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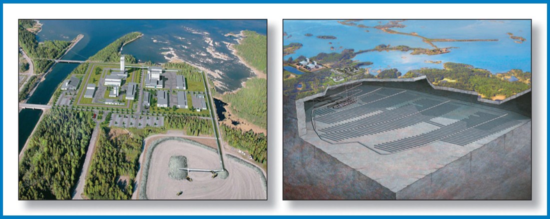
The Post-closure Radiological Safety Case for a Spent Fuel Repository in Sweden

An International Peer Review of the SKB License-application Study of March 2011



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NEA No. 7084

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The mission of the NEA is:

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The NEA Data Bank provides nuclear data and computer program services for participating countries. In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

Cover photos: Planned area for the spent nuclear fuel repository in Östhammar, Sweden (SKB).

Foreword

A major activity of the OECD Nuclear Energy Agency (NEA) in the field of radioactive waste management is the organisation of independent, international peer reviews of national studies and projects. It was at the request of the Swedish government that the NEA organised an international peer review of the post-closure radiological safety case produced by the Swedish Nuclear Fuel and Waste Management Company (SKB) in support of the application for a general licence to construct and operate a spent nuclear fuel geological repository in the municipality of Östhammar. According to its Terms of Reference (ToR), the peer review was to provide the Swedish government with a statement, from an international perspective, on the sufficiency and credibility of SKB's post-closure radiological safety case (SR-Site) for the licensing decision at hand. In order to fulfil the ToR, the NEA Secretariat established an International Review Team (IRT) made up of ten international specialists, including one member from the NEA. The experts chosen were to be free of conflict of interest with the SKB and to bring complementary expertise to the review, according to the ToR. One additional expert participated in the IRT as an international observer. All contacts between the SKB and the IRT were organised and managed through the Swedish nuclear safety regulator (SSM).

This report presents the consensus view of the IRT. In accordance with the ToR, this consensus view is based on the experts' review of the main report of the SR-Site project, the report on site selection, the report on choice of method and multiple supporting documents. In addition, the experts relied on information exchanged with the SKB in answers to questions raised by the IRT, and on direct meetings with staff from the SKB during working seminars and site visits in Sweden.

In keeping with NEA procedures for independent reviews, neither the Swedish government nor the SKB have commented on the IRT report. The SKB and the SSM were only given an opportunity to check for factual correctness. The IRT has made its best effort to ensure that all information is accurate and takes responsibility for any factual errors.

Acknowledgements

The members of the IRT would like to thank the SSM staff for their hospitality during the brief visits to Sweden, and for their excellent organisational support, which facilitated the work of the IRT. The IRT would also like to thank the staff of the SKB for the helpful and open way they responded to the review. Finally, the NEA acknowledges the many organisations that have made their experts available to carry out the review.

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High-level findings

Background

An international peer review has been conducted of the post-closure radiological safety case produced by the Swedish Nuclear Fuel and Waste Management Company (SKB) in support of its March 16, 2011 application for a general licence to construct and operate a spent fuel geological repository in the municipality of Östhammar. The peer review was carried out by 10 international specialists chosen to be free of conflict of interest and to bring complementary expertise to the review as specified in the Terms of Reference of the review (ToR). The International Review Team (IRT) reviewed all reports identified in the ToR as contributing to the SKB's long-term safety study (SR-Site, from now on) plus non-SKB literature, plus it had written and verbal exchanges with SKB staff. All such contacts between SKB and IRT were organised and managed through SSM, the Swedish nuclear safety regulator.

The SR-Site study of 2011 is a preparatory Preliminary Safety Analysis Report (PSAR). Namely, it is the first in a series of safety studies of increasing complexity that regulators will review before SKB can eventually build and routinely operate a spent fuel repository. It is understood that not all issues can be resolved at the time of the application for a general license – but these issues ought to be identified in the actual step. According to the Swedish licensing process SKB is not allowed to start underground construction and exploration until it receives in a next step of the licensing process an additional license by SSM for construction, for which SKB will apply if the government will grant SKB a general license. Also, should SKB receive a general license, it is foreseen that specific licensing conditions will play an important role in formalising requirements for the continued step-wise licensing process.

The IRT members received the documents supporting the post-closure radiological safety case and divided the main review responsibilities according to technical areas of expertise. The IRT did not conduct a detailed evaluation of calculations and individual parameter values used in the phenomenological modelling and in the safety analysis. Rather, the IRT used the specialist knowledge of its members and its collective understanding of international best practice to evaluate the information provided and to make findings and recommendations. The following thematic areas were reviewed in depth: geosphere; buffer and backfill; copper canister; fuel and cladding; biosphere; practical implementation; performance assessment; performance confirmation; societal aspects.

This report presents the consensus view of the IRT. The IRT has made its best effort to ensure that all information is accurate and takes responsibility for any factual errors. Also, the IRT wishes to confirm that enough information was available to the IRT to enable it to fulfil the ToR.

Key findings

The purpose of the review is to help the Swedish government, the public and relevant organisations by providing an international reference about the maturity of SKB's spent fuel disposal programme vis-à-vis the best practice of long-term disposal safety and radiation protection. Accordingly, the ToR indicates that the peer review should provide the Swedish government with a statement, from an international perspective, on the sufficiency and credibility of SKB's post-closure radiological safety case for the licensing decision at hand. In developing such statement, the International Review Team (IRT) was asked to refer to international best practice in specific areas. Namely: presentation of safety arguments, safety assessment methods, completeness, handling of remaining issues, selection of site and disposal method, feasibility.

Statement to the Swedish government

From an international perspective, SKB's post-closure radiological safety analysis report, SR-Site, is sufficient and credible for the licensing decision at hand. SKB's spent fuel disposal programme is a mature programme – at the same time innovative and implementing best practice – capable in principle to fulfil the industrial and safety-related requirements that will be relevant for the next licensing steps.

SR-Site was submitted to the Swedish authorities in March 2011 as part of the application for a general licence to construct and operate a spent fuel deep geological repository in the municipality of Östhammar. Once this general license is granted, additional licensing steps are necessary for the further construction and operation of the repository. For these future licensing steps additional safety analysis reports have to be provided with more detailed technical argumentations and evidence. Taking this into account, and within the Swedish licensing and permitting context, SR-Site can be described as a preparatory Preliminary Safety Analysis Report. This stepwise approach to repository development and licensing is well-established international practice.

The overall question that the IRT asked itself was: "Is the SKB long-term safety case convincing at this stage?" The detailed findings of the IRT show that SKB generally gives a convincing illustration and technical basis both for the feasibility of the future repository, according to the KBS-3 design, and for its radiological long-term safety. The arguments presented are generally sound, based on current status of science and on par with the international state of the art. Nevertheless, in several areas improvements are possible, which would enhance confidence in the results of the safety analysis. Recommendations are provided in the body of the IRT report.

A second important question was: "Does SKB identify the major aspects that need to be developed in the future?" The IRT finds that SR Site and its supporting documents cover all major aspects that need to be developed in the future. Nevertheless within specific major aspects improvements are possible and are identified in the body of the IRT report. An important observation is that, with the current licensing step, the repository project will leave the conceptual phase, which was mostly based on scientific research work. As a natural progression of the repository project, the industrial feasibility of the barriers and of the repository, including assurance of their quality, will now become increasingly important. More emphasis on these aspects is expected and will be necessary in the future. Another challenge for the future will be to both enhance and broaden the basis for the scientific evidence supporting long-term safety. To that effect, additional research and more detailed calculations will be needed for the safety cases supporting the next licensing steps.

The IRT also checked specifically whether there is anything “missing or amiss” in SR-Site. The IRT didn’t find any major omissions. Some improvements regarding completeness at a lower level are identified in the IRT report.

The above statement rests on the following high-level findings that arise from the ToR and are substantiated in the main body of the IRT report.

Presentation of safety arguments

The IRT concludes that SKB has presented its safety case for a repository clearly and in a well-structured manner, which generally allows the traceability and justification of its overall safety conclusions.

The IRT has noted some areas where clarity and traceability of the safety case could be improved, and has provided recommendations to address those areas.

Safety assessment methods

The IRT finds that the SKB safety assessment methods are generally on par with state-of-the-art, are sufficiently described, and that SKB has presented credible scientific bases (FEPs [features, events, and processes], models, data, etc.) in support of their analyses.

The IRT finds that the SKB’s measures for quality assurance of the licensing documentation are generally sufficient at this stage of repository development. The IRT has provided a recommendation to strengthen the discussion of quality assurance in the safety case and to improve the quality of the licensing documentation.

Completeness

The IRT has found that, in the areas examined by the IRT, SKB has taken the current state of knowledge into account properly and that nothing is missing or amiss at this stage of repository development. In some cases, the current state of knowledge is not yet complete because data from the actual subsurface excavation, which has not yet begun, are not available. The IRT expects that the completeness of SKB's safety case could be increased in future steps that address remaining technical issues.

Handling of remaining issues

The IRT finds that SKB has done a good job identifying remaining research and technical-development issues and has provided clear plans for their resolution.

The IRT has recommended that SKB clarify the linkage between the safety analysis and the licensing, design, construction and commissioning processes, and further develop plans for a comprehensive programme of testing and monitoring to confirm its safety-related assumptions.

Selection of site and disposal method

The IRT finds that SKB has selected and developed its KBS-3 disposal method within the widely and internationally accepted geological deep disposal strategy for disposing of spent nuclear fuel. SKB's arguments in presenting KBS-3 as a robust disposal method that is well suited to meet all safety requirements are convincing and cogent. SKB approaches to public outreach in the site selection and method development process are at the forefront of international practice.

The IRT has made observations in the area of BAT (best available technique), and recommendations in the area of assuring continuing competence, knowledge management, and stakeholder involvement.

Feasibility

IRT finds that, at the present level of the stepwise licensing development, the technical implementation of the KBS-3 method is sufficiently described and credible to justify SKB's assumption on the properties of the repository system.

The IRT has provided recommendations for SKB that would further increase confidence in SKB's assumptions on the feasibility of the initial state of the repository system.

1. Introduction

1.1 Background on the Swedish spent fuel disposal programme

The main actors

According to Swedish law the owner of a nuclear reactor has the full responsibility for the safe handling and final disposal of spent nuclear fuel and nuclear waste that is produced. To this effect, the owners of the Swedish nuclear power plants have jointly set up the Swedish Nuclear Fuel and Waste Management Company (SKB). The Swedish Radiation Safety Authority (SSM) is the regulatory body responsible for supervising nuclear (waste) safety and radiation-protection.

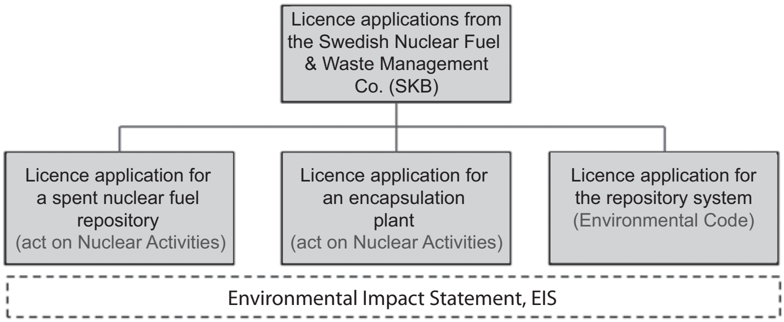
SSM's regulations and guidance on post-closure repository safety can be divided into two parts: radiation protection and safety regulations. The Swedish post-closure safety regulations are, in general, not prescriptive. Rather, they set out the general protection and safety objectives and requirements on safety reporting. They are legally binding. The corresponding guidance documents provide more details but are not legally binding.

The regulations SSMFS 2008:37 comprise basic requirements on the protection of human health (expressed as a risk target), on general environmental protection goals and on the application of optimisation and best available technique (BAT). The corresponding guidance gives additional advice on the reporting of risk, BAT and optimisation for different time periods after closure, selection of scenarios, calculation of risk, handling of uncertainty and risk dilution. The regulations on repository safety (SSMFS 2008:21) contain requirements on the design of the repository, barrier functions and safety reporting. In addition to these regulations there are several regulations applicable to the construction and operational phases of the repository.

A stepwise licensing process

On the 16th of March 2011 SKB submitted the applications needed for a KBS-3 type spent nuclear fuel repository system. In accord with the Act on Nuclear Activities, SKB filed two applications: (1) One for a spent nuclear fuel repository at Forsmark; and (2) a second for an encapsulation plant to be co-located with the existing interim storage facility for spent nuclear fuel (CLAB) in Oskarshamn (see figure below). SKB submitted the application for the encapsulation plant in 2006, and has now provided a supplement. In addition, SKB submitted a license application for the repository system according to the Environmental Code (EC). Finally, SKB filed an Environmental Impact Statement (EIS) common to all three applications.

The licensing review procedure



The current license application to construct, own, and operate a spent nuclear fuel repository is just the first step of a long decision-making process. The present safety study in support of the current license application is described by SKB as a Preparatory Preliminary Safety Analysis Report in the license application file.[1] Should the government grant SKB the requested license, SKB will need another permit from SSM before they can start the actual construction work at the repository site. The latter permit requires SSM's approval of a Preliminary Safety Analysis Report (PSAR). Such approval would be needed to build any nuclear facility licensed in accord with SSM's regulations SSMFS 2008:1. SKB will need still more permits from SSM, and will need to update its PSAR, before SSM will authorise the start of test operations and, eventually, routine operations. Nevertheless, the upcoming licensing decision is an important one because it is the last step with a broad societal involvement. This involvement is realised through the Environmental Impact Assessment process, the opportunity for municipal veto, and the actions SSM will take to submit SKB's license applications for national consultation (see below). Furthermore, it is at this point that final decisions on both disposal method and site will be reached. Hence, the Swedish decision-makers have to be convinced that the proposed repository system is feasible (can be constructed and operated as described in SKB's current preparatory PSAR) and that SKB will be able to show that the repository will meet applicable radiation protection and safety requirements. Because all issues in SKB's safety assessment cannot be resolved at this licensing step (SKB is for example not allowed to start underground construction and exploration until they have received a license for doing so) it is foreseen that licensing conditions will play an important role in formalising requests for resolution of remaining issues – should SKB receive a license.

1. The IRT was tasked with reviewing the long-term radiological safety aspects of this study.

History of the repository development programme

The current license applications are supported by almost 30 years of development of the KBS-3 disposal method by SKB. Significant research and development has been done at the Äspö Hard Rock Laboratory and, later, at the Canister and Bentonite Laboratories in the Oskarshamn region. SKB has also commissioned research at universities and research institutes. The siting process for the spent nuclear fuel repository has included a national screening of suitable regions and feasibility studies (desktop studies) in eight municipalities during the 1990s.

Every third year since 1986 SKB has presented completed, on-going and planned research, development and demonstration activities in their RD&D programmes, in accordance with the Act on Nuclear Activities. SSM coordinates a national consultation of each RD&D programme report and makes its own review report, which includes a review statement to the government. This duty belonged previously to SKI, the former Swedish Nuclear Power Inspectorate. The government in turn makes the final decision on SKB's RD&D programmes. SKB's latest RD&D programme dates to 2010 and describes research and development plans of relevance for the assessment of the current license application. However, all information on plans for resolution of remaining scientific and technical issues related to the KBS-3 repository should also be included or at least referenced in the current licensing documents.

In parallel with SKB's development, the SSM and its predecessors, SKI and SSI, have prepared for SKB's license applications for more than 25 years by reviewing SKB's work, including nine RD&D programmes, four preliminary safety assessments of the KBS-3 repository and SKB's site investigations. SSM has also conducted an independent research programme on a range of scientific and technical topics of importance for the review of post-closure safety. Because the Swedish authorities do not have access to a technical support organisation, most of the research has been conducted through a network of international academic experts and consultants. During the 1990s SKI also carried out two independent safety assessment projects of the KBS-3 disposal method, both of which was subjected to an international peer review organised by OECD/NEA.

During the last ten years, the former authorities SKI and SSI, have had a series of consultation meetings with SKB, on the scope of the site investigations and the content of the license applications. Given that there are few formal requirements in Swedish legislation on the content of a license application for a nuclear facility, these pre-licensing interactions between authority and industry have provided an important forum for SSM and its predecessors to clarify their expectations of the SKB's licensing documentation.

1.2 The context and purpose of SR-Site

The context and purpose of SR-Site were described as follows to the IRT:

- Role of SR-Site report in licence application:
  - To document SKB's analyses that evaluate the long-term safety of a KBS-3 repository at the Forsmark site.

- The main purposes of the SR-Site project were:
  - To assess the safety, as defined in applicable Swedish regulations, of the proposed KBS-3 repository at Forsmark.
  - To provide feedback to design development, to SKB's R&D programme, to detailed site investigations and to future safety assessment projects.

Regarding the last point it is relevant to recall that although SKB's latest RD&D 2010 programme describes research and development plans of relevance for the assessment of the license application, all information on plans for resolution of remaining scientific and technical issues related to the KBS-3 repository should be included or at least referenced in the current licensing documents.

1.3 Remit of the international peer review

The useful contribution provided to national programmes by earlier NEA reviews led the Swedish authorities to ask the NEA to carry out a peer review of SKB's post-closure radiological safety case. The remit of the peer review is to provide a statement, from an international perspective, on the sufficiency and credibility of SKB's post-closure radiological safety case for the licensing decision at hand.

In developing such a statement the International Review Team (IRT) was expected to address the following aspects of SKB's safety case.

Presentation of safety arguments

- Has SKB presented its safety philosophy and safety arguments clearly, and in a well-structured way?
- Are the overall safety conclusions traceable and justified?

Safety assessment methods

- Are SKB's safety assessment methods on par with the international state-of-the-art and sufficiently described?
- Has SKB presented a credible scientific basis in support of their analyses (FEPs, models, data etc.)?
- Are SKB's measures for quality assurance of the licensing documentations sufficient?

Completeness

- Has SKB taken the current state of knowledge properly into account?
- Is anything missing or amiss?

Handling of remaining issues

- Are remaining research and technical development needs properly identified?
- Are there clear plans for their resolution in the continued step-wise development and implementation programme?

Selection of site and disposal method

- Is SKB's argumentation for site selection and method development convincing and cogent, taking into account the international experience?

Feasibility

- Is the technical implementation of the KBS-3 disposal method sufficiently described and credible to justify SKB's assumptions on the properties of the repository system after closure (the initial state)?

The findings of the International Review Team (IRT) are to be based on the documentation that was provided, on additional inquiries with SKB staff during the review process, and on the understanding that this is one step in the stepwise development and licensing of a spent fuel repository in Sweden. Judgements on compliance with Swedish regulations are the responsibility of SSM and fall outside the scope of the international peer review.

The primary documents for the international peer review are:

- The main report of the SR-Site project: "Long-term safety for the final repository for spent nuclear fuel at Forsmark".
- The report on site selection: "Siting of the final repository for spent nuclear fuel".
- The report on selection of method: "Evaluation of strategies and systems to manage spent nuclear fuel".

English versions of the latter two reports were made available by SKB by June 2011. In order to fulfill its mandate, the IRT reviewed many secondary documents, such as the primary references to the SR-Site report. The complete set of documents that were the subject of the review by the IRT are much more numerous and are listed in Annex 2.

1.4 Organisation and conduct of the review

The international peer review was organised according to NEA's guidelines for international peer reviews for radioactive waste (OECD/NEA, 2005). The total review time was about one year.

The IRT was assembled independently by the NEA. In order to preserve independence and avoid conflict of interest, the experts chosen by the OECD/NEA were not, and have not been, involved (e.g. as consultants, employee or expert) either for SKB, or for the Finnish waste management organisation Posiva, in developing the disposal method or safety case. Criteria for assessing independence are described in the ToR of the peer review. The international peer review team was chosen to provide experience in long-term safety evaluations, including safety assessment methodology, expert knowledge for each of the key components of the KBS3-method (crystalline rock environment, waste form, and the engineered barrier components such as copper canisters and bentonite clay buffer), regulatory experience, and competence in the societal aspects of repository development. Furthermore, the team members were selected to have a broad international composition and to provide a balance between specialist competence from academia and experts with broad knowledge of waste management and safety assessment. One additional expert was attached to the IRT as an international observer. Annex 1 to this report lists the IRT members and the observer and provides brief biographical sketches. A recent NEA document (NEA, 2005) provides information on the nature of NEA-organised peer reviews in the field of radioactive waste management. The general guidelines that the report describes were adhered to for the SKB peer review, as for others before.

The IRT met for the first time at a three-day orientation meeting in Stockholm between the 17th and 19th of May 2011. During these three days, SSM presented its plans for the licensing review and applicable regulations. SKB staff gave a presentation of the license application with focus on post-closure safety. The IRT also discussed the Terms of Reference (ToR) for the review, and the division of the work among the review team members.

Within several months after the start of the review, the IRT sent three rounds of written questions to SKB. The questions include the standard set of questions developed for NEA-organised peer reviews (OECD/NEA, 2011) and questions specific to the current review. Secondary documents were reviewed as needed by the IRT. After SKB provided written answers to the IRT's questions, the IRT met for its 5-day main review meeting in Stockholm from the 12th to the 16th of December 2011. During this meeting the IRT conducted hearings of SKB to discuss outstanding questions identified by the IRT, summarised its preliminary review findings and planned for completing the review report. SSM staff and consultants participated in this meeting as observers, and the IRT gave a public, oral report to SSM on its impression of the review at the end of the meeting.

The IRT is satisfied that it obtained all the information necessary to meet its peer review obligations.

1.5 Organisation of this report

The report starts with a section on high-level findings meant for an audience of policy makers.

Chapter 1 presents background information on the Swedish repository programme, on SKB's post-closure radiological safety case, on the organisation of the international peer review, its ToR and the conduct of the review.

Chapter 2 answers the questions of the peer review remit and addresses the sufficiency and credibility of SKB's post-closure radiological safety case for the licensing decision at hand. It represents a more detailed version of the high-level findings that are presented earlier on in the review report.

Chapter 3 provides a summary of the technical findings in each of the main thematic areas that were reviewed. This chapter is written for a need-to-know audience of decision-makers and interested public. Its contents may be seen as the summary of Chapter 4.

Chapter 4 is the longest chapter and is aimed at the more technically interested reader. Its subsections are organised around the different disciplines that contributed to the post-closure radiological safety case, particularly those about the quality of the technical and scientific basis of the work undertaken.

The reference audience of this report is the Swedish government and the Swedish Radiation Safety Authority. Other institutions, organisations, companies, and generally interested parties involved in waste management may also benefit from the report. The review report presumes the reader is generally familiar with the aims and content of the license application, but not necessarily with all the details of the documentation.

2. Findings according to the remit of the review

The purpose of the review is to help the Swedish government, the public and relevant organisations by providing an international reference about the maturity of SKB's spent fuel disposal programme vis-à-vis best practice in long-term disposal safety and radiation protection. Accordingly, the Terms of Reference (ToR) of the review states that the peer review should provide the Swedish government with a statement, from an international perspective, on the sufficiency and credibility of SKB's post-closure radiological safety case for the licensing decision at hand. In developing such statement, the International Review Team (IRT) was asked to refer to international best practice in specific areas. Namely: presentation of safety arguments, safety assessment methods, completeness, handling of remaining issues, selection of site and disposal method, feasibility. This chapter presents the findings of the IRT vis-à-vis the remit of the review as described in the ToR.

The findings of the IRT are based on the documentation provided by SKB, on additional inquiries with SKB staff during the review process, public hearings and site visits, and on the understanding that this review is one step in the stepwise development and licensing of a spent fuel repository in Sweden. Judgements on compliance with Swedish regulations are the responsibility of SSM and fall outside the scope of the international peer review process.

The IRT used the specialist knowledge of its members and its collective understanding of international best practice to evaluate the information provided and to make findings and recommendations. The following thematic areas were reviewed in depth: geosphere; buffer and backfill; copper canister; fuel and cladding; biosphere; practical implementation; performance assessment; performance confirmation; societal aspects. For a more detailed treatment of these aspects the reader is referred to Chapters 3 and 4 of the present report.

2.1 Overall statement to the Swedish government

From an international perspective, SKB's post-closure radiological safety analysis report, SR-Site, is sufficient and credible for the licensing decision at hand. SKB's spent fuel disposal programme is a mature programme – at the same time innovative and implementing best practice – capable in principle to fulfil the industrial and safety-related requirements that will be relevant for the next licensing steps.

SR-Site was submitted to the Swedish authorities in March 2011 as part of the application for a general licence to construct and operate a spent fuel deep geological repository in the municipality of Östhammar. If this general license is granted, additional licensing steps are necessary for the further construction and operation of the repository. For these future licensing steps additional safety analysis reports have to be provided with more detailed technical argumentations and evidence. Taking this into account, and within the Swedish licensing and permitting context, SR-Site can be described as a preparatory Preliminary Safety Analysis Report. This stepwise approach to repository development and licensing is well-established international practice.

The overall question that the IRT asked itself was: "Is the SKB long-term safety case convincing at this stage?" The detailed findings of the IRT show that SKB generally gives a convincing illustration and technical basis both for the feasibility of the future repository, according to the KBS-3 design, and for its radiological long-term safety. The arguments presented are generally sound, based on current status of science and on par with the international state of the art. Nevertheless, in several areas improvements are possible, which would enhance confidence in the results of the safety analysis. Recommendations are provided in the body of the IRT report.

A second important question was: "Does SKB identify the major aspects that need to be developed in the future?" The IRT finds that SR Site and its supporting documents cover all major aspects that need to be developed in the future. Nevertheless within specific major aspects improvements are possible and are identified in the body of the IRT report. An important observation is that, with the current licensing step, the repository project will leave the conceptual phase, which was mostly based on scientific research work. As a natural progression of the repository project, the industrial feasibility of the barriers and of the repository, including assurance of their quality, will now become increasingly important. More emphasis on these aspects is expected and will be necessary in the future. Another challenge for the future will be to both enhance and broaden the basis for the scientific evidence supporting long-term safety. To that effect, additional research and more detailed calculations will be needed for the safety cases supporting the next licensing steps.

The IRT also checked specifically whether there is anything "missing or amiss" in SR-Site. The IRT didn't find any major omissions. Some improvements regarding completeness at a lower level are identified in the IRT report.

The above statement rests on the IRT findings in specific areas identified in the ToR. These findings are presented next.

2.2 Findings in specific areas identified in the ToR

2.2.1 Presentation of safety arguments

With respect to the questions:

- *Has SKB presented its safety philosophy and safety arguments clearly and in a well-structured way?*
- *Are the overall safety conclusions traceable and justified?*

The opinion of the IRT is that SKB has presented its safety philosophy and safety arguments clearly and in a well-structured way, and that in general the overall conclusions are traceable and justified. The SR-Site document presenting the safety case, TR-11-01, "Long-term safety for the final repository for spent nuclear fuel at Forsmark – main report of the SR-Site project", is a clear, easy to read, and well-structured document. The summary gives, in less than 50 pages, a clear overview of the main issues of the safety case. The outline of the "methodology in eleven steps", presented at the beginning of each chapter, contributes to the clarity of the statement. At the end of each chapter, conclusions are presented, including how the conclusions support the overall safety case.

The IRT notes that the relationship between features, events and processes (FEPs), safety functions, and analysis scenarios is well-described and appears to be sound. For example, the assignment of the buffer and backfill safety functions is pertinent and complete, and SKB has reasonably argued the comprehensiveness of the set of the established design premises by checking that all safety functions have indeed been considered in establishing these design premises. In the technical areas examined by the IRT, SKB has identified, described and handled the features, events, and processes very thoroughly. For example, the analysis and discussion of biosphere modelling and of fundamental mechanisms of rock mechanical behaviours are excellent and represent the state-of-the-art.

Although the SR-Site document is not a self-supporting document *per se* because of its frequent reference to many supporting documents, most of the technical documents supporting the SR-Site document are available on SKB's website and the most important ones are translated into English. This is much appreciated by the IRT and is seen as a strong contribution to establishing confidence in the safety arguments developed. The free availability of the majority of the SR-Site documentation is a sound approach for demonstrating transparency and open discussion.

The IRT has noted areas where the clarity and traceability of the safety case could be improved. The IRT recommends that:

- SKB consider defining intermediate-level safety functions that are not directly linked with the nature of the components and the processes involved. This would provide clarity regarding the appropriateness and use of the FEPs database.
- SKB refine (a) the number of realisations of the probabilistic underlying models in order to improve the clarity of the performance assessment results, and (b) undertake additional work to demonstrate the sensitivity of the performance assessment results to key uncertainties, such as in the hydrogeological model and in the sulphide concentration.
- SKB examine, as additional information becomes available, the sensitivity of the repository system to climate effects with respect to potential water pathways and rock properties between surface and repository depth.

In summary, the IRT concludes that SKB has presented its safety case for a repository clearly and in a well-structured manner that generally allows the traceability and justification of its overall safety conclusions. The IRT has noted some additional areas where clarity and traceability of the safety case could be improved, and has provided recommendations to address those areas in Chapter 3.

2.2.2 Safety assessment methods

With respect to the questions:

- *Are SKB's safety assessment methods on par with the international state-of-the-art and sufficiently described?*
- *Has SKB presented a credible scientific basis in support of their analyses (FEP's, models, data, etc.)?*
- *Are SKB's measures for quality assurance of the licensing documentation sufficient?*

It is the opinion of the IRT that SKB's safety assessment methods are generally on par with the state-of-the-art, are sufficiently described, and that SKB has presented credible scientific bases (FEPs, models, data, etc.). For example, the geological model of the target area is interpreted by state-of-the-art methods and constitutes a comprehensive conceptual model. The experimental procedures and analyses methods used are very comprehensive and represent current knowledge in rock mechanics and geotechnical engineering. In many areas SKB is at the forefront of current developments. Some examples include biogeochemical sampling techniques and modelling, understanding the role of microorganisms in repository performance, and understanding spent fuel dissolution processes. The assessment of doses to non-human biota in the performance assessment is quite innovative. Scenario selection is sound, and based on safety functions in a traceable way, which is on par with the international state-of-the-art. Along with these scenarios, SKB's presentation of stylised scenarios that represent the loss of the individual barriers, in order to evaluate their contribution to safety and the robustness of the concept, is seen as a good practice to build confidence in the safety case. It is important, however, that such stylised scenarios be used cautiously and with full understanding of their limitations.

With a few exceptions (as identified both in this report and by SKB), the IRT finds SKB's approach to estimating repository performance to be "conservative". Many of the properties of the geosphere, biosphere, and engineered barrier system are uncertain over the long assessment period. SKB has assumed bounding values for many of these properties in accordance with the fact that it is standard international practice to use bounding, or near-bounding, properties when the actual distribution or uncertainty range of geology and repository properties are not known. Although this does not mean the IRT is certain SKB has overestimated, for example, the buffer and canister failure rates or the dose rates to humans, the IRT notes that the understanding of the repository system based on the quantitative performance assessment results and their uncertainties could change if a "best estimate" approach were taken. The IRT recognises that SKB has addressed this in its responses to the IRT, and recommends that SKB provide an expanded discussion of insights on how a "best estimate" approach would change not only their quantitative results (most likely in a positive way), but more fundamentally, the understanding of the entire repository system.

The IRT finds that SKB's measures for quality assurance of the licensing documentation are generally sufficient at this stage of repository development. It is positively noted and acknowledged by the IRT that SKB has prepared plans for quality assurance (QA) and underlines the importance of QA in its safety assessment/safety case. The IRT has the impression that SKB is well aware of QA issues and has carried out considerable work in that field. However, the IRT notes that the present QA process does not yet address all relevant issues (in particular QA issues related to the manufacturing of the engineered barriers). Therefore, the IRT recommends the addition of a separate QA chapter to the SR-Site Report that addresses the full range of QA issues identified, their current status with respect to the on-going processes and the needs for further development. Also, the IRT is of the opinion that aspects of the quality assurance of the licensing documentation, specifically in the realm of document and data control, are below the norm in some international programmes and can lead to transcription errors and inconsistency between reports. As discussed in Chapter 4, the IRT recommends that SKB consider improving its data and document control system for future work in order to ensure than data is not transcribed incorrectly or that superceded versions of data or models do not remain in use. This would also improve transparency by ensuring that all documents supporting the safety case could be identified clearly and made available publically on the SKB website.

In summary, the IRT finds that the SKB safety assessment methods are generally on par with the state-of-the-art, are sufficiently described, and that SKB has presented credible scientific bases in support of their analyses. The completeness of the scientific basis is discussed in the following section. The IRT finds that SKB's measures for quality assurance of the licensing documentation are generally sufficient, and has provided a recommendation to strengthen the discussion of quality assurance in the safety case and to improve the quality of the licensing documentation.

2.2.3 Completeness

With respect to the questions:

- *Has SKB taken the current state of knowledge properly into account?*
- *Is anything missing or amiss?*

The IRT has found that SKB has, in the areas examined by the IRT, taken the current state of knowledge into account properly. For example, the geological model of the target area is well-supported by a large amount of high-quality field data; SKB has demonstrated a thorough understanding of the uranium dioxide fuel dissolution processes; the thermodynamic discussion used for the corrosion assessment is sound and complete; and SKB has described in significant detail how the landscape evolves due to isostatic rebound during glacial advance and retreat. It is to be noted, however, that the current state of knowledge is not yet fully complete because data from the actual subsurface excavation, which has yet to begin, are not available.[2] It should be emphasised that the completeness of the SKB's safety case can be increased in future steps addressing remaining technical issues, which are discussed in detail in Chapter 4.

The IRT supports the discussion on the probability of future large earthquakes and the corresponding scenario credibility, and notes that the uncertainties in the hydrogeologic DFN model that affect canister failure by corrosion are not likely to have any consequence for the demonstration of risk compliance. However, the IRT notes that the discussion of anoxic copper corrosion with hydrogen evolution is important and must be resolved, because SKB's calculations might not apply if other reactions or stoichiometries were at play. This could lead to new questions about the long-term durability of the copper canister.

Although the IRT is of the opinion that the current state of knowledge has been taken into account properly, and that nothing is missing or amiss at this stage of repository licensing, the IRT recommends additional work in a number of areas to improve confidence in the SKB safety case. Examples include:

- Assessment of the uncertainty in tectonic deformation zones and of hydrothermal alteration zones.
- Additional data collection to improve estimation of groundwater composition changes over longer time periods because of the potentially serious effects of intruding dilute glacial meltwaters.
- Additional research on paleoseismicity to strengthen the technical basis for estimating the frequency of future large earthquakes.
- Additional research on near-field seismicity to strengthen the technical basis for estimating the dynamic and static loads on canisters and repository system.
- Assessment of the effect of pore pressure drawdown due to underground excavations.
- Development of an improved understanding of the buffer erosion process.
- Assessment of the differences between the available types of commercial bentonites, especially those related to the sealing capacity and to the piping and colloid release processes of the material which will ultimately be emplaced.
- Development of an improved understanding of the potential for anoxic corrosion of copper.
- Adjusting the canister design load to better reflect the already proven properties of the actual canister design.

2. For example, related to the hydrogeologic DFN model and the upper end of the distribution of credible sulphide concentrations in groundwater.

- Development of an understanding of biosphere performance based on best estimates rather than on conservative estimates.
- Improved data on the partitioning of radium between liquid and solid phases.
- Addition of a separate QA chapter to the SR-Site Report, addressing the full range of QA issues, their current status with respect to the on-going process and the needs for further development.

The IRT notes that a modern safety case should include not only technical arguments supporting safety but should also pay attention to socio-political, organisational and management aspects that might affect the safety of a repository. The IRT therefore recommends that SKB outlines how it will assure that competent personnel, financial resources and knowledge about the facility are available until the repository is closed properly.

In summary, the IRT has found that, in the areas examined by the IRT, SKB has taken the current state of knowledge into account properly and that nothing is missing or amiss at this stage of repository development. In some cases, the current state of knowledge is not fully complete yet because data from the actual subsurface excavation, which is yet to begin, are not available. The IRT expects that the completeness of SKB's safety case will increase in future steps that will address remaining technical issues.

2.2.4 Handling of remaining issues

With respect to the questions:

- *Are remaining research and technical-development needs properly identified?*
- *Are there clear plans for their resolution in the continued step-wise development and implementation programme?*

The IRT is of the opinion that SKB has done a good job of identifying remaining research and technical development issues and of developing clear plans for their resolution. Remaining research needs are identified in the RD&D programme 2010 (TR-10-63). With respect to the geosphere, for example, research and development needs such as fracture mapping, treatment of spatial dilution, and analyses of the possible hydrogeologic effects of isolated fractures, are identified properly, as is work on issues that are triggered when water in isolated borehole sections is stagnant. Engineered barrier issues, such as the question of copper corrosion under anoxic conditions have been recognised and are documented in TR 10-67. SKB efforts to identify and resolve remaining issues are in keeping with IAEA document WS-R-4 that states: “Any unresolved issues at any step in the development, operation and closure of the facility will be acknowledged in the safety case and guidance for work to resolve these issues will be provided.” The IRT also understands that SKB will update its RD&D programme periodically, which is appropriate.

The IRT considers that a reference decision-making process could also be presented more formally, in particular with respect to the decision points and criteria that are used to validate a level of design before proceeding to the next step. The IRT is of the opinion that the coupling between the safety analysis and the licensing, design, construction and commissioning processes is not presented as clearly as it could be in the safety assessment. Furthermore, although remaining research and technical-development needs have been identified based on the current state of knowledge, the IRT recommends that SKB should approach construction fully prepared to seek out and evaluate relevant data at depth to test and confirm its safety-related assumptions. To this end, SKB should fully elaborate its plans for a comprehensive programme of in-depth performance confirmation testing and monitoring. The IRT is of the opinion that, in a broader sense, such plans will demonstrate that SKB is capable and ready to cope with unexpected findings at depth, in the unlikely event that they arise.

In summary, the IRT has found that SKB has done a good job of identifying remaining research and technical-development issues and has developed clear plans for their resolution. The IRT recommends that SKB clarify the linkage between the safety analysis and the licensing, design, construction and commissioning processes, and further develop plans for a comprehensive programme of testing and monitoring to confirm its safety related assumptions.

2.2.5 Selection of site and disposal method

With respect to the question:

- *Is SKB's argumentation for site selection and method development convincing and cogent, taking into account the international experience?*

The IRT finds that SKB has selected and developed its KBS-3 disposal method within the widely and internationally accepted geological deep disposal strategy for disposing of spent nuclear fuel. SKB's arguments in presenting KBS-3 as a robust disposal method that is well suited to meet all safety requirements are convincing and cogent. The IRT finds SKB's BAT analysis of design options to be reasonable and informative. The IRT notes as well that SKB could have added other aspects to their BAT analysis. For instance, the evolution of the canister design from the early 80's until today; the large effort SKB is applying now to automatising both the welding process and the emplacement of bentonite blocks; etc. Given that SKB has made conservative assumptions throughout the repository design development process, the IRT suspects that the repository may be "overdesigned", meaning SKB has made design improvements that go in the direction of reducing dose below the regulatory constraints and in the direction of BAT, i.e., of giving additional confidence about the repository performance.

SKB's approaches to public outreach for the site selection and for the method development process are at the forefront internationally, e.g., SKB's attention to community involvement in the decision-making process around siting and running nuclear waste management facilities. The IRT recommends that SKB strive not only to maintain its excellent record of public involvement at the local level, but also to expand stakeholder awareness and engagement at the regional and national levels at all future stages of the project. SKB should also outline how it will assure that competent personnel and financial resources, as well as knowledge about the facility, remain available until the repository is properly closed and beyond.

