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SKI's and SSI's review of SKB's safety report SR-Can

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Preface

This report summarises the Swedish Nuclear Power Inspectorate's (SKI) and the Swedish Radiation Protection Authority's (SSI) joint review of the Swedish Nuclear Fuel & Waste Management Co's (SKB) safety report SR-Can, on post-closure safety for a KBS-3 spent nuclear fuel repository at Forsmark and Laxemar respectively (SKB TR-06-09). As of 1 July 2008 the Swedish Radiation Safety Authority assumed the responsibilities that previously fell under the Swedish Radiation Protection Authority and the Swedish Nuclear Power Inspectorate. Information about the new authority and its operations is available on the web site (www.ssm.se).

The review is part of the ongoing consultation during the site investigation phase and is intended to provide SKB with guidance on the authorities' expectations on the safety report required for the planned licence application in 2009. The authorities have been assisted in their review by three independent review teams as well as other other consultants. The external reviews are presented separately in SKI's and SSI's report series.

The review by the authorities has been carried out by a project group with representatives of the Nuclear Material and Waste Safety Department at SKI and of the Nuclear Facilities and Waste Management Department at SSI.

The authorities' own review of SR-Can was carried out using the Swedish language and the original review report was also written in Swedish. Efforts have been devoted to correct errors in this English translation, but there may still be some language problems, and unintentional deviations from the original report.

The project managers were Björn Dverstorp (SSI) and Bo Strömberg (SKI).

The project group has consisted of Björn Brickstad (SKI), Georg Lindgren (SKI), Jinsong Liu (SSI), Öivind Toverud (SKI), Petra Wallberg (SSI) and Shulan Xu (SSI).

In addition, a number of experts at the respective authority have contributed texts and supporting material for the review, including Behnaz Aghili (SKI), Pål Andersson (SSI), Jan In de Betou (SKI), Mikael Jensen (SSI), Peter Merck (SKI) and Maria Nordén (SSI).

Summary

This report summarises SKI's and SSI's joint review of the Swedish Nuclear Fuel & Waste Management Co's (SKB) safety report SR-Can (SKB TR-06-09). SR-Can is the first assessment of post-closure safety for a KBS-3 spent nuclear fuel repository at the candidate sites Forsmark and Laxemar, respectively. The analysis builds on data from the initial stage of SKB's surface-based site investigations and on data from full-scale manufacturing and testing of buffer and copper canisters.

SR-Can can be regarded as a preliminary version of the safety report that will be required in connection with SKB's planned licence application for a final repository in late 2009. The main purpose of the authorities' review is to provide feedback to SKB on their safety reporting as part of the pre-licensing consultation process. However, SR-Can is not part of the formal licensing process.

In support of the authorities' review three international peer review teams were set up to make independent reviews of SR-Can from three perspectives, namely integration of site data, representation of the engineered barriers and safety assessment methodology, respectively. Further, several external experts and consultants have been engaged to review detailed technical and scientific issues in SR-Can. The municipalities of Östhammar and Oskarshamn where SKB is conducting site investigations, as well NGOs involved in SKB's programme, have been invited to provide their views on SR-Can as input to the authorities' review. Finally, the authorities themselves, and with the help of consultants, have used independent models to reproduce part of SKB's calculations and to make complementary calculations. All supporting review documents are published in SKI's and SSI's report series.

The main findings of the review are:

- SKB's safety assessment methodology is overall in accordance with applicable regulations, but part of the methodology needs to be further developed for the licence application.
- SKB's quality assurance of SR-Can is not sufficient for a licence application.
- The knowledge base needs to be strengthened for a few critical processes, such as buffer erosion, with potentially large impact on the calculated risk
- The link between assumed initial properties of repository components and quality routines of manufacturing, testing and operation need to be strengthened before the licence application.
- There is a need for a more elaborate reporting on the potential for early releases from the repository.

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1. Introduction

SR-Can is the Swedish Nuclear Fuel & Waste Management Co's (SKB) first assessment of post-closure safety of a KBS-3 repository at the selected candidate sites at Forsmark and Laxemar. This safety assessment is based on data from the initial stage of SKB's surface-based site investigations and on data from full-scale manufacturing and testing of the buffer and copper canister. According to SKB, the main purpose of the report is:

- to make an initial analysis of the safety of a repository at Forsmark and Laxemar,
- to provide feedback to development work on the engineered barriers, SKB's RD&D programme and to the continued site investigations,
- to stimulate a dialogue with the authorities SKI and SSI, on interpretation of applicable regulations as a preparation for the licence application.

SR-Can was initially intended to server as supporting material for SKB's application to construct an encapsulation plant. As of SKB's modified action plan, the function of SR-Can has changed, and it does not now serve as a formal basis for a licence application. However, the report may be regarded as a preliminary version of SKB's next safety analysis SR-Site, which is at present planned to serve as the basis for an application to construct a KBS-3 repository at Forsmark or Laxemar. According to the current plan, SR-Site will be published at the end of 2009. SR-Can has accordingly provided an opportunity for the authorities to state their points of view on SKB's safety assessment prior to the licence application.

SR-Can was presented for the authorities and their consultants on 1 November 2006 and consists of a main report (SKB TR-06-09) and nine main references totalling almost 3,000 pages. Furthermore, there are a large number of technical reports with supporting material. Bearing in mind SR-Can's preliminary status and the fact that the safety assessment is based on limited data, SKI and SSI have had a lower level of ambition for their input than if the review had been intended to serve as supporting documentation for a licence application. In this review, the authorities have not compared or taken a position on SKB's two candidate areas Laxemar and Forsmark.

As of 1 July 2008 the Swedish Radiation Safety Authority assumed the responsibilities that previously fell under the Swedish Radiation Protection Authority and the Swedish Nuclear Power Inspectorate. The Swedish Radiation Safety Authority is a new central regulatory authority with responsibility within the fields of radiation protection and nuclear safety.

An important objective of the review has been to provide guidance to SKB about the authorities' expectations regarding the safety report that SKB is to produce for the licence application. Important review areas include:

- SKB's compliance with the authorities' regulations
- SKB's methods for safety assessment
- SKB's follow-up of review comments from previous reviews of SKB's preliminary safety analyses
- further investigation needed to be made into critical research and technology-related issues before the licence application.

The review has been performed as part of the established consultation on system and safety assessment which SKB carries out with the authorities. This has made it possible to hold a number of expert meetings between the authorities and SKB during the course of the review. These meetings have been intended to clarify aspects of SR-Can and to draw SKB's attention to important issues that need to be dealt with before the licence application.

