed to calculate risk while preserving statistical veracity. Discussion is also required with SSI regarding their expectations for assessing impacts to the natural environment and how requirements might be met. The experience gained in SR 97, and the illustrations it provides, is useful background to these discussions.

A safety assessment should include a coherent discussion of the interpretation of the regulatory requirements and how the methodology satisfies, or could be extended to satisfy, the requirements. Indeed, one objective of SR 97 is to demonstrate the methodology for safety assessment, which should provide the results required by the Swedish authorities.

The SR 97 methodology could be consistent with the "Premises for regulations" issued by SKI (SKI 1997) which sets forth a suggested approach based on "main", "less probable" and "residual" scenarios and their impacts in different time scales. The recently prepared guidance from the SSI (SSI 1999) is a particular concern, however. For cases excluding human intrusion, the SSI guidance requires an estimate of annual radiological risk, conventionally defined[4], and further comments that this may be obtained by weighing together consequence and probabilities of event sequences (scenarios) (SSI 1999, p. 14). SR 97 does not estimate scenario probabilities nor describe how sequences of events or different scenarios would be combined to estimate overall risk. Nor, as discussed in Section 3.3, is the IRT satisfied that the "bounding estimate" of mean dose illustrated for the canister defect scenario is statistically suitable.

The applicable SSI regulations (SSI 1999) include requirements for the protection of the environment, for example, requiring evaluation of biological

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[4] The risk is the integral of the annual probability, p(D), of an individual receiving a dose in the dose range, (D, D+dD), integrated over possible doses, multiplied by the probability of harmful effects per unit dose, γ (0.073 per sievert). (SSI 1999, p.14)

effects to non-human species. These issues are not treated in SR 97, which relies on a common but unsupported statement that radiation effects on affected habitats and ecosystems is negligible if the radiation dose from the repository is less than background radiation. Discussion at the workshop indicated that SKB has begun considering the feasibility of evaluating environmental impacts, for example, by representing non-human biota in biosphere models. This work will be a useful addition to the international assessment experience, as this topic is also becoming a concern in other national programmes.

The IRT considers that the shortcomings noted above do not affect the broader conclusions in SR 97 of the overall safety of the KBS-3 concept. Further discussion is necessary, however, between SKB, SSI and SKI to explore the interpretation of various regulatory requirements, and this should help to focus of SKB's future assessments. The experience gained in SR 97, and the illustrations it provides, is useful background to these discussions.

3.5 Assessing whether the methodology may sufficiently describe the performance of the repository and consequences to the environment

The SR 97 methodology implements a bounding analysis approach that is geared towards demonstrating safety rather than investigating detailed aspects of performance. The methodology allows a sufficient description of performance in respect of safety. In future safety assessments, consideration should be given to incorporating more realistic descriptions of the performance of the facility. The adaptation and completeness of the present scenarios to the conditions of specific sites should also be considered.

The overall capability demonstrated in SR 97 is adequate for safety assessment at this stage. This includes the identification of FEPs, organisation and synthesis of the available scientific and technical information and data, the models representing the various barriers and key processes, and treatment of uncertainties. However, while some areas of the SKB assessment methodology are well advanced, others are less so, and there are weaknesses in the integration. This "unevenness" may arise because SR 97 is the first integrated safety assessment of KBS-3 since the mid-80s (see Section 2).

SR 97 has examined a suitable collection of scenarios, and presented convincing qualitative descriptions of the performance of the various components of the KBS-3 system. The quantitative estimates of dose and risk are reasonable indications of potential performance. The method of sensitivity analysis and, especially, the probabilistic analysis requires more thought.

The main and three supporting documents are generally well written and well presented. Considerable effort was required, however, to follow some specific issues through the documents and it was not always possible to follow the questions to satisfaction. Thus, there is a need to improve the traceability and transparency of the documentation. One possibility might be the use of a global index or equivalent that points to where topics are discussed in the various levels of documents. Another, mentioned in Section 3.3, is a set of reports describing the computer models.