In summary, the IRT finds that SKB has selected and developed its KBS-3 disposal method within the widely and internationally accepted geological deep disposal strategy for disposing of spent nuclear fuel. SKB's arguments in presenting KBS-3 as a robust disposal method that is well suited to meet all safety requirements are convincing and cogent. SKB approaches to public outreach in the site selection and method development process are at the forefront of international practice. The IRT has made observations in the area of BAT, and recommendations in the area of assuring continuing competence, knowledge management, and stakeholder involvement.

2.2.6 Feasibility

With respect to the question:

- *Is the technical implementation of the KBS-3 disposal method sufficiently described and credible to justify SKB's assumptions on the properties of the repository system after closure (the initial state)?*

For the present stage of stepwise license development, the IRT finds that SKB has sufficiently and credibly described the technical implementation of the KBS-3 method and that the described and retained properties of the repository system are justified. For example, the IRT is of the opinion that SKB's preliminary design for underground construction and SKB's design of the bentonite buffer and backfill elements reflect well-proven industrial techniques. SKB has made good use of surface-based techniques to obtain an understanding of the geosphere system down to the repository depth and has provided adequate plans for how it intends to collect information for each disposal drift. Buffer, backfill and closure production and disposal methods are sufficiently described and credible. Full-scale experimental tests are available in which the feasibility of the canister and buffer emplacement techniques has been proven and documented. Likewise, from the manner in which the canister production processes are described, the IRT concludes that these aspects can be handled soundly and in full compliance with all design parameters. The IRT notes that SKB has shown remarkable efforts in research and development of the proposed method to weld the lid onto the canister. The process that demonstrated and discussed in SR Site has been improved already by further development with respect to controlling the welding process.

To increase confidence in SKB's assumptions on the initial state of the repository system, the IRT recommends that:

- SKB specify the final practical deposition hole rejection criteria prior to beginning any underground excavation work, and update the canister failure scenario probabilities if the criteria currently applied are changed.
- SKB conduct more full-scale demonstration emplacements tests, including a demonstration of the entire buffer and canister deposition sequence under repository conditions (especially under wet conditions), to ensure its feasibility.
- Quality management system with procedures and specifications to ensure compliance of the produced canisters with the stipulated procedures.

Examples include processes to handle issues such as deviations at a specific step in the canister production procedure, or how to retrieve a defective canister from the repository.

In summary, for the present level of stepwise license development, the IRT finds that SKB has sufficiently and credibly described the technical implementation of the KBS-3 method and that the described and retained properties of the repository system are justified. The IRT has provided recommendations for SKB that would increase confidence in SKB's assumptions on the initial state of the repository system.

3. Summary of findings, recommendations and conclusions in key technical areas

The overall objective of the international peer review was to provide a statement, from an international perspective, on the sufficiency and credibility of SKB's post-closure radiological safety case for the KBS-3 method in support of the current license application. To that effect the overall questions that the International Review Team (IRT) asked itself were:

- Is the SKB long-term safety case convincing at this stage?
- Does SKB identify the major aspects that need to be developed in the future?
- Is there anything missing or amiss?

The findings of the IRT are based on the documentation provided by SKB, on additional inquiries with SKB staff during the review process, and on the understanding that this review is one step in the stepwise development and licensing of a spent fuel repository in Sweden. Judgements on compliance with Swedish regulations are the responsibility of SSM and fall outside the scope of the international peer review process.

This chapter summarises the IRT findings, conclusions and recommendations in the key components areas of:

1. Geosphere.
2. Buffer and backfill.
3. Copper canister.
4. Fuel and cladding.
5. Biosphere.
6. Practical implementation.
7. Performance assessment.
8. Performance confirmation.
9. Societal aspects.

3.1 Geosphere

3.1.1 Geological conditions in the target area

SKB explored the candidate area at Forsmark in detail during a two-staged investigation programme during the years 2002-2007. Based on these investigations SKB selected the northern part of the candidate area for the location of the proposed repository. The IRT has reviewed the existing surface-based data on the geological conditions in the target area and has concluded that the geological model of the target area is:

- well-supported by a large amount of high-quality field data at this early stage of development;
- is interpreted by state-of-the-art methods; and
- is a comprehensive conceptual model.

The IRT considers that the deterministically modelled deformation zones (those that extend over more than 1 000 m) are subject to uncertainty, as SKB describes in TR-11-01. SKB will obtain more geologic data as it develops tunnels and shafts down to the repository horizon. The IRT supports SKB's plan to conduct further studies to improve its knowledge of the deformation zones with a trace length smaller than 3 000 m in the repository volume. The IRT further recommends a systematic assessment of the spatial distributions (i.e., relative to the locations of deformation zones) and fabrics of hydrothermal alteration zones.

3.1.2 Hydrogeological and transport conditions

The IRT realises that the discrete fracture network (DFN) correlation models presented in TR-11-01 are based on current knowledge, which is not fully complete because confirmation from actual subsurface excavation has not yet begun. The IRT expects that, once the construction of the underground facilities starts (i.e., ramp, shafts, and central area) and data gathering is conducted, a more detailed evaluation on the appropriateness of the DFN correlation models and a more proper set-up of the fracture properties will be performed by SKB. The IRT notes and concurs that, upon the start of excavation, SKB plans to:

- develop further practical ways to map and interpret fractures on a scale of several meters to hundreds of meters in the subsurface investigations; and
- analyse the possible effects of isolated fractures on mass transport properties.

The IRT is of the opinion that the evaluation and confirmation of SKB's hydrogeological and transport modelling is very important, and will be better performed by using in situ measurement data. It will further strengthen the result of the safety analysis. At the same time, in situ measurements of pore pressures and fluid densities/salinities before and during the construction of subsurface openings can provide necessary and important information for a better understanding of the subsurface hydrogeological system. In addition, the IRT expects that SKB will continue to study the long-term mass transport processes, including the effect of temporal changes of the boundary conditions caused by climate change. Therefore, the IRT recommends that:

- SKB include measurements of undisturbed and transient pore pressures and fluid densities/salinities in the deeper part of the rock masses as one of the parameters to monitor during construction;
- SKB fully discuss the representativeness of the measured state variables with respect to the fracture-dominated system, once these data have been

obtained in the field and plans have been made to use these data for further study; and

- SKB confirm that SR-Site results from the long-term mass transport modelling can be treated as conservative because the spatial dilution process, caused by the changing flow paths as a result of climate change, is not taken into consideration.

3.1.3 Geochemical and biogeochemical conditions

The IRT is impressed with SKB's extensive studies of the geochemistry of fracture- and porewater in the host rock, as well as the extensive modelling studies on the evolution of the hydrogeochemical groundwater characteristics. The IRT is of the opinion that SKB is in full compliance with state-of-the-art techniques and in some areas (i.e., sampling techniques; modelling), SKB is at the forefront of international developments in this field.

The IRT agrees with SKB's conclusion that, from a repository safety point of view, the most important geochemical parameters of host rock groundwater are salinity, sulphide concentration and O_2 content.

The IRT agrees with SKB that the currently available hydrogeochemical data are sufficient to prove that suitable conditions prevail at the Forsmark site both at present and during the temperate period that should persist for at least the next several thousands of years. Nevertheless, the IRT is of the opinion that collecting more data would be advantageous to improve estimates of groundwater composition changes over longer periods and during glacial cycles, because of the potential dilution effects of intruding glacial melt water to the repository level on the safety case. The IRT understands that based on existing data, SKB has used pessimistic estimates for groundwater composition changes over longer time periods and during glacial conditions. Gathering further data will improve these estimates, and could lead to the exclusion of the possibility of dilution by intruding glacial melt water to repository levels.

SKB's work on the possible role of microorganisms on all aspects of a high level nuclear waste repository has in many respects been at the forefront of the developing knowledge in this field. There is still some uncertainty about the *in situ* concentration of sulphides naturally present in the groundwater in the Forsmark (and other) areas. The IRT supports SKB's initiation of further investigations at Äspö aiming at a better understanding of which processes are triggered when water in isolated borehole sections is stagnant.

The loss of considerable amounts of bentonite due to piping and/or colloid formation (the latter as a result of intruding dilute glacial melt water) could lead to a reduction in swelling pressure which in turn could negate the suppression of microbial activity in highly compacted bentonite. The IRT recommends further study by SKB on the issue of colloid formation and potential loss of bentonite density (see also Section 3.2).

3.1.4 Rock mechanical conditions

SKB has conducted a large amount of numerical investigations and rock and fracture mechanical laboratory tests. The results of these small-scale investigations were compared with data and observations from *in situ* experiments. The IRT is of the opinion that the experimental procedures and analyses methods used are very comprehensive and represent the current knowledge in rock mechanics and geotechnical engineering. The analysis and discussion of fundamental mechanisms of rock mechanical behaviours is excellent and represents the state-of-the-art. The *in situ* stress measurements cover a wide range of available methods, leading to estimates of mean principal stress orientations and magnitudes. The spatial variability is assessed only qualitatively and few stress measurements are available from the target volume as yet. The IRT assumes that small-scale variations of stress magnitudes and directions are significant in the fractured bedrock at Forsmark.

The opening of the underground excavations of the final repository at Forsmark will create a strong hydraulic sink with groundwater flow towards the excavations, a large scale change in hydraulic head fields, and a very significant reduction of pore pressures at the hectometre to kilometre scale around the excavations, especially if multiple galleries are open at the same time. If galleries are efficiently grouted, filled and plugged as excavation progresses, the effect should be less. The IRT recommends that:

- the potential for pore pressure drawdown to result in (under worst case conditions) shear reactivation of predominantly steeply dipping deformation zones and large scale surface deformations be studied in greater detail;
- large scale rock mass stiffness characteristics be re-assessed; and
- a high-resolution surface deformation monitoring programme be installed several years before the start of the excavation activities, in order to establish baseline data.

The assessment of the number of canisters expected to fail by earthquake-triggered shear dislocation along fractures intersecting deposition holes was carried out by SKB through a very complex process. The assessment relies on relatively short term datasets (on the order of 1 000 years or less). A comprehensive discussion of the uncertainty of large earthquakes at Forsmark during future periods of glacial ice retreat is given in TR-11-01. Because the observation periods reported are relatively short, and paleoseismological data sets from central Sweden are limited, the IRT concludes that knowledge about long term seismicity is far from complete. In addition, new observations of the near-field impacts of strong earthquakes on underground constructions suggest complex processes. Therefore, the IRT recommends that SKB prioritise research on paleoseismicity and near-field processes to strengthen the assumptions made in the safety analysis regarding shear failure of canisters by future large earthquakes.

3.2 Buffer and backfill

The IRT finds the assignment of the buffer and backfill safety functions pertinent and complete. Nonetheless, the IRT advises to also include the free swelling strain of the buffer as a safety function indicator, to ensure adequate, tight sealing of all the initial gaps and voids over the assessment period and thus to prevent significant and continuous preferential water pathways from forming.

The IRT also advises that the required swelling deformation of the bentonites to be applied in deposition holes, tunnels and boreholes should be compared with their available free swelling strain.

The IRT notes that SKB has reasonably argued the comprehensiveness of the set of the established design premises by checking that all safety functions have indeed been considered in establishing these design premises. The IRT considers that SKB has taken properly into account the general (and most relevant for safety) state-of-the-art knowledge about buffer, backfill and plug performance when establishing the design premises and the reference design. The IRT recommends that in future phases of SKB's development process the following design issues of the buffer (i.e., those closely related to bentonite erosion) should be taken into account:

- Comparison of the available types of commercial bentonites, with respect to the sealing capacity and piping (short term) and to the colloid release process (long term).
- Sufficiency of the designed buffer thickness around the canister.

The IRT considers that SKB has identified, described and handled the buffer and backfill internal processes very thoroughly. SKB has also recognised the relevant research needs with respect to the behaviour of the bentonite, that are to be developed in the future stepwise programme. The IRT recommends that future RD&D studies should cover the following topics:

- The conditions and expected time evolution of colloid release and movement at, and in, free groundwater- bentonite interfaces.
- The relevant aspects of the sealing capacity of the different candidate bentonites, including the required minimum potential free swell and the relationship between swelling strain and applied pressure.
- The time evolution of the swelling strain upon wetting of the different candidate bentonites.
- The suction state of the different candidate bentonites after they are fully saturated as well as the density of the adsorbed interlayer water and its time evolution.

The IRT considers that the RD&D 2010 programme of SKB addresses in a comprehensive way the declared main uncertain factors which are affecting the calculated risk, as well as main design issues with respect to buffer and backfill.

SKB recognises that it has an incomplete conceptual understanding of the buffer erosion processes. The IRT agrees that further research studies could reduce the degree of pessimism currently adopted. The IRT also agrees with the areas of interest identified by SKB, namely:

- the effect of Ca and mixed Ca/Na systems on swelling/colloid formation behaviour;
- erosion in fractures or slots;

- self-healing effects by the clogging of fractures by accessory minerals; and
- the effect of flow and water velocity on erosion.

The IRT understands SKB's approach in SR-Site of using an empirical model for piping/erosion, because this process is relevant only during the early evolution of the repository. The IRT acknowledges current research efforts of SKB (i.e., Eva project) to develop a quantifiable conceptual model, based on a detailed description of the system with elements of theoretical and empirical submodels (semi-empirical).

The IRT recommends that the relevance of the differences between the available types of commercial bentonites should be assessed carefully, especially those related to the sealing capacity and to the piping and colloid release processes of the material which will ultimately be emplaced. The IRT supports the research work conducted by SKB in collaboration with different international organisations in the Alternative Buffer Materials (ABM) project.

3.3 Copper canister

The IRT notes that the decision for the actual design of a copper canister with a cast iron insert is the result of a long process, including the consideration of several different designs. The evolution of the canister design appears to be straightforward and takes into account safety aspects as well as future production requirements. The IRT notes that the realisation of the planned design is crucial for the fulfilment of the safety case, and appreciates SKB's focus on the combination of safety and feasibility in the development process. The IRT finds the processes that lead to decisions regarding the production, NDT testing and welding methods for the canister and lid sound and well documented.

The IRT has noticed SKB's efforts and knowledge in quality management issues and would like to underline the importance of documentation and quality control for the performance of the canister.

The IRT notes that the inserts holding the spent fuel in place inside the canisters still bear a small uncertainty, because the design for PWR fuel currently has not been fully demonstrated to fulfil all design specifications.

The IRT is of the opinion that the decision to choose a material for the enclosure that is thermodynamically stable under repository conditions is the correct strategy with respect to attaining a high level of confidence that the encapsulation will remain intact for the necessary duration. The IRT is of the opinion that the thermodynamic discussion used for the corrosion assessment is sound and complete and that the conclusions are fully acceptable.

Overall, the IRT is of the opinion that the canister design chosen is able to fulfil the criteria specified in the safety case with respect to irradiation, mechanical stress and corrosion.

With respect to corrosion, however, the IRT notes that questions have been raised in the scientific literature pertaining to the possibility that copper may corrode in pure water, under exclusion of oxygen and with production of hydrogen.

SKB what-if calculations in TR 10-66 to address this potential corrosion mechanism are defensible as long as hydrogen evolution would come from the anoxic corrosion of copper with two copper atoms oxidised for each hydrogen molecule (H_2) produced. If, however, other reactions or stoichiometries are at play, then SKB's calculations do not apply and there may be new questions about the long-term durability of the copper canister. The IRT concludes that the discussion of copper corrosion by hydrogen evolution is important and must be resolved. Hence the interest of the new set of experiments that SKB are running already, e.g., under a joint protocol with KTH, amongst others.

The IRT notes that this (and other) open questions have been recognised by SKB and are documented in TR 10-67. The IRT expects that SKB will integrate the results of further studies in optimised application documents and fabrication procedures.

3.4 Fuel and cladding

With respect to radionuclide release from spent fuel upon breach of a canister, the IRT notes that:

- spent fuel dissolution processes are of fundamental importance with respect to radionuclide release from spent fuel; and
- redox conditions in the repository at the time of canister breach are the most important factor influencing the spent fuel dissolution processes.

The IRT is of the opinion that SKB has demonstrated a thorough understanding of the uranium dioxide fuel dissolution processes by carrying out extensive studies on spent fuel dissolution under relevant geochemical conditions (i.e., reducing conditions with H_2 present as expected from corrosion processes).

The IRT notes that, recently, SKB has investigated, in detail, the dissolution process of higher burn-up fuels, which differ from lower burn-up fuel by the characteristic rim structure. SKB has also performed extensive modelling studies of the spent fuel dissolution process.

The IRT is of the opinion that SKB is in full compliance with state-of-the-art techniques and, in many areas, SKB is at the forefront of current developments in understanding spent fuel dissolution processes.

The IRT is in agreement with the fuel dissolution rate distribution included in the safety assessment, and is of the opinion that these rates may be on the conservative side for fully reducing conditions.

The IRT is also in agreement with the handling of the instant release fraction in the safety assessment and the recent update of the instant release fraction to include higher burn-up and higher linear power rating fuels.

The IRT commends SKB for continuing to be involved in state-of-the-art studies on fuel dissolution and instant release, as evidenced from a very recent paper (Johnson *et al.,* 2012) co-funded by SKB and Nagra.

3.5 Biosphere

The IRT has reviewed SKB's approach to addressing the biosphere and finds it meets or exceeds international standards. Biosphere evolution is a significant consideration for a site near the Baltic Sea because of the isostatic rebound of the Fenno-Scandinavian peninsula after the end of the last major glaciation. SKB has described in significant detail how the landscape may evolve due to land rise from Baltic Seabed to shoreline to peat bogs, and finally to arable farmland or forests.

The IRT finds it is beneficial to system understanding to develop "best estimate" conceptual and numerical models and parameters. While SKB states it uses "best estimate" landscape conversion factors (LDFs) on page 628 of TR-11-01, it is clear that SKB has actually incorporated many conservative assumptions into the development of the LDFs. Hence, the IRT disagrees the LDFs SKB derived are "best estimate". Rather, the IRT considers it likely that many of the LDFs are overestimates.

As discussed in Section 3.7.5 and 3.8.2, the IRT notes the importance of understanding the repository performance using "best estimate" approaches. Therefore, the IRT suggests the biosphere conceptual and numerical modelling and the resulting ingestion/inhalation/external dose conversion factors be reviewed with respect to how the biosphere conceptual and numerical models might be altered if a "best estimate" approach (rather than the more conservative approach used in the current assessments) were used. This would include the impact on dose conversion factors and their uncertainties.

SKB uses the worst case (i.e., highest landscape conversion factor (LCF)) for each radionuclide during an interglacial period by selecting from a number of biosphere objects in a dynamic landscape. SKB finds even though the exact future landscape development is difficult to predict, the systematic landscape analysis and the approach for estimating doses encompasses a broad array of future landscape configurations. The IRT finds this approach to be more conservative than other assessments because the overall dose from all radionuclides will be derived from an inconsistent set of landscapes. A potentially useful study to evaluate the degree of conservatism that SKB uses would be to evaluate the assessed dose rate assuming all radionuclides are from a single landscape type, as this would be more realistic. Conservatism could be preserved if SKB selected the single landscape configuration that results in the highest overall dose rate estimate.

The IRT is not convinced that using the same critical group behaviour for both the interglacial and periglacial periods is appropriate. Furthermore, SKB assumes the average LCFs to the critical group for both drinking water and non drinking water pathways are the same as those for the interglacial critical group. Hence, the IRT recommends SKB provide:

- a rationale why the periglacial critical group would be able to derive not only part of their food supply, but part of their drinking water supply from areas other than the talik; or
- consider potentially a higher drinking water dose to the critical group for the periglacial periods; or

- reconsider the appropriateness of assuming the periglacial climate critical group engages in the same combination of agricultural practices and hunting/gathering assumed for the interglacial critical group.

For the dose-dominating Ra-226, SKB notes the partitioning coefficient between the solid and liquid phases (i.e. the K_d value) for the lower, upper, and mid-regolith layers contributed the most to the overall uncertainty. SKB's main reason for the large variation in K_d value for Ra-226 was that the available site data were insufficient to give a reliable estimate of the natural variation. Instead, SKB estimated the K_d value for Ra-226 from literature data spanning a wide range of geographical conditions and soils types. These seem like reasonable conclusions and approaches. However, given the importance of Ra-226 in the SKB assessment, and the lack of site-specific data for K_d values for Ra-226, the IRT encourages SKB to attempt to provide better site-specific data for future assessments if at all possible.

3.6 Practical implementation

3.6.1 Underground constructions

The preliminary design of the underground constructions follows other types of large scale projects. The IRT considers the preliminary design of excavation methods, the expected rock mass behaviour and the required support/grouting methods as justified. Detailed designs will be developed in future project stages.

3.6.2 Deposition hole rejection criteria

The IRT notes that the deposition hole rejection criteria have not been fixed definitively by SKB. Several aspects of these criteria were discussed by SKB during the IRT public hearings in December 2011. According to SKB corrosion failures spanning one million years should disappear in the reference evolution if it is possible to reject deposition holes where the long-term Darcy flux is higher than 0.001 m/yr. However, the IRT notes that the inflow rate to the deposition holes may be affected by skin effects and grouting during construction. Therefore, the IRT supports SKB's plan to evaluate the fracture transmissivity through pilot holes during the underground reconnaissance, and to apply the criterion to reject those holes that are crosscut by fractures containing grout materials.

The IRT considers it very important that SKB specify the final practical deposition hole rejection criteria prior to beginning any underground excavation work. If the criteria change with respect to the currently applied EFPC/FPC criteria, the canister failure scenario probabilities must be updated.

3.6.3 Feasibility of initial state and industrial production

Buffer and backfill

The IRT is of the opinion that, at the present level of the stepwise licensing development, the buffer and backfill production and emplacement methods are sufficiently described and credible. The assumptions with respect to initial state properties are properly justified and conform to the reference design. Full-scale experimental tests performed in the Äspö Hard Rock Laboratory (in which the feasibility of buffer emplacement techniques has been proven) have been documented already and are available.

The IRT considers that future production and quality-assurance of the designed bentonite buffer and backfill elements are inside the ambit of well-proven industrial techniques. The IRT expects neither the design nor construction of concrete plugs (and in general of the sealing elements) will pose serious engineering problems. Related Swedish and international experimental tests already performed [e.g., Äspö; Grimsel (ESDRED project); AECL's Enhanced Sealing Project (ESP)] showed very positive results.

The IRT recommends that SKB conduct more full-scale demonstration emplacements tests in the near future, including a demonstration of the entire buffer and canister deposition sequence under repository conditions in a deposition tunnel section, to ensure its feasibility, especially under wet conditions. The IRT suggests that the one-cm gap between the canister and the bentonite blocks may prove to be insufficient in case the bentonite takes on some water from the tunnel atmosphere and swells. The IRT suggests that this be tested.

SKB recognises that if spalling of rock occurs in sections around the canister, locally the calculated saturated density could be in the lower range or slightly lower than 1 950 kg/m^3. It is possible to increase the installed density by active selection of blocks with high density for the parts of the deposition hole where spalling occurs. As anticipated by SKB, the IRT finds that the intended corrective actions could prove unfeasible and hence other actions should be proposed. Nevertheless, the IRT understands that this is not a major feasibility problem. The pellet filling, even if the pellet density is lower than that of the blocks, will do the job of providing a sufficiently low hydraulic conductivity and high swelling pressure to prevent the development of advective conditions in those deposition hole sections affected by spalling.

Canister

From the presentations given by SKB, the IRT concludes that SKB is able to initiate and maintain a quality management system (QMS) for production of the containers. The structure presented by SKB is suitable for implementation of quality control for production of the canister, providing that all the necessary details will be covered by the QMS. The IRT points out that one aspect that must not be neglected is the implementation of a process that allows improvement of processes, because the proposed production time for the canisters will cover several decades.

The IRT notes that SKB has shown remarkable efforts in research and development of the proposed method to weld the lid onto the canister. The process window that was demonstrated and discussed in the safety case as completely sufficient has been already improved by further development with respect to controlling the welding process.

SKB has developed or is developing destructive and non-destructive testing methods for all components and manufacturing steps of the canister. The IRT is of the opinion that SKB has demonstrated or can demonstrate that these methods will allow the detection of all flaws or deviations to an extent that surpasses the deviations allowed in the safety case. The IRT concludes that the methods proposed are suited for the intended use and that the extent of automation is supporting reproducibility of the measurements. In case of standard production, the IRT notes that the handling of data and the verification of the results will be of great importance.

From the manner in which the production processes are described, the IRT concludes that these aspects will be handled soundly and in full compliance with all design parameters. However, the IRT is also of the opinion that it is not possible to assess the complete system at this state of the project. Remaining questions range from how to handle deviations at a specific step in the canister production procedure to how to retrieve a defected canister from the repository. In addition, regulatory issues are also not defined at present.

The development and supervision of the QMS will be important for the performance of the components as well as the repository in itself. It is the IRT's view that it will be necessary for SSM to prepare a set of specifications for these processes.

3.6.4 Management issues

The RD&D Programme 2010 (TR-10-63) presents, in a detailed way and for each production line, the technology development that is planned to proceed from schematic technical solutions to industrialised solutions. However, the IRT considers that a reference decision-making process also could be presented more formally, in particular the decision points and criteria to validate a level of design before proceeding to the next step.

TR 11-01 (Chapter 15.5) presents the feedback from the safety analysis on the reference designs and related design premises. The IRT is of the opinion, however, that the coupling between this feedback and the licensing, design, construction and commissioning processes is not clearly presented in the safety assessment. The IRT considers that it would be useful to describe more precisely how and when this feedback will be implemented in the design development, as well as to describe more precisely the decision process that is or will be used to decide to which extent feedback from the safety assessment is introduced in a given design step.

3.6.5 Document and data control

The IRT is concerned that there seems to be no independent process for document and data control, including the verification that the final data sets have been used and that there are no transcription errors in the data used in the assessment models. The IRT noted instances of inconsistent use of terms (in TR-11-01) between text, figures, and tables that probably have no impact on the assessment, but that underscore the difficulty of maintaining consistency throughout the reports. The reliance on the assessment modellers to ensure that the proper data sets and models have been used, along with ensuring there are no transcription errors is below the norm in some international programmes.

The IRT recommends that SKB consider designing and using a better (independent) data and document control system for future work.

3.6.6 Quality assurance process

It is positively noted and acknowledged by the IRT that SKB has prepared plans for quality assurance (QA) and underlines the importance of QA in its safety assessment/safety case. The IRT has the impression that SKB is well aware of QA issues and has carried out considerable work in that field. In general SKB's approach of having an initial plan for QA/QMS that will be revised and updated at later stages of the process is in accordance with international practice.

The IRT also notes, however, that the overall QA process does not yet address all relevant issues. Thus far, SKB has concentrated on aspects directly linked to the assessment process itself, such as quality of data, models and reports. QA aspects related to the realisation of the repository project are not yet part of the SR-Site Report itself.

In its RD&D programme (TR-10-63) SKB describes in detail the needs for technology development and the current status of work, in relation to the fabrication of the canister. However, although it is apparent from presentations provided to the IRT that appropriate QA procedures have been developed for specific elements such as canister production, QA issues related to the manufacturing of the engineered barriers are neither addressed comprehensively in the RD&D programme nor in the safety assessment/safety case.

It is the IRT's opinion that an initial plan for an overall, regularly updated QA process needs to address all relevant issues, i.e., at least those issues identified as in need of further development when approaching the state of realisation. Therefore, the IRT concludes that SKB's descriptions of QA cannot be regarded as complete within the scope of a long-term safety assessment.

The IRT, therefore, recommends the addition of a separate QA chapter to the SR-Site Report, to address the full range of QA issues identified, their current status with respect to the on-going processes and their respective needs for further development.

3.7 Performance assessment

3.7.1 Safety assessment methodology

The IRT finds that the safety assessment methodology developed by SKB relies upon long national experience and participation in several international working groups. The safety assessment is on par with the international state-of-the-art and is coherent with the guidelines established by OECD/NEA through long-lasting international cooperation.

The FEPs database completes the previous SR-CAN 97 FEP catalogue with components not treated in SR-CAN. Completeness was assessed by comparison/ mapping with other national database and the international NEA database. The fact that this FEP database is available on the web argues forcefully for the transparency and traceability of the safety case. The links between FEPs and long-term processes are clearly exposed.

The IRT considers that the methodology and safety demonstration takes the safety functions into account in an effective way. The IRT recommends that SKB considers defining, before using the FEP chart, intermediate-level safety functions that are not directly linked with the nature of the components and the processes involved. Using these intermediate-level safety functions could be of some use with respect to best available techniques (BAT), i.e., alternative ways of fulfilling a given safety function could be explored.

The IRT considers that SKB's scenario selection methodology, which is based on safety functions, is on par with the international state-of-the-art, i.e., it is described precisely and justified. The scenario analysis is clearly explained and described and appears to be sound.

The IRT considers that the dose calculations based on the technical conclusions drawn from scenarios analyses are sound. However, the IRT notes that the risk summation curve presents pulse-like features and this is actually an artefact due to the small number of realisations leading to canister failure. Although this does not have any consequence for the demonstration of risk compliance, the IRT is of the opinion that it is a weakness with respect to the clarity of the presentation of the results. The IRT recommends that, to remedy this, SKB refines the realisations of the probabilistic underlying models that control the points in time of canister failure.

The IRT notes that SKB's safety assessment includes dose calculations to non-human biota, which is consistent with regards to best practices.

SKB does not draw any strong conclusions from the assessment of future human actions. Nevertheless, the IRT considers it beneficial to assess the sensitivity of the results to the pessimistic assumptions made and to draw conclusions in the view of BAT that can reduce the risk, e.g., long-term memory, and the need for its development.

The IRT considers SKB's use of stylised scenarios (hypothetical cases where different barriers are assumed to be completely lost) as a good practice to build confidence in the safety case. These scenarios do not represent any physical reality. If used cautiously, however, and with full understanding of their limitations, they can give an illustrative view of the respective contributions of each of the barriers to safety and provide a check for the robustness of the design.

3.7.2 Credibility of scenarios

The IRT is of the opinion that from a methodological point of view, SKB's scenario selection is on par with international best practices. The IRT notes further that the general assumption of the repeatability of future glacial cycles is common to performance assessments.

Regardless of the high confidence SKB has expressed, the IRT recommends that sensitivity of the repository system to climate effects should be subject to further observation and assessment with respect to the increasing state of knowledge about potential water pathways and rock properties between surface and repository depth that will be developed during the coming project phases. The IRT recommends that future safety assessments should address this issue and provide updated information on whether the originally assumed favourable conditions are still valid. This would contribute to a higher degree of confidence in the independence of the repository evolution from climate-related effects.

The IRT concludes that, with respect to the scenario of isostatic load leading to canister failure, the conceptualisation of the maximum hydrostatic load is correct, although the estimated values for the various pressures that contribute to the isostatic load seem to be conservative.

The IRT also concludes that, with regard to the scenario of shear load leading to canister failure, fault reactivation from pore pressure drawdown induced by the repository excavations will most probably not lead to critical fault reactivations. However, SKB's assessment of the most critical earthquake triggering shear failure scenario (seismic slip > 5 cm) is very complex, and based on a large number of assumptions. Nevertheless, the IRT, although not staffed with a seismologist, supports the discussion on the probability of future large earthquakes (as described in TR10-01, Chapter 10.4.5) and the corresponding scenario credibility.

3.7.3 Corrosion failure

The analysis of the corrosion failure scenario highlights the main factors of uncertainty in this scenario, namely:

- Uncertainty related to the DFN model.
- Uncertainty related to the sulphide concentration.
- Questions regarding the potential for that copper may corrode in pure water under exclusion of oxygen and with production of hydrogen.

Several alternative DFN models are presented and assessed in SR-site. The selection of the correlation between fracture size and transmissivity on one hand and the chosen realisation of the model on the other hand, have a strong impact on the number of advective positions, on the number of failed canister and on the migration of released radionuclides. In order to capture this variability, SKB builds its assessment on a small number of realisations of the DFN models. SKB considers that this statistical treatment is sufficient to build confidence in the calculated mean number of failed canisters. Given the pessimistic assumptions adopted by SKB, the order of magnitude used for the risk summation seems convincing to the IRT, and hence also the fulfillment of the risk criterion.

However, the IRT still considers that the number of realisations is rather low with regard to the criticality of the issue of the hydrogeological model. Moreover, SKB does not justify clearly enough that the variability captured in these realisations corresponds to a rigorous confidence interval.

Sulphide concentration is a key factor for corrosion. Only the extreme value of the discrete sulphide concentration leads to a canister failure for most of the DFN models. Thus this end tail of the distribution is an important part of the distribution for the risk calculation, although its description is very rough, and is represented by only one data point. A more rigorous statistical analysis of the confidence that can be put in the sulphide distribution than the one SKB conducted in its sensitivity analysis would then be of interest. However, the IRT recognises that it is likely that the distribution used in SKB's calculations is a pessimistic one.

As discussed in Section 3.3 on the process of corrosion of copper by water, SKB's calculations in TR-10-66 are defensible as long as hydrogen evolution would come from the anoxic corrosion of copper with two copper atoms oxidised for each hydrogen molecule (H_2) produced. If, however, other reactions or stoichiometries are at play, SKB's calculations do not apply and this could lead to new questions about the long-term durability of the copper canister. The IRT notes that the discussion of copper corrosion by hydrogen evolution is important and must be resolved.

The IRT strongly recommends that, as soon as it can reduce uncertainties through further data acquisition, SKB should reassess the central corrosion scenario and its risk contribution, which could vary in a non-negligible range. Given the pessimistic assumptions taken by SKB in the safety case, this should lead to a reduction of the calculated risk, and thus should not jeopardise risk compliance.

3.7.4 Shear failure

The IRT notes that the observation periods used in the determination of frequency-magnitude relationships are relatively short (100-1 000 years) in comparison to the duration of the safety assessment. Therefore SKB systematically discussed the uncertainties of long term frequency relationships and included paleoseismic frequency indicators as derived from glacially-induced faulting. Although the IRT supports the discussion on the probability of future large earthquakes (as described in TR10-01, Chapter 10.4.5) and the corresponding scenario credibility, the IRT recommends additional studies on near-field conditions and paleoseismic investigations to augment the understanding of the impacts of long-term seismicity at Forsmark.

3.7.5 Evaluation of the total system performance assessment results

With the exception of relevant issues affecting overall repository performance discussed earlier in this report, and those identified by SKB itself, the IRT finds SKB's approach to estimating repository performance to be "conservative".

Many of the properties of the geology and repository design are uncertain over the long assessment period. SKB has assumed bounding values for many of these properties. This is in accord with standard international practice to use bounding, or near-bounding properties when the actual distribution or uncertainty range of geology and repository properties are unknown. This does not mean the IRT is certain SKB has overestimated the buffer and canister failure rates or the dose rates to humans. Both the IRT and SKB recognise that more work needs to be done to improve confidence of the repository system performance.

The IRT notes that the understanding of the repository system based on the quantitative performance assessment results and their uncertainties could change if a "best estimate" approach were taken. The IRT recognises that SKB has addressed this in its responses to the IRT, and recommends that SKB provide an expanded discussion of insights on how a "best estimate" approach would change not only their quantitative results, but more fundamentally, the understanding of the entire repository system.

3.8 Performance confirmation and best available technique (BAT)

3.8.1 Performance confirmation

SKB has not identified any new detrimental processes in recent years of surface testing. Thus, SKB infers that its derived set of safety function indicators are reasonably comprehensive and mature. For these reasons the IRT feels it is especially important that SKB approach construction fully prepared to seek out and evaluate relevant data at depth to test and confirm its safety-related assumptions. The IRT is of the opinion that data collected at depth during construction, operation and emplacement are essential for corroborating the applicant's safety case assumptions.

SKB should elaborate its plans for a comprehensive programme of testing and monitoring such that SKB will be able to confirm that the proposed repository will work as planned. These plans should also demonstrate that, in a broader sense, SKB is capable and ready to cope with unexpected findings at depth, in the unlikely event that they arise. This programme should be ready and in place before the start of construction. An adequate programme of performance confirmation would provide data to show whether:

- Actual subsurface conditions encountered and any changes in those conditions during construction and waste emplacement are within limits assumed in the licensing review.
- Natural and engineered systems and components that are designed or assumed to act as barriers after permanent closure will continue to function as intended and expected.

To demonstrate adequate preparation in advance, the IRT recommends that SKB should describe in detail a performance confirmation programme that includes:

- A continuing programme of measuring, testing, and geologic mapping, during repository construction and operation to confirm geotechnical and design parameters (including natural processes) pertaining to the geological setting.
- A continuing programme to monitor or test natural systems and components that are designed or assumed to act as barriers after permanent closure to ensure they are functioning as intended or expected.
- A continuing surveillance programme to monitor and evaluate subsurface conditions against design assumptions, to compare measured values with original design bases and assumptions, assess any significance for health and safety, and determine the need for any changes.

3.8.2 Best available technique (BAT)

SKB summarises its BAT evaluation of design options in Section 14.3 of TR-11-01. The IRT finds SKB's analysis of design options to be reasonable and informative. The IRT notes as well that SKB could have added other aspects to their BAT analysis. For instance, the evolution of the canister design from the early 80's until today; the large effort SKB is applying now to automatising both the welding process and the emplacement of bentonite blocks; etc. The IRT did not look at all these aspects comprehensively. To the extent that optimisation and BAT analyses are very much informed by the specific Swedish regulations and that compliance evaluation of optimisation and BAT are not in the remit of the review, the IRT did not form an opinion on these aspects in-depth.

3.9 Societal aspects

3.9.1 Public outreach, input and consent

The IRT is of the opinion that SKB has shown itself to be a world leader in its attention to community involvement in the decision-making process around siting and running nuclear waste management facilities. In both candidate communities, SKB succeeded in obtaining meaningful public awareness and local engagement in the decision about the project, thereby earning sufficient trust for going forward with the project thus far. The IRT encourages SKB to continue to expand upon its strengths in this area.

The IRT recommends that SKB keep the local community informed regularly of SKB's performance confirmation plans and activities and that, should construction be authorised, SKB should provide the results of underground studies as they become available. If new information emerges that departs from prior assumptions, it is, likewise, essential that SKB explain the impact of such data on the safety of the project. In addition to providing information, SKB may also consider offering even greater participation to stakeholders by affording, for example, more opportunities for comment, discussion and cooperation in decision making as the project progresses.

SKB should strive not only to maintain its excellent record of public involvement at the local level, but also to expand stakeholder awareness and engagement at the regional and national levels. The IRT encourages SKB to develop and expand, as appropriate, techniques for stakeholders involvement throughout the project.

The IRT is of the opinion that consideration of social aspects is fundamental to any successful repository project. By doing so, SKB is, and will in future, be in line with the state-of-the-art and international recommendations regarding this issue.

3.9.2 Continuity of knowledge

A sound safety case should not only include technical arguments supporting safety, but should also pay attention to socio-political, organisational and management aspects which might affect the safety of a repository. SKB should be able to illustrate how it will assure that competent personal and financial resources and the knowledge about the facility remain available until the repository is properly closed.