A further aim of the review has been to establish a review organisation including external experts and consultants which can be utilised as support in reviewing by the authorities in future consideration of the licence application. The review has also provided the authorities with a possibility of testing the independent models for, for instance, consequence analysis that have been produced in recent years. This review report will also serve as a basis for the authorities' examination of the programme presented by SKB for research, development and demonstration (RD&D programme 2007).

SKB has previously published an interim report for SR-Can (SKB TR-04-11), which was intended to exemplify the safety assessment methods produced for SR-Can. SKI and SSI have themselves reviewed this report (SSI, 2005) and also had an international expert group make an independent assessment (Sagar et al., 2005). The authorities also reviewed SKB's safety assessment SR-97 which was published in 1999 (SKI, 2000). At that time, an extensive international review was also carried out which was organised by OECD-NEA (NEA, 2000), and a review of external consultants (SKI, 2000b). SR-97 was not based on the existing places Forsmark and Laxemar but on three hypothetical sites A-berg, B-berg and C-berg, which were represented by data from earlier investigations at three sites (Äspö, Finnsjön and Gideå). SR-97 served as the basis for SKB's start of the current site investigations.

2. Regulatory criteria

This section provides an overview of the assessment criteria on which the authorities' review is based. As supervisory authorities for the Swedish nuclear waste programme, SKI and SSI exercise supervision under the Nuclear Activities Act (KTL) and the Radiation Protection Act (SSL).

The authorities' review report of SKB's Safety Report 97 (SKI, 2000) contained a detailed account of the regulations and international rules and guidelines applicable to applications for final disposal of nuclear fuel and nuclear waste. A short summary is provided here of earlier regulations and the general guidelines that have come into existence since 2000. Table 1 summarises applicable laws, regulations and general guidelines.

2.1 Radiation protection requirements

SSI's regulations on protection of human health and the environment in connection with the final management of spent nuclear fuel and nuclear waste (SSI FS 1998:1) came into force in 1999. These regulations stipulate the health and environmental requirements made by SSI for planning, design and construction of facilities included in a repository. SSI's regulations on protection of human health and the environment from releases of radioactive substances from certain nuclear facilities (SSI FS 2000:12) apply to operating facilities. The regulations SSI FS 1998:1 include both material and formal requirements. The material requirements concern, for example, levels of protection, optimisation of radiation protection and the best available technology (BAT) which governs the design and/or system. The formal requirements concern the report in an application for a licence or an environmental impact description. SSI (1999) describes the background to and comments on the regulations.

The general guidelines on application of SSI FS 1998:1, which came into force in 2005 (SSI FS 2005:5), provide guidelines on how the regulatory requirements can be met. These guidelines include, inter alia, the application of optimisation and BAT, calculation of risk, the definition of the most exposed group, choice of scenarios, evaluation of environmental protection and reporting over long periods of time.

In the first paragraph, which defines the area of application of the guidelines, it is emphasised that the whole system for taking care of waste must be taken into consideration to assess the protective capability of a repository and the impact on the environment. This means that all treatment of waste in early stages and handling of waste containers that may affect emissions from the repository are covered by the provisions.

SSI's requirement for optimisation and BAT may together be regarded as a total optimisation. For the situations when it is meaningful to make a risk analysis, the calculated risk should be used to choose the measures, technology and sites that provide the best radiation protection. The risk criterion is a blunt tool for more remote periods and more rigorous measures should be used when assessing which measures, technology and sites best minimise the consequences of the repository, for example, how the site and material choice best reduces the number of broken canisters or leakage from the repository.

The risk of harm for a representative individual in the most exposed group may, according to the regulations (section 5), not exceed one in a million per year. According to the general guidelines, one way of defining the most exposed group is to include individuals in the interval from the highest risk down to a tenth of this risk.

The assessment of the protective capacity and environmental impact of a repository should be based on a range of scenarios which together illustrate the most important course of events for the development of the characteristics of the repository, its environment and the biosphere. A realistic range of biosphere conditions should be associated to every climate evolution. The scenario should be selected so that they together illustrate the most important and reasonably predictable sequences of future climate conditions and their effect on the protective capacity and environmental impact of the repository.

As regards the analysis of the consequences for the environment, the report should, inter alia, cover exposure paths, concentrations in sediment and biota and an assessment of biological and ecological effects (see general guidelines, Annex 2). The current biosphere at the time of application should be used for the assessment of environmental consequences in a long-term perspective, although, taking into consideration known trends such as isostatic uplift. The current biosphere does not mean a limitation to exactly the circumstances that apply today at a candidate site. Characteristic elements of the landscape, for instance, various types of watercourse, and ecosystems in the area around the candidate site should be included in the biosphere models used to calculate future dose consequences from the repository. For future climates where current biosphere conditions are manifestly unreasonable, for instance in conditions of permafrost, it is sufficient to make an overview analysis based on the current state of knowledge of ecosystems.

The regulations (sections 10-12) state that an assessment of the protective capability of the repository should be made for two periods of time. The first is up to 1,000 years after sealing, when the effects on human health and the environment are to be based on quantitative analyses, and the time after 1,000 years, when the assessment of the protective capability of the repository is to be based on different conceivable courses of events. The general guidelines for the repository clarify that the risk analysis should at least cover the period up to 100,000 years or the period of a glaciation cycle. The repository should comply with SSI's risk criterion for this period of time. The analysis should subsequently be extended in time as far as it provides significant information on the ability to improve the repository's protective capability in accordance with the principle of the best available technology. For the period beyond 100,000 years, the assessment of the repository's protective capability can be made in a simplified way taking into account the evolution of the climate, biosphere conditions, and exposure paths. SSI does not make any requirements on radiation protection reports beyond a million years after sealing.

2.2 Safety requirements

The Swedish Nuclear Power Inspectorate's regulations on safety in final disposal of nuclear materials and nuclear waste (SKI FS 2002:1) apply to the repository after sealing and complement SKIFS 2004:1 on safety at nuclear facilities. These regulations contain provisions on requirements for barriers and their functions, the design and construction of the repository and on safety assessment and safety reports. Safety and sealing shall be maintained by a system of passive barriers which shall each contribute to sealing, preventing or delaying the spread of radioactive substances. There shall be several barriers that together display robustness in the face of events that can affect their performance. The barrier system shall be designed and constructed with the best available technology. SKIFS 2002:1 contains a definition of a repository as sealed when the tunnel volumes are filled up all the way to the surface level.