Although the methodology is adequate at this stage, further avenues of analysis should be explored and developed, and weaknesses revealed by the SR 97 demonstration, and its various reviews, should be considered. With subsequent, additional work, a more versatile methodology for safety assessment can be evolved that will be better poised to contribute to future decision-making. In particular, SKB might give further thought to developing their assessment methodology not only as a tool for safety illustration, but also to serve decision-making during site investigation and design optimisation.

4. THE FEASIBILITY OF TECHNICAL IMPLEMENTATION

The review has identified no issues that would prevent the technical implementation of the KBS-3 concept. A pertinent concern at this stage is the lack of a discernible link, within SR 97, between the results of safety assessments and the development of site investigations and siting criteria. SKB is in the process of documenting, separately from SR 97, which site-specific data it considers to be most significant and potentially to be obtained during the site characterisation programme. Incorporation of more comprehensive sensitivity and uncertainty analyses into the assessment methodology could help to support this effort in future studies.

Based on the examination of the SR 97 documentation, the IRT identified no issues that would prevent the technical implementation of the KBS-3 concept. The work at the Canister Laboratory at Oskarshamn gives confidence in the ability to manufacture the copper canisters that are a key feature of the concept. The emplacement tests that will be carried out at the Äspö Hard Rock Laboratory should confirm the ability to emplace the canisters and bentonite buffer. The geoscientific programme at Äspö gives confidence that the rock mass can be characterised at the level necessary to avoid undesirable site features and also to provide the information necessary to assess long term safety. Furthermore, the very robust engineered barrier system of the KBS-3 concept, specifically developed for conditions prevailing in Swedish bedrock, enhances the prospects of finding sites that will be suitable locations for a repository. Proving good isolation and retention properties of the geosphere at a potential site will still, however, be an essential element in demonstrating the proper implementation of the multi-barrier disposal concept.

Regarding site selection, SR 97 did not meet the expectation of the IRT generated by its "concrete purposes" 3 and 4 which state that SR 97 shall serve as the basis for specifying site selection factors and preliminary functional requirements (SKB 1999, pp. 18-19). The IRT was not able to discern the link between SR 97 and SKB's formulation of requirements for site investigation, setting site-selection criteria or deriving functional requirements on the engineered barriers. For example, it is not clear from the analysis what site-specific (or engineered barrier) data are most important to safety assessment.

As discussed in Section 3.5, the SR 97 methodology is geared towards demonstrating safety rather than investigating detailed aspects of performance, and this may limit the contribution it can make to specifying site selection factors or guiding site characterisation studies. For example, model simplifications and the use of conservative assumptions tend to mask features that might otherwise display differential behaviour. More specifically, in SR 97, the analysis assumes some degree of homogeneity when defining the geosphere and biosphere data for Aberg, Beberg and Ceberg. Thus the analysis does not include all differences between these three sites. The possible different effects of climate-related changes at each of the sites could have been more fully explored. The effect of time-dependent processes on different sites needs to be evaluated.

Considering these points, the IRT concludes that the quantitative results described in SR 97 are unlikely to be a sufficient source of information to guide site investigation and design optimisation studies. On the other hand, SKB have substantial practical experience from their geoscientific investigations at Äspö and this, and other studies, will guide their current effort. Incorporation of more comprehensive sensitivity and uncertainty analyses into the assessment methodology could help to support this effort in future.

During the workshop, SKB revealed that the formulation of requirements for site investigation, setting site-selection criteria and deriving functional requirements for the engineered barriers, formed part of other studies that were not yet complete. SKB presented a progress report and some preliminary findings from these studies. This, together with the IRT's knowledge of previous work by SKB in this area (*e.g.*, Andersson *et al.* 1998), indicates that SKB are preparing adequately in this area, but assessment of work in progress is beyond the scope of this review.