Knowledge must be preserved and transmitted to future generations about the repository's history, its significance, its contents and the importance of keeping it secure from inadvertent intrusion that could breach its engineered and natural barrier system. Such a mechanism could include for example:

- Identification of the site by monuments or markers that are designed, fabricated and emplaced to be as permanent as practicable.
- Placement of records in the archives and land records system of local, regional and national agencies as well as in any archives elsewhere in the world that would reasonably be consulted by potential intruders.
- Relevant records should include data collected about the site and repository during construction, performance confirmation, operation and closure as well as information on the nature and amounts of waste disposed.
- SKB should also consider creating reservoirs of knowledge, namely centres of interest in the past activities at the repository, so that a limited number of people may continue to understand and interpret the records and markers. In the same vein, SKB should consider creating a cultural link – or sense of heritage – between the repository and the host community or region.

The participation of SKB in the NEA project on Records, Knowledge and Memory Keeping Across Generations is positively noted.

4. Detailed findings from the review of specific technical aspects

This chapter presents detailed findings from the review of specific technical aspects of SKB's license application.

The primary documents reviewed by the IRT were:

- The main report of the SR-Site project: "Long-term safety for the final repository for spent nuclear fuel at Forsmark" SKB TR-11-01.
- The report on site selection: "Siting of the final repository for spent nuclear fuel" SKB R-11-07.
- The report on selection of method: "Evaluation of strategies and systems to manage spent nuclear fuel" SKB P-10-47.
- The report on the 2010 RD&D Programme: "Programme for research, development and demonstration of methods for the management and disposal of nuclear waste". SKB TR-10-63.

A list of the many other documents reviewed (whole or in part) by the IRT is given in Annex 2. The IRT also benefitted from SKB's answers to questions posed in three IRT questionnaires and from SKB's presentations and question-and-answer sessions during meetings in Stockholm between SKB and the IRT in May and December 2011. The text of the questionnaires and SKB responses, as well as copies of the presentations made during site visits conducted on 14 December 2011 and webcasts of the hearings conducted in December 2011, are available on the SSM website (www.stralsakerhetsmyndigheten.se).

This chapter discusses detailed findings in the key components areas of:

4.1 Geosphere.
4.2 Buffer and backfill.
4.3 Copper canister.
4.4 Fuel and cladding.
4.5 Biosphere.
4.6 Practical implementation.
4.7 Performance assessment.
4.8 Performance confirmation.
4.9 Societal aspects.

4.1 Geosphere

The initial properties of the geosphere are discussed in Section 4.1.1 (geology), 4.1.2 (hydrogeology) and 4.1.3 (hydrogeochemistry and microbiology). Some of these initial geosphere properties will be modified in response to the repository excavation, the emplaced waste, and future geological processes (reference evolution and selected scenarios in TR 11-01). Most of these changes are driven by mechanical processes. In Section 4.1.4 selected hydro-mechanical processes are evaluated that are considered critical for long term safety, such as hydraulic transmissivity change as a result of fracture reactivation or fracture shear dislocation as a result of strong earthquakes.

4.1.1 Geological conditions in target area

The IRT review of geological conditions in the target area is based on SKB reports (primarily TR 11-01 and R-02-43), SKB responses to IRT questions, and SKB presentations provided during IRT site visits on December 14, 2011.

Database: The *candidate area*[3] at Forsmark was explored in detail during a two-staged investigation programme during the years 2002-2007. The investigations included geological and structural surface mapping (natural outcrops and trenches), magnetic surveys, reflection (with 10 m shotpoint/receiver spacing) and borehole VSP seismics, with 25 cored drillings (> 16 km, 60 mm core, upper 100 m large diameter percussion drilling), most of them (19) reaching the repository level. Based on these investigations the northern part of the candidate area was selected as *target area*,[4] i.e the location of the proposed repository.

Rock types and rock domains: SKB subdivides the host rock in the *target area* at Forsmark into two rock domains called RFM029 and RFM045. The main part, forming the core of the target area, is rock domain RFM029 which is composed of medium-grained metagranite, pegmatitic granite or pegmatite, and subordinate amphibolite and other mafic to intermediate rocks. This steeply SE dipping rock domain is surrounded by aplitic granite, medium-grained granite and felsic volcanic rock belonging to different rock domains (inside the target area mainly RFM049). All these rocks belong to the Fennoscandian Shield, formed between 1.89 and 1.85 billion years ago during the Svecokarelian orogeny and show high grade metamorphic overprint.

Tectonic history: Tectonic deformations lead to ductile and brittle overprint of these rocks. A comprehensive 3D structural model was developed based on surface and borehole mapping, and seismic as well as magnetic surveys. Early ductile deformation has resulted in large-scale, high-strain belts and more discrete high-strain zones mainly striking NW-SE. Tectonic lenses, in which the bedrock is less affected by ductile deformation, are enclosed in between the ductile high-strain belts. The *candidate area* is located in the north-westernmost part of one of these lenses, called Forsmark tectonic lense. Whereas the northern part of the candidate

3. The area of the detailed 2002-2007 site investigations, including the target area and extending to the SE.
4. The target area corresponds to the smoothed footprint of the proposed repository layout.

area shows predominantly steeply dipping foliation (in the form of a large sheath fold), the foliation in the southern part of the candidate area is gently SE dipping. Cooling into the brittle field started about 1.75 billion years ago. Most of the ductile structures were reactivated and four stages of fracture infillings, from epidote, laumontite, pyrite to clay minerals, are observed. The latest mineral infillings with clay minerals are considered to be about 500 million years old (Phanerozoic). Several phases of sediment loading (up to 2 km, resulting in loading of about 50 MPa) and uplifting, erosion and unloading occurred until the Mesozoic. This suggests that stress released fractures were set up to form during the Mesozoic.

Deformation zones: Seismic investigations in the southern part of the candidate area show a large number of gently dipping highly persistent reflectors. Verification by core drilling showed that these reflectors are mainly ductile-brittle fracture zones with significant thickness (damage zone thickness of typically 20 meters), composed of dozens of sealed fractures, often showing old hydrothermal alterations but no gauge. It is suggested that the gently dipping foliation and layering has favoured the formation of gently dipping deformation zones. Single and cross-hole hydraulic testing demonstrate that these deformation zones have relatively high transmissivity over long distances (1 000 m). In the northern part of the candidate area, i.e. the target area which has been selected for the repository location, such gently dipping deformations zones occur only rarely and mainly in the hanging wall of the proposed repository level (470 m). Here deformation zones are mainly steeply dipping and ENE and NNE striking fracture zones, including crush zones, composed of fractures filled with a large variety of minerals. These steep deformation zones are not visible on seismic surveys and are mainly based on ground and airborne magnetic surveys verified by core drillings.

Deformation zone model: A deterministic 3D structural model constructed for the target area shows twenty-two steeply dipping zones that either show a trace length at the ground surface between 1 000 and 3 000 m or form minor splays or attached branches to such zones, at 400 to 600 m depth. Five gently dipping zones are also present at 400 to 600 m depth inside or immediately above the *repository volume*.[5] According to SKB TR 11-01 the majority (> 60%) of these deterministic deformation zones with trace length longer than 1 000 m are judged to have a high confidence of existence, and the occurrence of undetected deformation zones longer than 3 000 m is judged unlikely.

Fracture types and domains: Statistical fracture properties in rock volumes between deterministically modelled deformation zones are described by fracture domains. The target area shows a strong decrease in the frequency of open (non-mineral filled) fractures down to about 400 m depth, differing from the depth-independent distribution of open fractures in the SE part of the candidate are. This is mainly attributed to the observation that high fracture frequencies correlate with deformation zones, and that gently dipping deformations carry most of the open fractures. Outside deformations zones the most important open fractures are large subhorizontal sheet fractures mainly occurring in the uppermost 150-200 meters

5. Although not explicitly defined in TR 11-01 we consider the repository volume (target volume) to be the volume around the target area between 400 and 600 m depth.

below ground surface. This observation correlates with a strong reduction in seismic velocity below 200 m (R-02-43). Up to 60 m depth open sheet fractures with sediment infillings (presumably from Pleistocene glacial periods) are observed. Based on these observations SKB subdivided the rock mass in the target area in two deep fracture domains FFM01 (in rock domain RFM029) and FFM06 (in rock domain RFM045) showing a low frequency of open and partly open fractures, and a shallow fracture domain FFM02 characterised by a complex network of sub-horizontal or gently dipping, open and partly open fractures forming a well connected permeable network. At repository depth (entire candidate area) the frequency of open fractures ranges between 0.5 and 0.75 (1/m), while in the upper 200 m the open fracture frequency ranges between 0.8 and 1.7 (1/m).

According to SKB the most important uncertainty concerns the size-intensity relationship of fracturing in the potential repository volume, i.e. fracture domains FFM01 and FFM06. The main reason for this is the lack of data on fracture sizes in these sub-surface domains (see also Section 4.1.2). Direct data on fracture sizes in these domains can only be obtained from underground mapping, i.e. when the repository excavation has reached relevant depths.

IRT evaluation of geological conditions in target area

The IRT considers the geological model of the target area as well supported by a large amount of high-quality field data, interpreted by state-of-the-art methods and a comprehensive conceptual model.

Of highest importance for the performance assessment of a KBS-3 repository at Forsmark are the geological conditions in the target area at repository depth (470 m). The predicted conditions at repository level are mainly based on the results from 12 deep core drillings supported by findings from magnetic and seismic surveys. The IRT considers that the deterministically-modelled deformation zones (having an extent of more than 1 000 m) have the uncertainty specified in TR 11-01, even though the SKB and IRT assessments are only expert opinions. The IRT suggests that SKB also assesses the uncertainty of unknown deformation zones smaller than 3000 m trace-length in the repository volume.

Hydrothermal alterations in quartz-feldspar-rich basement rocks can strongly reduce rock mass strength and alter flow and transport properties through dissolution (and precipitation) processes. While hydrothermal fluids might initially flow along brittle deformation zones, zones of hydrothermal alterations are often found at large (>100 m) distances from these zones. They appear as large clouds of chemically altered rocks without significant macroscopic shear deformation. As such their location and dimension is nearly impossible to predict. The IRT recommends assessing the spatial distributions (relative to the locations of deformation zones) and fabrics of such hydrothermal alterations systematically.

4.1.2 Hydrogeological and transport conditions

The IRT review of hydrogeological and transport conditions is based on (parts of) SKB reports TR 11-01, TR 10-63, TR 10-52, TR 10-50, TR 10-21, TR 08-05, R 11-14, R 09-35, R 09-22, R 09-21, R 09-20, R 08-133, R 08-95, R 08-23, R 07-49, R 07-48, R 07-46 and R 06-54, as well as SKB responses to IRT questions, and SKB presentations provided during IRT site visits on December 14, 2011.

The safety functions expected from host rock environments are generally difficult to represent by simple criteria because processes in the geosphere are interrelated and complex. For example, groundwater flow processes control the geochemical conditions both spatially and temporally, and mechanical behaviour of rock masses and groundwater flow are coupled. The processes in the geosphere also determine the boundary conditions for buffer and backfill, and hence, the feedback should be considered for defining the safety functions for host rocks. However, it is possible to at least qualitatively identify conditions which should be favourable with regard to containment and retardation. The safety functions relating to hydrogeological and transport conditions are summarised as follows.

R2: Provide favourable hydrogeologic and transport conditions:

The functions common to containment and retardation are:

1. The flow-related transport resistance (F) of flow paths from the surface environment to the repository and those leading away from the repository should be sufficiently high. This can be achieved by limited hydraulic transmissivity of the water conducting features in combination with low hydraulic gradients.
2. Equivalent flow rate in the buffer/rock interface, Qeq, should be low.

The functions specific to retardation are:

3. The element-specific effective diffusivities and sorption coefficient of the rock matrix should be high.
4. Colloid concentrations should be low.

The first two functions are to be evaluated through understanding of the hydrogeological systems in fractured rock masses and the numerical simulation approach. The latter two are related to *in situ* geochemical conditions (discussed in Section 4.1.3) and *in situ* host rock conditions such as alteration adjacent to fractures. The unaltered rock conditions can be used as bounds for the sorption coefficient and are constrained. SR-Site evaluation shows that the favourable hydrogeologic and transport conditions are met in the target area. Considering the necessity to rely on the conceptual understandings and numerical approach to evaluate the hydrogeological and transport conditions in the subsurface, it is important to discuss how SKB worked out to model the subsurface fractured systems from surface-based investigations. The following are the IRT's evaluation of SKB's approach for their understanding and modelling of subsurface systems mainly from a hydrogeological point of view.

Development of hydrogeological models at the site

To analyse hydrogeological systems in fractured rock masses, it is necessary to estimate the spatial distribution and temporal changes of hydraulic properties, i.e., transmissivity and strativity, of the rock masses. Also, to apply a numerical modelling approach, a comparison of the current measured state variables such as pressure/hydraulic head and density/salinity, with calculated model results at least at the present conditions is necessary to confirm the appropriateness of the model results. A deterministic modelling approach to the entire modelled region is not possible for the fractured rock mass and hence, a stochastic approach should be introduced. The approach taken by SKB to estimate spatial distribution of hydraulic properties can be summarised as follows.

Based on the detailed geophysical and geological investigations together with borehole information, the deterministic deformation zones were described. The fractures that have trace lengths longer than 1 km fall in this category. Subsequently the transmissivities of the deterministic deformation zones were estimated based on the hydraulic data obtained from borehole hydraulic testing results. Because the transmissivities vary depending on the orientation of the deterministic deformation zones, the model takes into account the different transmissivity values for deformation zones with different orientations. In general, deformation zones with low dipping angles have higher transmissivities compared with those with steeply dipping fractures. Also, the transmissivities decrease as a function of depth, and this characteristic is also included in the model. Then, based on the data obtained from borehole hydraulic tests, a statistical approach is used to construct representations of transmissivities in the deterministic deformation zones.

The fractures existing in the rock masses in between deterministic deformation zones are treated stochastically, and a hydrogeological discrete fracture network (DFN) model is introduced to model the region. SKB took the following approach to construct the hydrogeological DFN model.

First of all, the fracture intensity of transmissive fractures is estimated based on (1) the relationships among the open fracture intensities observed through borehole investigations; (2) the flowing fracture intensities confirmed by PFL (Posiva Flow Log); and (3) the model-derived connected open fracture distribution. Then, the statistical model for the intensities of the transmissive fractures is constructed. In this process, the concept of tectonic continuum which is assumed in a geological DFN is used for estimating the intensities of all and open fractures, and the power-law distribution is applied. It is still up for discussion whether it is appropriate to assume a single, continuous relationship of fracture intensities between the borehole observation scale and the outcrop/lineament scales and this uncertainty propagates to the safety analysis. The reason for this uncertainty is due to the fact that the scales on which the actual measurements can be done are restricted to boreholes, outcrops, and lineaments at this stage. Especially, it is not clear whether surface data can be applied to the fracture rock domains FFM01 and FFM06 because these domains are defined only in the subsurface. However, it is highly expected that through the mapping of several different scales, i.e., boreholes, tunnels, and deposition holes, once the construction starts, data on the fracture intensities with different scales can be obtained which will reduce the uncertainty. SKB's plan for the construction of ramp, shafts, and central area can provide the possibility to map and characterise fractures with scales of tens to possibly hundreds of meters by careful analyses of the data obtained.

The second step is to estimate transmissivity values of the flowing fractures. Here, SKB used the results obtained from PFL rather than those from PSS (Pipe String System). This decision came from the fact that the results from PSS might be interpreted to be affected by a rather narrow region close to the boreholes such as isolated fractures with closed boundary. Considering that the SR-Site analysis mainly handles a relatively larger spatial scale, it is appropriate to use PFL data as representative ones. It should be noted that the obtained "transmissivity values" from PFL are not exactly the same as those of the fractures cross-cutting the borehole, but rather, they are the specific capacities of the "hydraulic choke" of the continuous fracture group including the fracture which cross-cuts the borehole. Then, it is necessary to develop models which relate the transmissivity and fracture size, and to conduct a calibration to find the appropriate model. At present, three correlation models (i.e., correlated, semi-correlated, and uncorrelated), are considered and these three models are used as variants for the safety evaluation. Thus, the uncertainties of these correlation models propagate into the uncertainties of the analysed results of the whole system. The IRT recommends and expects that, once the construction of the underground facilities starts and data gathering, especially on the hydraulic properties and geological mapping, is conducted, a more detailed evaluation on the appropriateness of the correlation models and a more proper set-up of the fracture properties will be performed by SKB.

To achieve a better understanding of the fracture distribution and the proper modelling that needs to be carried out, the IRT expects that SKB will develop further practical ways to map fractures with several meters to several tens of meters scales, and will interpret hundred meters of scales in the subsurface investigations. This is important for improving the hydrogeological DFN. Therefore, the IRT also expects that SKB will show the strategy how these data will be used to reduce the uncertainties in the hydrogeological DFN model.

For future research and development, the IRT also expects that the possible effects of isolated fractures detected by PSS and those of the "stagnant water" in fractures by channelling on mass transport properties will be analysed as described in "Radionuclide migration (page 841 of the main report)".

Evaluation of the numerical model through the comparison of measured and calculated state variables

Pore pressures/hydraulic heads obtained from hydraulic tests and those from ambient conditions are used to understand the shallow hydrogeological systems, mainly in the sediments and shallow fractured bedrocks. The data suggest that the heads are higher in sediments than those in shallow fractured bedrocks, and SKB offers the interpretation that groundwater recharges from sediments to the bedrock. Also, the existence of highly transmissive fractures in shallow bedrocks is shown through the detailed analysis conducted.

However, pore pressure/hydraulic heads measurements in the deeper bedrock region, i.e., the area where the disposal facilities will be constructed, have not been conducted to a significant extent. It is partly because the difficulties for data handling of deeper measurements to calculate environmental water heads, the problem on the representativeness of the measured data spatially in the fractured system, and the long-length of the measured intervals during the SR-Site field survey. Based on these challenges, it is understood that the measured pore pressures/hydraulic heads data are not used proactively. In fact, the data shown in the page 249 of R-07-49 indicate that the difference of the environmental water heads between the deeper and shallower intervals is only several tens of centimetres. In SDM (Site descriptive model), dilution measurements were applied to estimate hydraulic gradients (pages 289 to 291 of TR-08-05). However, the results obtained seemed to overestimate the hydraulic gradients which were estimated from the topographic gradients, and hence, the use of the estimated hydraulic gradients from dilution measurements is not straightforward.

Besides the approaches such as the dilution measurements, direct measurements of pore pressures and fluid densities/salinities in situ can provide necessary and important information for better understanding of the hydrogeological system. The IRT recommends that the representativeness of the measured state variables with respect to the fracture-dominated system should be fully discussed once these data have been obtained in the field, and plans have been made to use these data for further study.

The measured fluid pressures and densities/salinities in situ also can be used for assessing the appropriateness of the models even for the stochastic approaches, i.e., whether the representation cases by stochastic approaches describe the measured state variables adequately. It will further strengthen the result of the safety analysis, thus, the IRT recommends that SKB includes measurements of pore pressures and fluid densities/salinities in the deeper part of the rock masses during construction as one of the parameters to monitor.

The effect of temporal changes of external boundary conditions

According to the present approach by SKB, the fluid flow paths are calculated based on the temperate climate results. Subsequently the effects of the changes in the external boundary conditions are taken into account by scaling the Darcy flux at the deposition hole locations during different climate conditions for particle tracking analysis. Based on this approach, the parameters such as F-values (flow-related transport resistance) and advective travel times are calculated for each climate condition. This approach uses the flow paths from the temperate climate conditions, and hence, the effect of possible changes of flow paths on different climate conditions cannot be considered. The reply from SKB on the 3rd questionnaire (page 12) indicates that this problem has been studied by post SR-Site study and the preliminary results from the on-going studies suggest that the SR-Site results can be treated as conservative because the spatial dilution process caused by the changing flow paths is not taken into consideration. The IRT considers that the SKB's statement is reasonable, and the IRT expects that further study will confirm the statement.

Summary of IRT evaluation of hydrogeological and transport conditions

The IRT realises that SKB's plan for the construction of ramp, shafts, and central area provides the possibility to map and characterise fractures with scales of tens to possibly hundreds of meters.

The IRT also notes that, once the construction of the underground facilities starts and data gathering is conducted, a more detailed evaluation on the appropriateness of the correlation models and a more proper set-up of the fracture properties will be performed by SKB. It is expected that SKB will develop further practical ways to map and interpret fractures with scales of several meters to hundreds of meters of scales in the subsurface investigations.

For future research and development, the IRT notes that SKB expects to analyse the possible effects of isolated fractures on mass transport properties, as described in “Radionuclide migration (page 841 of the main report)”.

The IRT recommends that SKB includes measurements of pore pressures and fluid densities/salinities in the deeper part of the rock masses during construction as one of the parameters to monitor. At the same time, the IRT recommends that the representativeness of the measured state variables with respect to the fracture-dominated system should be fully discussed once these data have been obtained in the field, and plans have been made to use these data for further study.

The IRT notes that SKB expects to carry out further study to confirm that SR-Site results can be treated as conservative because the spatial dilution process caused by the changing flow paths through climate change is not taken into consideration.

4.1.3 Geochemical and biogeochemical conditions

The IRT review of geochemical and biogeochemical conditions is based on (parts of) SKB reports TR 11-01, TR 10-58, TR 10-54, TR10-48 (Chapter 5), TR 10-47, TR 10-39, TR 10-19, R-08-47 and P-10-18, as well as SKB responses to IRT questions, and SKB presentations provided during IRT site visits on December 14, 2011.

Safety features and functions

One of the two main safety functions of the geosphere that underpin SKB’s confidence that an KBS-3 repository that fulfills long-term safety requirements can be built at the Forsmark site is that the geosphere shall provide chemically favourable conditions. Within this safety function (R1) (identical for both containment and retardation) SKB has formulated a number of geochemical safety function indicators and indicator criteria (R1a – R1f) that need to be fulfilled at all times during the evolution of an KBS-3 repository during the entire 1 000 000 year safety assessment period.

R1a: Reducing conditions; Eh limited: A fundamental requirement is that of reducing conditions, to ensure that canister corrosion due to O_2 dissolved in the groundwater is avoided. In case a canister is penetrated, reducing conditions are essential in ensuring (1) a low fuel matrix dissolution rate; (2) favourable radionuclide solubilities; and (3) a redox state that is favourable for sorption of radionuclides in the buffer, backfill and host rock.

R1b: Salinity; TDS limited: Groundwaters of high ionic strength would have a negative impact on the buffer and backfill properties, in particular on the backfill swelling pressure and hydraulic conductivity. Ionic strengths corresponding to NaCl concentrations of approximately 35 g/L (0.6 M NaCl) are an upper limit for maintaining backfill properties. The corresponding upper limit for ionic strength for buffer is about 100 g/L (1.7 M NaCl/L). The limit of tolerable ionic strength is highly dependent on the material properties of backfill components. Since in particular for the backfill alternative materials are still to be evaluated, no specific upper criterion is given other than that there is a limit to the tolerable TDS.

R1c: Ionic strength; $\Sigma q[M^{q+}] > 4$ mM charge equivalent: The total charge concentration of cations should exceed 4 mM in order to avoid colloid release from buffer and backfill. In addition, the concentration of natural colloids should be low to avoid transport of radionuclides mediated by colloids. The stability of colloids is much reduced if the ionic strength exceeds a few mM/L. The criterion $\Sigma q[M^{q+}] > 4$ mM charge equivalent will ensure that release of colloids from buffer and backfill is avoided and that the concentration of naturally occurring colloids is kept low.

R1d: Concentrations of HS^-, H_2, CH_4, organic C, K^+ and Fe; limited: Besides low O_2 to prevent oxidative canister corrosion, there is a requirement to keep other canister corroding agents to a limit, especially sulphide (HS^-). In addition, the groundwater should have low concentrations of microbial nutrients (such as dissolved hydrogen, methane and organic carbon) that may be used by sulphate reducing bacteria (SRB) to produce sulphide. The overall quantitative effect of sulphide corrosion also depends on groundwater flow around the deposition hole and on the transport properties of fractures intersecting the hole. Other groundwater constituent concentrations important for long term stability of the backfill and buffer are potassium and iron. Potassium may aid in the conversion of smectite to illite, while iron can lead to the breakdown of the montmorillonite structure.

R1e: pH; pH<11: From the point of view of buffer and backfill stability, a pH < 11 is required. This is fulfilled for any natural groundwater in Sweden. However, other materials in a repository, in particular concrete and shotcrete may affect the groundwater pH and cause high pH values. This can be amended partially by the type of concrete used.

R1f: Avoid chloride corrosion; pH > 4 and $[Cl^-] < 2$ M: A further requirement is that the combination of low pH values and high chloride concentrations should be avoided in order to exclude chloride-assisted corrosion of the canister. This criterion was formulated as pH > 4 and $[Cl^-] < 2$ M. Both conditions are fulfilled in typical Swedish groundwaters.

IRT comments on safety function indicators and criteria: The IRT is in agreement with the safety function indicators against which the safety of the disposal system can be judged. Some of these safety functions have numerical criteria, others are less well defined. The IRT understands the difficulty in defining numerical criteria for the concentrations of HS^-, H_2, CH_4, organic C, K^+ and Fe. However, the IRT recommends that SKB will develop an upper criterion for TDS limitation once final materials for buffer and backfill have been defined.

Initial geochemical state of the Forsmark site

Explorative analyses of groundwater chemistry data, measured in samples from cored, percussion and soil boreholes at Forsmark and hydrogeochemical modelling have been used by SKB to evaluate the hydrogeochemical conditions at the site in terms of origin of the groundwater and the processes that control the water composition and characteristics.

Groundwater in the uppermost 100 to 200 m of the bedrock displays a wide range of chemical variability, with chloride in the range of 200 to 5 000 mg/L, suggesting influence of both brackish marine water (recent Baltic or Littorina Sea relicts) and meteoric water in the shallow bedrock. The system is controlled by flow along transmissive sub-horizontal fractures and sheet joints, and is still in the process of flushing out residual brackish marine (Littorina) groundwaters. Tritium

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content and C-14 analysis have shown that these shallow waters have relatively short residence times from a few decades to a few hundred years. At depths > 200 m the water composition is indicative of brackish marine water with chloride concentrations in the range of 2 000 to 6 000 mg/L, with a clear Littorina sea component (as deduced from Mg concentrations and Br/Cl ratios). This water can be seen down to 600 to 700 m in the transmissive gently dipping fracture zones in the south-eastern part of the candidate rock volume while the penetration depth in fracture domain FFM01 in the target rock volume is only 300 m due to low fracture frequencies. Below these depths in FFM01 the water composition indicates brackish to saline non-marine groundwaters (no Littorina signature) reflecting processes that have occurred prior to the intrusion of Littorina seawater. These deep waters are higher in calcium due to rock-water interaction processes in the low-flow to stagnant waters at these depths.

Porewaters in these rocks generally have lower chloride and are enriched in O-18 compared with the fracture water, indicating a prevailing transient state between porewater and groundwater to at least 650 m depth, despite groundwater ages in excess of one million years. A low chloride and magnesium and enriched O-18 signature preserved far away from water conducting fractures suggest that these porewaters evolved from an earlier, very long lasting circulation of old dilute glacial groundwater in a few fractures. In the shallower areas, where there is a high frequency of water conducting fractures, a situation close to steady state between porewater and fracture groundwater is found. There is a rapid circulation of significant volumes of water in this area of rock. Since the last glaciation, this cold-climate signature in the porewater has become overprinted with a Littorina and/or Baltic-type signature as indicated by chloride, magnesium and O-18 in porewater sampled close to the conducting fractures.

According to data analyses and modelling of the redox system, reducing conditions currently prevail at depth > 20 m. Most of the Eh values determined in brackish water (at depths between 110 and 646 m) seem to be controlled by the occurrence of an amorphous oxyhydroxide with higher solubility than a truly crystalline phase, but evolving towards more crystalline phases. Dissolved sulphide concentrations are low, possibly due to precipitation of amorphous Fe(II)-monosulphides, linked to activity of sulphate-reducing bacteria (SRB). At depths > 600 m, dissolved sulphide concentrations increase, consistent with SRB activity and precipitation of Fe(II)-monosulphides. The iron system at these depths seems to be limited by crystalline oxides, mainly hematite. Despite the obvious disturbances from drilling, the system has enough buffering capacity to maintain substantially reducing conditions and any previous oxidising events have not exhausted that buffering capacity as evident from the presence of fracture filling minerals such as chlorite and pyrite even in the shallow system. The amount of recent Quaternary minerals formed is very small.

The presence of limestone (calcite) and extensive biogenic activity in the Quaternary overburden give rise to pH values usually above 7, calcium concentrations usually between 50 and 200 g/L and bicarbonate concentrations in the range of 200 to 900 mg/L in near surface groundwaters down to about 20 m. Bicarbonate is relatively high in most of the brackish marine groundwaters in the upper 600 m of the gently dipping fracture zones southeast of the target volume, while brackish non-marine groundwaters below 300 m in fracture domain FFM01 have low bicarbonate contents. The pH buffering capacity in Forsmark groundwaters at depths > 100 m appears to be controlled by the calcite system, and modelling confirms that this water is in equilibrium with calcite. Calcite in fractures is abundant and no extensive leaching has occurred in response to past glaciation/and deglaciation events.

SKB states to have high confidence in the understanding of the current spatial distributions of groundwater compositions, from consistency between different analyses and modelling of the geochemical data but also from agreement between the hydrogeological and structural geological understanding of the area. One important remaining uncertainty concerns the increase in sulphide measured while monitoring, likely as a result of drilling disturbance having facilitated sulphate reduction in borehole intervals.

IRT comments on the initial geochemical state of the Forsmark site: The IRT agrees with SKB's expressed high degree of confidence in the spatial distributions of groundwater composition. The IRT is impressed by the development of M3 modelling during SKB's evaluation of the hydrogeochemical conditions at Äspö, Forsmark and Laxemar.

Geochemical evolution in and around the repository during excavation and operation

In addition to groundwater composition changes due to hydrological processes, other chemical aspects need to be considered during the repository excavation and operation period. This includes effects of grouting, introduction (and corrosion or dissolution) of foreign (stray) materials and entrapment of air in buffer and backfill.

R1a: Redox conditions: Large amounts of superficial water are predicted to percolate to repository level. These waters (meteoric, marine, lake or stream) will be equilibrated with atmospheric O_2, which may affect redox conditions in the rock volume above the repository. Microbial O_2 consumption takes place in the overburden and in sediments of water bodies and, therefore, the infiltrating waters are likely O_2 free within a few meters from the surface. Any other contaminants such as nitrate and nitrogen compounds (as a result of blasting for instance) that may find their way into the groundwater draining into the repository would be pumped out, or again microbial reactions will take care of these. SKB concludes that the reducing capacity of transmissive fractures is not affected during excavation and operation of the repository.

Trapped O_2 in buffer and backfill will be used up by microbes in the backfill and by microbes in the groundwater in fractures as well as by chemical processes, with a rate in decreasing order of (1) dissolution of Fe-containing carbonates; (2) oxidation of pyrite; and (3) oxidation of Fe-bearing silicates (e.g., mica and montmorillonite). Reduction of O_2 depends on many factors but all indications are that it will be fast (on the order of one month).

R1b, R1c, R1d and R1f: Salinity, ionic strength and K^+ concentration: The groundwater salinity may be affected during excavation and operation as a result of infiltration of meteoric water or Baltic seawater. The latter would increase the potassium concentration of the groundwater. Salinity could also be affected as a result of upconing of deep saline waters as observed in some boreholes at Äspö. Inflow can be reduced by injecting grout in the surrounding fractures, assuming this can be done succesfully. This would prevent the depression of groundwater levels near the ground surface and the corresponding inflow of meteoric and seawater as well as the upconing of saline waters. Although limited salinity effects will occur during the excavation and operational phase, SKB expects that groundwater salinities will return to normal conditions after repository backfilling because the rapid inflow will stop and saline upconed water will sink.

R1d: Organic materials, colloids: Remaining organic materials in the repository (biofilms on walls, plastics, cellulose, hydraulic fluids, surfactants and cement additives) can be degraded by microbes. An inventory of organic materials and an assessment of the impact on microbial processes have shown that they may lead to a quick consumption of any O_2 left in the repository as well as be followed by a combination of processes involving anaerobic degradation and sulphate reduction. The largest contribution of organic matter is that from buffer and backfill and it is likely that this organic matter is largely recalcitrant because it is a natural component of the mined clay materials. It is unlikely that all of this organic matter would dissolve and be available for microbial reactions. Due to the high density of the buffer, microbial activity will take place in the backfill and any resulting sulphide would likely be precipitated by Fe.

Colloids may be formed due to microbial activity, the microbial cells themselves, amorphous Fe precipitation products and bentonite erosion. These colloids are expected to be short-lived mainly because colloids tend to aggregate and sediment in moderately saline water.

R1e: pH: Grouting is needed to reduce meteoric and seawater influxes as well as saline water upconing. Injection of grout to reduce inflow will increase the groundwater pH. Cement formulations with a lower pH than standard Portland cement and silica sol have been and will be further developed and these will be used in the vicinity of the tunnels. Experience in Finland and at Äspö has shown that a short duration high pH pulse (pH up to 11.3) may occur but that this effect is of short duration (on the order of several days at Äspö) after which the pH drops down to normal values (pH 7.5). After closure a slightly alkaline plume may develop downstream of grouted fractures. Precipitation and dissolution of minerals may occur but this process does not influence the performance of the repository negatively.

IRT comments on the geochemical evolution in and around the repository: The IRT finds the assessment of the geochemical evolution in and around the repository while being excavated and operated thorough and sufficient. Introduction of stray materials such as organic materials can be limited by good housekeeping in a repository. The IRT recommends that, once materials for buffer and backfill have been chosen, its organic matter content and likely availability for microbial processes should be assessed further. While the IRT assumes that grouting of fractures will be successful, it has some concerns about the lack of detail regarding the grouting technique to be used.

Geochemical evolution during the temperate period

Three characteristic climate domains that can be expected to occur in Sweden in a 100 000 year time perspective were identified: (1) a temperate climate domain; (2) a peri-glacial climate domain (with permafrost development); and (3) a glacial climate domain.

The hydrological and geochemical evolution during the temperate period after repository closure involves two distinct intervals, repository saturation and the evolution of the saturated repository up until the start of the next glacial period. This evolution is simulated with the chosen initial (starting) geochemical conditions of deep saline water at depth with less saline groundwater above the repository being a mixture of deep saline groundwater, old meteoric waters and glacial melt waters.

During the temperate period, the infiltration of meteoric waters, the displacement of the Baltic shoreline and changes in annual precipitation will influence the hydrology of the site, implying possible changes in the geochemical composition of groundwater around the repository. The evolution of groundwater components was simulated using the results from the hydrogeological model as input to fully coupled chemical mixing and reaction calculations, using Phreeqc. The minerals calcite, quartz, hydroxyapatite and either a Fe(III) oxyhydroxide or an amorphous Fe(II) sulphide have been equilibrated with the mixtures at all points in space and time. The upper (less than 100 m) part of the domain is more affected by groundwater flow, mixing and infiltrating waters that are chemically more aggressive and the assumption of chemical equilibrium with the selected minerals is possibly less well justified than at greater depth.

R1a: Redox conditions: The hydrogeological model shows that the proportion of waters of meteoric origin at repository depth will increase with time, but this is not expected to affect the Eh at repository level because O_2 is quickly used up in the top layers (few tens of meters). The calculations for Forsmark show that the redox potentials increase slightly with time but remain well below -50 mV at the end of the temperate period. Anoxic conditions prevailing now will be maintained over the whole temperate period, in spite of the increased proportion of meteoric waters with time.

R1b and R1c: salinity and ionic strength: During the initial temperate period after closure groundwaters will be affected by increasing amounts of meteoric waters, leading to a slow decrease in groundwater salinity especially in the upper part of the modelled rock volume. However, from the modelling results SKB concludes that for the whole temperate period following closure cation charge concentrations at repository depth will in general remain above 4 mM.

R1d: Concentrations of HS^-, H_2, CH_4, organic C, K^+ and Fe: Sulphide in groundwater is controlled by a steady state between microbial sulphate reduction and the processes that remove sulphide, i.e., oxidation of, and precipitation with metals. Sulphide concentrations are often below detection limit but in some borehole sections sulphate reduction appears to be stimulated and high levels of sulphides are found, probably as a result of organic matter contamination in the borehole section. Proper sampling requires flushing of the borehole intervals, but the extent of flushing can only be determined from time series and this was not carried out for most of the samples. Therefore, some of the sulphide data may be unreliable. For practicality, it was assumed that for all of the groundwaters the sulphide concentration is < 1.3 x 10^{-5} M, with the exception of KFM01D at 343 m (1.2 x 10^{-4}M). From the sulphide data at Forsmark, the results from the hydrogeological and geochemical modelling and the understanding of the process of microbial sulphate reduction (including the potential reductants H_2, CH_4, DOC), SKB concluded that during the initial temperate period following repository closure the sulphide concentrations in the groundwaters will remain at the levels found at present in Forsmark.

Since there is still a degree of uncertainty about the detailed distribution of sulphide in groundwaters around repository, and because no dependency has been found between sulphide and other groundwater geochemical or hydrochemical parameters, the observed distribution of concentrations at Forsmark is propagated to the analysis of canister corrosion. The highest corrosion rate calculated due to 1 x 10^{-5} M/L sulphide, and for intact buffer is 0.6 mm in a million years. Even if the highest sulphide concentration (1.2 x 10^{-4}M) is used for all the deposition holes, the corrosion depth would be at most 7.8 mm for the one million years assessment period as long as the buffer is intact. Distribution of corrosion rates for the base case semi-correlated hydrogeological DFN model assuming advective conditions in all deposition holes remaining after rejection according to the EFPC criterion is shown in Figure 10-158 (page 532 in TR 11-01). The calculations show that only four deposition holes have sufficiently high flow rates for failure to occur within one million years and for all four, the highest concentration of sulphide in the set of discrete values, i.e., 1.2 x 10^{-4} M is required. Data transmitted by SKB to the IRT, shows that in other realisations of the hydrogeological model, the number of deposition holes where failures can occur vary in a range from 0 to 43. For some of them, failure can occur when concentration of sulphide is larger than 6.42 x 10^{-6} M.

The concentration of Fe(II) is regulated by a complex set of reactions: slow dissolution of Fe(II) silicates (such as chlorite, biotite), the precipitation of Fe(II) sulphides and redox reactions. The concentrations of Fe(II) are in general negligible in granite groundwater because the oxyhydroxides of Fe(III) are quite insoluble and precipitate quickly. Results from modelling show that the calculated Fe concentrations of groundwater at repository level are expected to increase with time as waters of meteoric origin, assumed to have [Fe] about 10^{-5} mol/L become increaseingly dominant.

All available groundwater data indicate that increased infiltration of meteoric water will not increase the K^+ content found at present. The mixing calculations give max K^+ values < 4 mM at any time for Forsmark.

Modelling results show that colloids will not be especially stable during the temperate period, because pH values, salinities and cation concentrations will be high enough to destabilise colloids. SKB‘s conclusion is that colloid levels will remain at levels that have been measured at Forsmark, i.e., < 200 μg/L.