The repository regulations and the appurtenant general guidelines also affect requirements or recommendations linked to the conduct of the safety assessment, for example, choice of scenarios, handling uncertainty, reporting supporting material for the safety assessment, in the form of data and models, design-basis cases, and traceability and documentation. According to the regulations, the safety assessment must cover the period that barrier functions are required (although at least 10,000 years). The justification for the time scale chosen may be based on how the dangerousness of the content of the repository develops over time in comparison with the hazard of radioactive substances occurring naturally. The guidelines also state that safety assessment linked to long-lived waste should cover an interval of time including large expected climate changes.

The safety regulations in nuclear facilities concerning nuclear facilities (SKIFS 2004:1) deal with the construction, possession and operation. These regulations guide when safety reports are to be produced and how safety reviews are to take place.
They contain requirements for application of basic safety principles for a nuclear facility. This includes the design of the facility, its operation, evaluation of safety, also its decommissioning. Measures during construction and operation of a repository do not only affect the prerequisites for operational safety but also long-term safety and the regulations therefore have an indirect link with safety after the sealing of a repository.

Table 1: Overview of laws and regulations applicable for review of SR-Can.

Legislation and regulations	**Brief description**
Radiation Protection Act (1988:220)	Basic requirements and principles for a repository are contained in sections 1 and 6
SSI FS 1998:1 Regulations on the Protection of Human Health and the Environment in connection with the Final Management of Spent Nuclear Fuel and Nuclear Waste.	Health and environmental requirements for planning, design and construction of facilities included in a repository.
SSI FS 2005:5 SSI's Guidelines on the application of the regulations (SSI FS 1998:1) concerning protection of human health and the environment in connection with the final management of spent nuclear fuel and nuclear waste	Guidelines on application of requirements for optimisation, best available technology, calculations of risk and of the most exposed group, choice of scenario, assessment of environmental protection and reporting over long periods of time.
Act on Nuclear Activities (1984:3)	Basic requirements and principles for a repository are contained in sections 3 and 4.
The Swedish Nuclear Power Inspectorate's regulations on safety in final disposal of nuclear matter and nuclear waste (SKI FS 2002:1)	Requirements for the barrier's functions, design and construction and on safety assessment and safety reports.
SKI FS 2004:1 SKI's regulations on safety at nuclear facilities	Requirements on measures required to maintain safety during construction, possession and operation of nuclear plants. The regulations include provisions on technical, organisational and administrative measures, which may also be important for safety after sealing.

3. Implementation of the review

SKI's and SSI's review of SR-Can has been carried out within the framework of an inter-agency project group with one project manager from SSI and one from SKI (SKI and SSI hereinafter referred to as the authorities). A number of officials from each authority have contributed with in-depth reviews of particular issues. The authorities' review was carried out during the spring and autumn of 2007. This review was based on reports from three independent international review groups, consultancy assistance on specific issues and independent modelling studies. These studies have been organised and carried out on behalf of the authorities. However, they are to be regarded as independent which means that the points of view in these reports do not necessarily agree with those of the authorities.

The authorities have not completely reviewed the site-descriptive models bearing in mind their extent and preliminary nature. However, there is ongoing review work within the context of consultations during the site investigation phase, which will address the final report from the site investigations. There are also other areas where the review contributions have been limited. The authorities have not, for instance, carried out independent calculations as a basis for assessments of SKB's large-scale rock mechanics modelling. This means that review comments associated with this area are not as detailed as for the areas where independent calculations have been made.

International review groups
Three international expert groups have reviewed SR-Can on the basis of the following perspectives: 1) integration of site data in SR-Can, 2) representation of engineered barriers, 3) methods for safety assessment. The groups first produced written questions to SKB on SR-Can on the basis of these three review perspectives. In a special hearing session in March 2007, the expert groups were able to ask supplementary questions to SKB. The groups' review reports, which are central supporting material for the authorities' review, are published separately in SKI's and SSI's report series (see also Annex 1). The three groups consist of:

- Group for review of how SKB used the site investigation data in SR-Can, whose report is hereinafter referred to as SIG ("Site Investigation Group"). Participants: Neil Chapman (chairman), Chin-Fu Tsang, Ove Stephansson, Adrian Bath, Joel Geier, Sven Tirén, Roger Wilmot (secretary), Anders Wörman, Clifford Voss, Richard Klos.
- Group for review of how SKB dealt with questions relating to engineered barriers in SR-Can, whose report is hereafter referred to as EBS ("Engineered Barrier System"). Participants: Dave Savage (chairman), David Bennett (secretary), Mick Apted, Göran Sällfors, Timo Saario, Peter Segle
- Group for review of safety assessment methodology in SR-Can, whose report is hereinafter referred to as SAM ("Safety Assessment Methodology"). Participants: Budhi Sagar (chairman), Mike Egan (secretary), Klaus-Jürgen Röhlig, Neil Chapman, Roger Wilmot

External experts and consultants
The authorities have also used external experts and consultant for in-depth reviews of special issues. In most cases, these consultants have previously been involved in the authorities' research programmes but the commissions have been focused on matters directly relevant to the review of SR-Can. The authorities have also carried out independent calculations to check important results in SR-Can with the assistance of external consultants. The work of the

external consultants is published within the framework of SKI's and SSI's report series. The external contributions to the authorities' review are included in Annex 1.

Municipalities and environmental organisations
The site investigation municipalities Östhammar and Oskarshamn as well as the Swedish NGO Office for Nuclear Waste Review (MKG) and the Swedish Environmental Movement's Nuclear Waste Secretariat (MILKAS) which receive funds from the Nuclear Waste Fund have been invited to submit points of view on SKB's report in SR-Can. They have provided additional supporting material for the authorities' review.

4. Documentation and quality issues

SKB reports how quality issues are dealt with in section 2.8 of SR-Can Main Report (SKB TR-06-09). The points of view of the authorities are based on their own observations and independent calculations. A consultant has made a special examination of quality assurance of models and certain data (Hicks and Baldwin, 2008). This examination is to be regarded as a random sample test. It would not have been justified to make a complete review of all quality issues in the extensive documentation in the main report and supporting references since SR-Can is not linked to an application.

SKB states that a plan for quality assurance of the safety assessment has been developed, although only partially applied in SR-Can. The plan aims at guaranteeing that all relevant factors for long-term safety have been dealt with in an adequate way and includes

- project management
- identification of features, events and processes (FEP)
- expert judgment of how different FEP are dealt with
- quality assurance of models and data.