Finally, it should be remembered that the regulations applying to the disposal of spent nuclear fuel in Sweden are still under development (SKI) or have only been recently promulgated (SSI). Some questions related to their interpretation were identified during the review that will impact on the future development of SKB's assessment methodology. It is important that SKB, SKI, and SSI continue their dialogue on the interpretation of regulatory guidance with pragmatism and with a view to minimise difficulties and promote clarity in the eventual judgement of compliance.

5. CONCLUSIONS

The KBS-3 disposal concept has the essential elements of a sound concept for the disposal of spent nuclear fuel in a geologic repository. It provides defence-in-depth through a set of passive barriers with multiple safety functions. The concept is based on well-established science and a firm technological foundation, is well defined, and appears to be implementable.

SR 97 provides a sensible illustration of the potential safety of the KBS-3 concept that takes account of the conditions in Swedish bedrock, based on data from three sites. The documentation is generally well written and the arguments well presented, but there is room for improvements in the completeness of arguments, traceability and transparency.

Given the current state of expertise of the SKB geoscience and engineering programmes and the favourable indications from SR 97, SKB's desire to move to a site-selection phase is well founded. This is reinforced by the observations that the performance of the geosphere barrier is site-specific and data are needed from potential sites to better develop, focus and test the SKB assessment methodology.

The review has not identified urgent issues that must be resolved prior to proceeding to the investigation of potential sites. Several observations and recommendations are made that SKB and the safety authorities may wish to consider in the future development of the Swedish safety assessment programme for spent fuel disposal:

- A high-level, periodically updated document describing the SKB's safety strategy should be prepared. This would reveal the evolution of the KBS-3 concept and show how various technical studies have contributed to its development and to the understanding of the requirements for safety.
- More frequent, iterative safety assessments would facilitate the timely evaluation of the significance of new scientific and engineering information and enhance the role of safety assessment as a means to integrate the programme. More frequent assessments would also

develop and ensure the continuity of staff experience and skills required to conduct such assessments.

- A number of technical issues have been identified, the resolution of which would enhance the robustness and transparency of the descriptions and arguments that support the safety case. More important examples relate to:
  - Documentation of the evidence and arguments leading to confidence in the maintenance of reducing groundwater conditions at repository depth,
  - Improved understanding of the origin and evolution of groundwater solutes,
  - Interpretation of the "flow-wetted surface" parameter including methods to provide field data necessary to support its use, and
  - Definition of the expectations and requirements of biosphere modelling consistent with Swedish regulatory guidance and scientific constraints.
- Better definition of SKB's strategy for scenario selection could clarify the representativeness and purpose of the different scenarios, and how they build to an integrated evaluation of safety. In future assessments, more formal scenario development or selection techniques would be preferable.
- It would be beneficial to develop an integrated, and more comprehensive, approach to uncertainty and sensitivity analysis that covers a fuller range of parameter and model uncertainties and evaluates multi-parameter sensitivities. Improved transparency is needed in the selection of parameter values defined as "realistic" or "pessimistic" in SKB's current method. Methods that permit the construction of probability distributions from limited amounts of data should be reconsidered.
- Discussion is required between SKB, SKI and SSI on the interpretation of the Swedish regulatory requirements related to risk and probability, the authorities' expectations, and practical methods that might be employed to calculate desired endpoints while preserving statistical veracity. Discussion is also required with SSI regarding their expectations for assessing impacts to the natural environment and how requirements might be met.
- In future safety assessments, consideration should be given to incorporating more realistic, as opposed to conservative, descriptions of the performance of the facility. The adaptation and completeness of the present scenarios to the conditions of specific sites should also be considered.
- Incorporation of more comprehensive sensitivity and uncertainty analyses into the assessment methodology could help to guide site investigations, and specifically, to identify which site-specific data are

most important to safety and potentially to be obtained during the site characterisation programme.