R1e: pH (and alkalinity): For pH values and bicarbonate concentrations, the mixing and reaction calculations are dominated by the precipitation and dissolution of calcite. The pH values remain in the range of 6.5 to 8, while bicarbonate values increase over time. The partial pressure of CO_2 increases because of the assumption that infiltrating meteoric water has a higher CO_2 content than the other waters in the system.

Leaching of grout material leads to precipitation of calcium silica hydrates (CSH phases). This may continue until all grout has dissolved (about 100 000 years). The higher pH and lower bicarbonate (precipitation as calcite) may affect radionuclide solubility and hence mobility although the precipitated calcite will clog pathways. SKB concludes that the effect of grout in fractures will be to increase the pH in deformation zones to values ≈ 9 for relatively long periods of time, probably lasting throughout the first glacial cycle (≈ 120 000 years). pH values of ≈ 9 are within the criterion for the safety function indicator R1e (pH < 11). Radionuclide sorption data have been selected for the pH range 7-9, and are adequate as long as "low pH" materials are used for grouting or as long as silica gel, if used for grouting, will re-crystallise and keep porosity low. Superplasticsers in grout may slowly leach out and could be used by microbes but effects on dissolved organic carbon of groundwater are expected to be negligible.

R1f: Avoid chloride corrosion: pH > 4 and [Cl^-] < 2 M: The modelling has shown that groundwater concentrations of chloride at repository level tend to decrease with time as waters of meteoric origin become increasingly dominant during the temperate period.

IRT comments on the geochemical evolution during the temperate period: The IRT agrees with SKB's handling of the modelling for the temperate period after repository closure. There is still some uncertainty about the in situ concentration of sulphides naturally present in the groundwater in the Forsmark (and other) areas. Microbial activity in stagnant water of the boreholes is thought to affect the concentration of sulphides but it is not clear entirely yet what processes and chemical parameters are involved. The IRT supports SKB's initiation of further investigations at Äspö aiming at a better understanding of the processes triggered when the waters in isolated borehole sections are stagnant. Proper sampling that provides reliable sulphide concentrations requires flushing of the borehole intervals but the extent of flushing can only be determined from time series and this was not carried out for most of the Forsmark samples, and SKB has stated that some of the sulphide data obtained from Forsmark may be unreliable. The IRT is pleased that SKB has carried our further work to determine the true sulphide concentrations in Forsmark groundwaters. The current approach to sulphide modelling during the temperate period uses an already high sulphide concentration and is, therefore, pessimistic.

A further concern may be the illitisation of bentonite induced by microbial reduction of structural Fe(III) in bentonite. This process was not discussed in any detail in SKB's submission but was addressed in the question and answer exchanges between the IRT and SKB in December 2011. The process has been shown in the laboratory but does not seem to be very common in nature. The IRT agrees with SKB that this is most likely due to a lack of nutrients, which would also be the situation in a repository.

With respect to illitisation as a result of high (> 100°C) temperature and the presence of potassium, SKB has concluded that such transformation of the montmorillonite in the buffer would be very slow (Figure 12-13 in TR-11-01) and is not expected to have any significant effect on the important buffer properties. Although the occurrence of a narrow altered buffer zone next to the canister cannot be excluded entirely, a major part of the buffer would have to be transformed in order for the buffer swelling pressure to fall below the pressure criterion of 1 MPa, which is judged most unlikely. The IRT concurs with this conclusion.

Geochemical evolution during the peri-glacial and glacial periods

The modelling for the periods during which the repository is below permafrost during peri-glacial climatic conditions or under an ice sheet during glacial conditions is basically the same as for the temperate period. The chemical compositions of the groundwaters are modelled through advection, mixing and chemical reactions with fracture filling minerals. The different components of the modelling are not fully coupled. The results of the regional scale groundwater flow model are used as input to a geochemical mixing and reaction model. Contrary to the modelling for the temperate period, the models for the (peri)-glacial periods have not included the fractions of selected reference waters. In the geochemical model, either for the glacial scenario without permafrost or for the glacial scenario with permafrost, the rock volume initially contains a mixture of two end-member waters, a deep saline groundwater and a water of meteoric origin. The proportions of these end-members can be obtained from the salinity at any point. With the advance and retreat of the glacier the proportion of a third mixing end-member (glacial melt water) is calculated from the decrease in salinity at any point in space.

During the glacial cycle of the reference evolution the ground will be frozen 30% of the time to a depth of $\geq$50 m. There is very little information concerning the chemical characteristics of groundwaters under permafrost. This is due to practical difficulties when drilling and sampling at ambient temperatures where freezing of drilling fluids and groundwater samples occurs. However, many geochemical characteristics of groundwaters are expected to be almost unaffected by the permafrost. Because there is also almost no information on groundwater chemical compositions in fractured rock below an ice sheet, the evaluation of geochemical characteristics of groundwater during a glacial period must rely almost exclusively on modelling results and, most importantly, chemical reasoning at present.

R1a: Redox conditions: The perennial freezing of rock volumes will effectively shut down the hydraulic circulation in the bedrock, at least locally, during permafrost conditions. For the glacial period SKB concluded that based on observations and results from pessimistic modelling, O_2 intrusion to repository depth in highly transmissive deformation zones cannot be discarded. However, the model results for a recharge O_2 concentration of 0.3 mM indicate that more than 1 000 years of the worst glacial situation would be needed for O_2 to reach the canisters in the repository in non-negligible concentrations. Since such circumstances do not occur in the reference evolution, it is concluded that reducing conditions will prevail in the repository satisfying the safety function indicator criterion.

Alternative evolutions aimed at capturing more pessimistic situations with respect to O_2 penetration to repository depth are considered in the corrosion scenario. With the ice front advance ceasing for up to about 1 000 years, the penetration of O_2 can be disregarded if the ground is frozen or submerged under a melt water lake. But if the sheet is stationary for 1 000 years over the repository on unfrozen ground and if the repository area is not submerged, calculations with a pessimistic O_2 content in the melt water of 1.5 mM, and other pessimistic assumptions (e.g., exclusion of microbial reactions and reactions with fracture minerals), show that O_2 could reach the deposition locations that have the smallest flow-related transport resistance. Consequences for corrosion in such a case have been calculated and shown that the calculated corrosion depths are in the millimeter scale. Furthermore, the probabilities of the 1 000 year and 200 year still-stands occurring during the 1 000 000 year assessment period are estimated at 0.012 and 0.12, respectively. Therefore, SKB concludes that effects of O_2 penetration can be excluded from the corrosion scenario. The IRT concurs with this conclusion.

R1b and R1c: salinity and ionic strength: When water freezes slowly the solutes in the water will not be incorporated in the crystal lattice of the ice but will tend to accumulate at the propagating freeze-out front. This can give rise to an accumulation of saline water to the depth of the frozen front. The saline waters formed in this manner within fractures and fracture zones will sink rapidly due to density gradients. Calculations show that even for the most extreme permafrost extent simulated, the calculated groundwater salinities in the repository volume do not exceed those found at present (that will become diluted with meteoric water during the temperate period). When the permafrost melts and decays, there will be a release of dilute meltwater from the upper highly permeable network of deformation zones. At this stage the low permeability matrix which has preserved (or accumulated) its salinity, especially at greater depths, will probably be more saline than the surrounding groundwaters. The more dilute waters will tend to stay on top and slow mixing will occur. However, the salt concentration at repository level due to freeze-out will not become so high as to lower the buffer swelling pressure. The charge concentration of cations is expected to increase during permafrost periods and satisfy the criterion for the safety function indicator R1c (> 4 mM). This situation will not be changed during permafrost decay and a transition to a temperate period.

Dilute waters of glacial origin are expected under a warm-based ice sheet. Salinities in the upper part would be very dilute (< 2 g/L). Mixing proportions of end-member waters were obtained by calculations and these mixing proportions were then used as input into the Preeqc code which imposes equilibrium with calcite, quartz, hydroxyapatite and Fe(II) oxyhydroxide. The modelling showed that dilute meltwaters with < 4mM may occur within the candidate repository volume for some period of time during the advance and retreat of an ice sheet, violating the criterion for the safety function indicator R1c. The resulting consequence is that during the glacial period, slightly less than 2% of the deposition hole locations would experience dilute conditions during an advancing ice front whereas only slightly more than 1% of the deposition holes experience dilute conditions during an assumed period of 100 000 years corresponding to glacial maximum conditions. It would take up to 60 000 years for temperate conditions (intrusion of meteoric waters) to reach dilute conditions in 1% of the deposition hole locations. For permafrost conditions all arguments indicate that groundwaters below permafrost will not become more dilute than under temperate conditions.

R1d: Concentrations of HS^-, H_2, CH_4, *organic C,* K^+ *and Fe*: The major groundwater components such as Cl, Na, Ca, sulphate and other cations will follow the trends of salinity. Other components such as bicarbonate, K, Fe, FeS etc. that are controlled by relatively fast chemical reactions, are expected mostly to remain unaffected by permafrost (fulfilling R1d). Sulphide concentrations are generally expected to be lower than or at similar levels to those found during the temperate period preceding the periglacial conditions, because microbial reactions may decrease due to lower temperatures. While the sulphate concentration may increase due to freeze-out, the limited supply of organics, H_2 or CH_4 (needed for sulphate reduction), will limit sulphate reduction and the production of sulphide. Various arguments suggest that sulphide concentrations during peri-glacial conditions could be generally lower than those observed during the site investigations, which are used in the analysis of canister corrosion during the peri-glacial time. Current sulphide levels are considered high because of the fairly recent intrusion of seawater (Littorina, Baltic).

For the glacial period, sulphate reduction is expected to be lower than during the temperate period, with similar arguments as those for permafrost. Most indications suggest lower sulphide concentrations during a glacial period. Again, sulphide concentrations for the glacial and submerged conditions are assumed to be the same as the observed distribution of sulphide in groundwaters during the present temperate conditions and these values are considered high because of the recent period of intrusion of marine sulphate-rich waters. These higher values are used for canister corrosion rates estimates during glacial and submerged conditions.

R1e: pH (and alkalinity): Calculations show that glacial conditions may result in a general increase in pH values (an effect observed at Grimsel, Switzerland), but that pH values will remain <11 (R1d). Grout and shotcrete effects during peri-glacial and glacial periods will be similar as those during temperate period. The effect of grout in fractures will be to increase the pH in deformation zones to values ≈ 9 for relatively long periods of time, probably lasting throughout the first glacial cycle (≈ 120 000 year). However, pH values of ≈ 9 are within the criterion for the safety function indicators R1e and R1f.

IRT comments on the geochemical evolution during the (peri-)glacial period: The IRT is in agreement with the modelling carried out by SKB for the peri-glacial and glacial periods. The main uncertainties in this modelling are the salinity and O_2 intrusion effects. The IRT is pleased that SKB together with NWMO and Posiva have started a joint project that attempts to drill boreholes and sample groundwaters in permafrost and near the boundaries of glaciers in an area close to Kangerlussuaq in Greenland. Any new information with respect to O_2 and salinity levels in the melt water could improve the current pessimistic modelling results.

IRT conclusions on geochemistry and microbiology

SKB has performed extensive studies of the geochemistry of fracture- and porewater in the host rock, as well as extensive modelling studies on the evolution (by advection, diffusion, mixing and reactions) of the geochemical groundwater characteristics. As such the IRT is of the opinion that SKB is in full compliance with state of the art techniques and in some areas (i.e., sampling techniques; M3 modelling) probably at the forefront edge of the international developments in this field.

The IRT agrees with SKB's conclusion that, from a repository safety point of view, the most important geochemical parameters of host rock groundwater are salinity, sulphide concentration and O_2 content. Sulphide can cause corrosion of the copper containers. Copper corrosion by O_2 in groundwater could have an even larger effect on the containers, especially in deposition holes affected by bentonite erosion, but only if oxygenated water is able to reach the deposition holes. The salinity of the groundwater at repository depth determines the stability of the bentonite buffer. Eh and pH in general have an important effect on the dissolution of the waste form and on radionuclide mobility.

With respect to the issue of in situ sulphide concentrations in groundwater, the IRT has heard and read with interest the increased efforts by SKB to solve this question and agrees with SKB that the lower sulphide concentrations found after pumping the boreholes are the correct in situ sulphide concentrations. The IRT also agrees with SKB's planned further effort in this area to improve predictions of future sulphide concentrations.

The IRT is impressed by the development of M3 modelling during SKB's evaluation of the hydrogeochemical conditions at Äspö, Forsmark and Laxemar. This M3 model has made it possible to determine that several mixing processes since the last ice age have contributed to the current in situ geochemical characteristics of the groundwater. These processes include the penetration of glacial melt water, high density sinking of Littorina stage seawater and penetration of meteoric water (the latter when the Äspö, Laxemar and Forsmark sites rose above sea level). The M3 model was also capable in certain circumstances to discriminate between the effects of mixing and in situ chemical reactions. The M3 model is a helpful tool in predicting the evolution of groundwater in the future and quantifying these evolutionary effects on salinity, sulphide and O_2, the three most important geochemical parameters from a safety point of view.

The IRT agrees with SKB that, although the currently available hydrogeochemical data are clearly sufficient to prove that suitable conditions prevail at the Forsmark site at present and also during the temperate period that should persist for at least the next several thousands of years, a continuing of data collection effort would be advantageous. Estimation of groundwater composition changes over longer time periods and during glacial cycles is more difficult and SKB has accommodated for this by using pessimistic estimates. Gathering of further data will improve confidence in these estimates, and may potentially lead to the exclusion of the possibility of intruding dilute glacial melt water to repository levels. The IRT strongly supports efforts in this area because of the potentially serious effects of intruding dilute glacial melt water to the repository level on the safety case for the repository.

The work SKB has carried out in relation to the possible role of microorganisms on all aspects of a high level nuclear waste repository has in many respects been at the forefront of the developing knowledge in this area. SKB has sponsored extensive research to characterise the microbiological populations in the waters of the Fennoscandian Shield and the many journal publications that have resulted from this work illustrate its high and novel quality. SKB has also developed a world-class microbial laboratory in the Äspö hard rock laboratory where measurements of microbial activity are taking place in an environment as close as possible to in situ repository conditions.

One of the main concerns with in situ microbiology is the formation of sulphide by sulphate-reducing bacteria (SRB). Sulphide is a highly corrosive agent for copper containers. SKB has shown that SRB are naturally present in both groundwater and bentonite buffer material. However, formation of sulphides from naturally present sulphate is severely suppressed in highly compacted bentonite, if swelling pressures are in excess of 2MPa. Since swelling pressure depends on the density, it is important that a high density is maintained in buffer in order to suppress microbial activity near the containers. SKB has shown that sulphate reduction taking place in groundwater in fractures in contact with highly compacted bentonite is not detrimental for the containers for a period of > 100 000 years because very little of the sulphide will in fact reach the copper containers, due to a combination of a very slow diffusion path through the bentonite and in situ precipitation with Fe(II) present in the bentonite. Several outstanding issues may to a certain extent affect this conclusion. The loss of considerable amounts of bentonite due to piping and/or colloid formation (the latter as a result of intruding dilute glacial melt water) could lead to a reduction in swelling pressure which in turn could negate the full suppression of microbial activity in highly compacted bentonite. The issue of colloid formation and loss of density is one that needs further attention and work by SKB.

There is still some uncertainty about the in situ concentration of sulphides naturally present in the groundwater in the Forsmark (and other) areas. Microbial activity in stagnant water of the boreholes is thought to affect the concentration of sulphides but it is not clear entirely yet what processes and chemical parameters are involved. The IRT supports SKB's initiation of further investigations at Äspö aiming at a better understanding of which processes are triggered when the waters in isolated borehole sections are stagnant.

4.1.4 Mechanical conditions

The IRT review of mechanical conditions is based on SKB reports (TR 11-01, TR 10-52, TR 10-23, TR 10-48, R 09-19, and R-08-69 (unpublished)), SKB responses to IRT questions, and SKB presentations provided during IRT site visits on December 14, 2011.

An important safety function of the geosphere is to provide mechanically stable conditions, mainly with respect to shear loading of the canisters (safety function R3) and transmissivity changes of reactivated fractures (safety function R2). On the one hand these safety functions are controlled by the current in-situ rock stresses, rock mass strength, fracture stiffness and shear strength, and on the other hand by future stress changes and strains resulting from repository and deposition hole excavations, repository drainage, temperature effects, glacial cycles and earthquakes. The IRT has focused its review on rock-mechanical and hydro-mechanical processes, such as the relationships between fracture reactivation and fracture transmissivity, large scale deformations resulting from repository drainage, and shear dislocation from large nearby earthquakes.

In-situ stress: Estimates of in-situ stresses are based on both direct measurements (overcoring, hydraulic fracturing, HTPF) and indirect methods (core disking, borehole breakouts) in fracture domains FFM01, FFM02, FFM03. According to SKB the maximum horizontal stress direction is well known and oriented in the range of N120° to 150°. The stress model of the target volume implies a most likely value of the maximum horizontal stress of ~ 41 MPa and ~ 23 MPa for the minimum horizontal stress at 500 m depth in fracture domain FFM01, but there is considerable uncertainty regarding the horizontal stress magnitude. The estimated vertical stress at this depth is ~ 13 MPa. The layout of deposition tunnels has been designed according to these principal stress directions. Based on results of numerical modelling, SKB infers that the steeply dipping deformation zones in the target volume cause only small perturbations in the stress field, whereas the effect of the gently dipping zones A2 and F1 is more pronounced, with significantly higher stress magnitude below relative to that above these zones.

Pore pressure changes: On the one hand, the simulated water table drawdown above the final repository during the operational stage is low (a few meters maximum). On the other hand, both the SFR (i.e., the repository for low- and intermediate-level waste in Forsmark) and final high-level waste repository generate (and will generate) large-scale and high magnitude (up to c. 5 MPa) pore pressure drawdown at depth, extending several kilometres beyond the footprint of both underground constructions (R 09-19, Fig. 5-18). The time necessary to re-saturate the backfill and for pore-pressure build-up to hydrostatic conditions at depth varies between 200 and 1000 years (R 09-19, p. 74).

Fracture normal and shear stiffness: Normal and shear stiffness as determined from direct shear tests on 29 samples from open fractures in fracture domain FFM01 and 10 samples from three deformation zones intersecting the target volume give mean values of 650-660 MPa/mm normal fracture stiffness and 31-34 MPa/mm shear stiffness at 20 MPa (with a uncertainty of mean of 22 % and 11%, respectively). From plate loading tests at the SFR fracture normal stiffness, k_n, varies between 200-400 MPa/mm for fractures spacing of 0.5-1 m, and a rock mass elastic modulus of 40 GPa (under a load of 2 MPa). For the Singö deformation at the location of the SFR tunnel passage, the deformation modulus has been estimated to be 45 GPa.

Earthquake-triggered shear displacements of fractures: Shear failure of canisters triggered by large earthquakes is considered a major failure scenario in the safety assessment of SR-Site. The scenario is based on the damage of a canister, surrounded by a bentonite buffer, resulting from shear deformation along a discrete fracture intersecting a deposition hole. Safety function R3 of the Geosphere is to provide mechanically stable conditions. The most important safety function indicator criterion is shear dislocation along fractures intersecting the canisters of less than 0.05 m.

The number of canisters that are expected to fail by earthquake triggered shear dislocations higher than 0.05 m is assessed through a complex process illustrated in Figure 4-7 of TR-10-48. This number is derived from a series of critical inputs, such as:

1. The assessment of the probability of one or more earthquakes with magnitude 5 or larger within a 5 kilometer radius around the repository (P1, determined for time scales of 1 000 years, 120 000 years, and 1 000 000 years, Figure 4-6 of TR-10-48).

2. Identification of potential postglacial faults generating future earthquakes with magnitude 5 or larger (TR-10-48 lists 30 potentially unstable deformation zones with a potential rupture area exceeding 1 km^2 within a 5 kilometer radius).
3. Minimal fracture size (critical radius) that can generate a slip of $\geq$ 0.05 m induced by a strong earthquake on a nearby fault (TR-10-48 lists 5 potentially reactivated fractures intersecting the D2 deposition area at Forsmark. For a small distance of 200 m to the earthquake fault, 0.05 m dislocation is generated on 300 m diameter planar fractures, Fälth *et al.,* 2010).
4. The number of critical canisters expected to shear 0.05 m or more (N1, determined from the Discrete Fracture Network model, the efficiency of the FPI criterion used to detect and avoid critical fractures, and the slip distribution within and among such reactivated fractures).
5. The likelihood that the bentonite backfill emplacement density exceeds 2 500 kg/m3, the maximum allowable value, thereby potentially causing canister failure at fracture slips less than 0.05 m.

Transmissivity of reactivated fractures: TR 11-01 and 10-23 discuss transmissivity of reactivated fractures for a series of events ranging from excavation of the tunnel to the mechanical effects of glacial loading. The assessment is based mainly on laboratory test results and numerical simulations of stress changes and shear displacement with the code 3DEC. Important laboratory tests considered are shear box experiments under a range of normal stresses on joint samples of granitic rock and plaster, where actual mechanical aperture, flow changes or dilation angles were measured. It is suggested from these experiments that high normal fracture stresses (20 MPa) suppress transmissivity effects. According to the 3DEC simulations effective normal fracture stresses will approach 10 MPa already at a few meters distance from the repository openings. Therefore transmissivity changes from reactivated fractures, i.e. changes that extend more than a couple of meters from the openings, only occur after the thermal load is applied.

A detailed study of 613 fracture transmissivities derived from Posiva Flow Logging (PFL) and calculated in-situ normal stresses from the candidate area has been conducted by Martin and Follin 2008 (SKB R-08-69). The correlation analysis shows that for all flowing fractures at Forsmark no clear or only weak correlations exist between fracture transmissivity and normal stress, ranging between 10 and 40 MPa. Field fracture flow data suggests the laboratory relationship likely overestimates hydro-mechanical coupling effects. It is more likely that the transmissivity values are controlled by fracture roughness, open channels within the fracture and fracture infilling material. For a friction coefficient of 0.8 gently dipping fractures and faults (with normal stresses ranging between 1 and 13 MPa) should slip and dilate, i.e. most likely they have been reactivated in the past and will be reactivated in the future. On the other hand steeply dipping fractures should not slip. While the mean transmissivity values are similar for the steep and gently dipping fractures (presumably due to the high stress levels), the maximum transmissivity is clearly highest for the gently dipping fracture set.

IRT evaluation of mechanical conditions

Rock mechanical properties and processes: SKB has conducted a large amount of numerical investigations, rock and fracture mechanical lab tests and compared these small-scale investigations with data and observations from in-situ experiments. The experimental procedures and analyses methods used are very comprehensive and represent the current knowledge in rock mechanics and geotechnical engineering. The analysis and discussion of fundamental mechanical mechanisms is excellent and represents the state-of-the-art. The in-situ stress measurements cover a wide range of available methods leading to estimates of mean principle stress orientations and magnitudes. The spatial variability is assessed only qualitatively and few stress measurements are available from the target volume. The IRT assumes that, based on detailed analysis of borehole breakouts (like Valley & Evans 2010a,b[6]), small scale variations of stress magnitudes and directions are significant in fractured bedrock like Forsmark.

Large scale hydro-mechanical coupling: As illustrated in R 09-19 the opening of the underground excavations of the final repository at Forsmark will create a massif hydraulic sink with groundwater flow towards the excavations, a large scale change in hydraulic head fields, and a very significant reduction of pore pressures at the hectometre to kilometre scale around the excavations. As shown in Zangerl *et al.,* 2008a,b[7] and Strozzi *et al.,* 2011[8] such a pore pressure drawdown in fractured gneisses and meta-granites can cause significant surface deformations (up to around 10 cm), possibly supported by shearing of pre-existing large scale fractures (indicated by numerical investigations, but not definitely verified by field data), and followed by seismic activity. New unpublished data from the Gotthard Base Tunnel in the Swiss Alps show that settlements in the centimetre range also occur above lower permeability tunnel sections (with typical long term inflows of a few liters/second per kilometre of tunnel) and stiff rock masses with a moderate frequency of weak fault rocks. Surface deformations also include significant horizontal strains (extension and compression) and typically develop over very long periods of time (decades) in response to transient pore pressure diffusion in the fractured rock

6. Valley, B. and Evans, K.F. (2010a). Stress Heterogeneity in the Granite of the Soultz EGS Reservoir Inferred from Analysis of Wellbore Failure. In: World Geothermal Congress, Bali, 25-29 April 2010.

   Valley, B. and Evans, K.F. (2010b). Stress orientation to 5 km depth in the basement below Basel (Switzerland) from borehole failure analysis. Swiss J. Earth Sci. 102, 467-480.

7. Zangerl, C., K. F. Evans, E. Eberhardt, and S. Loew (2008a). Consolidation settlements above deep tunnels in fractured crystalline rock: Part 1-Investigations above the Gotthard highway tunnel, Int. J. Rock. Mech. Min. Sci., 45, 1195-1210.

   Zangerl, C., E. Eberhardt, K. F. Evans, and S. Loew (2008b). Consolidation settlements above deep tunnels in fractured crystalline rock: Part 2-Numerical analysis of the Gotthard highway tunnel case study, Int. J. Rock. Mech. Min. Sci., 45, 1211-1225.

8. Strozzi, T., Delaloye, R., Poffet, D., Hansmann, J. and Loew, S. (2011). Surface subsidence and uplift above a headrace tunnel in metamorphic basement rocks of the Swiss Alps as detected by satellite SAR interferometry. Remote Sensing of Environment, 115 (6): 1353-1360.

mass presumably originating from brittle faults intersecting the subsurface excavation. As such deformations are observed whenever high-resolution surface deformation data have been collected at appropriate time scales, it is suggested, that these hydro-mechanical processes occur regularly also in stiff fractured bedrock. The observations also suggest that, at least occasionally, fractured and intact rock stiffness as derived from laboratory data underestimates rock mass compressibility at tunnel (or repository) scales. Pore pressure recovery as observed around a hydropower tunnel after grouting has led to a partial recovery of surface settlements, indicating that at least parts of these deformations are elastic and reversible.

Such mechanisms could also occur at Forsmark, leading under worst case conditions to shear reactivation of predominantly steeply dipping deformation zones and large scale surface deformations. *The IRT recommends that these mechanisms are studied in greater detail, that large scale rock mass stiffness characteristics are re-assessed, and a high resolution surface deformation monitoring programme is installed several years before the start of the excavation activities.*

Earthquake-triggered canister shear failure: As mentioned in Chapter 4.4.1, the assessment of the number of canisters expected to fail by earthquake-triggered shear dislocation along fractures intersecting deposition holes was carried out by SKB through a very complex process. Many inputs of this assessment have a large uncertainty, which was often translated into conservative assumptions. Presumably the most important uncertainty in this chain of modelling investigations is related to the magnitude-frequency relationship for long time scales. The key reference cited in many places in the Geosphere Process Report is Bödvarsson *et al.*, 2006 (R-06-67). This reference considers time periods of 100 (instrumental data) and 1 000 years (historic data), earthquake catalogues from Helsinki University and the Swedish National Seismic Network, and recent surface deformations from GPS systems. According to this reference, south-east Sweden (including Forsmark) is relatively inactive today, typical for a stable shield area, with approximately one magnitude 5 earthquake every 100 years in a large region (650 km radius around Forsmark), a magnitude 6 every one thousand years, and a magnitude 7 every 10 000 years. From magnitude-frequency relationships, which are poorly defined above magnitude 3, scaled frequencies are derived for smaller areas. For example, for a 100 km radius circle around Forsmark, 0.021 magnitude 5 events are expected in 100 years; or for 10 km radius around Forsmark, 0.009 magnitude 5 events are expected in 100 years (Bödvarsson *et al.*, 2006). For such small areas geological considerations of the existence of faults capable of generating such earthquakes become very important. In SR-Site (TR-10-48) 30 such faults have been identified and the probabilities shown above have been re-scaled for an area of 5 km radius. The IRT considers these short term assessments as reliable.

However, seismicity is episodic in nature and there are paleoseismological arguments for increased earthquake activity with magnitudes of about 8 at late stages of deglaciation. A comprehensive discussion of the uncertainty of large earthquakes at Forsmark during future periods of glacial ice retreat is given in TR-11-01 (Chapter 10.4.5), where also some paleoseismological studies from Sweden are quoted. As the observation periods reported above are very short, and paleoseismological data sets are limited, our knowledge about long-term seismicity is far from complete. According to TR-10-48 this uncertainty is compensated in SR-Site by assuming that all magnitude 5 earthquakes will break the ground surface, even though the instrumental data report a typical depth of 20 km. It has been shown on many occasions that underground facilities are in general less vulnerable to earthquakes in comparison with above-ground infrastructures, but the seismic impacts on tunnels in the near field of seismogenic faults that generate strong earthquakes is a complex process which has been underestimated in the past. *To strengthen the assumptions made in the safety analysis regarding shear failure of canisters by future large earthquakes, the IRT recommends that research on paleoseismiciy and near-fault conditions*[9] *be prioritised.*

4.2 Buffer and backfill

The IRT review of the performance of the buffer and backfill is based on SKB reports TR 11-01, TR 11-10, TR-10-15, TR-10-16, TR 10-17, TR 10-47, TR 10-63, TR 09-22 and P 10-47, as well as SKB responses to IRT questions, and SKB presentations provided during IRT site visits on December 14, 2011.

4.2.1 Safety functions

The role of the buffer and backfill in the safety concept of the KBS-3 repository is defined by means of the safety functions that should be fulfilled throughout the entire assessment period. A number of safety indicators are defined that if met, indicate the safety functions are upheld as desired.

The buffer and backfill safety functions related to containment, along with their associated indicators and criteria are summarised in Figure 8-2 of TR 11-01. The main function of the buffer is to limit the advective transport of dissolved copper corroding agents to the canister (Buff1). Other important buffer functions are to reduce microbial activity (Buff2) and to protect the canister from rock shear movements (Buff3). For the backfill, the main function is to counteract the buffer upward expansion (BF1) in order to keep the buffer in place.

The buffer and backfill safety functions related to retardation, along with their associated indicators and criteria are summarised in Figure 8-3 of TR 11-01. Should a canister be breached, the main function of the buffer is to limit the advective transport of potential radionuclides releases from the canister. Other important buffer functions are to sorb radionuclides (Buff8) providing a limitation to radionuclide transport, and to allow gas passage (Buff9) in order to avoid potential damage to the repository. For the backfill, the main functions are common to those of the buffer namely, to limit advective transport (BF2) and to sorb radionuclides (BF3).

The plugs are designed to close the deposition tunnels, keep the backfill in the tunnels in place and prevent water flow past the plugs until the main tunnel has been saturated after repository closure. The most important properties for the

9. See for example Corigliano M., Scandella L., Lai C.G., & Paolucci R. (2011) Bull Earthquake Eng, DOI 10.1007/s10518-011-9249-3.

function of the plug are its water tightness and strength. The plug needs to be designed to maintain its functions during the operational phase of the repository. While SKB assigns no barrier (safety) function to the plugs, the plugs must not decrease significantly in volume or contain materials that may impact the safety functions of the engineered barriers or rock.

The IRT finds the assignment of the buffer and backfill safety functions pertinent and complete. Nonetheless, it might also be advisable to include the free swelling strain of the buffer as a safety function indicator (complement of the swelling pressure indicator), in order to assure, along the assessment period, the adequate tight sealing of all the initial gaps and voids, thereby preventing relevant and continuous preferential water pathways (potential advective transport). The required swelling deformation of the chosen bentonites needed in the different repository elements (deposition holes and tunnels, boreholes) for a complete and efficient sealing should be compared with their available free swelling strain. After all, what is essentially required from a good buffer material is to fill in all initial voids and gaps with a material that maintains a sufficiently low hydraulic conductivity along the time.

4.2.2 Design premises and reference design

The specifications (design premises) established by SKB define the reference design that is assessed in SR-Site. They have been thoroughly studied during the "Conceptual Phase" in SKB's development process, including the previous safety assessment SR-Can. The safety-related design premises differ from the safety function indicators in that the former refer to the initial state, while the latter ideally should be upheld during the entire assessment period.

The design premises comprise the properties and parameters to be designed and are mainly based on the barrier functions (Table 2-1 in SKB TR-10-15 and Table 2-1 in SKB TR-10-16). According to SKB, the buffer shall prevent flow of water and protect the canister. For that, its important properties (related to its montmorillonite content and density) are the hydraulic conductivity, swelling pressure and stiffness/strength. The backfill shall keep the buffer in place and limit groundwater flow through the deposition tunnels; and its relevant properties are the same as those of the buffer. The plugs shall close the tunnels providing adequate water tightness and strength. The buffer, backfill and plugs must conform to design premises related to production and operation of the repository facility.

The IRT notes that SKB has reasonably argued the comprehensiveness of the set of design premises established by checking that all safety functions have indeed been considered in the establishing of the design premises.

In the reference design, the buffer is bentonite with montmorillonite content of 80-85 wt%. Figure 3-3 in TR-10-15 shows the installed buffer (solid and ring-shaped compacted blocks). The gap between the blocks and the hole walls is filled with bentonite pellets. The reference design has been verified by calculations and laboratory tests; and it conforms to the design premises. However, if the accepted extreme values in the hole geometry and buffer densities are combined (situation deemed unlikely), the calculated buffer saturated density may locally fall outside the accepted interval (1 950-2 050 kg/m^3). The reference backfill is bentonite (montmorillonite content of 50-60 wt% with an accepted variation of 45-90%). SKB requires at least 60% of the tunnel volume to consist of compacted blocks, and the rest of pellets (Figure 3-2 in TR-10-16). It has been concluded that bentonites with the specified montmorillonite contents conform to the design premises.

The IRT considers that SKB has taken properly into account the general (and most relevant for safety) state-of-the-art knowledge about the buffer, backfill and plug performance when establishing the design premises and the reference design.

The IRT also recommends, however, that future phases of SKB's development process include the following design issues for the buffer that are closely related to bentonite erosion:

- Comparison of the available types of commercial bentonites: different bentonites do behave differently in the initial state and farther along in time. There are advantages and disadvantages of each of them related to their hydraulic, mechanical, thermal and geochemical performance. The relevance of the differences should be carefully assessed, especially those related to the sealing capacity and piping (in the short term) and to the colloid release process (long term).
- Evaluate whether the time to reach equilibrium Na/Ca ratios throughout the entire thickness of the buffer that are on the order to thousands to tens of thousands of years is sufficiently rapid to take place before the first glacial/melting event (more than 60 000 years in the reference glacial cycle).
- Sufficiency of the designed buffer thickness around the canister. There are advantages and disadvantages of increasing this thickness. If greater, gaps will close faster upon wetting, as the volume ratio gap/bentonite would be smaller, and also the safety margin against potential bentonite mass loss will be even higher. Besides, a thicker buffer would improve the damp rock shear safety function. On the other hand, the temperature at the canister-bentonite contact would also increase.

The initial state of the buffer and backfill, including the production and emplacement procedures, as well as the assessment of its technical feasibility are dealt with in Section 4.6.

4.2.3 Internal processes

All processes identified within the system boundary relevant to the long-term evolution of the system are described by SKB in dedicated Process reports. The identification of relevant processes is based on earlier assessments and FEP screening. For each process, its general characteristics, the time frame in which it is important, the other processes to which it is coupled and how the process is handled in the safety assessment are well documented.

According to SKB, modelling of the buffer and the near field will be performed to evaluate canister and buffer peak temperatures; to describe the hydraulic evolution; to address the swelling after saturation; and to estimate the chemical evolution during the thermal phase of the buffer. Most other processes (such as "freezing") are not affected during the early saturation and thermal phases. The long-term chemical evolution (including montmorillonite transformation) will be addressed using several models. Also, bentonite colloidal release needs to be modelled if intrusion of dilute groundwater is not excluded. The potential effects of the bentonite chemical evolution on its swelling pressure, hydraulic conductivity and mass redistribution will be evaluated using empirical relationships.

In the case of canister failure the release of gas will be addressed according to experimental studies; the diffusion of radionuclides through the buffer calculated taking into account their speciation and using experimental data; and the transport of fuel colloids estimated by a bounding case (this process can be neglected if the buffer density exceeds a specified value).

Regarding the backfill processes in the early phase, its saturation, swelling, and potential erosion and piping needs to be evaluated. Temperature increase will be not relevant. In the long-term, ion-exchange, osmosis, colloid release and montmorillonite transformation can be the most important processes. Also, in the case of a canister failure, radionuclide transport in the backfill will be calculated.

In the IRT's view, SKB has identified, described and handled the buffer and backfill internal processes very thoroughly. SKB has also recognised the relevant research needs about the behaviour of the bentonite, to be developed in the future stepwise programme. The IRT recommends that future RD&D studies should cover the following issues (and all of them for the two or three commercial bentonites candidates for the buffer and backfill):

- The conditions and expected time evolution of the colloid release and movement, in the bentonite-free groundwater interfaces. Besides the groundwater geochemical composition (especially salinity), and its changes during glacial cycles, the hydromechanical factors having potential impact on the process should be addressed. Some of them could be the aperture, continuity, roughness and tortuosity of the open cracks intersecting the deposition holes; adhesion of the bentonite colloids on the crack walls; and the groundwater flow velocity in these specific cracks, near the bentonite (also assuming that it has partially filled the cracks). Experiments where free water is in direct contact over a relatively big open surface of swelling bentonite might provide excessively conservative results about the colloid release phenomenon (i.e., significant overestimation of the mass loss). It should also be addressed whether the progressive and relevant loss of bentonite mass takes place only for water velocities (in the cracks, and near the bentonite infill) above a threshold value. The water velocity actually required to cause colloid erosion will be a function of local fracture aperture and colloid characteristics. Hence, using a single velocity value needs to be reviewed in this context.
- Some relevant aspects of the sealing capacity should be further understood and documented; specifically the required minimum potential free swell and the relationship swelling strain-applied pressure (for different initial dry densities and temperatures). Different bentonites do show different swelling strains for the same values of the dry density, applied pressure and temperature. For instance, for the Febex bentonite, temperature reduces the final swelling strain (under constant stress). However, the reverse

behaviour with temperature has been reported for other bentonites. The implications and reasons for these different behaviours should be studied and better clarified. In any case, it should be considered that the higher (and quicker) the swelling strain the better the sealing capacity, and also the higher the safety margin against the potential loss of bentonite mass due to erosion phenomena.

- Time evolution of the swelling strain upon wetting of the different bentonites, as a function of the dry density, temperature and applied pressure. This issue may be relevant in the period of time immediately following the buffer and backfill emplacements; and also for the adequate borehole sealing. If the swelling rate is relatively high, initial gaps and voids will be filled quickly, and the risk of potential bentonite erosion or piping greatly reduced.
- Suction state of the different bentonites after fully saturated. Density of the adsorbed interlayered water and its time evolution. There is increasing evidence that, after fully saturated (i.e., all the voids with no air phase), highly compacted bentonites still have a suction state, keeping the potential of absorbing more free, pure water, if available. The characteristics of the interlayered water in these highly expansive materials are very different from those of free water. More specifically, experimental studies do suggest that the water density between the montmorillonite layers is greater than 1.00 t/m^3, at least in some bentonites (e.g., Febex bentonite). Some analyses of the buffer hydration performance are quite sensitive to the water density value and its time evolution (there is a lack of knowledge about this specific issue). For instance, the actual suction state of the highly compacted bentonites usually remains active much longer than predicted by the available numerical models. The research about the retention properties after full saturation of the different bentonites considered as candidates for use as buffer, and a more complete explanation of their hydration process (taking into account their micro and macrostructure) should be pursued. If nothing else, this research will contribute to a better understanding of the buffer performance (e. g., improving the predictions of the period of time that the buffer will remain in suction), adding confidence about the analyses of its safety functions.