The authorities consider that SR-Can contains central components of the quality assurance which is necessary prior to SR-Site, e.g. templates for documentation of FEP, data, processes and scenario choices. Several deficiencies in the application of the quality plan have, however, been identified and it can be noted that quite a lot of development work remains to be done before the quality assurance can be considered to be acceptable for a licence application. The authorities wish to emphasise that SKB as soon as possible should present a complete programme for quality assurance which can be discussed in the continued consultations for the site investigation phase.

The authorities and SAM consider that SKB in preparation for the licence application needs to show that there is a credible system for quality assurance of the safety assessment, including through making regular documented audits of the quality programme, and to produce proposals for improvement measures. Another important question concerns plans for qualification of old data and references which have still not been quality assured which need to be referred to in SR-Site.

The credibility of the safety assessment is also highly dependent on there being a sufficient quality assurance of manufacture and testing of engineered components, construction of the repository and emplacement etc. The authorities consider that SKB is well on the way to developing quality assurance routines for the canister. There is still a need to develop routines and criteria for other components, e.g. the buffer and the backfill. The authorities also consider that the link between this type of quality issues and the assumptions made about the assumed initial state of the repository in the safety assessment needs to be strengthened prior to SR-Site.

The following section includes specific points of view on different documentation and quality assurance issues in SR-Can. Concrete examples of deficiencies for the respective issue are reported separately in Annex 2. Further points of view on the use of data and models are presented by Hicks and Baldwin (2008).

4.1 Structure of the documentation

The hierarchical structure for reporting of the safety assessment has the main report at the highest level followed by the main references (data, process, initial state and climate reports, etc.) and supporting technical reports and scientific publications at the lowest level. The authorities consider that this structure for the documentation is appropriate for the purpose and that it can also be used for SR-Site. However, it is important that the reference management is designed in such a way as to clearly show which documents or parts of documents at the third level are included in the safety case since these documents then have a binding formal status.

SKB's ambition is to structure the main report according to the ten steps in the safety assessment method. However, the SR-Can report is repetitive and, in some respects, complex. The authorities therefore consider that SKB may need to review the pedagogical aspects of the presentation prior to SR-Site. One example concerns the description of the method for safety assessment which is spread over several chapters, e.g. the strategy for uncertainty and sensitivity analysis, choice of scenarios, formulation of probabilistic and deterministic calculation cases, and risk summation. A description and justification of a compilation of the methods chosen for the safety assessment are needed (see also SAM). Furthermore, the summary in SR-Can should be developed to provide a better overview of the safety concept with the most important safety arguments and critical uncertainties.

4.2 Documentation of data and processes

Documentation of processes and data is a central part of the quality assurance of the safety assessment and is therefore specially commented on here. The authorities consider that the standardised format templates produced by SKB to document management of data and processes are appropriate for their purpose and can provide a good structure also for SR-Site. The structure of the process reports is logical, which makes it easy to find the information sought after.

However, the authorities consider that there are deficiencies in the documentation. Justifications and descriptions in the process reports are of uneven quality and a large part of the material is still preliminary. In many cases, the descriptions are too brief and rudimentary to enable an assessment to be made of whether a particular issue has been dealt with in a reasonable way. There is a need of more detailed references to international scientific publications for certain processes. Justifications or references are lacking for certain important claims.

It is evident from the process reports that a large part of the expected supporting material has not been available at the time of compilation of SR-Can (e.g. it is stated that an issue is a matter for future studies or that the issue is quite simply not dealt with within SR-Can). Some formulations draw attention to a safety problem or indicate considerable uncertainty which does not seem to be subsequently taken into account and dealt with in the safety assessment. This is understandable to some extent since SR-Can is a preliminary safety assessment which does not claim to be comprehensive. However, the extent of incomplete handling of processes and data is relatively large.

The authorities wish to emphasise that it is very important that SR-Site is based on sufficiently detailed process descriptions. There will still be uncertainties at the time of SR-Site, but it should then be clear that these have been dealt with and taken into account in some way. If the assessments in the process reports of important uncertainties still indicate that they have not been taken into account, the authorities may have to conclude that SR-Site is not complete and accordingly not a sufficient basis for the licence application.

The process tables in the main report and the process reports contribute to overview and understanding, although to a varying extent. To facilitate future examinations, more use should be made of references and cross-references in the process tables (e.g. information about where a particular influence has been dealt with). If indirect influences are specially stated, these should be explained since they are seldom evident and cannot be understood intuitively (in principle, there may be indirect links between all processes) (see chapter 6).

The authorities consider that excluded processes should be justified to a greater extent with scoping calculations rather than just loose judgments which are difficult to check. In one or two cases, there are scoping calculations in the process table but these lack references and it is therefore unclear whether these scoping calculations are documented.

The systematic and structured headings in every section in the data report (SKB TR-06-25) create good prerequisites for justification of the selected data. For SR-Site, SKB should, however, endeavour to make the data report more traceable so that it is really evident where the specified data comes from. Statistical processing of data and tests should also be explained and presented in more detail. The data report contains far from all data that can be utilised in some way in SR-Can. A more complete version is needed prior to SR-Site, where the extent and limitation of the presentation is clearly justified.

The authorities note that the level of ambition for justification of the selected data and distribution functions in the data report vary and it is unclear whether this depends on safety-related importance or other causes. In the view of the authorities, there should be a clearer link between the documentation of different data and its importance for the safety assessment in SR-Site.

Examples of deficiencies are presented in Annex 2. Points of view for the procedures for assessments of data and processes are commented on especially in the section on expert judgment below (section 4.6).

4.3 Documentation of models and reproducibility of calculations

Documentation

It is positive that SKB has increased the level of ambition for documentation of models. The special model report (SKB TR-06-26), flow diagrams for models (AMF) as well as the tables showing how processes are dealt with in different models, e.g. Table 6-7 in the main report, all contribute to a better overview of the models and codes used in the safety assessment. The production of an in-depth documentation of the near-field model COMP23 (SKB R-04-64) is another good example. The templates for documentation of models in the model report is good, although the documentation is still of varying quality and needs to be reviewed prior to SR-Site. This applies, for example to the discussion on the applicability of the models for different parameter intervals and conceptual uncertainties. The calculation models for the risk-dominating emission scenarios (advective conditions in the deposition holes) are, of course, particularly important to document in great detail.