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APPENDIX – MEMBERS OF THE INTERNATIONAL REVIEW TEAM

Andrew Campbell
(Nuclear Regulatory Commission, United States of America)

Dr. Andrew Campbell is a Senior Staff Scientist with the Advisory Committee on Nuclear Waste (ACNW) of the US Nuclear regulatory Commission. He has nine years of experience in nuclear waste management with specific expertise in regulatory applications of risk analysis, developing and conducting performance assessments, and applying radionuclide chemistry and geochemical modelling to waste disposal. Dr. Campbell is currently on a six-month rotation in the NRC's Office of Research, Division of Risk Analysis, as a Team Leader for the radionuclide transport and decommissioning program. His responsibilities include managing a team of eight researchers, studying sorption models for use in performance assessment, and leading reviews of performance assessments.

At ACNW Dr. Campbell's responsibilities have included reviews of the DOE and NRC high-level waste programs, DOE's Viability Assessment, Total System Performance Assessments, elicitation of expert judgement in nuclear waste facility licensing, risk-informed, performance-based regulation at the NRC, and the scientific and technical issues for modelling radionuclide release and transport. He has also organised and conducted workshops on the performance of engineered barriers in the near-field environment at Yucca Mountain, low-level waste time of compliance, radionuclide transport in the saturated and unsaturated zones, and application of probabilistic risk assessment to waste management.

Prior to working at ACNW Dr. Campbell was overall project manager for the NRC's LLW Performance Assessment Program. In this role, he was responsible for developing guidance for LLW performance assessment and developing performance assessment models for LLW disposal. He also worked on regulatory applications of geochemical and hydro-geologic models. Dr. Campbell joined the NRC in 1991 from the Massachusetts Institute of Technology, where he was a Research Associate conducting geochemistry studies of submarine hydrothermal vent fluids and particles using the submersible ALVIN. He obtained a Ph.D. from Scripps Institution of Oceanography (marine geochemistry). He also has an M.S. in Chemistry and a B.A. in Chemistry and Philosophy, with Honors in English, from the University of Arizona.

Margaret Federline, IRT Chairperson
(Nuclear Regulatory Commission, United States of America)

Mrs. Federline is the Deputy Director of the Office of Research at the US Nuclear Regulatory Commission (NRC). The Office of Research conducts independent analyses and experiments, develops the technical basis for realistic safety decisions, and prepares the agency for the future by evaluating safety issues involving current and emerging technologies. In her managerial capacity, Mrs. Federline oversees a complex technical programme of approximately two hundred staff and over forty million dollars. Mrs. Federline draws on extensive experience in the fields of environmental assessment, radiation safety, and waste management gained in managerial, policy and professional scientific positions with private industry and the Federal government. As the Deputy Director of the Division of Waste Management at the NRC, she directed programs for the regulation of low-level and high-level radioactive waste, uranium recovery, and decommissioning which involved a large research program at a dedicated Federally Funded Research and Development Center. As Chief of the Performance Assessment Branch she directed the development and implementation of performance assessment methodologies for waste management applications. Mrs. Federline is active with international counterparts in the fields of waste management and decommissioning, and is currently serving as a member of the Bureau of the OECD Nuclear Energy Agency Radioactive Waste Management Committee. In addition, she recently participated in an International Commission on Radiation Protection Working Group to develop radiation protection recommendations for the disposal of long-lived solid radioactive waste.

Bruce Goodwin
(GEA Consulting Inc.)

Dr. Bruce Goodwin is a scientist with a wide range of experience in applied R&D environments. Much of his studies are focused on the Canadian nuclear fuel waste management program. These studies started in 1979 when he joined Atomic Energy of Canada Limited (AECL) and continued from 1998 when he became a private consultant.

While at AECL, Dr. Goodwin was charged with the preparation and documentation of a long-term environmental assessment of the concept for disposal of Canada's nuclear fuel waste. He provided technical direction for a group of scientists and programmers who developed SYVAC, a computer code that provides a systematic analysis of the effects of parameter uncertainty. He was the lead author of two long-term safety assessment reports that were presented and defended at public and peer review meetings conducted by a federally appointed Panel. The Panel's report, released in 1998, concluded that the safety of the concept had been adequately demonstrated from a technical perspective. Dr. Goodwin has also been active in the international arena, notably with working groups established by the OECD Nuclear Energy Agency. These groups include the Probabilistic Systems Assessment User Group (where he served as the first chairman), the Working Group on the Identification and Selection of Scenarios for Performance Assessment and the Working Group to Develop an International Database of FEPs. He has presented many papers at international symposia, including invited papers at a course on risk analysis at the JRC in Ispra, Italy and at a workshop on radioactive waste disposal in Taiwan. In addition, Dr. Goodwin organised and participated in an international workshop that brought together performance assessment and communication specialists from Canada, Sweden, Switzerland, Finland and Japan.