4.2.4 Appropriateness of the RD&D programme of SKB

In this subchapter the appropriateness of the RD&D programme of SKB is considered by the IRT. The assessment is simply made in terms of making sure the RD&D 2010 programme addresses in a comprehensive way the declared main uncertain factors which are affecting the calculated risk (Table 13-13, TR-11-01). In addition, RD&D activities related to main design issues are also considered.

Mechanistic understanding of buffer erosion: The IRT notes that SKB recognises an incomplete conceptual understanding of the buffer erosion processes. This is of particular relevance for the case of buffer erosion through colloid release since this is a long term process that cannot be ruled out in the assessment of long term safety. The empirical transport model used in SR Site was developed in the frame of the "Bentonite Erosion" project, and is based on a pure Na system that probably overestimates the erosion. The IRT agrees with SKB in that further research studies could reduce the degree of pessimism currently adopted. The IRT also agrees in the areas of interest identified by SKB, namely:

- The effect of Ca and mixed Ca/Na systems on swelling/colloid formation behaviour.
- Erosion in fractures or slots.
- Self-healing effects by the clogging of fractures by accessory minerals.
- Effect of flow and water velocity on the erosion.

On the one hand, some of these issues will be addressed by SKB in the frame of the recently launched EC co-financed project Belbar, co-ordinated by SKB and with the participation of several European organisations from different countries.

On the other hand, piping/erosion is only relevant during the early evolution of the repository, basically until the closure of the deposition tunnels with water tight plugs. Therefore it is not a long term process and the IRT understands SKB approach in SR Site of using an empirical model. Current research efforts of SKB (Eva project) to improve the existing approach by developing a quantifiable conceptual model, based on a detailed description of the system with elements of theoretical and empirical submodels (semi-empirical) are acknowledged by the IRT. This additional research will result in the re-formulation of design premises related to inflow into deposition holes.

Groundwater salinity: The IRT agrees with SKB that, although the currently available hydrogeochemical data are clearly sufficient to prove that suitable conditions prevail at the Forsmark site at present and also during the temperate period that should persist for at least the next few thousands of years, a continuing of data collection would be advantageous.

On the other hand, SKB is also conducting RD&D studies related to main design issues:

Long-term durability of the available types of commercial bentonites: Two different bentonite materials are used as buffer component in SR-Site: MX-80 and Ibeco RWC (formerly Deponit CA-N). SKB notes that they should be seen as relevant illustrations of possible alternatives to be used in the repository. It is also indicated that, taking into account the operational phase extension over several decades, different bentonites could be used in different parts of the repository.

There are advantages and disadvantages of each of them related to their hydraulic, mechanical, thermal and geochemical performance. The IRT recommends that the relevance of the differences is carefully assessed, especially those related to the sealing capacity and to the piping and colloid release processes of the material which will be finally emplaced, since they are affecting the calculated risk. The IRT supports the research work conducted by SKB in collaboration with different international organisations in the Alternative Buffer Materials (ABM) project. The main objective being the comparison of different buffer materials (including of course MX-80 and Ibeco RWC) concerning mineral stability and physical properties, both in laboratory tests and field tests performed in Aspö under repository like conditions.

As a conclusion, the IRT considers that the RD&D 2010 programme of SKB addresses in a comprehensive way the declared main uncertain factors which are affecting the calculated risk as well as main design issues with respect to buffer and backfill.

4.2.5 Concluding remarks

In the future development of the licensing process, improvements of the detailed understanding of some issues about the actual behaviour of the different available bentonites could further contribute to show, even more clearly, the highly conservative safety margins of the design premises and scenarios, related to the buffer and backfill. Also, these studies will contribute to demonstrate that all the relevant bentonite issues have been thoroughly considered and properly evaluated. Even more, it is possible that, at least in some aspects, present safety margins and highly conservative assumptions could be reasonably reduced.

4.2.6 Summary of IRT evaluation of buffer and backfill

The IRT finds the assignment of the buffer and backfill safety functions pertinent and complete. Nonetheless, it might also be advisable to include the free swelling strain of the buffer as a safety function indicator (complement of the swelling pressure indicator), in order to assure, along the assessment period, the adequate tight sealing of all the initial gaps and voids, and then preventing relevant and continuous preferential water pathways (potential advective transport). The required swelling deformation of the chosen bentonites needed in the different repository elements (deposition holes and tunnels, boreholes) for a complete and efficient sealing should be compared with their available free swelling strain.

The IRT notes that SKB has reasonably argued the comprehensiveness of the set of design premises established by checking that all safety functions have indeed been considered in the establishing of the design premises. The IRT considers that SKB has taken properly into account the general (and most relevant for safety) state-of-the-art knowledge about the buffer, backfill and plug performance when establishing the design premises and the reference design. The IRT recommends that in future phases of SKB's development process the following design issues of the buffer which are closely related to bentonite erosion, should be taken into account:

- Comparison of the available types of commercial bentonites: with respect to the sealing capacity and piping (in the short term) and to the colloid release process (long term).
- Sufficiency of the designed buffer thickness around the canister.

The IRT considers that SKB has identified, described and handled the buffer and backfill internal processes very thoroughly. SKB has also recognised the relevant research needs about the behaviour of the bentonite, to be developed in the future stepwise programme. The IRT recommends that future RD&D studies should cover the following issues:

- The conditions and expected time evolution of the colloid release and movement in the free groundwater-bentonite interfaces.

- The timing to reach equilibrium Na/Ca ratios throughout the entire thickness of the buffer, for the different bentonites.
- Relevant aspects of the sealing capacity, such as the required minimum potential free swell and the relationship between swelling strain and applied pressure, for the different bentonites.
- Time evolution of the swelling strain upon wetting of the different bentonites.
- The suction state of the different bentonites after they are fully saturated and the density of the adsorbed interlayer water and its time evolution.

The IRT considers that the RD&D 2010 programme of SKB addresses in a comprehensive way the declared main uncertain factors which are affecting the calculated risk as well as main design issues with respect to buffer and backfill.

The IRT notes that SKB recognises that they have an incomplete conceptual understanding of the buffer erosion processes. However, the IRT considers that this conceptual uncertainty is well addressed in SKB's safety analysis, through the scenarios considered, namely scenarios with advective conditions in all deposition holes and 100% of the time. The IRT agrees with SKB in that further research studies could reduce the degree of pessimism currently adopted. The IRT also agrees with the areas of interest identified by SKB, namely:

- The effect of Ca and mixed Ca/Na systems on swelling/colloid formation behaviour.
- Erosion in fractures or slots.
- Self-healing effects by the clogging of fractures by accessory minerals.
- Effect of flow and water velocity on the erosion.

The IRT understands SKB's approach in SR-Site of using an empirical model for piping/erosion, because piping/erosion is only relevant during the early evolution of the repository. The IRT acknowledges current research efforts of SKB (Eva project) to develop a quantifiable conceptual model, based on a detailed description of the system with elements of theoretical and empirical submodels (semi-empirical).

The IRT agrees with SKB that, although the currently available hydrogeochemical data are clearly sufficient to prove that suitable conditions prevail at the Forsmark site at present and also during the temperate period that should persist for at least the next few thousands of years, a continuing of data collection would be advantageous. The IRT strongly supports efforts in this area because of the potentially serious effects of intruding dilute glacial melt water to repository level on the safety case for the repository.

The IRT recommends that the relevance of the differences between the available types of commercial bentonites should be carefully assessed, especially those related to the sealing capacity and to the piping and colloid release processes of the material which will ultimately be emplaced. The IRT supports the research work conducted by SKB in collaboration with different international organisations in the Alternative Buffer Materials (ABM) project.

4.3 Copper canister

The IRT review of the performance of the copper canister is based on SKB reports (SKB TR-90, TR 81-05, 98-08, 01-09, 01-23, 02-07, 04-05, 05-06, 05-18, 06-01, 07-07, 09-20, 09-22, 09-28, 10-04, 10-14, 10-2810-30, 10-46, 10-63, 10-66, 10-67, 10-69 and 11-01), SKB responses to IRT questions, and SKB presentations and questions and answers during the IRT site visit to the canister laboratory on December 14, 2011.

4.3.1 Canister design

The SKB decision for the actual design of a copper canister with a cast iron insert is the result of a long process, including the consideration of several different designs. The IRT understands that the details of the process and decisions leading up to the choice of copper for the disposal canisters are described in KBS-80, which unfortunately is not available in English. The discussions with, and explanations given by, personnel working at SKB's canister laboratory nevertheless provided considerable insight in the decisions that led to the actual design and the proposed fabrication processes. The different designs presented in the technical development showed a clear convergence towards the combination of safe encapsulation with reliable feasibility from an industrial viewpoint. Earlier designs, for instance, showed a lack of retrievability if a failure would occur during the encapsulation leading to problems in repacking the fuel. The IRT regards it as a clear improvement the change from embedded fuel in molten metal or powder metallurgy to a design with channels for the fuel assembly.

The evolution of the canister design took into account safety aspects as well as future production requirements and it is understandable. As the industrial realisation of the planned design is crucial for the fulfilment of the safety case, the IRT appreciates SKB's focus on the combination of both safety and feasibility in the development process.

The quality of copper is described extensively in the SKB documentation. The fabrication of the copper canister was demonstrated in two production processes (pierce-and-draw and extrusion) leading to copper claddings of comparable quality. SKB picked the process of extruding copper to the chosen size and showed its feasibility by producing about 40 tubes. The demonstration runs verified the feasibility of producing copper canisters according to design. The tubes produced were then used to develop and demonstrate techniques for the welding of the lids as well as for non-destructive testing (NDT) methods to ensure the products meet design specifications. The selected welding process, friction stir welding, is deemed more reliable than electron beam welding and SKB developed it further especially for the fabrication of the copper canister. The processes that led to the decision are sound and documented elaborately.

The parameters for the welding process given in SR-Site have been improved significantly in later developments, through optimisation of the welding control system. The actual process is conducted by an elaborate controller, allowing much smaller deviations and resulting in higher quality welds.

Two types of inserts were designed to accommodate fuel from the two different types of nuclear reactors operated in Sweden. The different sizes of the fuels require different inserts with distinct properties with respect to fabrication and mechanical strength. The inserts holding the fuel still bear a small performance uncertainty, because the design for PWR fuel currently has not yet been fully demonstrated to fulfil all design specifications. Due to the process window of the casting process, additional input and verification is needed. For the inserts, the need for quality control and NDT is thus obvious. Nevertheless, the resistance against isostatic load remains high, even with defects in the insert, which results in the possibility of withstanding a higher value for isostatic load than that required for the safety case.

As quality control is a major concern and goal, methods have been developed for testing both the canister and the weld. The methods chosen have been verified to be able to detect inconsistencies and failures below the design limits of the safety case and have been documented in a large number of papers and publications. These methods follow international standards for NDT procedures. Installations for automatising the test procedures have been developed and will be further improved, ensuring reproducibility of the tests. The development of two independent NDT methods for the examination of the welds is appreciated with respect to redundancy and enhanced safety. The techniques proposed for production of the inserts and the canisters have already been fully demonstrated, with the exception of details for one of the insert designs (for PWR fuel) which shall be completed in 2013.

The IRT is of the opinion that the canister design chosen is able to fulfil the criteria specified in the safety case with respect to irradiation, mechanical stress and corrosion (see also next two Sections for a discussion of the corrosion aspects).

4.3.2 Corrosion

The IRT concurs with SKB decision to choose a material for the canister that is thermodynamically stable under repository conditions. Arguing thermodynamic stability is the most defensible way to be sure that the encapsulation is able to remain intact for the necessary duration. The data from archaeological findings are indicative but not quite as cogent for two main reasons: one is the lack of comparability of the environments; while the other pertains to the question of documentation and the still relatively short timescale of the archaeological data. Natural analogues are more telling perhaps. Copper is one of the few metals found in its native state in the geological environment also in connection with uranium. Questions could still be raised, however, about the pertinence of the diagenesis of the copper nodules or deposits vis-à-vis a spent fuel repository environment. It is positively noted that SKB has widely studied both archaeological artefacts and natural analogues.

SKB presents a comprehensive discussion concerning the availability of corroding agents and treats possible corrosion reactions in an extensive way. The corrosion scenario is subdivided into an initial state and a long-term state. The availability of oxygen is correctly assumed as possible only during the initial state. The remaining corrosive agent for long-term corrosion is correctly identified as sulphide, which is treated extensively in the safety case. The assumptions concerning the possible sulphide concentrations are comprehensive and discussed at several places in that report. Measures are taken to avoid sulphide build-up due to materials used for repository construction. The SKB argumentations appear to be complete and traceable and reflecting the current state of knowledge.

SKB's treatment of localised corrosion and mechanically-induced corrosion is sound and comprehensive. Due to the way the canister is manufactured, stress relief will take place provided the heat treatment is conducted correctly.

Experiments supporting the assessed behaviour, such as the minican experiments will give additional insight in the behaviour of the canister in the time period immediately following placement. Data collected in these experiments have to be evaluated carefully as some of the applied tests tend to overestimate the actual corrosion rates. While the experiments are helpful and needed, the long-term behaviour cannot be described by short-time experiments. Overall, the IRT is of the opinion that the thermodynamic discussion is sound and that the conclusions are completely acceptable with respect to the database and assessment used. There is no alternative to the thermodynamic approach considering the lifetime of the repository.

Nevertheless, there are some open questions concerning the corrosion resistance under repository conditions that have been raised recently in the scientific community. These questions mainly concern the possibility that copper may corrode in pure water, under exclusion of oxygen and with production of hydrogen. Namely, a group of scientists (Szakalos, Hultquist) at KTH[10] has conducted an experiment showing progressive copper corrosion under hydrogen evolution. There are several ongoing research projects at SKB dealing with this particular corrosion question.

Of main importance is the question of corrosion due to water decomposition leading to hydrogen evolution. For this case two aspects seem important: first the proof whether this corrosion process can occur under repository conditions and second if this process may questions significantly the current safety case results. While experiments are ongoing to answer the first question, SKB has addressed the second question by treating this corrosion process as a "what-if case" in its corrosion calculations. In TR 10-66 SKB concludes, on the basis of the evolution of H_2 pressure derived from hydrogen transport migration processes under repository conditions, that, even in the worst case of an eroded buffer, the corrosion is in the mm scale. The thinning of the copper would be much smaller in the case the buffer would be in place and H_2 migrated by diffusion. The mitigating effect of diffusion was also found by Schweitzer and Sastre[11] in a paper on copper corrosion in a rock salt environment. The IRT considers that, given the recent experimental results, it is a good thing that SKB took this process in consideration. The IRT finds that SKB's

10. Szakálos P, Hultquist G, Wikmark G, 2007. Corrosion of copper by water. Electrochemical and Solid-State Letters, 10, pp C63–C67.

    Hultquist, G. *et al.,* 2009. Water corrodes copper. Catal. Lett. Springer Published online 28 July 2009.

11. Schweitzer, D.G.; Sastre, C.A., 1989, Long-term isolation of high-level radioactive waste in salt repositories containing brine, *Nuclear Technology*, 1989, 305.

calculations in TR 10-66 are defensible as long as hydrogen evolution would come from the anoxic corrosion of copper with two copper atoms oxidised for each hydrogen molecule (H_2) produced. If, however, other reactions or stoichiometries are at play, SKB's calculations do not apply and this could lead to new questions about the long-term durability of the copper canister.

These (and other) open questions have been recognised already by SKB and are documented, e.g., in TR 10-67. For a final evaluation of the application, the results and conclusions from this future work are very important. The additional projects planned and already begun by SKB are necessary to resolve open questions that challenge the reliability of the copper canister as a barrier. The IRT assumes that SKB will integrate the results in updated application documents and fabrication procedures, respectively.

4.3.3 Corrosion failure

The details of the corrosion issue are already given above. The thermodynamic data used are complete and sound. Failures due to localised corrosion and/or mechanically induced corrosion are treated effectually in the safety case. The treatment of pitting corrosion in the safety case is extensive and takes in to account all relevant scientific data for a conservative estimation of maximum penetration of the canister. The documentation shows a development of the method from using pitting coefficients from literature of the late seventies to the elaborate model based on multiple parameters developed in TR-01-23. Stress corrosion cracking depends on the media, the state of the material and the material itself. The way the risk of SCC is treated in the safety case is traceable and sound. The IRT is of the opinion that the production quality control of the copper canister should include data for the mechanical state and the microstructure of the canister in addition to the description given in the safety case.

The system of evaluation up to now is based on thermodynamic considerations and excludes corrosion after the initial state. Up to now, SKB's evaluation of copper corrosion has been based on thermodynamic considerations that minimise the potential for corrosion after the initial, oxidising state has returned to reducing conditions some time after repository closure. Overall, the IRT finds the thermodynamic arguments sufficient for SKB to rule out copper corrosion caused by reactions with oxygen such that the dominant corrosion mechanism under reducing conditions is interaction with sulfides. On the other hand, the recent issue of copper corrosion by hydrogen evolution is important and has to be resolved scientifically in a comprehensive way, because the possibility of corrosion under oxygen exclusion may change the assessment of corrosion performance leading to three possible conclusions:

1. Copper is stable under repository conditions considering exclusion of oxygen.
2. Copper can corrode under repository conditions by hydrogen evolution, and this has important consequences on the safety case.
3. Copper can corrode under repository conditions by hydrogen evolution, and this does not have important consequences on the safety case.

TR 10-67 and TR 10-66 describe the efforts taken by SKB to resolve this issue. The hypothesis 2 is the least probable at this stage, but the discussion of copper corrosion by hydrogen evolution is important and has to be resolved experimentally. The IRT strongly recommends that SKB continues its best efforts to resolve it.

4.3.4 Canister design load

The mechanical strength is realised mainly by the behaviour of the insert. As described above, for the PWR insert it remains to be shown that all parameters are fulfilled with sufficient safety margins. The isostatic case as the "normal operation" load has been fulfilled by the design for the BWR already, but optimisation of the PWR production process is to be done to verify this as well. For the shear load case, work is still ongoing to provide evidence of compliance to the design parameters. For quality control the shear load case is determining the size of acceptable defects for the inserts as they are more susceptible to defects.

As a result of the assessments performed, SKB has recognised that the original isostatic design load of 45 MPa for the canister might be inappropriate when considering contributions from higher ice sheet thicknesses. On the other hand, the canister in its current specification is physically capable to bear more than twice the original design load.

As the safety margin between the original design load and possible isostatic loads is considered to be small, the IRT supports the idea to strengthen confidence in the canister design parameters by adjusting the original design load towards the already demonstrated canister properties, thus securing that the achievements made during the development of the canister are preserved and applied when the repository reaches the state of realisation. In this regard, SKB stated during the hearing in December 2011 that the new design load remains to be determined, that this should be done based on identified loads in the repository, and that 60 MPa is seen as an extreme upper bound.

4.3.5 Summary of IRT evaluation of copper canister corrosion

The IRT notes that the decision for the actual design of a copper canister with a cast iron insert is the result of a long process, including the consideration of several different designs. The evolution of the canister design takes into account safety aspects as well as future production requirements. The IRT notes that the realisation of the planned design is crucial for the fulfilment of the safety case, and appreciates SKB's focus on the combination of safety and feasibility in the development process. The IRT finds that the processes that lead to decisions regarding the production, NDT testing, and welding methods for the canister and lid are sound and well documented.

The IRT is of the opinion that the decision to choose a material for the encapsulation that is thermodynamically stable under repository conditions is the correct strategy with respect to attaining a high level of confidence that the encapsulation will remain intact for the necessary duration. The IRT has noticed SKB's efforts and knowledge in quality management issues and would like to underline the importance of documentation and quality control for the performance of the canister.

The IRT notes that the inserts holding the spent fuel in place inside the canisters still bear a small uncertainty, because the design for PWR fuel currently has not been fully demonstrated to fulfil all design specifications.

The IRT is of the opinion that the thermodynamic discussion used for the corrosion assessment is sound and complete and that the conclusions are fully acceptable.

Overall, the IRT is of the opinion that the canister design chosen is able to fulfil the criteria specified in the safety case with respect to irradiation, mechanical stress and corrosion.

With respect to corrosion, however, the IRT notes that questions have been raised in the scientific literature pertaining to the possibility that copper may corrode in pure water, under exclusion of oxygen and with production of hydrogen. SKB addresses this potential corrosion mechanism with "what-if" calculations in TR 10-66. These calculations are defensible as long as H_2 evolution would come from the anoxic corrosion of copper with 2 Cu atoms oxidised for each H_2 molecule produced. If, however, other reactions or stoichiometries are at play, then SKB's calculations do not apply and there may be new questions about the long-term durability of the copper canister. The IRT concludes that the discussion of copper corrosion by hydrogen evolution is important and must be resolved. Hence the interest of the new set of experiments that SKB is running already, e.g., under a joint protocol with SSM and KTH, amongst others.

The IRT notes that this (and other) open questions have been recognised by SKB and are documented in TR 10-67. The IRT expects that SKB will integrate the results of further studies in optimised application documents and fabrication procedures.

4.4 Fuel and cladding

The IRT review of the performance of the fuel and cladding is based on SKB reports TR 11-01, TR 10-46 and TR 10-13, as well as SKB responses to IRT questions.

SKB plans to dispose of complete fuel assemblies in its canisters. Most of these assemblies will be intact but a small percentage may have failed. A fuel assembly includes not only the fuel itself, but also the "cladding", the long metal tubes into which the solid fuel pellets are placed and then sealed (called fuel "pins"), and the fuel assembly hardware that maintains the fuel tube geometry. This fuel geometry allows both the nuclear chain reaction to occur, and the heat generated by the nuclear reaction to be removed via cooling water passing between the tubes. A single fuel assembly contains on the order of 100 fuel pins. The cladding is typically made of zirconium with alloying elements up to a few percent of the toal mass. The fuel assembly hardware is composed of various metals with alloying elements – one of which is nickel. SKB will only allow fuel of the oxide form to be disposed in a KBS-3 repository.

In order to sustain a nuclear chain reaction in the types of reactors in use in Sweden [pressurised water reactors (PWRs) and boiling water reactors (BWRs)], there must be sufficient fissile material in the fuel. Natural uranium must be enriched in U-235, the primary fissile isotope. Plutonium from reprocessing contains two fissile isotopes: Pu-239 and Pu-241. When only uranium dioxide fuel is used (UO_2, called "UOX"), the maximum U-235 enrichment allowed by SKB for disposal is 5% and the maximum average UOX assembly burn-up (a measure of the amount of energy released from the fuel during reactor operation per unit mass of fuel) is 60 MWd/kgU. For "MOX" fuel, a combination of plutonium oxide and unenriched uranium oxide is used, and the maximum burnup SKB allows for disposal is 50 MWd/kgU for MOX fuel. The majority of the fuels to be disposed of consists of irradiated UO_2 fuel from all of the commercial reactors in Sweden, with minor amounts of MOX fuel and of miscellaneous other oxide fuels from research programmes.

Hence, the radioactive species that comprise the spent fuel to be disposed of at Forsmark are of the following three major types:

- Fission products: these are the radionuclides generated when the fissile U-235, Pu-239 and Pu-241 atoms split during the fission reactions. Many of these fission products undergo further decay into other radioisotopes, with each decay event releasing more radiation in the form of alpha particles, beta particles, neutrons, and x- and gamma-rays.
- Actinides: some heavy isotopes absorb neutrons and convert to even heavier forms, such as thorium, uranium, plutonium, and curium – all of which are radioactive.
- Activation products: these are caused by the absorption of neutrons from lighter weight elements found in assembly hardware and cladding. The most important activation product in terms of radiation is Co-60 caused by the activation of nickel found primarily in assembly hardware.

All of these radioactive decay events produce heat as a by-product. The relative radioactivity of, and the amount of decay heat from, a particular radionuclide is dependent on:

- the relative abundance of the radionuclide in the waste;
- the "half-life", or the amount of time it takes for half of the radionuclide to decay away; and
- the type of radioactivity decay that occurs, include how much energy is released.

The vast majority of the radionuclides in the waste to be disposed of in a geologic repository will have decayed away well before they even have a chance to escape from the waste container after the container fails. Once the waste container fails, the cladding must also fail before the fuel is exposed to groundwater. Then the fuel must dissolve in the groundwater, pass through the clay buffer and through the rock fractures before the remaining radionuclides can enter the biosphere. Thus, only those radionuclides in the waste that have very long half-lives and that are highly soluble and highly mobile will contribute to the dose to humans and other biota.

Disposal requirements are:

- Total decay power in each canister $\leq$ 1 700 W so as to no exceed the 100C temperature limit for the bentonite buffer.

- No occurrence of criticality under any circumstances.
- Amount of water left in each canister < 600 g to minimise corrosion inside the disposal canister.
- Canister atmosphere at the time of encapsulation shall be ≥ 90% argon to minimise corrosion inside the disposal canister.
- Radiation dose rate at canister surface ≤ 1 Gy/h to avoid the need for a large amount of radiation shielding during waste encapsulation, transport and emplacement underground, and to minimise corrosion effects caused or enhanced by radiolysis of water into more corrosive constituents.

Handling of the spent fuel comprises:

- Transport of fuel from reactor to interim storage facility (Clab/Clink).
- Interim storage for typically 30-40 years (Clab/Clink).
- Selection of wet fuel, transport to encapsulation facility and drying of fuel (Clink).
- Placement of dried fuel in canister, exchange of air with Ar and sealing (Clink).

4.4.1 Initial state of fuel

The initial state refers to the properties of the spent fuel and the gases and liquids in the canisters after final sealing. Burn-up and number of assemblies per canister are the most important parameters for the radionuclide inventory of each canister. From simulations, eight type canisters were selected as a basis for descriptions of the radionuclide inventory in individual canisters and the total inventory. The summed total inventory of all nuclides in the type canisters slightly exceeds that of the reference scenario, justifying this aspect of SKB's canister approach.

The radionuclides in the inventory are found in the fuel (including cladding), in the materials that form the fuel assembly, in the crud and in the control rods (PWR canisters). A fraction of the inventory is located in parts which are assumed to rapidly release the radionuclides in the event of a canister failure. This instant release fraction (IRF) includes radionuclides in all parts except the fuel matrix, such as along the fuel matrix grain boundaries and the fuel pellet/clad gap. This fraction is termed "instant release" because the release rate is high compared to the dissolution rate of the fuel matrix. On the time scale of interest for geologic disposal, the release of many of the fission products from these areas can be considered instantaneous. Certain elements, originally formed in the fuel matrix, have high enough mobility during reactor operation that a fraction of the inventory will transfer to the fuel grain oudaries and fuel/cladding gap and thereby contribute to the IRF. The size of this fraction can, for some elements, be estimated from measured and calculated fission gas (Xe, Kr) release (FGR). The FGR is strongly correlated to the linear heat generation rate of the fuel and fuel burnup, which in turn will depend on the thermal effect of the reactor core and how the fuel assemblies were used during reactor operation. FGR of the assemblies in the different type canisters were estimated based on the average burn-up of the assemblies in the canisters.

The fraction of the mobile radionuclides I-129, Cs-135 and Cs-137 has an IRF which is, at most, equal to the FGR, while some other radionuclides (e.g., Se-79, Sr-90, Tc-99, Pd-107, Sn-126) also have a very small IRF, not correlated to the FGR.

The spent fuel properties and geometrical arrangement in the canister should be such that criticality is avoided even when water should enter the canister. Criticality implies a self-sustaining nuclear chain reaction for which the number of neutrons generated by nuclear fission equals the number of neutrons absorbed by all materials in or around the fuel (effective multiplication factor $k_{eff} = 1$). After a preliminary selection of fuel assemblies to be encapsulated is made based on decay power, this selection is checked against the criterion to avoid criticality. If the effective multiplication factor k_{eff} is < 0.95 for all individual assemblies, i.e., if their combination of enrichment and burnup lies under the calculated loading curve, they can be encapsulated without further check. If there are assemblies with $k_{eff} > 0.95$, the criticality is calculated for the full set of preliminary selected assemblies. In these calculations, the assembly with $k_{eff} > 0.95$ is placed in the worst position for criticality in the canister. If calculations show that k_{eff} is > 0.95 for the whole canister, the selection is not encapsulated but a new set of assemblies is selected. Low burnup assemblies with $k_{eff} > 0.95$ on the criticality side of the loading curve may be combined with high burnup assemblies on the non-criticality side of the loading curve, in order to arrive at the criticality criterion $k_{eff} < 0.95$ for the combination. Should it not be possible to combine certain assemblies in a non-criticality combination, the ultimate measure would be to dismantle those assemblies.

The content of gases and liquids in the canisters depends on the result of drying and gas exchange procedures used during encapsulation. SKB states that there is no reason to believe that the water content in the canisters will exceed 600 g given as a premise, or that the Ar content will be below the acceptable level of at least 90%. The time required to remove water such that no more than 600 grams are left in the canister at the time of encapsulation depends on the decay heat of the fuel, the condition of the fuel assemblies (a small percentage may have failed cladding), and the drying process. Higher decay heat, intact fuel assemblies, and a drying process using a hot, recirculating gas would result in the shortest drying times. SKB provided information on the basis for the < 600 grams or residual water criterion in a written response to IRT questions (SKB document 1292468, response Q2.9.1). The IRT agrees with SKB's response that this value of remaining water would be insufficient to corrode the cast iron insert to a level to jeopardise its mechanical behaviour requirements. The IRT also has confidence that SKB will set up drying procedures to ensure no more than 600 grams of water remain.

The IRT agrees with the assessment of the initial state of the fuel directly after encapsulation. The concept of type canisters is acceptable. The calculation of IRF's for various radionuclides is according to state-of-the-art. The IRT is also in agreement with the handling of the IRF in the safety assessment and the recent update of the IRF to include higher burn-up and higher linear power rating fuels.

4.4.2 Safety functions for retardation

Should a canister be breached, a number of additional phenomena and processes related to the release and transport of radionuclides, i.e., relating to the retarding function of the system, become relevant. Should a canister failure occur, release limitation and retardation is provided by safety functions (F1 – F3), safety function indicators and, where applicable, safety function indicator criteria.

F1: Contain radionuclides

The fuel matrix cannot be controlled by the design of the repository. Nevertheless, the fuel types to be deposited have a matrix structure that is very stable (very low rate of dissolution or chemical conversion) in a reducing repository environment characterised by very low levels of dissolved oxygen (and other oxidising agents) in the groundwater and, therefore, provide an important function by containing radionuclides. The spent fuel dissolution rate is a suitable indicator for this safety function. The dissolution rate is lower for reducing conditions, hence providing reducing conditions is a safety function of the host rock also from the point of view of retardation.

The structural metal parts of the fuel assemblies and elements also contain radionuclides. The corrosion rate of these metals is, therefore, also an indicator for the containment function of the fuel.

F2: Precipitation

Many of the most hazardous radionuclides have limited solubilities in a reducing repository environment, thereby providing an important limitation on radionuclide release from a failed canister. The elemental solubilities are suitable indicators for this safety function. The solubility of many elements is lower under reducing conditions; hence providing reducing conditions is a safety function of the host rock.

F3: Avoid criticality

The fuel properties and geometrical arrangement in the canister should be such that criticality is avoided if water should enter a defective canister, but there is no meaningful simple criterion that can be used for such an evaluation as there are many factors that govern the number of neutrons generated and absorbed. Qualitatively, the fuel reactivity should be low and it is a design premise that k_{eff} for the encapsulated fuel in a water-filled canister should not exceed 0.95 including uncertainties.

The canister insert should have a favourable geometry and material composition with respect to prevention of criticality. This is reflected in geometrical constraints on the canister design that limits the amount of water that can reside inside the canister, and on limitations on the contents of C and Si in the cast iron insert.

4.4.3 Spent fuel dissolution rate

Based on a review of the experimental data (obtained with both relatively fresh spent fuel and alpha-doped UO_2), SKB has derived a constant fractional spent fuel dissolution rate with a triangular probability density function in log_{10}-space with lower limit, best estimate and upper limit of 10^{-8}, 10^{-7} and 10^{-6}, respectively, in the safety analysis calculations. This constant rate neglects the almost certain reduction in the spent fuel dissolution rate over time. SKB has also evaluated the conditions for which this triangular distribution is valid (e.g., redox conditions, pH, temperature, ionic strength, geochemistry and colloids), and has been able to conclude that the triangular spent fuel dissolution rate distribution is valid for all evolutions that were considered in SR-Site, even for groundwater conditions in which a clay slurry may contribute to the outward transport of uranium.

4.4.4 Evaluation of spent fuel degradation processes left out of the safety assessment

The IRT concurs with SKB's reasoning to leave a number of processes out of the safety assessment. One particular process, omitted from the analysis but worth mentioning, is the structural evolution of the fuel matrix as a result of (mainly) alpha decay. The IRT agrees with SKB's argumentation to omit this process. The main impact of this process would be on the segregation of fission products to the grain boundaries of the fuel matrix. However, reported results indicate that radiation-enhanced diffusion in the fuel matrix is too limited to have any effects in the timescale of interest for the safety assessment. Therefore, SKB's judgement is that this process is negligible for the fuel types and burn-up range relevant for SR-Site. The cautious handling of the IRF's of the radionuclide inventory in the assessment calculations is judged by SKB to cover remaining uncertainties (with respect to IRF's in fuel with higher burn-ups than the fuels produced so far). The IRT concurs with this conclusion.

Another process, omitted from the safety analysis, but worth mentioning is helium production in the fuel. Helium is produced in the spent fuel due to alpha decay of actinides. This could lead to a pressure build-up inside the fuel rods, which in turn could lead to mechanical rupture of the rods, with a subsequent pressure build-up in the canisters. Based on estimates of the amount of helium that can be generated and the assumption that all generated helium is released to the canister interior, the pressure increase in the canister interior has been calculated and found to be considerably lower than the pressure external to the canister. Based on these results, SKB concludes that the consequences of helium production for the mechanical stability of the canister can be neglected, and that there is nothing in the completed scenario- and risk assessment that questions this neglect. With respect to the fuel rods, the assumption is that they are all ruptured and that their inventories are accessible to water, as soon as the canister has been penetrated. Although there are some remaining uncertainties related to future fuels with higher burn-ups than produced so far, the cautious handling of the instantly released fractions of the radionuclide inventory in the assessment calculations is judged by SKB to cover these remaining uncertainties. The IRT concurs with this conclusion.

SKB states that, given the importance of the spent fuel dissolution rate for the amount of radionuclides released, research on fuel dissolution should continue. This research should focus both on data under repository-like conditions and on understanding of basic processes contributing to fuel dissolution. Findings from this research could reduce the calculated risk further. The IRT agrees fully with this position.

4.4.5 Summary of IRT comments and findings related to spent fuel

Spent fuel dissolution is of fundamental importance and the redox conditions in the repository at the time of canister breach and the start of the dissolution process are the most important factor influencing this process.

SKB has demonstrated a thorough understanding of the uranium dioxide fuel dissolution processes by carrying out extensive studies on spent fuel dissolution under relevant geochemical conditions (i.e., reducing conditions with H_2 present from iron corrosion processes). SKB recently has also investigated in detail the fuel dissolution process of higher burn-up fuels, which differ from lower burn-up fuel by the characteristic rim structure. As well, SKB has performed extensive modelling studies of the spent fuel dissolution process. The IRT is of the opinion that SKB is in full compliance with state-of-the-art techniques and in many areas probably at the forefront edge of the developments in understanding spent fuel dissolution processes.

The IRT is in agreement with the fuel dissolution rate distribution included in the safety assessment, and is of the opinion that these rates may be on the conservative side for fully reducing conditions. The IRT is also in agreement with the handling of the instant release fraction in the safety assessment and the recent update of the instant release fraction to include higher burn-up and higher linear power rating fuels.

The IRT commends SKB for continuing to be involved in state-of-the-art studies on fuel dissolution and instant release, as evidenced from a very recent paper (Johnson *et al.,* 2012) co-funded by Nagra and SKB.

4.5 Biosphere

The IRT review of the biosphere is based on SKB reports TR 11-01 and TR 10-09, as well as SKB responses to IRT questions, and SKB presentations provided during the two hearings in May and December 2011.

4.5.1 General description of the SKB biosphere model

On page 631 in TR-11-01, SKB describes the Landscape Development Model. The model produces a description over time in spatial detail (20 m by 20 m) of landscape properties and features, including topography, location of the shoreline, regolith depth, areas and depths of present and future lakes and sea basins, stream network, and vegetation and potential land use. This description is used to extract time-dependent properties of the biosphere objects that are input parameters to the radionuclide model for the biosphere.

The evolution of the landscape is needed to capture major changes in the landscape due to major climate change anticipated to continue to occur for at least the next one million years (the time period of the assessment). SKB considers three major climate periods that repeat a total of six times over the next one million years: temperate (the existing climate), periglacial, and glacial. SKB also considers a greenhouse climate representative of a potential global warming episode that is a departure from the assumed temperate/periglacial/glacial climate cycle.

SKB assumes the existing temperate climate period will continue for the next 10 000 years. This period will be characterised by a continued but slowing rate of land uplift that will raise portions of the Baltic Sea floor up to and through several different biosphere types (biosphere "objects"), such as forest, lakes, marsh, fens and bogs, arable land, and surface and groundwater. One example of an evolution would be what is currently Baltic Seabed will rise to become a freshwater lake; the lake will subsequently evolve into fens and bogs; additional land rise may convert the fens and bogs into arable land. Surface water and groundwater will also occur where parts of the Baltic Sea previously existed.

Assuming the engineered barriers of the repository fail during the assessment period, SKB models radionuclides exiting the geosphere into the biosphere at locations governed by the faults and fracture zones and the land and seabed topography. Radionuclides may accumulate initially in parts of the seabed sediments that are later uplifted and evolve into some of the biosphere objects described above. Hence, the seabed sediments into which radionuclides were initially deposited may eventually become arable land. The deposited radionuclides then may be transferred through various exposure pathways to the "most exposed" human group.

The most exposed group is defined as the group of individuals that receives the highest exposure across all potential release areas (i.e. biosphere objects) in the landscape. A representative individual of the most exposed group is assumed to spend all his/her time in the contaminated area, and to get his/her full supply of food and water from this area. This is typical of a "maximally exposed individual" (MEI), whereas some use a "reasonably maximally exposed individual" (RMEI) or a representative member of a "critical" group – both of which are somewhat less conservative.

SKB derives landscape dose conversion factors (LDFs) for each radionuclide and each biosphere object with the use of multiple quantitative factors (such as deposition/erosion, soil sorption, plant root uptake, fish and animal production rates, and human ingestion, inhalation, and external exposure factors). The LDFs are the annual effective doses to future inhabitants of the Forsmark area per unit constant release rate or per unit released in a single pulse to potential release areas (biosphere objects).

The radionuclide model for the biosphere is a compartment model, where system components that are considered internally homogeneous in their properties are represented by distinct compartments. This is standard practice.