The authorities have started a more detailed review of SKB's quality work with respect to codes (Hicks, 2005) and experiments (Hicks, 2007). Hicks and Baldwin (2008) have also carried out a supplementary review of SR-Can (see chapter 13). The authorities intend to follow this review work up within the framework of continued consultations during the site investigation phase.

Reproducibility
SKB states in SR-Can that the goal is to make it possible for others to reproduce (i.e. recreate) all analyses of importance for the long-term safety and radiation protection (SKB TR-06-09, page. 62).

To investigate whether SKB lives up to this ambition, the authorities themselves, and with the aid of consultants, have carried out independent checks of calculations related to repository evolution, radionuclide transport and dose calculations (Xu et al., 2008; Maul et al., 2008, Rutqvist and Tsang, 2008). It has been possible to reproduce important parts of the radionuclide transport calculations even if certain uncertainties remain, e.g. with respect to calculations of dose factors for the well scenario and description of the transport path through a fracture in the deposition tunnel (Q3) in the near-field model. However, work on recreating SKB's calculations has been impeded by insufficient, and in certain cases incorrect, documentation (see example in Annex 2). In certain cases, supplementary information has been required after information and discussions with SKB.

Maul et al (2008) point to certain difficulties in repeating the calculations related to the repository's evolution, e.g. with respect to the thermal evolution and re-saturation of the repository. A contributory cause is that a lot of work is required to trace all parameter values and assumptions in supporting technical reports. They also emphasise corrosion calculations for the advection corrosion scenario as an area where improved documentation and argumentation for the validity of the models are needed, bearing in mind that the calculated canister failure distribution is critical for the risk estimate.

Overall, it is a pass grade for SKB that the authorities have succeeded in reproducing parts of SKB's calculations in SR-Can. However, it is important that SKB remedies the problems of traceability of the model calculations which were identified in the review of SR-Can. All input data and model descriptions need to traceable and available for the upcoming review of SR-Site. To facilitate reproduction of SKB's calculations, SKB should also produce considerably more detailed background information that describes how the different models have been used, how they have been linked and the data used for deterministic and probabilistic calculation cases. The authorities also share the point of view of Maul et al (2008) that a greater component of deterministic calculation cases would facilitate understanding of the results of the probabilistic calculations.

Access to reports on SKB's website has been valuable for the review. To facilitate reproduction of SKB's calculations in future reviews of SR-Site, it would be good if SKB could also make more detailed data and calculation supporting material available in digital form.

4.4 Reference management and traceability issues

Consistent and clear reference management is necessary for being able to follow the reasoning in the hierarchical and extensive documentation of SR-Can. Although the report structure provides good prerequisites for traceability, the authorities, SAM and other consultants have identified traceability problems that impeded the review and which need to be remedied prior to SR-Site:

- In a number of cases, references were lacking for assessments and claims
- References to supporting documents were far too imprecise in certain cases
- Incorrect cross-references

As stated above in the section on documentation of data and processes, the authorities also consider that SKB should refer to a greater extent to scientific publications to support critical assumptions for the safety assessment.

4.5 Inconsistent data handling

SKB's assessments of processes and data are based in many cases on a number of steps of analyses with references to different supporting reports. In their review, the authorities have, for instance, found examples where input data and model assumptions are not consistent between different supporting analyses, e.g. in the analyses of infiltration of oxygen with glacial melt water. There are also some examples of partly contradictory assessments within the main report for SR-Can (see Annex 2). Even though the authorities are aware that SR-Can is not completely quality assured, the review shows that there are problems in the reasoning in issues of key importance for the repository's functioning which need to be remedied prior to SR-Site.

4.6 Expert judgment

SKB's expert judgments are an integrated part in practically all aspects of the safety assessment. Two main levels are presented in SR-Can for expert judgment; assessments at expert level and assessments within the project group for SR-Can. The first level refers to the assessments made by specialists in different areas of technology and scientific disciplines with respect to data, processes, models etc. in the main references to SR-Can. These assessments are audited, and reconsidered in certain cases, by a smaller group ("SR-Can team") within the project group SR-Can before they go into the analyses of the main report. Formal expert elicitations have not been used in SR-Can. SKB states that uniform formats have been produced for expert judgment of data, processes and models, with instructions on what the experts should take into account in their assessments. For reasons of traceability, the expertise and roles of the different experts was documented in a special database. SKB states that the database will be developed prior to SR-Site. Important reports are also reviewed within SKB and by external experts. These reviews are documented in special review records.

The authorities consider that SKB's system for documentation of different types of expert judgments has prerequisites to contribute to traceability of the data and assumptions on which the calculations in the safety assessment are based. However, SKB should clarify the roles of the different experts and the different levels of expert judgments. There are many examples of different experts having dual or unclear roles, see example in Annex 2. The authorities also consider that the difference between the SR-Can team and the project group for SR-Can should be explained more clearly.

SKB states in the data report (SKB TR-06-25; page. 32) that the SR-Can team has made the final assessments of the parameter values and intervals used in the safety assessment, but that these assessments have been examined by relevant experts. It is unclear whether it is the experts that have contributed expert judgments who have reviewed the SR-Can team's assessments and how these reviews have been documented. The authorities also consider that the description of how the different experts (outside SR-Can team) have contributed with their expert judgment is insufficient. The subject authors in the SR-Can team have, as far as the authorities understand, summarised the reports of the experts in the data report. However, it is not clear whether this is only a compilation of assessments in the underlying expert reports or whether there has been any dialogue between the experts and the SR-Can team. The process reports have a different structure than the data report. The process report for the geosphere contains, for example texts contributed by a number of experts, but persons from the SR-Can team are also named as authors and no distinction is made between the assessments of other experts and those of the SR-Can team.

It is good that SKB aims to document the experts that have contributed different types of assessments. However, the authorities consider, like SAM, that it is unavoidable that different experts may evaluate the same data and uncertainties in different ways. It is therefore important that SKB can show that the experts have been chosen so as to obtain the breadth in the scientific assessments required for an all-sided clarification of critical issues for the functioning of the repository (especially bearing in mind the lack of clarity on the roles of different experts identified above). Taking into consideration the relatively limited group of SKB experts, the authorities also consider that the instructions in the data and process reports should be developed so as to make it clearer whether and how discrepant scientific assessments have been taken into account in critical issues.

The authorities consider that SKB should improve the documentation of the assessments of data and processes made by the project group (or SR-Can team). This applies particularly to the cases where the project group does not accept the experts' assessments.