As a private consultant, Dr. Goodwin has continued his ties with the nuclear fuel waste management program in Canada. He has been an active contributor to the Used Fuel Disposal Program at Ontario Power Generation in the development of tools for use in safety assessment.

Jean-Marie Gras
(Élecricité de France, France)

Graduate, École Nationale Supérieure de Chimie de Paris, France, 1972 ; PhD in corrosion, CNRS, France, 1974.

Dr Gras joined the Division of Research and Development of Électricité de France (EDF) in 1975. Directly involved in the study of corrosion problems for new energy systems and nuclear power generation, he became Head of the Corrosion Group from 1985 till 1991. Since 1992, he is engaged in the appraisal of the French programme in nuclear waste management, and assures, within EDF, the co-ordination of the R&D on High-Level-Waste disposal and on the interim-storage at long term of spent nuclear fuels.

His interests include, especially, corrosion behaviour of spent fuel and metallic container materials for geological disposal of HLW, as well as materials evaluation of interim spent fuel dry storage for extended service. He has currently a teaching assignment on the conditioning of HLW at the École Nationale Supérieure de Chimie de Paris.

Claudio Pescatore, IRT Secretariat
(Nuclear Energy Agency of the OECD)

Dr. Pescatore holds a Ph.D. in nuclear engineering from the University of Illinois, Urbana-Champaign (USA). He has 20 years' experience in the field of nuclear waste covering low-level waste, high-level waste and spent-fuel storage and disposal.

Dr. Pescatore joined the Brookhaven National Laboratory in 1982 and was directly involved in the study of high-level waste and spent-fuel disposal concepts in basalt, salt, and tuff formations: reliability and modelling studies of waste package materials during storage and disposal, analyses of gaseous and aqueous pathways for radionuclide migration, peer reviews of environmental impact assessments studies and site characterisation plans. At Brookhaven, he was group leader for Radioactive Waste Performance Assessment. Till 1995, he was also adjunct Professor of Marine Environmental Sciences at the University of New York, Stony Brook.

Dr. Pescatore joined the NEA/OECD in 1992 in the Division of Radioactive Waste Management and Radiation Protection, where he has been Acting-Head of the Division. He has been at the centre of several recent international initiatives such as the ASARR and GEOTRAP projects, the GEOVAL '94 symposium, the IPAG studies, etc. He assures the technical secretariat of several NEA committees: the Radioactive Waste

Management Committee (RWMC), the RWMC Regulators' Group, the Performance Assessment Advisory Group, etc. On behalf of the NEA he has organised numerous international peer reviews of national studies. Namely: SKI's Project-90 (Sweden), AECL's Environmental Impact Statement of the Disposal of Canada's Nuclear Fuel Waste, the 1996 Performance Assessment of the US Waste Isolation Pilot Plant (WIPP), the SKI's SITE-94 project (Sweden), the NIREX methodology for scenario and conceptual model development (UK), and JNC's H-12 Project to establish the technical basis of HLW disposal in Japan.

Javier Rodriguez

(Consejo de Seguridad Nuclear, Spain)

Dr. Rodriguez received his Ph.D. in geology in 1989 from the Complutense University of Madrid, Spain. His dissertation was a model of the origin and movement of pore water and solutes in a clayey aquitard in the surroundings of the Donana National Park (Spain). Granted by the Fulbright Programme for postgraduate students, he studied groundwater flow and transport modelling at the Department of Earth and Planetary Sciences at the Johns Hopkins University in Baltimore (Maryland, USA) during the period 1988-89. He serves as Associate Editor of *Hydrogeology Journal*, the official journal of the International Association of Hydrogeologists (IAH), since 1997.