4.5.2 The biosphere during the temperate period following repository closure

The biosphere during the temperate period following repository closure is described in Section 10.3.3 of TR 11-01. SKB finds there are small areas of the Baltic Sea floor that potentially may show continuous sediment accumulation since the latest deglaciation. If so, then this is the area that will likely contain the greatest concentration of radionuclides sorbed onto sediments. SKB also notes much of the newly formed land will be unsuitable for farming due to boulder- and stone-rich deposits, but there are large areas in central Öregrundsgrepen with fine-grained sediments that can be cultivated. If this area becomes arable farmland, then agricultural exposure pathways need to be modelled. The IRT understands these pathways have been modelled.

IRT agrees with SKB that the proportion of land that is possible to cultivate will increase as new land areas are formed due to post-glaciation tectonic uplift. Thus, the potential food productivity in the total modelled area is expected to increase during the period. The IRT is unclear how this increase in arable land and potential food productivity is factored into the SKB conceptual and numerical models including uncertainty and variability. It may be however, that this documentation exists already, but the IRT did not review it. If this has been done, the IRT recommends this be included in a higher-level summary of the biosphere conceptual model description.

Similarly, IRT agrees that the availability of freshwater for human supply is expected to gradually increase during the temperate period. This is because new groundwater sources that are potentially useful as drinking water will be available when the shoreline moves eastwards. The IRT agrees that SKB's interpretation of the evolution of the biosphere during the temperate period also means new lakes and streams will form, but most of the lakes will be short-lived due to their shallowness. SKB has appropriately considered these biosphere evolutions in its conceptual and numerical models. SKB has considered evolution of groundwater divides in estimating groundwater availability and the likely entry points of radionuclides into the biosphere groundwater. It is less clear to the IRT how uncertainties in the biosphere evolution have been carried into the numerical models.

The IRT agrees that SKB's description of the landscape development during the initial temperate period is associated with three major uncertainties:

1. The configuration of the landscape, e.g. location and size of future lakes and streams, and depth and stratigraphy of regolith layers.
2. The timing of different events, e.g. withdrawal of the sea, and isolation and infilling of lakes.
3. The composition and properties of species and communities inhabiting the future landscape.

SKB notes uncertainties in the development of the landscape configuration in Forsmark are not handled explicitly in the modelling. Thus, the modelled landscape development should be seen as an example of a possible future, based on a thorough understanding of present-day geometries and an expected shoreline displacement. The IRT agrees this is also appropriate based on the uncertainties, but will still sufficiently capture the important landscape elements.

The IRT finds SKB has appropriately considered both the evolution of and uncertainties in the biosphere objects with time during the initial temperate period. For example, low-lying areas that potentially will be affected by discharge of deep groundwater, are identified and described over time.

SKB assumes each biosphere object will evolve through successive biosphere objects as described above. This means the biosphere objects transform both in size (rough a factor of 100), timing, and rate of succession from one biosphere object to the next. The IRT agrees this is an important consideration, and finds that it has been appropriately handled in SKB's conceptual biosphere model.

SKB handles uncertainties associated with the depth and development of regolith layers, the infilling of lakes, the future surface hydrology and the properties of species and communities that may inhabit the future landscape either as parameter uncertainties or in systematic studies of alternative scenarios in the modelling of radionuclide transport and accumulation in the surface system. This also seems appropriate. The example above is of high potential significance, as the amount of sediments potentially containing sorbed radionuclides and the type of vegetation will have an effect on biouptake and potential ingestion pathways.

In the biosphere assessment SKB selects the worst case (i.e. highest risk) for each radionuclide during an interglacial period from a number of biosphere objects in a dynamic landscape, covering landscape configurations from a fully submerged to an entirely terrestrial landscape. SKB argues this accommodates the difficulty of predicting the exact evolution of the entire system.

This approach is more conservative than other assessments as the overall dose from all radionuclides will be derived from an inconsistent set of landscapes. A potentially useful study to evaluate the degree of conservatism SKB uses would be to evaluate the assessed dose rate assuming all radionuclides are from a single landscape type, as this would be more realistic. Conservatism could be preserved if SKB selects the single landscape configuration that results in the highest overall dose rate estimate.

4.5.3 The biosphere for the rest of the climate cycles

In Section 10.4.2 of TR 11-01 summarises SKB's treatment of the periglacial and glacial cycles. As the region enters the periglacial time domain SKB assumes Forsmark is shows biosphere characteristics similar to those of the later parts of the initial temperate period, i.e. the landscape will consist of terrestrial ecosystems, mainly forests and mires, with few or no lakes and no sea. Parts of the area, especially those with fine-grained sediments in central Öregrundsgrepen, can potentially be used for long-term agriculture. Small areas with mainly organic soils are assumed to be cultivated for limited periods. SKB also assumes the pattern for discharge of deep groundwater, as well as the conditions determining transport and accumulation of radionuclides in the landscape will be similar to those prevailing during the late part of the initial temperate period.

IRT finds all these assumptions reasonable and consistent with assumptions made for the initial temperate period. The general assumption of the repeatability of future glacial cycles is common to performance assessments.

The periglacial time periods are assumed to involve freezing of almost all the land surface with only limited, unfrozen areas called taliks. Taliks often occur under lakes or rivers in the permafrost region, and are the only spots in the periglacial landscape where radionuclides released from the repository can be transported up to the biosphere. Given that lakes and streams often are locations for human settlement and land use, SKB posits that taliks are potentially the locations where humans could be exposed to radionuclides upwelling from the geosphere. SKB reasonably assumes the generally low productivity in the permafrost region would require use of larger areas to supply the resources needed by even a small community. Therefore, IRT understands that SKB assumes humans living near taliks would derive some of their food from contaminated groundwater with higher concentrations of radionuclides than might be found during interglacial periods, but that not all their food would come from this area. Unlike the interglacial time period for which SKB seems to assume 100% of the critical group food sources come from contaminated areas,[12] SKB assumes some of the periglacial climate critical group's food supply may be more contaminated than that for a critical group living in a temperate climate, while other parts of the periglacial climate critical group food supply would be completely uncontaminated. Hence, the *average* dose to the periglacial climate critical group might be similar to that of the critical group living in the interglacial periods.

This seems reasonable for bioaccumulation in food, but does not address the potentially larger contribution to dose from drinking water assuming future humans drink water exclusively from the taliks, which seems like it would be the only place where unfrozen water would appear at the surface. Hence, IRT recommends SKB provide:

- a rationale why the periglacial critical group would also be able to derive part of their drinking water supply from areas other than the talik; or
- consider potentially a higher drinking water dose to the critical group for the periglacial periods; or
- reconsider the appropriateness of assuming the periglacial climate critical group engages in the same combination of agricultural practices and hunting/gathering assumed for the interglacial critical group.

For glacial conditions, the IRT agrees with SKB that the only situation under when humans or other biota may be exposed to high concentrations of radionuclides from the repository is when the retreating ice-front is situated near the Forsmark area and the area is submerged. SKB also notes that no long-term radionuclide accumulation is likely during glacial conditions due to the rapid turnover rate of groundwater in the retreating ice front reservoir. It was nevertheless useful that SKB considered the potential existence of radionuclide pathways to humans during the glacial periods.

SKB also assumes the main uncertainties in the landscape development during the remaining part of the reference glacial cycle are essentially the same as those dominating during the initial temperate period, i.e. 1) the configuration of the landscape, 2) the timing of different events, and 3) the composition and properties of species and communities inhabiting the future landscape. The IRT agrees that even though it is impossible to describe in detail the landscape development during a complete glacial cycle, the systematic landscape analysis and the approach for estimating doses encompasses most of the potential future landscape configurations for the reference glacial cycle.

12. IRT is assuming this about SKB's assumptions about the temperature period from the words SKB uses to describe the critical group behaviour for the periglacial time periods, although an explicit statement by SKB to this effect was not found by the IRT.

For the global warming climate, SKB states that: "the prerequisites for transport and accumulation of radionuclides in the biosphere during temperate periods of the global warming variant are assumed to be similar to those in the initial temperate period of the reference evolution." This also seems a reasonable assumption, if true. The IRT evaluated whether the differences in biosphere LDFs for both the current interglacial and the hypothesised global warming biosphere were significant in terms of the calculated total dose rate versus time. Global warming is considered by SKB to have an effect on temperature (increase of the annual air temperature of 3.5°C and increase in mean annual precipitation by 20 mm). This effect has been examined by SKB through specific LDF's (landscape dose conversion factors). Figures 13-7 and 13-8 in TR-11-01 show that the global warming biosphere LDF's can be higher than during the interglacial period (i.e., agriculture in temperate conditions) for a few radionuclides, but are very close to the interglacial LDF's, i.e., not more than a factor of 10 for two elements (Cs-135 and U-238). SKB considers that a tenfold increase of these nuclides would not affect the final risk. The IRT evaluated how important the dose contributions from U-238 and Cs-135 are to the overall dose assessment. For example, Figures 13-15 and 13-16 in TR-11-01 provide the contributions to the total estimated dose rate for those radionuclides contributing the most to the total calculated dose rate. In the text for these figures, SKB notes: "The legends are sorted according to descending peak annual effective dose over one million years". Since neither of these two radionuclides appears in these figures, neither radionuclide contributes more than a small amount to the total dose estimates. As a result, dose/risk assessments are performed for a single biosphere representative of the interglacial climate. While the justification for this could be better documented, via, for example, a calculation case using the global warming LDF's, the IRT agrees that assuming the LDFs for the interglacial climate is justified.

4.5.4 Biosphere assessments and derivation of landscape dose conversion factors for a glacial cycle

In Section 13.2 of TR 11-01, SKB summarises how the *Landscape dose conversion factors* (LDFs) were derived for each radionuclide and for each biosphere object. The LDFs are the annual effective doses to future inhabitants of the Forsmark area per unit constant release rate or per unit released in a single pulse to potential release areas (biosphere objects). As discussed earlier, SKB multiplies the *maximum* LDFs over all biosphere objects and time points with modelled radionuclide release rates from the geosphere under different release scenarios to estimate the annual doses used to assess compliance with the regulatory risk criterion. This approach seems more conservative than international practice. It would be better to pick just one landscape for all radionuclides even if the particular landscape chosen does not have the highest LDF for all radionuclides. In fact, it would add additional insight to examine which landscape(s) provide the highest overall dose rate estimates and why.

The IRT also agrees with SKB's observation that "the potentially highest exposure of humans and other organisms to radionuclides from the repository is expected when at least parts of the site have emerged from the sea. However, at what stage in the ecosystem succession, and in what part of the landscape a specific radionuclide will cause maximum exposure will vary due to the properties of the specific radionuclide and of the potential release location." For the purposes

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of compliance assessment, it is unnecessary for SKB to be able to identify the exact stage in the ecosystem succession or the exact location of the potential release.

SKB states that it developed "best estimate" LDF values for the critical group based on deterministic simulations. SKB also addressed the effects of parameter uncertainties, assumptions and conceptual uncertainties on the estimated LDFs through probabilistic simulations, alternative models and informed assumptions.

The IRT disagrees that SKB used "best estimate" models and numerical values in developing its LDFs. Many conservative assumptions and data values were made by SKB such that the resulting LDFs are very likely overestimates – potentially significant overestimates.

Furthermore, SKB then uses the maximum LDF values for each radionuclide regardless of time or biosphere object. SKB argues this is appropriate, but "is certainly an overestimate." The IRT agrees it is an overestimate, and also recognises that to provide more realism would be a lot more work, and difficult to justify in some cases. Nevertheless, it would be valuable to conduct one or two simple studies to understand the potential degree of conservatism.

SKB also had to decide which biosphere objects to model. SKB makes the following assumptions to accomplish this:

- The size of a discharge area that receives groundwater from the repository over extended periods of time (e.g. areas situated above the repository) decreases substantially when the area emerges from the sea.
- Changes in the hydrological forces due to the moving shoreline directly affect the discharge of deep groundwater such that the discharge in terrestrial areas will cease with time, and new discharge areas will appear in the emerging landscape and in shallow parts of the sea along the new coastline.

Based on SKB's geosphere model that predicts discharge points in the biosphere, the clusters of discharge points were used to identify the location of biosphere objects in the Forsmark area. SKB identified a total of 17 biosphere objects. Most of these objects contain a discharge area during some period of the Holocene interglacial, but some additional biosphere objects located downstream of the discharge areas are also identified.

The IRT agrees that the size of the discharge area will decrease once the discharge area emerges from the sea. The IRT also agrees with the approach of using the clusters of discharge points as the locations for which biosphere objects need to be developed.

SKB's radionuclide model for the biosphere can handle different types of sources and properties of radionuclides by assuming *a constant release rate of radionuclides, under steady-state conditions. Parameter values for constant releases under steady state conditions were then used. SKB argues this simplifying approach is possible since the releases from the fuel matrix and corroded metals in the repository are in most cases approximately constant on the time scale of the biosphere assessment (i.e. 20 000-70 000 years)*.

The IRT finds this to be a reasonable approach to make the assessment of the LDF simpler. Steady state conditions assumptions will also be conservative as the radionuclides will have been assumed to build up to their steady state levels in the biosphere object components (soils and sediments, vegetation).

SKB also developed a modified version of the LDF models to handle pulse releases.

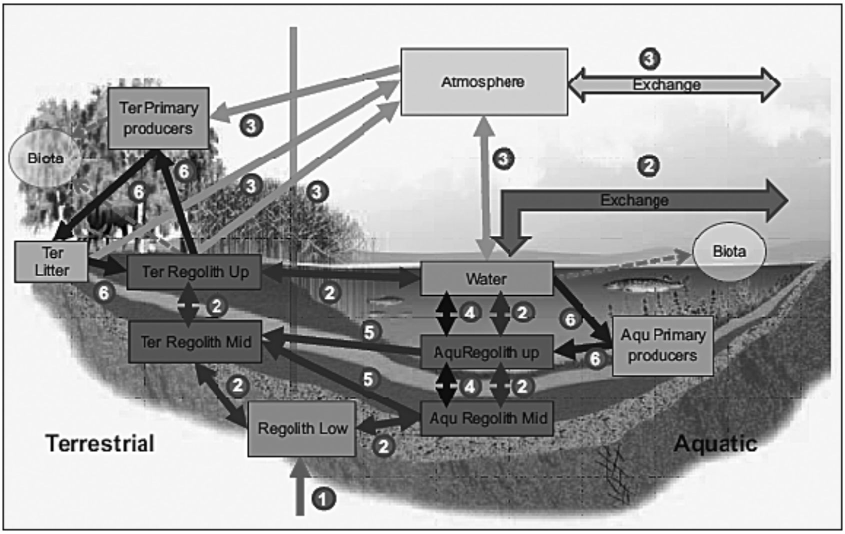
SKB further assumes that the released radionuclides also reach a hypothetical well drilled into the bedrock, as soon as a biosphere object has emerged from the sea. The activity concentration in well water (Bq/m^3) was calculated by dividing the release rate (Bq/y) by the well capacity (m^3/y). The capacity of the well was selected to represent drilled wells in the central part of the site investigation area, where they would have the possibility to receive released radionuclides from the repository. While this is a reasonably simplifying approach to modelling wells, The IRT finds this also somewhat non-conservative as the well capacity of wells in the central part of the research area is likely higher than that for wells located in biosphere objects that have recently emerged from the sea.

Radionuclides released to the lower regolith compartment are distributed to the upper layers of the ecosystems by advection and diffusion. The effect of radionuclide sorption on the advective and diffusive transport is taken into account by assuming equilibrium between the porewater and the solid phase of the different compartments. The model also considers the transport of radio-nuclides absorbed to suspended particles, driven by surface water fluxes, sedimentation and resuspension processes. The IRT finds this to be standard practice.

The radionuclide transport mediated by biota is, for both terrestrial and aquatic ecosystems, described in the model through fluxes driven by net primary production. It is assumed that equilibrium is established between the activity concentrations of radionuclides in the newly produced biomass and in the corresponding environmental media (upper regolith for terrestrial and water for aquatic ecosystems). Losses from the upper regolith and surface waters via degassing processes are pessimistically neglected for all radionuclides, except for C-14 for which this process has been explicitly considered since uptake from air through photosynthesis is the dominant pathway for incorporation into terrestrial primary producers. The IRT also finds this to be standard practice.

The radionuclide model for the biosphere is a compartment model, where system components that are considered internally homogeneous in their properties are represented by distinct compartments. This is standard practice. The compartment model SKB uses is illustrated below. The figure clearly illustrates the various compartments and their connections. The IRT finds SKB's compartments and connections between compartments appropriate.

Conceptual illustration of the radionuclide model for the biosphere
(Figure 13-6 from TR-11-01)



Boxes represent compartments, thick arrows fluxes, and dotted arrows concentration computations for non-human biota (these are not included in the mass balance). The model represents one object which contains an aquatic (right) and a terrestrial part (left) with a common lower regolith and atmosphere. The source flux (1 Bq/y) is represented by an arrow (1). The radionuclide transport is mediated by different major processes, indicated with arrows for water (2), for gas (3), for sedimentation/resuspension (4), for terrestrialisation (5), and for biological uptake/decomposition (6). Import from and export to surrounding objects in the landscape is represented by arrows marked "exchange".

SKB's assessment of the dose is based on a strong international cooperation in Biosphere assessments. The biosphere analysis for the safety assessment of SR-Site relies upon the application of the IAEA BIOMASS methodology. The exposure of the most exposed group was calculated for a constant release rate of radionuclides to the biosphere, and for a pulse release. Environmental activity concentrations were used to assess the radiological impact on the environment. Only one group is explored (considered as the most exposed group): a family farming wetlands. The justification for this group is its complete self-sufficiency with respect to food and drinking water supply. However, the IRT is of the opinion that some points would benefit from a more precise justification.

The most exposed group is defined as the group of individuals that receives the highest exposure across all potential release areas (i.e. biosphere objects) in the landscape. A representative individual of the most exposed group is assumed to spend all his/her time in the contaminated area, and to get his/her full supply of food and water from this area. This is typical of a "maximally exposed individual" (MEI), whereas some use a "reasonably maximally exposed individual" (RMEI) or a representative member of a "critical" group – both of which are somewhat less conservative. It is unclear to the IRT whether the choice of a “most exposed group” is consistent with the SSM regulations summarised in TR-10-09 Section 3.3.3.

When the wetland in a biosphere object has emerged to sufficiently high elevation above the sea level to avoid periodic seawater flooding, SKB assumed it can be drained and used for agricultural purposes. SKB assumes in the assessment that human inhabitants will drain and subsequently use wetlands situated two meters or more above sea level for crop (cereals, root crop, and vegetables) and livestock production. This seems a reasonable assumption to the IRT, as land less than two meters above sea level is likely to be of too high a salinity to support crop and livestock production.

SKB assumes that all available food sources from both aquatic and terrestrial parts of a biosphere object are utilised by human inhabitants. Additionally, it is assumed that wetlands will at least partly be converted to agricultural land when this is possible. SKB makes no assumptions regarding food preferences of future individuals. Instead, SKB assumes the human diet is directly determined by the potential production of different types of food in the object. The IRT is of the opinion this is more conservative than most other biosphere modellers assume. Often, there is an assumed fixed diet. Using a fixed diet has some advantage as the diet is partially based on satisfying nutritional needs. The assumption made here may or may not result in a realistic result regarding satisfying nutritional needs.

The IRT agrees with SKB that the highest activity concentrations of radionuclides in agricultural soil are expected in the period directly after drainage. The 50 years following immediately after drainage are conservatively used by SKB to assess the average annual dose from the use of contaminated agricultural soil during a human lifetime. SKB also conservatively assumes the wetland is converted to agricultural land at the point in time when it results in the largest annual dose.

SKB assumes future humans acquire their drinking water by equal contributions from a well drilled into the bedrock, and from the surface water in the lake or stream passing through the object. Livestock are assumed to consume water from the same sources. These assumptions seem arbitrary. The IRT requests SKB provide either a basis for these assumptions, or conduct a simple sensitivity study of the impact on the LDF values using variants of these assumptions.

SKB assumes exposure from contaminated drinking water is considered from the point in time when a biosphere object has emerged from the sea. This seems inappropriately conservative and inconsistent with the earlier assumption that crops and livestock will not be grown until the biosphere object is at least two meters above sea level. Since half the water is assumed to be from wells drilled into the bedrock, the biosphere object would have to be higher than two meters above sea level for the well water to be potable.

SKB calculates the average exposure over the entire life of individuals by averaging predicted unit release annual doses over a period of 50 years. However, ICRP Report 103, which is listed as a reference by SKB, recommends the study of infants and children (because the dose factor can vary for those categories). This should be justified by SKB.

The uncertainty analysis approach described on page 637 of TR-11-01 is standard practice. The IRT did not review the selected parameter values and uncertainties in the synthesis report, however.

SKB finds for most radionuclides, the LDFs for the interglacial period differ marginally between the situations with and without agriculture. This implies to the IRT that the drinking water pathway provides the dominant contribution to the calculated LDF values. However, SKB notes that for a few radionuclides (i.e. C-14, I-129, Nb-54,[13] Ni-59, U-238), the LDFs differ by more than an order of magnitude between these two situations. This seems likely for these radionuclides as exposure pathways other than drinking water are commonly found to dominate the LDFs in some other assessments.

SKB also determined the LDFs clearly vary among biosphere objects, and the degree of variation depends on the properties of different radionuclides. For radionuclides for which food ingestion is the dominant exposure pathway (i.e. C-14, Cl-36, I-129, Nb-94, Np-237, Se-79, Sn-126, and Tc-99), SKB finds the LDFs typically vary by two to three orders of magnitude among objects. However, for radionuclides for which drinking water is an important exposure pathway (e.g. Am-241, Pa-231, Pu-239, Pu-240, Pu-242, Ra-226 and Th-229), the variation in LDFs among objects is typically less than a factor of three. For most radionuclides, SKB notes the rank order of objects with respect to LDF is similar. This makes sense and is consistent with other biosphere assessments.

As discussed earlier, the IRT agrees with the SKB statement that the use of maximum LDF values in the calculation chain disregards the fact that discharges may affect several objects, and that different nuclides will give maximum LDF values during different successional stages of the biosphere. Thus, the maximum LDF used in the assessment overestimates the potential risk.

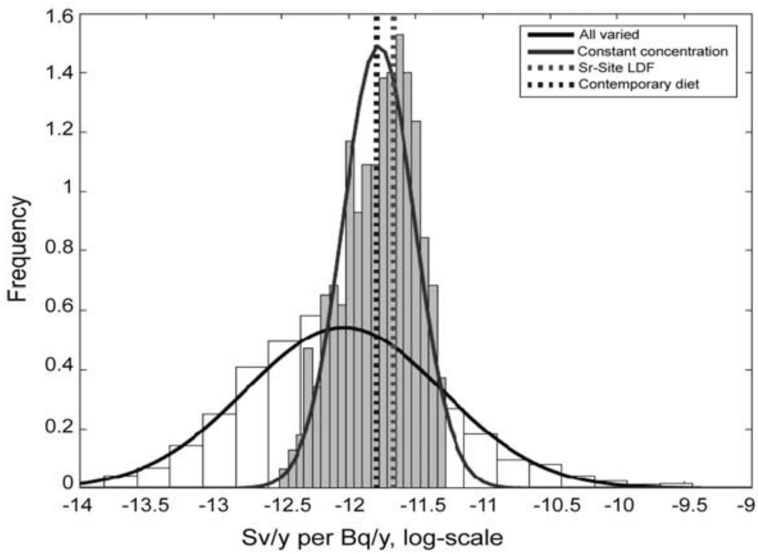
The IRT also agrees with SKB's statement: *"It is concluded that the biosphere objects used to represent the future Forsmark landscape give a reasonable representation of the range of discharge areas that may receive contaminated groundwater from the repository, and consequently uncertainties with respect to the properties of future discharge areas have been incorporated in the LDF values used in the safety assessment. It is also concluded that the concept of unit release rate and the application of maximum LDF values in the risk assessment means that the risk is overestimated."*

For the dose-dominating Ra-226, SKB notes the partitioning coefficient between the solid and liquid phases (i.e. the K_d value) for the lower regolith layer explained approximately 60% of the overall uncertainty, and additionally 7% was explained by K_d for the upper and mid-regolith layers. SKB's main reason for the large variation in K_d value for Ra-226 was that the available site data were insufficient to give a reliable estimate of the natural variation. Instead, SKB estimated the K_d value for Ra-226 from literature data spanning a wide range of geographical conditions and soils types. These seem like reasonable conclusions and approaches.

13. Nb-54 is a typographical error. Hence, it is unclear which radionuclide SKB meant to specify.

However, SKB notes that use of literature data "clearly exaggerate the uncertainty of Ra-226 retention at the site". Thus, SKB decided to use the uncertainty in the Ra-226 K_d estimated from the site data in the probabilistic simulations that addressed the effect of parameter uncertainty. The resulting LDF uncertainty spans several orders of magnitude as shown in the figure below. Given the importance of Ra-226 in the SKB assessment, and the lack of site-specific data for K_d values for Ra-226, the IRT encourages SKB to attempt to provide better site-specific data for future assessments if at all possible. SKB should also consider that such a large uncertainty in the Ra-226 LDFs could mean that better data would result in some other radionuclide or radionuclides dominating the overall dose rate to the most exposed group. This further underscores the usefulness of obtaining additional, site-specific data for Ra-226.

Distribution of dose from Ra-226 (and daughter radionuclides) originating from ingestion of contaminated food (Figure 12-3 from TR-10-09)



Results were obtained from two Monte-Carlo simulations: the grey line corresponds to dose distribution resulting from uncertainty in land use and food productivity. The black line corresponds to dose distribution resulting from uncertainty in land use, food productivity and activity concentration in food. The grey dotted vertical line shows the dose corresponding to SR-Site LDF. The black dotted vertical line shows the value corresponding to a diet based on contemporary food statistics.

4.5.5 Summary of IRT findings and recommendations on the biosphere

Summary of findings:

- The IRT has reviewed SKB's approach to addressing the biosphere and finds it meets or exceeds international standards. Biosphere evolution is a significant consideration for a site near the Baltic Sea because of the isostatic rebound of the Fenno-Scandinavian peninsula after the end of the last major glaciation.

SKB has described in significant detail how the landscape evolves due to land rise from Baltic Seabed to shoreline to peat bogs, and finally to arable farmland or forests.

- The IRT finds it is beneficial to system understanding to develop "best estimate" conceptual and numerical models and parameters. While SKB states it uses "best estimate" landscape conversion factors (LDFs on page 628 of TR-11-01), it is clear that SKB has actually incorporated many conservative assumptions into the development of the LDFs. Hence, the IRT disagrees the LDFs SKB derived are "best estimate". Rather, the IRT considers it likely that many of the LDFs are overestimates.

Summary of IRT recommendations:

- A higher-level IRT recommendation is related to understanding the repository performance using "best estimate" approaches. Therefore, the IRT suggests the biosphere conceptual and numerical modelling and the resulting ingestion/inhalation/external dose conversion factors be reviewed with respect to how the biosphere conceptual and numerical models might be altered if a "best estimate" (rather than the more conservative approach used in the current assessments) approach were used. This would include the impact on dose conversion factors and their uncertainties.
- SKB uses the worst case [i.e. highest landscape conversion factor (LCF)] for each radionuclide during an interglacial period by selecting from a number of biosphere objects in a dynamic landscape. SKB finds even though the exact future landscape development is difficult to predict, the systematic landscape analysis and the approach for estimating doses encompasses a broad array of future landscape configurations. The IRT finds this approach to be more conservative than other assessments because the overall dose from all radionuclides will be derived from an inconsistent set of landscapes. A potentially useful study to evaluate the degree of conservatism SKB uses would be to evaluate the assessed dose rate assuming all radionuclides are from a single landscape type, as this would be more realistic. Conservatism could be preserved if SKB selects the single landscape configuration that results in the highest overall dose rate estimate.
- The IRT is not convinced using the same critical group behaviour for both the interglacial and periglacial periods is appropriate. Furthermore, SKB assumes the average LCFs to the critical group for both drinking water and non drinking water pathways are the same as those for the interglacial critical group. Hence, the IRT recommends SKB provide:
  - a rationale why the periglacial critical group would be able to derive not only part of their food supply, but part of their drinking water supply from areas other than the talik; or
  - consider potentially a higher drinking water dose to the critical group for the periglacial periods; or

  - reconsider the appropriateness of assuming the periglacial climate critical group engages in the same combination of agricultural practices and hunting/gathering assumed for the interglacial critical group.

- For the dose-dominating Ra 226, SKB notes the partitioning coefficient between the solid and liquid phases (i.e. the K_d value) for the lower, upper, and mid-regolith layers contributed the most to the overall uncertainty. SKB's main reason for the large variation in K_d value for Ra 226 was that the available site data were insufficient to give a reliable estimate of the natural variation. Instead, SKB estimated the K_d value for Ra 226 from literature data spanning a wide range of geographical conditions and soils types. These seem like reasonable conclusions and approaches. However, given the importance of Ra-226 in the SKB assessment, and the lack of site-specific data for K_d values for Ra 226, the IRT encourages SKB to attempt to provide better site-specific data for future assessments if at all possible.

4.6 Practical implementation

4.6.1 Construction of underground openings and deposition holes

The IRT review of the construction of underground openings and deposition holes is based on SKB reports TR 11-01 and TR-10-18, as well as SKB responses to IRT questions, and SKB presentations provided during IRT site visits on December 14, 2011.

According to SKB, the final layout of the repository (i.e., the location of deposition tunnels and boreholes with respect to important faults) and the detailed support and permeation grouting measures will only be developed after the host rock has been characterised from the existing underground excavations. This adaptive design method is called "observational method". The observational method applied for design and construction requires the identification of the range of expected rock mass behaviour, the identification of geotechnical and hydrogeological hazards (for example large inflows) and the definition and application of corresponding monitoring parameters and control programmes.

The design excavation method for the deposition tunnels is drill and smooth blasting. The reference method for excavating the deposition holes is a full-face, down-hole drilling technique. From existing knowledge about in-situ stress conditions at repository depth (400-500 m) and rock strength, SKB expects only minor stress-induced failure around the deposition tunnels, i.e. spalling, as long as these excavations are oriented parallel to the maximum principal stress direction. For operational safety reasons, the impacts of spalling shall be eliminated by roof support with shotcrete or wire. The reference design mainly includes rock support aimed at reducing structurally-controlled failures, i.e. overbreak, to acceptable levels.

Permeation grouting with cement will be used intensively in shafts and ramps of the upper 100-200 m below ground surface, where a high frequency of transmissive fractures is expected (fracture domain FFM02). Below 200 m depth it is expected that selective pre-grouting, based on results from probe hole investigations, will be carried out, mainly in deformation zones and water-bearing fractures. Below 400 m, at repository level, it is anticipated only 2% of the 20 m sections between deformation zones will require grouting. For some water-bearing fractures in deposition tunnels, the required sealing efficiency might only be achieved with new technologies, such as silica sol.

The underground constructions at Forsmark also have to fulfill a series of design premises, which go beyond classical safety, stability and durability considerations as applied to standard underground constructions such as traffic tunnels and hydropower excavations. The design premises related to long term safety are summarised in Chapter 5.2.1 of TR-11-01 and include chemical conditions (impacting grout type), thermal conditions (impacting deposition hole spacing and repository depth), rock mass permeability (impacting repository depth, repository layout, and rejection of specific deposition holes), earthquake fault reactivation (impacting distance to deformation zones and the rejection of specific deposition holes), and spalling and EDZ formation along deposition holes and deposition tunnels (impacting repository depth and repository layout).

IRT evaluation of underground constructions

The preliminary design of the underground constructions follows other types of large scale projects. The IRT considers the preliminary design of excavation and support methods for the expected rock mass behaviour as appropriate. The IRT understands SKB has not yet decided on the method to seal boreholes and fractures at the repository level. Given the importance to repository performance, the IRT suggests SKB complete and demonstrate the borehole and fracture sealing design at the proposed repository depth at the earliest appropriate time.

4.6.2 Deposition hole rejection criteria

The IRT review of the deposition hole rejection criteria is based on SKB reports TR 11-01 and R-09-22, as well as SKB responses to IRT questions, and SKB presentations provided during IRT site visits on December 14, 2011.

From the viewpoint of piping erosion of buffer material, up to 100 kg of dry bentonite may be lost due to erosion without jeopardising the function of the buffer. This condition is considered to be fulfilled if the volume of water entering to the deposition hole before saturation is smaller than 150 m^3. However, this criterion may not be practical because it is very difficult to estimate and/or measure the volume of water entering the deposition hole after installing the buffer material. From the viewpoint of canister shear failure, another set of deposition hole rejection criteria has been developed with aims at limiting shear dislocation along pre-existing fractures intersecting deposition holes to 0.05 m. Furthermore, thermal diffusion properties and spalling failure of deposition holes lead to additional considerations in selecting deposition holes. Therefore, SKB has established and applied a series of deposition hole rejection criteria for locating the deposition holes to be used for disposing spent fuel canisters. Some of these criteria are also used in the modelling process of deposition hole rejection and canister failure scenarios.

Fracture intersections: To avoid the effect of the fault reactivation, deposition holes must be more than 100 m away from the deterministic deformation zones of which trace lengths are longer than 3 km. Also, it has been decided that the deposition holes must not be located at the deterministic deformation zones, i.e., the zones of which trace length are longer than 1 km. In addition, the so-called EFPC (extended full perimeter intersection criterion) is applied. The EFPC requires that a canister position must not be intersected by a fracture that also fully intersects the deposition tunnel perimeter. Furthermore, canister positions that are intersected by fractures that also intersect four or more adjacent positions are rejected (in R-11-14, this criterion is described to be "intersect five or more adjacent positions are rejected").

EDZ transmissivity: During excavation of the deposition holes, it might be possible that spalling occurs and an excavation damaged zone (EDZ) with new macroscopic fractures develops. This will result in an increase of the transmissivity around the deposition holes and deterioration of the performance of the disposal system due to the development of an EDZ. For this reason another deposition hole rejection criterion is defined by a connected effective transmissivity integrated along the full length of the deposition hole and as averaged around the hole that shall be smaller than 10^{-10} m^2/s.

Fracture flow rate: At present, for rejecting deposition holes with high flow rates, SKB has applied the FPC (full perimeter intersection criterion): deposition positions with potentially water-bearing fractures are rejected when fractures intersect the full tunnel perimeter and the deposition hole (not the canister position in the deposition hole, as for EFPC). Also, a transmissivity/fracture length (T/L) criterion is applied to avoid minor deformation zones with a radius larger than 250 m (and with an expected effective transmissivity larger than 10^{-6} m^2/s) based on the expectation that the detailed investigations during repository construction will make it possible to detect such fractures.

IRT evaluation of deposition hole rejection criteria

The deposition hole rejection criteria have not been fixed definitely by SKB and several aspects of these criteria were discussed by SKB during the IRT public hearings of December 2011. According to SKB, corrosion failures for one million years should disappear in the reference evolution if it is possible to reject deposition holes where the long-term Darcy flux is higher than 0.001 m/yr. Thus, it is expected that if rejection criteria based on the appropriate long-term Darcy flux could be developed, rejection of the deposition hole locations would be more reliable and efficient. Locations where the long-term Darcy fluxes are higher than 0.01 m/yr should almost all be rejected already by the EFPC/FPC criteria. In addition it has been suggested in SR-Site that long-term Darcy fluxes higher than 0.01 m/yr can be avoided by rejecting the deposition holes with inflow rates higher than 0.1 L/min (according to SR-Site an inflow rate to a deposition hole of 0.1 L/min corresponds to a fracture transmissivity of $4x10^{-9}$ m^2/s). However, the inflow rate to the deposition holes may be affected by skin effects and grouting during construction. Thus, the IRT understands the importance of SKB's plan to evaluate the fracture transmissivity during the underground reconnaissance with pilot holes and to apply the criterion to reject the deposition holes that are crosscut by fractures that contain grout materials. The IRT supports SKB's activity to develop a practical implementation strategy for achieving this plan.

The IRT considers it very important to specify the final practical deposition hole rejection criteria prior to the beginning of any underground excavation works. If the criteria change with respect to the currently applied EFPC/FPC criteria, the canister failure scenario probabilities have to be updated.

4.6.3 Feasibility of initial state and industrial production

The IRT review of the feasibility of the initial state and industrial production is based on SKB reports (TR 11-01, TR 10-15, TR 10-16 and TR 10-17), as well as SKB responses to IRT questions, and SKB presentations provided during IRT site visits on December 14, 2011.

Buffer and backfill

According to SKB, the methods to manufacture buffer and backfill components and to inspect their properties are based on established techniques from similar industrial applications. The reference method to manufacture blocks is uniaxial compression and the reference method to manufacture pellets is roller compaction of small briquettes. The buffer blocks are installed by controlled placing of the blocks in the deposition hole with a gantry crane. In the period between the installation of the blocks and pellets the blocks are protected by a rubber sheet and the deposition hole is drained. The pellets are poured into the gap when the auxiliary equipment has been removed.

The bottom bed in the deposition tunnel is installed by a screw feeder and compacted to a flat layer. The blocks are installed layer by layer by a lifting tool, and the pellets are sprayed into the space between the blocks and the rock surface.

At the present level of the stepwise licensing development, the IRT is of the opinion that the buffer and backfill production and emplacement methods are sufficiently described and credible. The assumptions on their properties (initial state) are well justified and conform to the reference design. Full-scale experimental tests (where feasibility of the buffer emplacement techniques has been proven) performed in the Äspö Hard Rock Laboratory are already available and documented.

Future production and quality-assurance of the designed bentonite buffer and backfill elements could be considered inside the ambit of the well-proven industrial techniques. Neither the design nor construction of concrete plugs (and in general of the sealing elements) will pose serious engineering problems. Related experimental tests already performed (Äspö, Grimsel, in the ESDRED project) did show very positive results.

Of course, SKB will need to conduct in the near future more full-scale demonstration tests of the buffer, canister and backfill emplacement operations (especially under wet conditions), and in general of the other closure elements. The IRT has specifically found the following aspects of the buffer and canister emplacement operations that may deserve further attention during the "Design Phase" in SKB's development process:

- The canister emplacement operation is carried out by remote control with the aid of a deposition machine. SKB has tested this operation roughly 200 times, but with a dummy metallic buffer. In different experiments (e.g Prototype project) SKB has tested the emplacement operation manually, which removes the demonstration aspect.

As a consequence of the above, the IRT recommends to demonstrate the entire buffer and canister deposition sequence under repository conditions in a deposition tunnel section (especially under wet conditions) to ensure its feasibility. The 1 cm gap between the canister and the bentonite blocks may prove to be insufficient in case the bentonite absorbs some water from the tunnel atmosphere and swells.

- SKB recognises that if spalling occurs in sections around the canister, assuming the blocks are selected randomly and the depth of the rock spallation exceeds the nominal diameter by 40 mm, the calculated saturated density of the buffer will locally be in the lower range or slightly lower than 1 950 kg/m3, which is the minimum buffer density criterion. However, seen over the whole cross section the density will lie within the acceptable limits for all acceptable deposition holes. It is possible to increase the installed density by active selection of blocks with high density for the parts of the deposition hole where spalling occurs.

As anticipated by SKB during the visit to Äspö of some members of the IRT, the intended corrective actions might be judged to be unfeasible and hence other actions should be proposed. Nevertheless, the IRT understands that this is not a major feasibility problem. The pellet filling, even if the pellets density is lower than that of the blocks, will do the job of providing a sufficiently low hydraulic conductivity and high swelling pressure as to prevent the development of advective conditions in those deposition holes sections affected by spalling.