SKB has identified questions in SR-Can where the knowledge base for the safety assessment is deficient, e.g. within the areas copper creep, glacial hydrology, buffer erosion, hydrogeological models and bentonite transformations. Further research and investigation is planned within these areas prior to SR-Site. However, it is probable that there will remain knowledge gaps and uncertainties even when SR-site is produced. The authorities wish to repeat the recommendation from the review of the interim report for SR-Can that SKB should consider expert elicitations for special issues of great importance for the safety assessment where the knowledge base cannot be improved by additional measurements.

5. Safety functions

SKB's safety strategy is based on the primary safety functions isolation and delay, of which isolation is considered most important. The safety function of the repository is to provide the prerequisites to comply with the requirements for long-term safety and radiation protection. In SR-Can, SKB has defined a number of more specific underlying safety functions, which should be complied with to achieve the desired levels of isolation and retardation. However, SKB states that compliance with all underlying safety functions is not necessary but that the analysis will be facilitated if this is the case. To assess underlying safety functions, SKB has defined a number of function indicators which are variables that provide information about the status of the underlying safety functions. Furthermore, numerical criteria for the functional indicators are needed, which state when they are considered to be complied with. According to SKB, assessment of function indicators facilitates the safety assessment. This contributes supplementary information about the state of the repository at different times only in relation to assessment of risk and dose. The use of safety functions in SR-Can (SKB TR-06-09) is described in Chapter 7.

5.1 Safety functions and function indicators

Figure 1 shows the safety functions, function indicators and function indicator criteria which SKB has used in SR-Can (SKB TR-06-09, page. 204). There are safety functions for the canister, the buffer, backfilled deposition tunnels and the rock. According to SKB, the status of the canister is crucial for isolation and the safety functions for isolation are therefore oriented towards the three identified canister rupture mechanisms corrosion rupture, isostatic collapse and shear rupture. They are shown in the diagram in red, green and blue respectively. Buffer and rock are important for the canister and there are therefore also safety functions for these which are primarily related to the three canister rupture mechanisms. Function indicators associated with retardation are shown in yellow in Figure 1. In this case, the canister does not play an important part. It may be noted that there is a large overlap between function indicators which affects radionuclide transport and canister corrosion. In this case, it is primarily a matter of hydrological and geochemical conditions which have a similar impact both on any leaking radionuclides and corroding substances which may react with the canister. In the case of the other canister rupture mechanisms (isostatic collapse, shear rupture), pressure conditions, temperature and possible movement of the rock play a dominant role.

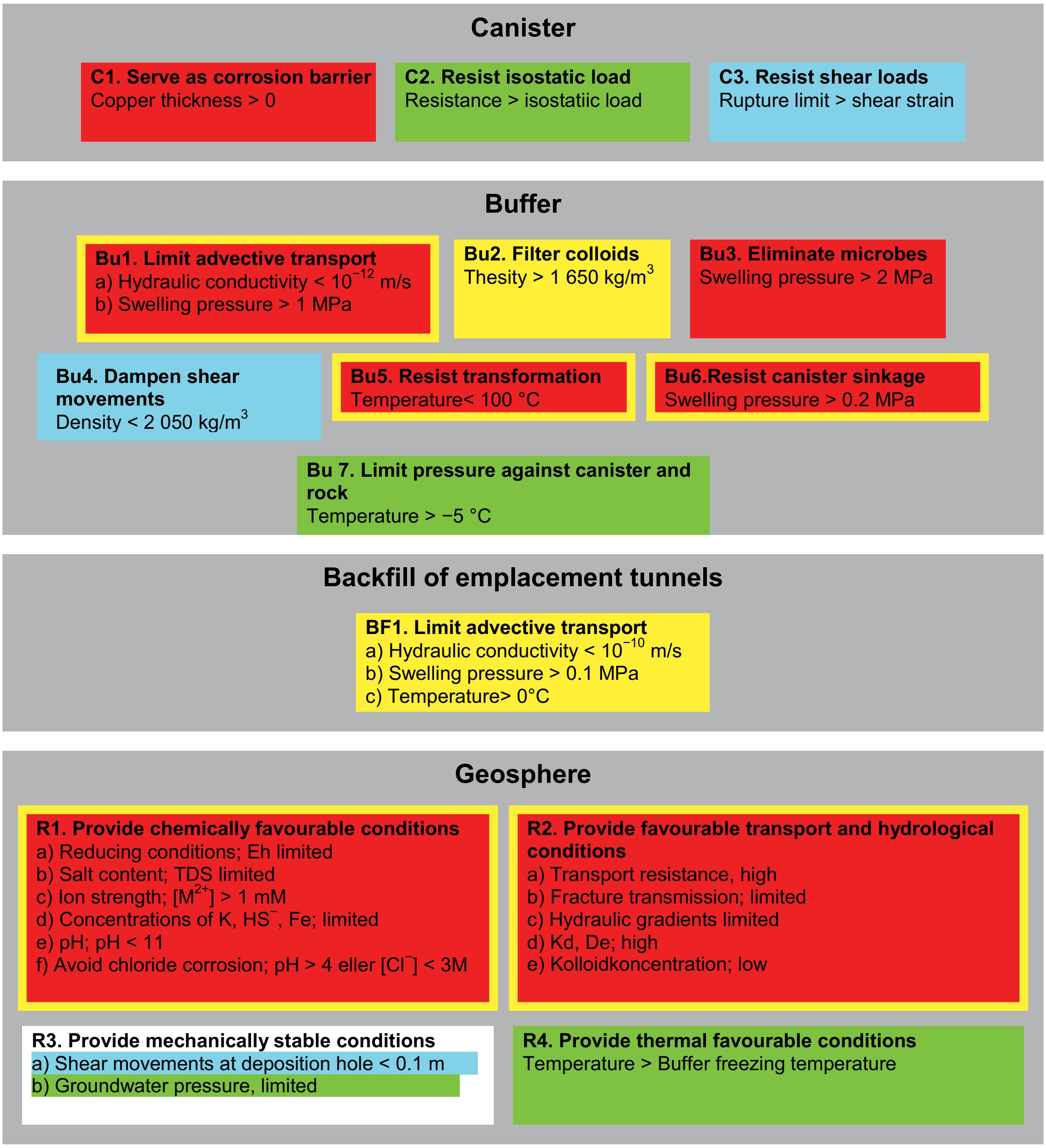

Figure 1: Safety functions (bold), safety function indicators and criteria for safety function indicators which SR-Can has been based on (SKB TR-06-09). Coloured coding shows how the functions contribute to the canister's safety functions C1 (red), C2 (green), C3 (blue) or to delay (yellow). Many functions contribute to both C1 and delay (red box with yellow border).