Dr. Rodriguez joined the CSN in 1989 in the Branch of Siting and participated in the CSN review for the licensing of the construction and the operation of the El Cabril low-level radioactive waste disposal facility, and the dismantling and site restoration of the disused Andújar uranium mill. He participated also in the updating of the studies for the characterisation of seven nuclear power plant sites. Since 1996 he has been working in the Branch of High-Level Waste and has been directly involved in the CSN activities regarding the safety of high level waste geologic disposal. He co-ordinates several studies and research projects focused mainly on modelling aspects of performance assessment and approaches for confidence building in order to increase the CSN technical capabilities for the review of the safety assessment of high-level waste disposal.

Dr. Rodriguez has participated in several international activities of the European Union and the OECD Nuclear Energy Agency, being the CSN representative in the Co-ordinating Group for Site Evaluation and Design of Experiments (SEDE) of the Radioactive Waste Management Committee (RWMC) of the OECD/NEA.

Trevor Sumerling

(Safety Assessment Management Ltd., United Kingdom)

Trevor Sumerling obtained a 1st class honours degree in physics from Lancaster University in 1975. He spent 8 years at the UK National Radiological Protection Board where he gained experience in the fields of *in vivo* monitoring, internal dosimetry and environmental transfer of radionuclides, and became responsible for the *in vivo* measurement facilities and various environmental field studies at the NRPB. For the past 15 years he has worked in scientific and engineering consultancies on aspects of radioactive waste disposal safety and assessment management. In this period, he has contributed significantly to nuclear waste disposal programmes in the UK, Switzerland, Sweden, Canada and Japan. He is Director of Safety Assessment Management Limited, an independent consultancy specialising in radioactive waste disposal assessment.

His more recent experience has included:

- The co-ordination of an independent performance assessment of the Sellafield site and review of the proponent's safety documentation on behalf of the UK regulator, as well as development of assessment procedures and contributions to UK regulatory guidance documentation;
- Scenario methodology development and application to both the Kristallin-I (HLW) project and Wellenberg (L/ILW) site, as well as technical work and editing contributing to the Kristallin-I and Opalinus Clay safety assessment reports, for the Swiss National Co-operative for Radioactive Waste Disposal;
- Carrying out an international comparison of disposal concepts and assessments of nuclear fuel wastes for Atomic Energy of Canada Limited as input to the federal review process in Canada;
- Participation in the NEA OECD "International FEP Database", "Integrated Performance Assessment" and "Clay FEP" working groups and, also, the NEA/IAEA International Review of the WIPP 1996 Performance Assessment;
- Co-ordination for UK Nirex Ltd. of an evaluation of the retrievability of waste from a ILW/LLW repository in the UK and development of a strategy for retrievability including possible design and operation modifications to enhance retrievability.

Hideki Sakuma
(Japan Nuclear Cycle Development Institute, Japan)

Hideki Sakuma holds the degree of M.A. in oceanography from Tokai University, Japan. His professional career started in 1977 as a member of Overseas Uranium Exploration Project of Japan, which gave him opportunities to become familiar with a variety of geology in the world including Canada, Australia and China. Since 1987, he has been working for Japanese HLW Management project. He has been Japanese representative on a number of international and bilateral projects and conferences in the area of HLW management. Among others, he was the Japanese representative on the Joint Technical Committee of the OECD/NEA International Stripa Project. On the other hand, he has been a senior research scientist for Kamaishi and Tono Underground Research Projects. He was a member of the Core Group for the First Progress Report (H-3) on the HLW research and development project in Japan and he was an main author of the Supplementary Volume of the Second Progress Report (H-12) of the Japanese program which underwent an international peer review organised by OECD/NEA earlier this year. His current position is a Senior Scientific Research Co-ordinator of Japan Nuclear Cycle Development Institute.