Canister

Production/quality: The next step for SKB will be to develop a canister production scheme that includes a complete quality management system (QMS). This production scheme will be a crucial step for the safety of the repository and needs to ensure that:

1. all necessary features of the parts are completely described; and

2. the surveillance of the production processes is complete in such a way that compliance to the features of the reference system is maintained.

The presentations according to SKB's quality policy show that SKB is able to set up and maintain a QMS that complies with the specifications given above. The structure presented by SKB is suitable for the implementation of quality control for the production of the canister providing that all the necessary details will be covered by the QMS. The IRT points out that one aspect that must not be neglected is the implementation of a safety culture that allows improvement of processes, because the proposed production time for the canisters will cover several decades. The expected progress in science and technology may well lead to possible improvements in all details of the technologies used for the implementation of the repository. The development of the QMS has to take into account this special aspect and include procedures for implementation of this process. At this time the QMS is still preliminary, leaving many aspects and/or details undefined. This pertains to SKB's descriptions of the production process as well as SSM's regulatory requirements. While at this time the procedures demonstrated by SKB appear to be able to achieve the design features given in the safety case, the transformation of all features and characteristics of the canister from research to production will be of crucial importance for the performance of the repository and appears to be one of the main issues to follow in the further development of the repository.

Fabrication of the weld: After loading the canister, the weld to close the lid of the canister is a crucial step. SKB has shown remarkable efforts in research and development of the proposed method to achieve this weld (method friction stir welding, FSW). The process window that was demonstrated and discussed in the safety case as completely sufficient has already been improved by further development with respect to controlling the welding process in such a way that this process in itself can now be accomplished with much smaller variations in the parameters, which leads to a more uniform quality of the weld. A procedure for rewelding a lid has not been developed and is not considered necessary. In the case of a failure, the canister will have to be unloaded and discarded.

Testing of components: SKB has developed, or is developing, destructive and non-destructive methods for all components and manufacturing steps of the canister. The IRT is of the opinion that SKB has demonstrated that the methods are able to detect all flaws or deviations to an extent that surpasses the deviations allowed in the safety case. The IRT concludes that the methods proposed are suited for the intended use and that the extent of automation is supporting reproducibility of the measurements. In case of standard production, the IRT notes that the handling of data and the verification of the results will be of great importance. For example, in its probabilistic assessment of repository performance, SKB assumes a certain probability of a welding flaw in combination with not detecting a weld with a critical flaw size. The probability is "low". It is unclear to the IRT what the basis for this number is, given the limited number of weld and NDT exams that were completed. The IRT suggests SKB provide the technical basis for its current probability value for undetected manufacturing defects.

Fabrication: The details of the fabrication process of the canister are still being developed, and as a result, the processes for quality control and production surveillance during the canister fabrication process are not entirely complete either. At this time it has been demonstrated successfully that the canister and inserts can be fabricated with the exception of the PWR inserts, for which work is in progress on verification of compliance with the design features.

SKB states that the quality management and the production surveillance of canister and insert fabrication will follow standard procedures. The insight given into SKB's QMS gives confidence that SKB will be able to develop and implement such a system appropriately.

From the manner in which the production processes are described (e.g., welding process), the IRT concludes that these aspects will be handled soundly and in complete compliance with all design parameters. However, the IRT is also of the opinion that it is not possible to assess the complete system at this state of the project. Remaining questions range from how to handle deviations at a specific step in the canister production procedure to how to retrieve a defected canister from the repository. In addition, regulatory issues are also not defined at present.

The following is an example for the need for detailed quality management procedures: The calculations given in SKB Report 1175236 concerning the estimated production quality of the canister lid welds underline the need for a comprehensive quality management system. If the calculations are to be accepted, it has to be ensured that all fabricated welds comply with the reference parameters. This is a complex task, both on paper as well as in reality. The effort shown by SKB in the development of the production and testing of the components up to now underscores that SKB has understood this necessity.

For the safety of the repository, compliance of the produced canisters (and all the other parts of the repository as well) with the stipulated procedures is vital. The development and supervision of the QMS will be important for the performance of the components as well as the repository in itself. It is the IRT's view that it will be necessary for SSM to prepare a set of specifications for these processes.

4.6.4 Management issues

Process to go to the industrial state

The IRT review of the process to go to the industrial state is based on SKB reports (TR 11-01 and TR-10-63), as well as SKB responses to IRT questions, and SKB presentations provided during IRT site visits on December 14, 2011.

The IRT understands that SKB's application is based on a "conceptual design" of the repository, as was stated by SKB during the hearings. The output of this conceptual design phase is a "reference design" that fulfills design premises, and is based on a verification of feasibility and performance through laboratory tests and some full-scale tests. The level of detail of the reference design at this time is recognised by SKB to be insufficient to define precisely the industrial implementation of the system.

SKB is considering the following steps to proceed to industrial implementation:

- A system design phase, which has already begun: it will develop and optimise the design, verify its industrial feasibility, and define plans for industrialisation and inspection methods. Its output will be available for the preliminary safety report, before the construction license.
- A detailed design phase will give a sufficient level of technical data to begin construction and implementation. Given that the time for implementation differs between different components of the repository, the time left for finalising the detailed design also differs. For example, the repository access detailed design shall be finished before the construction license, as it is the first component to be built, whereas detailed design for systems in the deposition area will be reported in the Safety Assessment report before the test operation license.

The RD&D Programme 2010 (TR-10-63) presents, in a detailed way and for each production line, the technology development that is planned to proceed from schematic technical solutions to industrialised solutions. However, the IRT considers that a reference decision-making process could be also presented more formally, in particular the decision points and criteria to validate a level of design before proceeding to the next step.

The feedback of safety assessment conclusions on design is assessed in TR 11-01 (Chapter 15.5) where the feedback from safety analysis to reference design and related design premises is presented. However, the IRT is of the opinion that the coupling between this feedback and the licensing, design, construction and commissioning process is not clearly presented in the safety assessment. The IRT considers that it would be useful to describe more precisely how and when this feedback will be implemented in the design development, as well as to describe more precisely the decision process that is or will be used to decide to which extent feedback from the safety assessment is introduced in a given step of design.

4.6.5 Document and data control

The IRT has reviewed SKB's approach to data quality assurance and control as described not only in Sections 2.8, 2.9 and Section 9 in TR-11-01, but also in TR-06-09 Section 2.8. In general, the approach to data qualification seems on par with international standards in that there is a rigorous approach to ensuring data to be used in the SKB analyses are appropriately selected taking into account the quality of the data, consideration of uncertainties, and the use of expert judgement.

Given the significant evolution of the repository design, analysis methods, and applicable data, it is essential that SKB employs not only appropriate selection of models and data, but an appropriate system for revision control. This will ensure the analyses conducted and reported are all based on the most current and consistent set of data and assumptions. Without a rigorous data and document control procedure in place, it is conceivable that incorrect or outdated data and models are selected for analysis, or that incorrect or outdated data are transferred to text, figures, and tables in the documents forming the licensing basis. SKB recognises the need for revision control as described in Section 9.6 of TR-11-01:

- "The supplied, quality assured input data must also be used in a correct manner in the modelling. Common errors that may appear in the usage of data are that i) the final version of the data set is not used ii) errors and misprints are made in inputting the data in the programme code iii) an incorrect data set is used (for example a groundwater composition for temperate instead of for glacial conditions)."
- "After the completion of the *Data report*, it falls upon the modeller to check that the final data sets have been used. In doing this, the modeller also checks that there are no errors or misprints from inputting the data in the code. A specific instruction on 'Final control of data used in SR-Site calculations/modelling' has been developed as part of the Quality assurance plan for the safety assessment SR-Site."

The IRT was unable to review the approach to revision control in the QA procedures. The IRT infers from Table 2-2 in TR-11-01 that the revision control procedures are set out in Item 17: "Instruction for final control of data used in SR-Site calculations/modelling". IRT was unable to find this particular instruction, however. The IRT is concerned that the document and data control is left to the modeller to check that the final data sets have been used and that there are no transcription errors. Without a better system to manage the data sets and avoid transcription errors, some mistakes will inevitably occur. For example, in its review of just a few of the SKB reports, the IRT found one table with incorrect values (Table 5-8 in TR-11-01). In response to that observation, SKB noted:

- "All the values in Table 5-8 (taken from an early version of Table 2-5 of Spent fuel report, SKB TR-10-13, and not corrected according to the published version) are erroneous. We thank the reviewer for noticing the error and will include the correct values for Table 5-8 in the errata list. Table 5-8 should be the same as in the published version of SKB TR-10-13."[14]

In another section of TR-11-01, SKB notes:

- "Firstly, it should be noted that some of the figures reported are not correct. The calculated dose rate to a member of the drilling personnel should be 130 mSv/hour and not 500 mSv/hour as reported on page 748. Similarly, the dose rate reported for the case when 3% of Ag-108m is brought to the surface is wrong. The calculated dose rate should be about 4 mSv/hour and not 15 mSv/hour as stated on page 748. (The SR-Site FHA report, TR-10-53 gives the correct figures.)" [SKB document 1292468, 6 September 2011]

Some errors may be more innocuous, but indicate the difficulty of relying on the modeller to ensure text descriptions of data, processes, or models are consistent between documents. For example, the IRT requested a more detailed description of particular hydraulic gradients than that found on page 128 of TR-11-01. SKB noted:

- "The statement in TR-11-01 on p. 128 is unfortunately not a proper summary of the original discussion given on p. 289 in TR-08-05. There, it is concluded that different types of errors are incorporated in the inference of deep hydraulic gradients. The reviewer is kindly asked to read the original text." [SKB document 1292468, 6 September 2011]

In discussions with SKB, the IRT noted other instances of inconsistent use of terms between text, figures, and tables that probably have no impact on the assessment, but merely underscore the difficulty of maintaining consistency throughout the reports.

The IRT has also pointed out to SKB that the tables and figures in the top-level documents, such as TR-11-01 do not have any sort of control number associated with them. Hence, confirmation of the use of the correct data, models, and reporting seems to be all performed manually.

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14. SKB's response to NEA's second questionnaire on postclosure safety in SKB's licence application, document ID 1292468, 6 September 2011.

The reliance on the modeller to ensure the proper data sets and models have been used, along with ensuring there are no transcription errors is below the norm in some international programmes. For example, the U.S. Department of Energy Yucca Mountain Project used a strict document and data control database that, among other features, "locked out" outdated data and models from future use, and assigned a control number to all figures and tables generated. This provides for better traceability and leaves less room for human error. The IRT suggests SKB consider using a better data and document control system for future work.

4.6.6 Quality assurance

The IRT review of the SKB quality assurance programme is based on SKB reports (TR 11-01, SDK 003, TR-10-12, TR-10-15, TR-10-63), as well as SKB responses to IRT questions, and SKB presentations provided during IRT site visits on December 14, 2011.

General assessment

SKB has described its approach for quality assurance (QA), especially QA of the licensing documentation, as well as the principles of the quality management system (QMS) in several documents. The QA approach is described, for instance in Section 2.9 of its main report and SDK 003 (Quality assurance plan for the safety assessment). The principles of the QMS are outlined for instance in the license application (TR-11-01) and report TR-10-12 Section 5. According to further explanations given during the Review process, the quality control needs further development (see SKB`s answer to QFU 2.5.2 in the 3rd questionnaire). Revised plans for quality control are planned to be presented in the PSAR, which is the next main document to be provided, following the SR-Site Safety Assessment (or A-PSAR).

It is positively noted and acknowledged by the IRT that SKB has prepared plans for QA and underlines the importance of QA in its safety assessment/safety case. The IRT has the impression that SKB is well aware of QA issues and has carried out considerable work in that field. In general SKB's approach of having an initial plan for QA/QM S which will be revised and updated at later stages of the process is in accordance with international practice.

However, it is also noted that the QA does not yet address all relevant issues. Thus far, SKB has concentrated on aspects directly linked to the assessment process itself, such as quality of data, models and reports. QA aspects related to the realisation of the repository project are not yet part of the SR-Site Report itself.

In its RD&D programme (TR-10-63) SKB describes in detail the needs for technology development and the current status of work, e.g., related to the fabrication of the canister. SKB explains that different components of the canister could be fabricated in a way that they meet the requirements. However, QA issues related to the manufacturing of the engineered barriers are neither comprehensively addressed in the RD&D programme nor in the safety assessment/safety case.

It is the IRT's opinion that an initial plan for an overall QA process with a perspective of being regularly updated needs to address all relevant issues as identified, at least as issues in need of further development when approaching the state of realisation. Therefore, SKB`s descriptions of QA cannot be regarded as complete within the scope of a long term safety assessment.

QA of industrial manufacturing processes of the engineered barriers (canister and buffer)

In SR-Site the canister and the buffer are correctly identified as the main barriers, meaning both are of highest relevance to safety. SKB recognises that canister and insert have to meet rigorous design premises (e.g. SKB[1] TR-11-01 Vol. 2 p. 435, Vol. 3, p. 766, p. 817, p. 822) and that "given the technical challenges in meeting the rigorous requirements and non-destructive testing (NDT) capability, it might be considered appropriate to relax the requirements for the canister…" (SKB Vol. 3, p. 822).

SKB stated that the desired material properties of the buffer will be specified at ordering (SKB Vol. 1, p. 181). The requirements how the buffer is to be manufactured and emplaced in a quality assured manner are described in detail in the Buffer Production Report (TR-10-15). SKB explains that it will develop a routine for qualification of suppliers comprising "inspection of the quality assurance measures and systems applied by the suppliers as well as laboratory tests of bentonite samples" (TR 10-15). It is further stated that SKB intends to develop a plan for inspections as a part of the QA for the buffer. The IRT understands that SKB is planning to have a combination of its own quality controls and requirements which have to be met by suppliers, but a QA process for the manufacturing of the buffer has not yet been presented.

SKB also states that the quality control of the manufacturing process will be supervised in a separate process by an authorised body. This body has not yet been appointed but will need to be accredited by a government authority (Swedac) and approved by SSM (see SKB`s answer to Q 2.5.1 in the 2nd questionnaire and answer to QFU 2.5.2 in the 3rd questionnaire).

Following this approach it is obvious that aspects related to the manufacturing and testing of the engineered barriers plus the related QA are not yet addressed in the current SR-Site report for the long term safety assessment.

However, if SKB argues that the engineered barriers are the main barriers in its repository concept, QA measures to confirm that canister and buffer can be manufactured and tested in such a way that they can fulfil the defined requirements are an essential part of the safety demonstration from the beginning. Not including this information leads to a lack of confidence in the safety case, as its argumentation is not covering all safety relevant information. Thus, the industrial feasibility and required quality of producing and testing engineered barriers seem to have not yet been demonstrated adequately – even for this stage of development.

International recommendations e.g. by IAEA or OECD/NEA (see examples in the Appendix at the end of this Chapter) strengthen the understanding that the manufacturing process of canister and buffer (the engineered barriers) and its QA have to be included in the safety case/safety assessment. Documents to be considered in this regard are, for instance:

- IAEA[15] Specific Safety Requirements No. SSR-5: Disposal of Radioactive Waste (2011).
- IAEA[16] Draft Safety Standard DS 355: The Safety Case and Safety Assessment for Disposal of Radioactive Waste (Draft status: 06/2011).
- OECD/NEA[17]: Post-closure Safety Case for Geological Repositories – Nature and Purpose (2004).

IRT recommendations

During the hearing in Stockholm in December 2011 SKB demonstrated that SKB is aware that the Swedish spent fuel repository project needs to be accompanied by comprehensive QA measures at all stages and that this has to be planned in advance. Nevertheless, the handling of QA-related aspects within the SR-Site Safety Assessment Report seems to be incomplete in its current state.

As QA issues are very important, the IRT, therefore, recommends the addition of a separate QA chapter to the SR-Site Report, addressing the full the range of QA issues, their current status with respect to the on-going process and the needs for further development.

Summarising all relevant information on QA in one place would allow readers to obtain a good overview of SKB's QA approach, demonstrating that SKB itself is aware of the current status and of upcoming tasks related to the desired progress in the QA procedures, and would nevertheless ease the updating at later project stages.

Furthermore, the IRT recommends that an initial QA plan needs to address all relevant issues. Therefore, the QA measures for industrial manufacturing processes regarding the main barriers need to be addressed in the report, at least as relevant issues that need to be developed further.

4.7 Performance assessment

The IRT review of the SKB performance assessment is based on SKB reports (TR 11-01), SKB responses to IRT questions, and SKB presentations provided during IRT site visits on December 14, 2011)

4.7.1 Safety assessment methodology

The argumentation developed in the TR 11-01 report follows strictly the eleven steps of the safety assessment methodology developed by SKB. This methodology leans upon a long national experience and participation in several international working groups. The safety assessment is on par with the international state-of-the-art and is coherent with the guidelines established by OECD/NEA through

15. Download: www-pub.iaea.org/MTCD/publications/PDF/Pub1449_web.pdf, published 2011, superseeding WS-R-4 Geological Disposal of Radioactive Waste (2006).
16. Draft version from 2011-06-01, download: www ns.iaea.org/committees/files/CSS/1084/DS355.doc.
17. Download: www.oecd-nea.org/rwm/reports/2004/nea3679-closure.pdf.

long-lasting international cooperation. It makes use of the different tools developed and shared among countries working on safety cases of geological repositories: FEPs, safety functions, safety functions indicators, scenarios, stylised biosphere modelling, etc.

FEPs (features, events and processes)

The first step of the methodology is the FEP processing (TR 11-01 Chapter 3), in order to identify the features, events and processes that are to be included in the safety analysis. The FEPS database is a key input of the SKB safety case, and is thoroughly described in the FEP report TR-10-45. It completes the previous SR-CAN 97 FEP catalogue with components not treated in SR-CAN. Completeness was assessed by comparison/mapping with other national database and the international NEA database. The fact that this FEP database is available on the web is a strong element for transparency and traceability of the safety case. The links between FEPs and long term processes are clearly exposed.

Safety functions

The SKB safety strategy is based on two primary functions, containment and retardation. Containment is considered as the prominent safety function, which, in the view of the IRT, is justified in the KBS-3 concept. The methodology and safety demonstration takes this into account in a satisfactory way.

More differentiated safety functions are introduced in Chapter 8 of the TR-11-01 report. They are used to focus the assessment on important factors for long-term safety. These safety functions are defined on the basis of the link established between component properties and identified FEPs. In particular, the causes for the failure of canister, which constitute the main components to fulfil the containment objective, are a main driver to the definition of safety functions. As a consequence, there is a close link between the safety functions and the output of the FEP chart, which allows the identification of routes to the loss of containment/retardation. The fact that the FEP chart is only presented after the safety function definitions can thus be somewhat unsettling to the reader. Nevertheless, the IRT is of the opinion that this does not impair the methodology, given the fact that SKB conducted an iterative process to define the safety functions and the FEP chart, during the several safety evaluations of the KBS-3 concept already carried out by SKB. An alternative way to proceed would have been to define, before using the FEP chart, intermediate-level safety functions not directly linked with the nature of the components and the processes involved. For example, the intermediate-level safety function for the buffer would be to "provide favourable hydraulical, mechanical and chemical conditions to canister". A second step would then lead to the level of safety functions identified by SKB, on the basis of the analysis of the FEP chart. However, the IRT does not consider that this remark undermines the validity of SKB's approach to safety demonstration, but a better assessment of these intermediate-level safety functions could be of some use with respect to BAT; i.e., alternative ways of fulfilling a given safety function could be explored.

Scenario selection

On the basis of the previous step and the description of the reference evolution of the repository, SKB selects a small number of representative scenarios. The selection focuses on addressing the safety-relevant aspects as described by the safety functions (TR 11-01 Chapter 11). Safety function indicators are used by SKB for the purpose of evaluating the fulfillment of safety functions. The evaluation of the fulfillment of safety functions is the major input, together with the FEP database, for scenario selection. The selection of scenarios aims at covering all reasonable future evolutions, with regard to the concern that the safety functions, measured by their safety indicators, could be lost. For example, the three canister safety functions related to containment allow the identification of three distinct canister failure modes, i.e., corrosion, isostatic pressure and shear movement and, therefore, the generation of three scenarios associated with these safety functions.

This scenario selection methodology, based on safety functions is on par with the international state-of-the-art, i.e., it is described precisely and justified.

The IRT would like to underline that safety function indicators are a methodological tool, and are not a measure of the overall system performance. While it should certainly be a design goal to have high confidence that all components of the repository system contribute to minimising health risk and radionuclide release over the entire assessment period – as measured against SKB's self-imposed safety function indicators – it may not be absolutely necessary for every component in the repository system to maintain its safety function for the entire assessment period in order to comply with the regulations.

The IRT evaluation of the credibility of selected scenarios is given in Section 4.7.2. SKB is to be commended for also including in its assessment residual scenarios that SKB considers extremely unlikely (i.e., having a zero probability of occurrence), but that some members of the public have asked to be included. This is a clear example of SKB's interest in addressing public concerns.

Scenario analysis

Selected scenarios are analysed in TR 11-01 Chapter 12 for the containment potential and in Chapter 13 for the retardation potential. Besides the main scenario, possible routes to each other scenario are assessed, and conclusions are drawn either to rule the scenario out or to consider it as a less probable scenario or a residual scenario. Only less probable scenarios are included in risk summation. Relevant combinations of scenarios are considered. This analysis is clearly explained and described and appears to be sound. SKB concludes that two scenarios are to be evaluated: the canister failure due to corrosion, and the canister failure due to shear load. The IRT analysis of these scenarios is exposed in Sections 4.7.3 and 4.7.4 below.

Dose calculations

The evaluation of scenarios allows for the calculation of a dose and risk summation, and the conclusions whether the regulatory risk criterion is fulfilled. The risk dilution issue is addressed in a rigorous manner (TR-11-01, chapter 13.9.4): SKB explicitly considers the case of short term releases and calculates an "accumulated short-term risk", following the method suggested in Appendix 1 to SSMFS 2008:37. The result is below the risk limit.

Although the dose calculation based on the technical conclusions drawn from scenarios analyses is sound, the IRT submits the following comment on the presentation of the result: the risk summation curve presents pulse-like features and this is actually an artefact due to the small number of realisations leading to canister failure. Although this does not have any consequence for the demonstration of risk compliance, it is a weakness with respect to the clarity of the demonstration for two reasons:

- It is quite surprising for a curve representing a mean to present such pulses at some precise dates in the future. A reader may not understand why the situation in for instance 299 149 years from now has to be so different from the one in 310 000 years.
- The resulting curve will notably change if another Monte-Carlo simulation is conducted. This means that the detailed features of the curve are not stable if they are recalculated. This is not in favour of traceability of the demonstration.

The IRT recommends that, to remedy this, SKB refine the realisations of the probabilistic underlying models that control the dates of canister failure (DFN model, sulphide concentrations, see Section 4.7.4 below). This can be done for example by performing more realisations of the DFN models or using methods such as the importance sampling Monte Carlo method, that allows to carry out more realisations in the end tails of the probability distributions, where canister failures occur, than in the median zone, where realisations result in a zero contribution to dose.

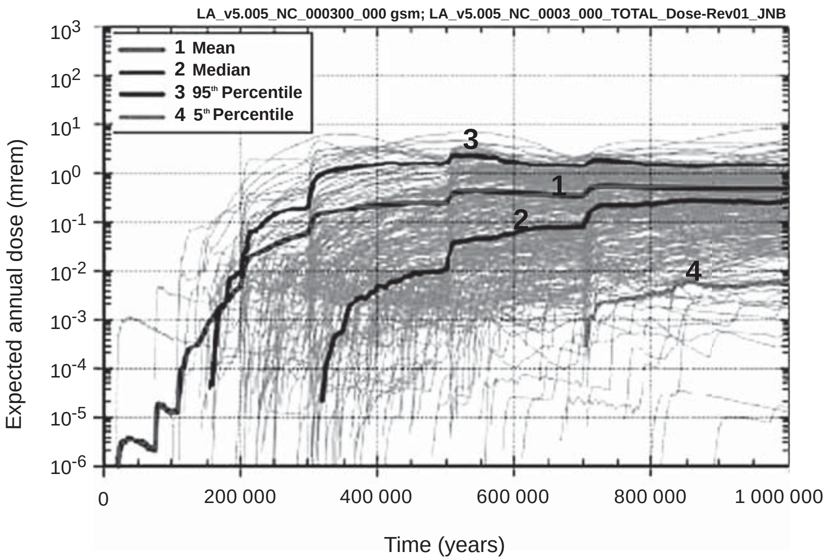
One possible approach to reporting the results of the SKB performance assessment would be the use of "horsetail" plots that shows the dose versus time estimate for every Monte Carlo realisation, along with summary statistics. An example of such a horsetail plot using 300 Monte Carlo realisations developed by the US Department of Energy for the Yucca Mountain site is provided in the figure below.

The safety assessment includes dose calculations to non-human biota, which is consistent with regard to best practices for performance assessments in countries for which there are national or regulatory requirements regarding protection of non-human biota.

Future human actions (FHA)

In accordance with SSM regulation, SKB assesses scenarios linked with future human actions. These scenarios are not included in the risk summation, according to SSM's General Guidance SSMFS 2008:37. The scenarios were selected on the basis of a systematic approach developed during the past fifteen years and described in SKB's report TR 10-53: "A technical analysis identifies human actions that may impact the safety functions of the repository". These actions are compared to the FEP database. A societal analysis identifies framework scenarios

TSPA-LA results for the nominal scenario
(excerpted from DOE/OCRWM, 2008; Yucca Mountain-License Application Ch. 2 Figure 2.4-22a)



to describe feasible societal context that can lead to such actions. On this basis, representative cases are quantitatively evaluated and reported in TR 11-01 (Chapter 14.2) as residual scenarios. The drilling scenario leads to significant dose, but, as SKB mentions, the assumptions underlying the calculation are quite pessimistic.

SKB does not draw any strong conclusion from this FHA scenario assessment. Nevertheless, the IRT considers it beneficial to:

- Assess the sensitivity of the result to the pessimistic assumptions made.
- Draw conclusions in the view of BAT that can reduce the risk, e.g., long-term memory, and the need for its development (see Section 4.9.2).

Stylised scenarios

Along with the selected scenarios on the basis of a systematic analysis of safety functions, SKB presents a number of hypothetical cases where different barriers are assumed to be completely lost. These scenarios do not represent any physical reality. If used cautiously, however, and with full understanding of their limitations, they can give an illustrative view of the respective contributions of each of the barriers to safety and provide a check for the robustness of the design. The IRT views SKB's use of stylised scenarios as a good practice to build confidence in the safety case, and as consistent with international practice.

4.7.2 Credibility of scenarios

SKB has developed a methodology for the selection of scenarios whereby a main scenario, closely related to the reference evolution of the system, is defined. Additional scenarios are then selected, based on the safety functions related to containment and retardation. These scenarios consider cases where the possibility and consequences of partially or completely losing one or several of the safety functions are evaluated.

For the buffer component, the IRT is of the opinion that this methodology has allowed SKB to come up with a list of additional scenarios which can be considered as credible and complete, in the sense that all physically conceivable different buffer evolutions leading to a potential "failed" state of the buffer have been taken into account and analysed thoroughly.

Out of the three additional buffer scenarios, only the buffer advection scenario qualifies as "less probable" (likelihood pessimistically set to one) while the buffer freezing and buffer transformed scenarios are rightly considered as "residual" and are logically not propagated to the consequence analysis in combination with canister scenarios.

Concerning buffer freezing, SKB states that freezing of water (affecting the buffer) at repository depth can be excluded, referring to the today's base of knowledge. Another argument states that surface denudation (affecting repository depth and subsequently the range of permafrost influence) is supposed to be very small during the assessment period. SKB describes the climate-related conditions used in the safety assessment and underlying assumptions comprehensively in the "Climate Report" (TR-10-49). During the review process, SKB pronounced its confidence in the planned repository depth and supported its viewpoint with a set of arguments. SKB has, therefore, demonstrated during the hearing in December 2011 that the repository depth is, i.e., the result of weighting different risk contributing effects, such as for instance climate influence, permafrost, fracture frequency, and rock permeability (all generally decreasing with depth) as well as construction risks and footprint (increasing with depth). Regardless of the high confidence SKB has expressed, sensitivity of the repository system against climate effects should nevertheless be subject to further observation and assessment with respect to the rising state of knowledge about potential water pathways and rock properties between the surface and repository depth that will be achieved during the coming project phases. Future safety assessments should therefore address this issue and provide updated information on whether the originally assumed favourable conditions are still valid. This would contribute to a high degree of confidence in the independence of the repository evolution from climate related effects.

For the canister component, SKB comes up with a list of additional scenarios on the basis of the physically conceivable different canister evolutions leading to a potential "failed" state of the canister identified by SKB. Three cases of failure are examined: canister failure due to corrosion, canister failure due to isostatic load and canister failure due to shear load. The first and the third one are considered as "less probable scenario" by SKB and the second one as "residual scenario". The IRT's opinion on these scenarios is expressed below.

Regarding the corrosion leading to canister failure, the IRT is concerned about the inconclusive nature of the experiments and models related to the relative importance of hydrogen as a copper corrosion mechanism. Given the potential impact on the ability of the copper canisters to perform their required safety function, the IRT also encourages SKB to proceed with their plans to settle this issue as soon as possible.

Regarding the isostatic load leading to canister failure, the assumptions for ice thickness during future glacial cycles are fundamental. However, the IRT's limited experience in glaciology and climatology has not allowed a thorough assessment of the validity of the maximum ice thickness at Forsmark. The value that enters into the isostatic load scenarios is 3,670 meters (which is large compared to, for instance, isostatic load from ice in the Alps). In addition to the (maximum) water pressure related to this ice load (26 MPa), a phreatic water pressure of 4.5 MPa (a column of water reaching to land surface) is added, plus a bentonite swelling pressure of 13 MPa. This swelling pressure equals the vertical stress level at repository depth (which is assumed to be the minimal principal stress). The conceptualisation of maximum hydrostatic load is correct, while the assumed magnitudes seem to be conservative. Furthermore, the combination of the high assumed magnitudes of the hydrostatic load and SKB's design of the canister insert, along with the load testing of the insert showing considerable margin in the structural capacity of the insert to withstand the assumed maximum hydrostatic load, leads to the conclusion that canister collapse is highly unlikely.

Regarding the shear load leading to canister failure, the IRT can also support the selection of scenarios. Fault reactivation from pore pressure drawdown induced by the repository excavations will most probably not lead to critical fault reactivations. However, SKB's assessment of the most critical earthquake-triggered shear failure scenario (seismic slip > 5 cm) is very complex, and based on a large number of assumptions, some of which are recalled in Section 4.1.4 of this report. The IRT, even though not staffed with a seismologist, suggests that additional paleo-seismological and near-field investigations be performed to further constrain the probability and magnitude of long term canister shear failure scenarios.

4.7.3 Corrosion failure

The analysis of the corrosion failure scenario highlights the main factors of uncertainty in this scenario: uncertainty related to the DFN model; uncertainty related to the sulphide concentration; and uncertainty in the importance of the copper-hydrogen-water interaction.

The data related to these site characteristics is scarce, due to the lack of field data at the depth of the repository. This is of course an unavoidable consequence of a safety assessment conducted before the construction of the repository. Also, the data and evidence for the relative importance of hydrogen-assisted copper corrosion seems somewhat inconclusive. However, in the view of IRT, this raises two remarks:

Statistical treatment of uncertainties: Several alternative DFN models are presented and assessed in SR-Site. The selection of the correlation between fracture size and transmissivity on one hand and the chosen realisation of the model on the other hand, have a strong impact on the number of advective positions, on the number of failed canisters and on the migration of released radionuclides. In order to capture this variability, SKB builds its assessment on several realisations of the DFN models (10 realisations for the semi-correlated model, 5 realisations for the fully correlated model and for the non-correlated model), as it is documented in report TR-10-66 and confirmed by SKB during the hearings. SKB considers that this statistical treatment is sufficient to build confidence in the calculated mean number of failed canisters. Given the pessimistic assumptions adopted by SKB, the order of magnitude used for the risk summation seems convincing to the IRT, and hence also the fulfillment of the risk criterion. However, the IRT still considers that the number of realisations is rather low with regard to the criticality of the issue of the hydrogeological model. Moreover, SKB does not justify clearly enough that the variability captured in these realisations corresponds to a rigorous confidence interval (although some elements of justification were transmitted by SKB after the hearings in the document 1323497). It would for example have been of interest to expose a calculation case with a pessimistic realisation of the DFN-model, in order to show the sensitivity of risk to the effective hydrogeological conditions.

Regarding the sulphide concentration, as stated by SKB, it is a key factor to corrosion, and, in calculation cases, canister failure occurs only if the randomly sampled sulphide concentration is in the upper tail of the distribution. For most of the DFN models, only the extreme value of the discrete sulphide concentration ($1.2.10^{-4}$ M) leads to a canister failure. Thus this end tail of the distribution is the interesting part of the distribution for the risk calculation, although its description is very rough, and is represented by only one data point. To overcome this uncertainty, SKB presents a sensitivity analysis in which a case is evaluated where a point is added to the sulphide concentration distribution, with twice the highest concentration ($2.4.10^{-4}$ M). The effect on canister failure is significant: the mean number of failed canister (in the semi-correlated DFN model) almost doubles (from 0.12 to 0.21). However, it is not justified that this sensitivity analysis captures completely the uncertainty. A statistical analysis of the confidence that can be put in the sulphide distribution would permit to confirm this point. However, IRT recognises that it is likely that the distribution used in SKB's calculations is a pessimistic one.

Detailed investigations to be conducted: Acquisition of site data to lower uncertainty on hydrogeological conditions and hydrogeochemistry is planned by SKB. It is strongly recommended that, as soon as the uncertainties are reduced from this data acquisition, SKB will reassess the central corrosion scenario and its risk contribution, which could vary in a non-negligible range. Given the pessimistic assumptions taken by SKB in the safety case, this should lead to a reduction of the calculated risk, and thus should not jeopardise the risk compliance.

4.7.4 Shear failure

The assessment of the number of canisters expected to fail by earthquake-triggered shear dislocation along fractures intersection deposition holes was carried out by SKB through a detailed and complex process. Many inputs of this assessment have a large uncertainty, which was often translated into conservative assumptions. In general south-east Sweden is relatively inactive today, typical for a stable shield area, with approximately one magnitude 5 earthquake every 100 years, a magnitude 6 every one thousand years, and a magnitude 7 every 10 000 years. These recurrence periods refer to a large region (650 km radius) around Forsmark. However, seismicity is episodic in nature and there are arguments for increased earthquake activity with magnitudes of about 8 at late stages of deglaciation. The observation periods used in the determination of frequency-magnitude relationships are very short (100-1000 years) in comparison to the duration of the safety assessment. Therefore, SKB systematically discussed the uncertainties of long-term frequency relationships and included paleoseismic frequency indicators as derived from glacially-induced faulting. The IRT submits that the knowledge about long-term seismicity at Forsmark is far from complete and should be complemented by additional paleoseismic investigations.

4.7.5 Factors governing the total system performance assessment

As discussed earlier, the radioactive species that comprise the spent fuel to be disposed of at Forsmark are of the following three major types:

- Fission products: these are the radionuclides generated when the fissile U-235, Pu-239 and Pu-241 atoms split during the fission reactions. Many of these fission products undergo further decay into other radioisotopes, with each decay releasing more radiation in the form of alpha particles, beta particles, neutrons, and x- and gamma-rays.
- Actinides: some heavy isotopes absorb neutrons and convert to even heavier forms, such as uranium, plutonium, and curium – all of which are radioactive.
- Activation products: these are caused by the absorption of neutrons from lighter weight elements found in assembly hardware and cladding. The most important activation product in terms of radiation is Co-60 caused by the activation of nickel found primarily in assembly hardware.

The relative radioactivity of a particular radionuclide is dependent on:

- The relative abundance of the radionuclide in the waste.
- The "half-life", or the amount of time it takes for half of the radionuclide to decay away.
- The type of radioactivity decay that occurs, include how much energy is released.

For a particular radionuclide to contribute significantly to the overall dose assessment, the radionuclide must have the following properties:

- Is of sufficient abundance in the spent fuel.
- Has a relatively high solubility in groundwater.
- Has a relatively short travel time through the rock fractures to the biosphere. This is dependent on the sorption characteristics of the radionuclide onto the rock.

- Has a relatively high LDF.
- Will be able to escape from the repository before it decays significantly. This is dependent upon:
  - The location of the radionuclide in the spent fuel. Since the spent fuel dissolution rate is slow, the shorter-lived radionuclides must also be found in locations of the spent fuel where it can be dissolved more quickly than the bulk of the spent fuel, such as in the fuel/cladding gap or along fuel particle grain boundaries.
  - The half-life of the radionuclide.
    - If it is relatively short, the radionuclide may only provide a significant contribution to dose at earlier times. Even then, it can only contribute to dose at earlier times if the buffer and canister have *both* failed at earlier times, the radionuclide is able to escape from the spent fuel quickly, and the geology does not provide much retention of the radionuclide as it travels to the biosphere.
    - If the half-life is longer, then it could contribute at times all the way out to one million years. There are some radionuclides with half-lives in excess of one million years.

The vast majority of the radionuclides in the waste to be disposed of in a geologic repository will have decayed away well before they even have a chance to escape from the waste container after the container fails. Once the waste container fails, the cladding must also fail before the fuel is exposed to groundwater. Then the fuel must dissolve in the groundwater, pass by the clay buffer and through the rock fractures before the remaining radionuclides can enter the biosphere. Thus, with the exception of cases where both the buffer and canister fail at early times, the doses to humans from radioactive waste in deep geologic disposal will be from very long half-life, soluble, and mobile radionuclides in the waste.

4.7.6 Evaluation of the total system performance assessment results

The IRT has reviewed the performance assessment results presented in TR-11-01, including the sensitivity studies, and choice of fixed and uncertain variables included in the probabilistic performance assessment. The primary conclusions from the total system performance assessment (TSPA) are:

- For the reference scenario, the mean number of deposition holes for which the buffer would lose its function (due to advective conditions leading to buffer erosion) is 23 out of 6000 in one million years, or 0.4%.

- For the reference scenario, even assuming 100% of the deposition holes suffered advective conditions from the very start, the mean number of canister failures is 0.17 out of 6000, or 0.003%.[18]
- The peak dose to an individual in the most exposed group for the canister failure due to corrosion scenario is:
  - negligible for times up to approximately 50 000 to 100 000 years after repository closure;
  - about two orders of magnitude below the regulatory limit at 100 000 years[19]; and
  - about one order of magnitude below the regulatory limit at 1 000 000 years.[20]
- The peak dose to an individual in the most exposed group for *the canister failure due to shear scenario* is:
  - about three orders of magnitude below the regulatory limit at 1 000 to 10 000 years after repository closure; and
  - about two orders of magnitude below the regulatory limit at 1 000 000 years.
- The single radionuclide contributing the most to the dose estimate is Ra-226, except for the dose estimates for the canister shear failure scenario at times prior to about 50 000 years for which C-14 and Nb-94 dominate the dose estimate.