SAM considers that SKB should describe more explicitly how the different barriers contribute to the safety functions isolation and retardation. A report of this kind should include the relative importance of the barriers in different scenarios, and their importance to show that the repository system has a built-in reserve capacity. SAM considers that the analysis of the safety function indicators is a good complement to the analysis of radionuclide transport.

However, a clearer description is needed of the link to the safety strategy and the assessment of BAT (best available technology) and optimisation of radiation protection.

The authorities take a positive view of SKB's development of more detailed safety functions (compared with only isolation and retardation), which can be evaluated with selected appropriate function indicators. This is an important component in method development since SR 97 (SKB TR-99-06). In the continued review in this report, reference will be made to the different safety functions in Figure 1. The function indicators provide good support for the choice of less probable scenarios, even if there are certain limitations which are discussed in more detail in Chapter 14. The authorities consider furthermore that the safety functions with function indicators may be used in the assessment of optimisation and best available technology (BAT) and in the development of design-basis cases.

The authorities consider that, before SR-Site, there is a need for further development of safety functions, function indicators and appurtenant criteria (SKB TR-06-09, page 204). SKB should, for example, investigate whether function indicators can be made more robust and complete. There are other important state functions for repository components which are discussed in the process reports but which are not represented by the function indicators (e.g. indicators associated with creep and stress corrosion cracking). SKB should state clearly whether there are supplementary and possibly more detailed requirements and criteria for the state of the repository which are dealt with outside the function indicators.

The fuel is by definition not a barrier although it has an important safety function since the limited fuel dissolution rate is important for compliance with the risk criterion. Another important safety aspect of the fuel is the need to avoid criticality in the repository environment. SKB should therefore consider defining safety functions and function indicators for the fuel as well.

An important prerequisite for use of safety functions is that controlling processes in the repository are well investigated and documented. In cases where there is extensive uncertainty about process understanding, the basis for a function indicator and subsequent processing can be called into question. The authorities do not consider that the documentation in the process reports provides sufficient support for safety functions and function indicators at present (see also section 4.2).

SKB states in the main report that there is freedom in certain cases to choose indicator (since dependent quantities can have the same effect on a safety function). It is stated, for example, that density replaces pore size distribution for the safety function filter colloids. The authorities consider that this may be acceptable if the most primary characteristic for long-term safety is identified and reported.

5.2 Criteria and limit values

In a review of the specific limit values for the canister and buffer, the process reports summarised most often did not include sufficient explanations to justify the limit values selected. In a number of cases, there were discussions about particular processes, which were evidently relevant for the limit value, but no discussion about the limit value as such. The authorities therefore consider that SKB before SR-Site should more explicitly justify the limit values selected and endeavour to take into consideration all relevant processes when selecting limit values.

Changes in limit values can, of course, occur if new knowledge is obtained. Recurrent changes of limit values for the function indicators without good reasons may, however, entail a loss of confidence in SKB's concept of function indicators. The authorities therefore consider that it is important that SKB, if such changes come into question, makes a detailed analysis and documents the consequences of the change. MKG (SKI dnr. 2006/985) points out the risk of a gliding description of requirements and wishes associated with the assessment of rock conditions.

SKB includes general discussions in SR-Can on safety margins for the limit values and notes that these may vary depending on the character of the limit values and that there is therefore no systematic approach to margins. The authorities consider that compliance with the limit values for function indicators is not a formal requirement per se. However, it is important that SKB's application of function indicators in the safety assessment is robust and takes uncertainties into account to a sufficient extent. SKB should therefore produce a more developed approach as to how margins are to be applied for the limit values selected for the function indicators.

In certain cases, safety margins may be applied when designing and dimensioning barriers. The risk contribution from certain scenarios can be eliminated or greatly reduced when large margins can then be indicated when assessing corresponding safety functions (in SR-Can e.g. isostatic collapse, freezing of the buffer). This constitutes the most effective approach to uncertainties, a basis for the long-term safety of the repository as well as a demonstration of the robustness of the barrier system (5 § SKIFS 2002:1). Sufficiently large safety margins in relation to the limit values applied can also provide arguments for limiting the assessment in the following steps of the safety assessment (e.g. minor earthquakes). However, there are processes in SR-Can for which safety margins can hardly be indicated even if all reasonable design measures have been taken into account. These will be dominant in the risk analysis and central for the demonstration of compliance with the requirements in relation to the risk criterion (in SR-Can major earthquakes and buffer erosion). The handling of these processes needs to be clarified from a BAT/optimisation perspective.

The authorities note that certain function indicators have been insufficiently clarified in SR-Can. One example is the temperature criterion 100°C which is justified in SR-Can with the requirement for chemical stability of the buffer. In the part of the buffer process report referred to, it is indicated that the criterion is based on the activation energy for illitisation of smectite (effects are shown by application of the Arrhenius equation). In other parts of SR-Can, temperature-controlled cementation of the buffer is discussed as a considerable uncertainty. Another effect of higher temperature is greater uncertainties for chemical data. Additional examples of effects of higher temperature are more difficult to predict thermo-hydro-mechanical-chemical (THMC) couplings and larger rock stresses.

6. System description

The system description in SR-Can is based on an FEP database ("Features Events Processes") which is described in SKB TR-06-20. The database is implemented in FileMaker Pro and is based on previous interaction matrices developed within SKB as well as the FEP database from SR-97 (SKB TR-99-06). Furthermore, SKB has reconciled it in relation to NEA's international FEP database. As its main categories, the SR-Can database has internal processes, external factors and variables. There are also a smaller amount of FEP associated with events that may affect the initial state and site-specific factors. Biosphere and method issues are stated as categories although no account is provided of these. The FEP database is based on summary information either from the main report for SR-Can (SKB TR-06-09) or one of its main references (process reports, climate report, data report, etc.).

Important information from the system description is structured as process tables (in SR-Can SKB TR-06-09, page 159), influence tables (in the process reports), FEP diagrams (SKB TR-06-09, page 192) and model diagrams ("AMF", SKB TR-06-09, page 173).