With the exception of the relevant issues affecting overall repository performance discussed earlier in this report, and those identified by SKB itself, the IRT finds SKB's approach to estimating repository to be "conservative" – meaning SKB is likely to have overestimated the number of buffer failures, the number of canister failures, and the assessed dose rates to a human in the most exposed group. Many of the properties of the geology and repository design are uncertain over the long time periods required for SKB to conduct an assessment. For many of

18. The buffer and canister failure rates are the means of a probabilistic distribution in which the number of failures is calculated for many different input values. Each, single calculation using a set of input values sampled from a distribution is called a "realisation". For the canister mean failures, the number is less than one because many of the results from individual realisations had zero canister failures in one million years while a few of the realisations resulted in estimates of one or more canister failures in one million years. Averaging over all realisations results in the mean value of 0.17 canister failures. The same process was used to derive the mean number of buffer failures of 23 in one million years.
19. Note that the IRT is in no way providing an assessment of whether or not SKB has complied with the regulations. That assessment is the responsibility of SSM and other national organisations, and involves much more than a simple comparison of the calculated dose rates against the regulatory criterion.
20. The IRT is aware that the dose or health risk criterion in the SSM regulations does not apply out to one million years.

these properties – but not all – SKB has assumed "bounding" property values, i.e., those property values that would maximise the estimated number of buffer and/or canister failures. While the goal is to characterise the uncertainties well enough to be able to use a reasonable distribution of geology and repository properties, it is standard international practice to use bounding, or near-bounding properties when the actual distribution or uncertainty range of geology and repository properties are not known. *This does not mean the IRT is certain SKB has overestimated the buffer and canister failure rates or the dose rates to humans*. Both the IRT and, more importantly, SKB itself recognise more work need to be done to improve confidence of the repository system performance.

A few examples of properties for which the uncertainty *should* be reduced are:

- Canister properties at the time of production – particularly the reliability of both the welding process and the ability to detect welding flaws of sufficient size to jeopardise the ability of the canister to provide its required safety function. The IRT understands that at the time the TR-11-01 report was produced, testing of only eight tubes and 20 lids formed the basis for SKB's estimates of container failures. IRT recommends and SKB is already planning to increase the number of tests of these canister components.
- Similarly, the buffer initial density distribution estimate SKB uses is based on just 25 blocks (10 ring-shaped, and 15 solid). Yet Table 5-12 in TR-11-01 provides buffer densities out to the 99.9% confidence interval.

Regarding the radionuclides that dominate estimated doses, the IRT finds the dominant radionuclides sensible. For the cases in which SKB determines both the buffer and canister fail at shorter times, both C-14 and Nb-94 have higher LDFs, are in sufficient abundance, are soluble, are present in the fuel gaps and/or between fuel grains, and are not well sorbed onto rock surfaces. Their half-lives, however, are not long enough to contribute to dose estimates at very long times.

The IRT also finds that Ra-226 contributes to long-term dose estimates reasonable. There are, however, other long-lived radionuclides that could contribute to long-term dose rate estimates. The IRT is not fully convinced that the dominance of Ra-226 is "real" in the sense that the SKB dose estimates, which are based on many assumptions about radionuclide solubilities, travel times, and LDFs, may be dependent on the particular choice of SKB's assumptions. SKB did provide a response to the IRT's question about this particular issue, however (SKB document 1334122), although the response does not fully put to rest IRT's concerns.

4.8 Performance confirmation

4.8.1 Specific points

SKB rests its safety case on locating a repository in a geologic environment that provides long-term stability. SKB chose materials that it expects will perform as durable barriers in that stable environment and has gathered information over decades of research to support its conclusions. SKB's assertion that its chosen site at Ősthammar provides this favourable combination of both natural and engineered safety also rests on multiple years of surface-based testing leading to what SKB describes as a "mature model" of the site. The detailed specification of the engineered parts of the proposed repository and SKB's demonstration of how it will produce the engineered components in a quality assured manner, result in what SKB asserts will be a quality- assured initial state. SKB has been able to identify no new detrimental processes in recent years of surface testing. Thus, SKB infers that its derived set of safety function indicators are reasonably comprehensive and mature. SKB's demonstration of long-term safety thus far has necessarily relied on the use of complex predictive models that are supported by limited data from field and laboratory tests, site-specific monitoring, and natural analog studies. For these reasons the IRT feels it is especially important that SKB approach construction fully prepared to seek out and evaluate relevant data at depth to test and confirm, to the extent feasible, its safety-related assumptions.

During construction and trial operation, SKB must be prepared to actively look for and evaluate any significant changes from those conditions and features relied upon or assumed in its safety assessment, if such deviations could reduce post closure safety. Suitable preparation should include a well-thought-out and well-documented programme of performance confirmation. Such preparation will enable SKB to corroborate fundamental key assumptions and models that support projections of long-term safe repository performance. Key geotechnical and design parameters, including interactions between natural and engineered systems and components should be monitored during construction and emplacement to indentify significant changes in the conditions assumed in the safety assessment.

The focus of this confirmation programme should be on subsurface conditions and their effects on natural and engineered systems that SKB designs or relies on to act as barriers after permanent closure. The performance confirmation programme should be distinct from other monitoring and testing performed in other contexts (*for example,* to "study how repository construction and operation affects the environment" [p. 205, Sec. 5.8.2, SR-Site] or to "consider material deliveries, workmanship and control of the as built and operated facility relative to the design and specification of operational activities." [SKB reply to IRT Q2.6.2].

The IRT understands that SKB has stated that "[t]hese observations <u>may</u> also provide important data for the hydrogeological and hydrochemical modelling and verification of such models… [emphasis added]" [p. 205, Sec.5.8.2, SR-Site]. The IRT is of the opinion that data collected at depth during construction, operation and emplacement are essential for corroborating the applicant's safety case assumptions. Confidence of both the regulator and the public depend on their faith that SKB has anticipated, is adequately prepared for, and is open to collecting new safety information at depth. SKB should evince its commitment to obtaining new data, even if such data could contradict pre-existing models and many years of work and surface-based testing.

SKB should elaborate its plans for a comprehensive programme of testing and monitoring such that SKB will be able to confirm that the proposed repository will work as planned. These plans should also demonstrate that, in a broader sense, SKB is capable and ready to cope with unexpected findings at depth, in the unlikely event that they arise.

Documentation of such a programme should accompany the safety case. This programme should be ready and in place before the start of construction. An adequate programme of performance confirmation would provide data to show whether: (i) actual subsurface conditions encountered and any changes in those conditions during construction and waste emplacement are within limits assumed in the licensing review; (ii) natural and engineered systems and components that are designed or assumed to act as barriers after permanent closure are functioning as intended and expected. This programme would include *in situ* monitoring, laboratory and field testing, and *in situ* experiments, as appropriate. Such a programme, which may have begun during site characterisation, would continue until permanent closure.

To demonstrate adequate preparation in advance, the IRT therefore recommends that SKB should describe in detail a performance confirmation programme that includes:

1. An acceptable continuing programme of measuring, testing, and geologic mapping, during repository construction and operation to confirm geotechnical and design parameters (including natural processes) pertaining to the geological setting.
2. An acceptable programme to monitor or test natural systems and components that are designed or assumed to act as barriers after permanent closure to ensure they are functioning as intended or expected.
3. An acceptable surveillance programme to monitor and evaluate subsurface conditions against design assumptions, to compare measured values with original design bases and assumptions, assess any significance for health and safety, and determine the need for any changes.

In sum, a sound safety case must include a solid basis for confidence the applicant has adequately prepared to collect, adapt and respond to new information that may challenge preconstruction modelling assumptions and designs.

4.8.2 Optimisation and best available technique (BAT)

Part of the regulatory requirements is that SKB must provide an assessment of whether it used the "best available technique" (BAT, General Guidance to SSMFS 2008:37) in selecting and designing the repository. This is to be done in conjunction with an "optimisation" assessment. Optimisation is to be evaluated on the basis of calculated risks. BAT means that: "The siting, design, construction, operation and closure of the repository and appurtenant system components should be carried out so as to prevent, limit and delay releases from both engineered and geological barriers as far as is reasonably possible." SSM advices that BAT be given precedence over optimisation whenever the two may be in conflict. This would also include cases where the uncertainty in calculated risks is high. Specifically, SSMFS 2008:21 states that: "The use of the best available technique means that the technology, from a technical and economic standpoint, shall be industrially feasible for application within this area. This means that the technique must be available and not merely at the experimental stage."

Optimisation allows SKB to evaluate whether trade-offs between the repository design and the calculated risks are balanced appropriately upon using best available technology. For example, SKB may consider making changes to the repository design to lower risks, such as moving the repository level even deeper, or constructing an even thicker copper canister or thicker buffer, provided the technologies are available, e.g., for welding the canister appropriately. Optimisation allows SKB the option of *not* lowering the calculated risk if the effort to modify the repository design is large and the risk reduction is small. BAT, on the other hand, does not always allow SKB this option; where optimisation and BAT are in conflict, SKB *must* improve its design to limit and delay releases from both engineered and geological barriers as far as is reasonably possible as long as the technology is industrially feasible from a technical and economic standpoint.

SKB summarises its BAT evaluation of design options in Section 14.3 of TR-11-01. General design options SKB considered are:

- *Repository depth*. A shallower depth would place the repository in an area with a greater number of fractures, whereas an even deeper repository would be more difficult to construct, and would not reduce the fracture density significantly.
- *Buffer and backfill properties*. This option pertains to buffer type, buffer thickness, and buffer and backfill initial density. In the case of increasing the buffer thickness around the canister, a negative consequence that needed to be considered was the increase in temperature at the buffer/canister interface due to the lower thermal conductivity of the buffer relative to the surrounding rock.
- *Canister thickness*. This pertains to a factor of two thinner and a factor of two thicker were considered. A factor of two thinner only increases the mean number of canister failures, which is already small, by less than a factor of two. Increasing the canister thickness does decrease the mean number of canister failures, but the number is already small.
- *Deposition hole acceptance criteria*. Tighter acceptance criteria would lead to a slightly lower buffer and canister failure rate, but could result in there not being enough acceptable canister locations to dispose of the required inventory. Looser acceptance criteria would increase the number of canister failures, which SKB considered unacceptable.
- *Deposition tunnel acceptance criteria*. The current criteria allow a small excavation damage zone (EDZ) around the tunnels. SKB determined that the EDZ currently allowed was reasonable from the standpoint of currently available industrial technology, and even a somewhat larger EDZ would not increase the assessed dose significantly. SKB concluded that the proposed technology is BAT.
- *Reduce the potential for canister shear failure* by some combination of increasing the canister insert strength, increasing the copper shell strength, tightening the borehole rejection criteria, or altering the buffer density. SKB argues that the mechanical properties of the canister and the buffer are

already optimised or BAT, and tightening of the borehole rejection criteria was already considered. SKB concludes that its approach to minimising canister shear failure is BAT.

The IRT finds SKB's analysis of design options to be reasonable and informative. The IRT notes as well that SKB could have added other aspects to their BAT analysis. For instance, the evolution of the canister design from the early 80's until today; the large effort SKB is applying now to automatising both the welding process and the emplacement of bentonite blocks; etc. The IRT did not look at all these aspects comprehensively. To the extent that optimisation and BAT analyses are very much informed by the specific Swedish regulations and that optimisation and BAT are not in the remit of the review, the IRT did not form an opinion on these aspects in depth.

The IRT makes, however, the following observations that may be of interest. Namely, (a) internationally, optimisation and BAT are not commonly-understood practice for geological repositories. For instance, the USNRC regulations and those of STUK do not mention optimisation; (b) depending on how optimisation and BAT are interpreted, it may be seen that the way SSM regulations are written does not allow SKB to "fully" optimise. In this sense, the IRT understands, and is sympathetic to, the SKB's conclusion that SKB could only use additional techniques to lower the dose, and hence, was not able to "optimise"; (c) given that SKB has made conservative assumptions throughout the repository design development process, the IRT suspects that the repository may be "overdesigned", meaning SKB has made already design improvements that go in the direction of reducing dose below the regulatory constraints and in the direction of BAT, i.e., of giving additional confidence about the repository performance; (d) in any event, optimisation should be looked at as a forward-looking process of questioning of the current work and improvement of the design that will end with the final closure license of the repository, and is important that review points such as this by the IRT are foreseen in the Swedish repository development process.

4.9 Societal aspects

The IRT review of societal aspects is based on SKB reports (TR 11-01), SKB responses to IRT questions, and SKB presentations provided during IRT site visits on December 14, 2011).

4.9.1 Public outreach, input and consent

In accordance with the Swedish Environmental Code, SKB has consulted extensively with the public and municipal representatives since 2003. These consultations are well documented in several reports which are available on SKB's website. A final consultation report summarising their outcomes was prepared for the Environmental Impact Statement that accompanies the application to build a final repository for spent fuel. With these consultations, SKB fulfills the Swedish legal requirements for public involvement. Additional international consultations have been organised in accord with the Espoo Convention.

Also, SKB informs the public via its website, print media and directly at the Forsmark site. The IRT acknowledges that SKB has made available extensive documentation supporting its application to build a final repository, publishing it on its website for public download. This affords broad access for all to study and assess safety and environmental-related information according to one's own special interests. It is positively noted that this approach fosters transparency and open discussion.

On its website, SKB clearly explains how it based its choice of the Forsmark site on reasons of long-term safety. In explaining its choice of site, SKB cites a comprehensive discussion of its comparison of the Forsmark site with the Laxemar site in Oskarshamn during which SKB also examined factors of environmental, health and social impacts. The IRT is of the opinion that consideration of social aspects is a fundamental part of a repository project. In the view of the IRT, SKB has shown a consideration of social impacts that is consistent with the state of the art and international recommendations. In both communities, SKB succeeded in obtaining meaningful public awareness and local engagement in the decision about the project, thereby earning sufficient trust of the public for going forward with the project thus far. This suggests many years spent building relationships of trust, which takes time, dedication, and sensitivity to how a radioactive waste management facility will affect local needs and community aspirations.

The IRT is of the opinion that SKB has shown itself to be a world leader in its attention to community involvement in the decision-making process around siting and running nuclear waste management facilities. Preserving that awareness and engagement will be essential for a successful realisation of the project. SKB must therefore keep affected communities, as well as national stakeholders, involved as it moves forward with repository licensing and development. SKB's participation in the NEA/FSC international workshop of the NEA – at Gimo, in May 2011, indicates that SKB is aware of, and proactive on, these challenges.

The IRT encourages SKB to continue to build on its strengths in this area. The IRT encourages SKB to further develop and practice appropriate techniques for involving stakeholders at all future stages of the project. SKB should strive not only to maintain its excellent record of public involvement at the local level, but also to expand stakeholder awareness and engagement at the regional and national levels. The IRT recognises that the success of SKB's effort and the success of all such projects will depend on more than technical excellence alone. If construction of a repository at Forsmark is authorised, it will be important that SKB keep all stakeholders, and especially the local community, informed regularly of SKB's performance confirmation activities and provide the results of underground studies as they become available. This will bolster public confidence that SKB is vigilant in its efforts to ensure that any new information obtained underground continues to corroborate SKB's original repository assumptions and designs. If new information emerges that departs from prior assumptions, it is, likewise, essential that SKB explain the impact of such data on the safety of the project.

In addition to providing information, SKB may also consider offering even greater participation to stakeholders, affording them, for example, more opportunities to comment, discuss and cooperate in decision making as the project progresses. IRT recommends an accompanying evaluation of the participation process to document the results of public participation and the adjustments SKB has made to the project as a consequence of that participation.

4.9.2 Continuity of knowledge

In its application SKB raises the issue of preservation of knowledge for future generations. According to SKB "information on the repository must be preserved for the future so that future generations can make well founded decisions and avoid inadvertent intrusion in the final repository." SKB explains in its application that it will prepare an action plan for long-term preservation of information in international cooperation. The IRT welcomes SKB`s activities in accord with the announced action plan and regards the continuity of knowledge to be essential to the realisation of final disposal of radioactive waste. The IRT notes positively that SKB is one of the funding participants in the NEA international project on Records, Knowledge and Memory Preservation Across Generations.

A sound safety case should not only include technical arguments supporting safety, but should also pay attention to socio-political, organisational and management aspects which might affect the safety of a repository. For example, SKB should be able to demonstrate how it will assure that competent personal and financial resources and the knowledge about the facility remain available until the repository is properly closed.

The placement of records in the archives and land records system of local, regional and national agencies as well as in any archives elsewhere in the world that would reasonably be consulted by potential intruders is an important issue. Relevant records should include data collected about the site and repository during construction, performance confirmation, operation and closure as well as information on the nature and amounts of waste disposed. Crucial information should be identified and designated to be preserved as long as possible, without implying that there is a deadline beyond which it is no longer relevant.

However, IRT points out that continuity of knowledge implies more than preservation of information via record keeping systems. Important, as well, is the transfer of knowledge and skills necessary as practiced by the repository operator, supervisory authority and the community in charge of the repository site.

The conservation and transfer of knowledge within the repository operator and supervisory authority, especially during the pre-closure and the early post closure phase of the repository, is crucial because of the well known problem of ageing staff in the nuclear field. SKB needs to address how it will ensure that competent personnel will remain available until the release of the closed repository from institutional control.

Compare ***IAEA Draft 355****: "6.13. The safety case should contain updated information about the management system with emphasis on the following:*

- *The organisational structures and procedures that are in place to ensure good management of the safety assessment work and good quality control for data acquisition, especially site data;*
- *The overall planning of activities, in particular plans for involvement of the regulatory body and other interested parties;*
- *Implementation of the record keeping system, which should cover both site data and the safety case and supporting safety assessment;*

- *Appropriate allocation of resources to continue with the subsequent steps of the project.*
- *It must also be shown that there is an appropriate allocation of resources to continue with the following step of the project."*

The question of retaining knowledge in the community over generations touches questions of integration of the repository in the community as well as marking the repository site in such a way as to keep its memory a part of the community culture.

If the SKB obtains approval to start construction, the IRT encourages SKB to do all it can to build on the constructive relationship it has built with the local community to preserve local and regional knowledge about the repository and its significance. Essential to a sustainable relationship between the host community and a safe repository will be the ability of future citizens to retain knowledge about the repository over the long term. Knowledge must be preserved and transmitted to future generations about the repository's history, its significance, its contents and the importance of keeping it secure from inadvertent intrusion that could breach its engineered and natural barrier system. Among the mechanisms SKB could consider are:

1. Identification of the site by monuments or markers that are designed, fabricated and emplaced to be as permanent as practicable.
2. Placement of records in the archives and land records system of local, regional and national agencies as well as in any archives elsewhere in the world that would reasonably be consulted by potential intruders.
3. Inclusion of relevant records collected about the site and repository during construction, performance confirmation, operation and closure as well as information on the nature and amounts of waste disposed.
4. Creation of reservoirs of knowledge, namely centres of interest of past activity at the repository, so that people can continue to understand and interpret the records and markers. In the same vein, SKB could consider creating cultural links – a sense of heritage – between the repository and the host community region.

Appendix to Chapter 4

Excerpts regarding QA from the cited international recommendations and guidelines (underlining done by author)

IAEA[21] Safety Requirements No.SSR-5: Disposal of Radioactive Waste (2011)

4.6. The development of a safety case and supporting safety assessment for review by the regulatory body and interested parties is central to the development, operation and closure of a disposal facility for radioactive waste. The safety case substantiates the safety of the disposal facility and contributes to confidence in its safety. The safety case is an essential input to all important decisions concerning the disposal facility. It has to provide the basis for understanding the disposal system and how it will behave over time. It has to address site aspects and engineering aspects, providing the logic and rationale for the design, and has to be supported by safety assessment. It also has to address the management system put in place to ensure quality for all aspects important to safety.

IAEA[22] Draft Safety Standard DS 355: The Safety Case and Safety Assessment for Disposal of Radioactive Waste (Draft status: 06/2011)

2.4. As national programmes for the development of radioactive waste disposal have developed, considerable effort has been put into developing systematic and internationally recognized approaches for demonstrating the safety of disposal facilities and for preparing safety cases for specific facilities. The safety case is defined as "the collection of arguments and evidence to demonstrate the safety of a facility" [2]. The demonstration of an acceptable level of safety of a disposal facility depends on the arguments in the safety case about the characteristics of the site and the facility engineering (e.g. the system of engineered barriers), the results of safety assessment and the management arrangements for ensuring quality in all aspects of safety related work."

4.60. […] "Management systems to provide for the assurance of quality shall be applied to all safety related activities, systems and components throughout all steps of the development and operation of a disposal facility." […]Application of a suitable management system will contribute to confidence in the safety case and an assessment should be carried out as to the adequacy of the management system governing all safety related work including provision of the necessary financial and human resources.

21. Download: www-pub.iaea.org/MTCD/publications/PDF/Pub1449_web.pdf, published 2011, superseeding WS-R-4 Geological Disposal of Radioactive Waste (2006).
22. Draft version from 2011-06-01, download: www-ns.iaea.org/committees/files/CSS/1084/DS355.doc.

4.97. Confidence in the safety case will be reduced if it is perceived not to have addressed relevant issues. Completeness is one of the first things that regulatory body is likely to consider in its review of the safety case […]. Other interested parties may also wish to verify that issues important to them have been addressed. It is advisable, therefore, to use various methods to demonstrate that the safety case addresses all relevant issues, including the relevant uncertainties. The range of issues to be addressed will depend on the stage of development of the disposal facility and may derive from several sources, including legislation, regulations and concerns of interested parties. Methods for demonstrating completeness may, therefore, include well-structured cross references or mappings that provide a link from these sources to the safety case.

OECD/NEA[23]: Post-closure Safety Case for Geological Repositories – Nature and Purpose (2004)

"4.1. Components of assessment basis

The assessment basis is the collection of information and analysis tools for safety assessment and includes:

- *The system concept, which is the description of the disposal system, its components and their safety functions and, depending on the stage of planning and development, the construction, operation, monitoring and control procedures in as far as they impact on the feasibility of implementation and post closure safety, as well as quality management procedures to assure that the specification of the engineered features are met.*
- *…*
- *The quality and reliability of a safety assessment is contingent on the quality and reliability of the assessment basis. A discussion of the assessment basis and the presentation of evidence and arguments to support the quality and reliability of its components is thus a key component of the presentation of a safety case."*
- *"…It must be shown that the system considered in the safety assessment is one that can be realized in practice. The description should thus also include:*
- *site characterization procedures that have or will be carried out to support the properties of the geological environment assumed in the safety assessment;*
- *any quality management procedures and waste acceptance criteria to ensure that the specifications of the engineered features, including the waste form* itself are *met; and*
- *An evaluation of feasibility of actually implementing (constructing, operating and closing) the facility at the selected site."*

23. Download: www.oecd-nea.org/rwm/reports/2004/nea3679-closure.pdf.

Annex 1

Members of the International Review Team and Observer

Michael, Sailer – Chairman

Graduate (Dipl.-Ing.) in chemical engineering (Technical University of Darmstadt, Germany, 1982).

He has more than 30 years of experience in the field of nuclear energy, most notably regarding the safety of nuclear power plants and other nuclear installations, the storage of nuclear waste and the final disposal of radioactive waste. He is currently CEO of Oeko-Institut. Previously he was head of Oeko-Institut's Nuclear Engineering and Facility Safety Division.

Oeko-Institut e.V. (Institute for Applied Ecology) is an independent scientific research institute with some 145 staff; it was founded in 1977 and is a non-profit association. It gives scientific advice to governmental and non-governmental organisations. Major fields of its national and international work are:

- Nuclear safety and waste management.
- Energy and climate issues.
- Sustainability regarding products and resources.
- Governance and public participation.

He is chairman of the Nuclear Waste Management Commission (ESK), which advises the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Recent work includes the development of safety guidelines for final disposal facilities and proposals for a new finding process for a final disposal site. He was a member of AkEnd (Arbeitskreis Auswahlverfahren Endlagerstandorte, Committee on a Site Selection Procedure for Repository Sites). He regularly participates in international meetings regarding the safety issues of final disposal.

Pescatore, Claudio – NEA Convenor

MS and PhD in Nuclear Engineering (University of Illinois at Urbana-Champaign) and a Laurea *cum laude* in Applied Physics (University of Bologna, Italy).

He has over 30 years experience in the field of radioactive waste management. He is presently Principal Administrator in charge of the programmes of the Nuclear Energy Agency (NEA) of the OECD in the fields of decommissioning and radioactive waste management. Previously, he has been staff scientist and group leader for repository performance assessment at Brookhaven National Laboratory and adjunct professor of Marine Environmental Sciences at the University of New York at Stony Brook.

The OECD/NEA plays a lead role in helping the governments of the most industrialised countries and their specialists gain a shared understanding of the state of the art in radioactive waste management and decommissioning, and moving these fields forward.

At the international level Dr. Pescatore is well known for his role in the elaboration of the modern concept of a safety case for disposal, for launching and developing the NEA programmes on stakeholder confidence, and for helping open the field of regulation to wider discussion and review. He has organised 13 international peer reviews of national safety studies for disposal, four of which in Sweden. Overall, he is helping shape the profile of the modern waste management profession.

Claudio Pescatore regularly represents the Nuclear Energy Agency at national and international events and joint initiatives with other international institutions. He is a member of the ICRP task group charged with developing updated international guidance on the application of the ICRP concepts and principles to geological disposal as well as a member of the Standing Group of Experts that advise the French Nuclear Safety Authority in the field of waste disposal.

Boissier, Fabrice

Postgraduate degree in mathematics and in economics (*Paris École Normale Supérieure*, France), and graduate engineer (Paris School of Mines, France).

He is presently Director of the Risk Management Division in the French National Radioactive Waste Management Agency (Andra). In this position, he is mainly responsible for the safety of Andra's waste repositories, existing or in project. Throughout his career, Mr Boissier has always been highly involved in issues concerning environment, safety, mining activity and energy. From 2006 to 2009, he was director of the geothermal energy department in BRGM, France's leading public institution in the field of Earth Science. Before that, he was deputy head of the Languedoc Roussillon Regional Authority for Industry, Research and Environment.

Andra is an independent public body in charge of the long-term management of radioactive waste in France, under the supervision of the Ministries in charge of Energy, Ecology, and Research. It benefits from 40 years' experience in the management of radioactive waste. Andra is notably in charge of designing a reversible deep geological disposal for long lived waste and is to submit the licence application for this disposal in 2015. Within his position, Mr Boissier is more particularly in charge of the preparation of the safety case for this licence application.

At the international level, Mr Boissier is member of the core group of the Integration Group for the Safety Case (IGSC), the main technical advisory body on deep geological disposal to the Radioactive Waste Management Committee (RWMC) of the OECD/NEA.

Erning, Johann Wilhelm

Diploma in Chemistry from the University of Bonn and PhD in Chemistry at the University of Bonn and the Research Centre Jülich working on energy conversion topics.

He has more than 15 Years of experience in corrosion science and failure analysis, working for the German Federal Institute of Material Research and Testing (BAM), now as acting head of the division: Corrosion Protection of Technical Plants and Equipment. Corrosion of copper and copper alloys is one of his main activities in this field.

BAM is the national authority for safety in transportation and disposal of dangerous goods in Germany. The topics covered are summarised under the guideline: Safety in technology and chemistry. About 1750 employees work in the main fields:

- Analytical chemistry.
- Safe handling of dangerous materials and dangerous goods.
- Safe and environmentally compatible use of materials.
- Safe operation of technical systems and processes.
- Damage mechanisms and damage analysis.

He is Head of the EFC (European Federation of Corrosion) Working Party: Corrosion and corrosion protection in drinking water. He is also Head of GfKORR (Gesellschaft für Korrosionsschutz) Working party: Failure Analysis. He is also a member of national and international Groups dealing with corrosion and failure analysis.

Kessler, John

BS and MS in Nuclear Engineering (University of Illinois at Urbana-Champaign), PhD in Hydrogeology (University of California, Berkeley).

John Kessler has 30 years of experience in the fields of used fuel and HLW storage, transportation, and disposal. He is currently the manager of the Used Fuel and High-Level Waste Management Programme at the Electric Power Research Institute. Dr. Kessler led EPRI's 15-year effort in developing an approach to understanding the overall impact of disposing of used nuclear fuel in the candidate repository at Yucca Mountain. He currently works on the technical bases to support used fuel storage and transportation, particularly very long-term storage issues, and on the impacts of advanced fuel cycles on used fuel and high-level waste management.

Prior work experience includes design of used fuel storage and transportation systems, quality assurance auditing, and the development of waste forms for defense high-level waste.

At the international level, he has been an active participant in various International Atomic Energy Agency programmes in the fields of biosphere model development (BIOMOVS II and BIOMASS, including chairing a BIOMASS subcommittee on the definition and use of "critical groups"), management of high burnup and irradiated MOX fuel, and technical bases for extended storage of used fuel. In 2000, Dr. Kessler participated in a SKI-funded international review of SKB's preliminary safety assessment for a proposed deep repository for long-lived and intermediate-level waste (SFL 3-5). He also organised the Extended Storage Collaboration Programme – an international programme composed of participants actively pursuing long-term storage R&D, and was a lead organiser of the 1998, 2001, and 2003 International High-Level Radioactive Waste Management conferences.

Kotra, Janet

Ph.D. in Analytical, Nuclear and Environmental Chemistry (University of Maryland, USA) and B.S. Chemistry (University of Hawaii, USA).

She has over 28 years of experience in radioactive waste management and has been employed by the U.S. Nuclear Regulatory Commission (NRC) since 1984. She has served as a postdoctoral fellow for the NRC's Advisory Committee on Reactor Safeguards (1984-85), as a technical assistant for three NRC Commissioners (1985-1993, 2002), and as a member of the staff of NRC's Office of Nuclear Materials Safety and Safeguards since 1993.

Dr. Kotra was a major contributor to the development of NRC's regulations for the proposed repository at Yucca Mountain, Nevada, and is a principal author of NRC staff guidance on elicitation of expert judgement when evaluating the performance of high-level waste geological repositories. Between June 2008 and September 2010, she worked as part of NRC's team of independent scientists and engineers reviewing the license application for the proposed repository at Yucca Mountain, Nevada, as submitted by the U.S. Department of Energy. She contributed to the preparation of the NRC staff's safety evaluation report and three technical evaluation reports based on the staff's review of the Yucca Mountain license application.

Dr. Kotra currently serves as a senior project manager in NRC's Division of Spent Fuel Alternative Strategies. She has organised and participated in more than three dozen public meetings with citizens of affected counties and Tribes near Yucca Mountain, Nevada. She has spoken with a vast array of interested stakeholder groups about NRC's role as an independent regulator and spent more than a decade explaining NRC's public hearing and licensing processes for deciding whether or not to allow construction of a proposed repository.

In 2003, she served on a task force chartered by NRC's Chairman to evaluate NRC's effectiveness when communicating with the public. In 2000, Dr. Kotra became a charter member of the Forum on Stakeholder Confidence, an international forum sponsored by the Nuclear Energy Agency of the Organisation for Economic Cooperation and Development. Since 2006, she has served as its Chairman.

Löw, Simon

Diploma and PhD in Earth Sciences (Basel University), Full Professor for Engineering Geology ETH Zurich since 1 September 1996.

At ETH Zurich he directs a large interdisciplinary research and teaching unit focussing on hydro-mechanical processes in fractured rocks. He is responsible for an MSc Programme majoring in Engineering Geology and a Continued Education Programme in Applied Earth Sciences. Research of his large group focuses on the hydromechanical behaviour of fractured rock masses at project relevant scales. Current research projects concern ground settlements above deep tunnels, hydro-mechanical processes around repository drifts for nuclear wastes, permeability structure and ground water circulation systems in fractured rocks, and the formation of large rocks slope instabilities. Between 1986 and 1996 he has been acting as project geologist and manager of a profit centre at AF-COLENCO, working in the field of waste disposal and groundwater protection.

He has 25 years of working experience in nuclear waste disposal, mainly in Switzerland and Germany. He has been intensively involved in the study of crystalline basement rocks in northern Switzerland and the Alps. His group is currently leading large research projects in the Mont Terri Underground Research Facility funded by the Swiss Regulator ENSI. Since 2008 he is the President of the Swiss Expert Group for nuclear waste disposal (KNE, EGT) supporting the Swiss Regulator and other parties involved the Swiss site selection and repository design project (Sectoral Plan). In addition he is involved as an international expert and consultant in the field of deep tunnelling, nuclear waste disposal and rock slope instabilities.

Mayor, Juan Carlos

MS in Civil Engineering (Stanford University, CA) and Mining Engineer (Madrid School of Mines, Spain).

He has over 20 years working experience in the field of radioactive waste management. He is presently Senior Project Manager in charge of the R&D programme of the Site Engineering Dept. of the Spanish Radioactive Waste Management Company (ENRESA) in the fields of Rock Mechanics and Hydrogeology. Previously, he has been staff project engineer at CGS and GYA, two private Spanish consultancy companies in mining, geotechnical engineering and hydrogeology.

ENRESA is a public company founded in 1985 by the Spanish government for the management of radioactive wastes, including:

- Design, construction and operation of facilities for the disposal of low-level waste (LLW); interim storage and final disposal of spent fuel, vitrified high-level waste and intermediate-level waste (SF/HLW/ILW).
- Decommissioning of nuclear facilities, including nuclear power plants (NPP).
- Reclamation of old uranium mining sites.

At the international level Mr. Mayor has maintained strong cooperation with many of the WMOs, particularly through the EURATOM programme, by participating and coordinating different R&D projects in various URLs (Mont Terri, Grimsel, Hades, Asse mine), including the on-going project PEBS (Long-term Performance of the Engineered Barrier Systems). He is a member of the Steering Committee of the Mont Terri Project (Switzerland) and represents ENRESA at the Executive Group of the Technology Platform on Implementing Geological Disposal of Radioactive Waste (IGD-TP) and at the NEA-IGSC working group on the Characterisation, the Understanding and the Performance of Argillaceous Rocks as Repository Host Formations. He participated as well in various phases of the international DECOVALEX and INTRAVAL projects.

Stroes-Gascoyne, Simcha

PhD in Civil Engineering (McMaster University, Hamilton, Canada); Equivalent of B. Eng. and M. Eng. in Environmental Engineering (Agricultural University, Wageningen, the Netherlands).

She has almost 30 years of research experience in the field of geological disposal of high level nuclear fuel waste. She holds the position of Senior Research Scientist at Atomic Energy of Canada Limited (AECL), Whiteshell Laboratories, Pinawa, Canada, where she has been employed since 1982.

AECL, a federal science and technology organisation is Canada's leading nuclear science and technology laboratory. For over 50 years, AECL has been a world leader in developing peaceful and innovative applications from nuclear technology through its expertise in physics, metallurgy, chemistry, biology and engineering.

Initially, her work was focussed on the dissolution of spent fuel in groundwater under a wide range of geochemical conditions; on determining instant release fractions of radionuclides for source term development; and on determining the effects of alpha-radiolysis on the dissolution mechanism of UO_2. She was also active in various fuel characterisation and dry storage projects. Since the mid 1990's her main interest has been subsurface microbiology in the context of nuclear waste disposal, in order to determine the effects of microbial reactions on nuclear waste disposal. She was in charge of the experimental programme on microbiology at AECL's Underground Research Laboratory until its closure in 2010.

She has participated in several large-scale international underground research laboratory experiments in Canada and Switzerland. Her recent work, funded by Canada's Nuclear Waste Management Organisation, included determining how microbial activity can be controlled in clay-based buffer and backfill materials. She is the author of more than 60 published articles and conference proceedings and more than 65 published reports, and has collaborated with scientists and engineers in Switzerland, Belgium, France, UK, Japan and USA. She is an Associate Editor for the journal Applied Geochemistry.

Tokunaga, Tomochika

PhD in Applied Earth Sciences (University of Tokyo), B. Sc., M. Sc., in Structural Geology (University of Tokyo).

He is a professor and the head of the Department of Environment Systems, Graduate School of Frontier Sciences, the University of Tokyo. He is a specialist in the field of hydrogeology and rock physics, and his interests include long-term stability of subsurface environments, dynamics of saltwater/freshwater behaviour near the coast with respect to climate change both short and long-term, and coupling processes of deformation and fluid flow in geological formations. Between 1997 and 1998, he was a visiting researcher at the Department of Geology and Geophysics at the University of Wisconsin-Madison where he conducted both theoretical and experimental analyses on the behaviour of anisotropic poroelastic materials.

He serves as a member of the Domestic Technical Advisory Committee of the Nuclear Waste Management Organisation of Japan (NUMO). He also works as committee members of the several Japanese projects related to nuclear waste disposal programme implemented by NUMO, the Japan Atomic Energy Agency (JAEA), the Central Research Institute of Electric Power Industry (CRIEPI), the Nuclear Safety Research Association (NSRA), and the Radioactive Waste Management Funding and Research Center (RWMC).

Compton, Keith – NRC observer

BS in Physics (Rhodes College, Memphis, USA) and PhD in Environmental Engineering and Science (Clemson University, SC, USA)

He has fifteen years of experience in the field of environmental risk analysis. He is currently a Senior Systems Performance Analyst in the Office of Nuclear Material Safety and Safeguards (NMSS) in United States Nuclear Regulatory Commission (USNRC). His work at the USNRC has been in the area of regulation of geologic disposal of spent nuclear fuel and high level waste, focusing on the integrated risk analyses of both postclosure and preclosure safety. He has also been active in efforts for the integration of spent fuel regulatory activities. He has co-authored a textbook on environmental risk analysis, and has served in the US Navy as a nuclear trained submarine officer.

Within the United States, the USNRC regulates commercial uses of nuclear material, including nuclear power. Within the USNRC, NMSS is responsible for regulating activities which provide for the safe and secure production of nuclear fuel used in commercial nuclear reactors; the safe storage, transportation and disposal of high-level radioactive waste and spent nuclear fuel; and the transportation of radioactive materials regulated under the Atomic Energy Act.

At the international level, he worked for several years at the International Institute for Applied Systems Analysis (IIASA) in Austria. At IIASA, he analysed health risks from radioactive contamination due to weapons production and naval nuclear propulsion in the former Soviet Union, and also examined mechanisms for integrating engineered and financial measures for mitigating urban flood risks.

Annex 2

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The Post-closure Radiological Safety Case for a Spent Fuel Repository in Sweden

Sweden is at the forefront among countries developing plans for a deep geological repository of highly radioactive waste. There is no such repository in operation yet worldwide, but Sweden, Finland and France are approaching the licensing stage. At the request of the Swedish government, the NEA organised an international peer review of the post-closure radiological safety case produced by the Swedish Nuclear Fuel and Waste Management Company (SKB) in support of the application for a general licence to construct and operate a spent nuclear fuel geological repository in the municipality of Östhammar. The purpose of the review was to help the Swedish government, the public and relevant organisations by providing an international reference regarding the maturity of SKB's spent fuel disposal programme *vis-à-vis* best practices in long-term disposal safety and radiological protection. The International Review Team (IRT) consisted of ten international specialists, who were free of conflict of interest with the SKB and brought complementary expertise to the review. This report provides the background and findings of the international peer review. The review's findings are presented at several levels of detail in order to be accessible to both specialist and non-specialist readers.

OECD Nuclear Energy Agency
12, boulevard des Îles
92130 Issy-les-Moulineaux, France
Tel.: +33 (0)1 45 24 10 15
nea@oecd-nea.org **www.oecd-nea.org**

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