Assessment by the authorities
Like SAM, the authorities consider that SKB has developed a good system for documentation of system components and links between FEP and the modelling in the safety assessment with the aid of process tables, progress diagrams, influence tables, FEP diagrams and AMF. The digital database is also a useful component. However, the report is relatively complex with a large number of tables and diagrams and the method description for handling processes is furthermore spread over a number of chapters in the main report (SKB TR-06-09, Chapters 2, 3 and 6). To provide the reader with a better overview, the authorities consider that SKB should produce an overview description of how all tables and diagrams are related and how they are used in the analyses.

The authorities view it as positive that SKB has carried out an extensive reconciliation of SR-Can's FEP database in relation to OECD Nuclear Energy Agency's international FEP database. The authorities agree with SKB that it is not necessary to repeat this reconciliation for the application. However, the authorities assume that SKB will update its database with the appurtenant documentation (process reports, etc.) taking into consideration the continued handling of matters within SKB's programme and new relevant scientific findings.

The process reports for the various system components have a good structure and provide a good basis for the analyses of the evolution of the repository. As stated in Chapter 4 of this review, the authorities consider, however, that the quality of the documentation in the process reports needs to be improved prior to SR-Site. The authorities and SAM consider furthermore that the screening of processes (SKB TR-06-09, Chapter 6) needs to be better justified, for example, by estimates, and linked more clearly to the safety functions. SKB refers in certain cases to scoping calculations in SR-Can although references are lacking in many cases. The authorities also consider that SKB should consider some form of assessment/check of the importance of excluded processes after implementation of the analyses in the main scenario, in particular as regards the combined effects of different FEPs. The authorities also wish to draw to SKB's attention that the importance and treatment of "indirect influences" in the influence tables is unclear. A comparison between Table 5-1 in the process report for the geosphere (SKB TR-06-19) and Table 2-16 in the process report for the buffer and backfill (SKB TR-06-18) illustrates that different points of departure are used for the assessment of what is an indirect influence. The authorities consider that SKB should clarify the definition of the indirect influences and explain how completeness is achieved or review the treatment of the tables.

SKB considers (Section 2.2 of SKB TR-06-09) that the work of producing a process report for the biosphere is in progress and that the FEP database must be supplemented when the process report is ready. The authorities share SIG and SAM's opinion that the lack of a process report for the biosphere has made the review of SR-Can difficult. The authorities consider that it is very important that SKB in SR-Site can convincingly show that a systematic approach has been applied to identify all important processes which are important for radionuclide transport, accumulation and dose in the biosphere. It is also important that the biosphere is included as an integrated part of the safety report. The authorities also consider that there is a need for a more detailed AMF for the biosphere models. The authorities, SIG, SAM and Stark (2008) consider that it is difficult to understand the link between the different models in the biosphere analysis, e.g. which results from carbon models have been used as parameters in the radionuclide transport models (SKB R-06-82 and SKB R-06-83).

SKB states that variables which have been defined relating to certain sealing measures, tunnel plugs, borehole plugs, the bottom plate in deposition holes etc. shall be regarded as preliminary and based on simplified assumptions in SR-Can (SKB TR-06-20, pages 15 and 18). The authorities consider that it is important that the supporting material is more complete in SR-Site.

7. Geosphere conditions

Critical issues relating to the geosphere are discussed in this section. Processes in the geosphere which relate to the evolution of the repository are taken up in the sections on the evolution of the repository (Chapters 11 and 12). The following section covers structural geology, rock mechanics and the thermal characteristics of the rock. There is also a discussion of near-surface hydrology and hydrogeology, geochemistry and the transport characteristics of the rock. This review has been focused on a safety assessment perspective and the site-descriptive models have therefore not been completely reviewed in connection with SR-Can. The reason for this is the supplementary review work which is taking place in connection with consultations during the site investigation phase (see, for example, the reports SKI-INSITE TRD-05-12 and TRD-06-03) and that a large quantity of new information has already been collected and analysed by SKB after version 1.2 of the site-descriptive models that SR-Can was based on.

7.1 Structural geology

SKB has produced a basic model for Forsmark in the site-descriptive modelling version 1.2 (SKB R-05-18) which reports on identified deformation zones. The candidate area is limited by three regional NNW-SSE steeply dipping deformation zones (Forsmark, Singö and Eckarfjärden). In the candidate area, towards the south and south-east, there are also gently dipping zones with an increased frequency of open fractures probably affected by a rapid pressure relief during the most recent deglaciation. In addition to these, there are further two bands with vertical and steeply dipping zones in the WNW and NW and NE directions. These fracture networks consist of sealed joints. There is also a fourth set of steeply dipping zones of subordinate importance in a NS direction. As well as the base model produced, SKB presents a basic variant and an alternative model. SKB has not noted any indications of recent rock movements after earthquakes after the most recent glaciation in the candidate area.

The structural geology at Laxemar is presented in the site-descriptive modelling (SKB R-06-10). At Laxemar, which constitutes the western part of the site investigations at Oskarshamn, NS and EW relatively steeply dipping zones predominate. To date, a gently dipping zone has been included in the structural model for Laxemar based on reflexion-seismic measurements. The area to the east is delimited by the regional SW-NE Äspö shear zone.

An important question to investigate is the effect of deformation zones on the stress field in particular within the candidate area at Forsmark where rock stresses are relatively high. The authorities consider that SKB should report in SR-Site on how the stress field varies and is affected by the position of the deformation zones.

The site-descriptive model for Laxemar contains a description of the current model for deformation zones and the development that has taken place since earlier model versions (SKB R-06-10, page 184 pp). The site-descriptive model for Forsmark contains a description of the main uncertainties in the model for the deformation zones. SKB needs to show that there is a high level of confidence in the existence and extent of the deformation zones since this is very important for the suitability of the location. According to SKB, undetected deformation zones may exist (SKB TR-06-09, page 104). The authorities consider like SIG that SKB needs to deal with and discuss the significance of this conclusion prior to SR-Site. There are also remaining issues associated with extrapolation and characterisation of the indicated zones as regards depth as well as the connections between the zones.

The models for discrete fracture networks (DFN) are of key importance for the safety assessment since they affect the flow models, the rock mechanics, the degree of utilisation of emplacement positions and the respect distance. The DFN models in the site-descriptive models v1.2 are, however, only based on fracture radii of less than10 m and greater than 1000 m (SKB R-05-45, SKB R-05-26). The authorities expect that the MDZ project ("Minor Deformation Zone") can contribute additional supporting material to support the chosen "power-law" distribution of fracture intensity.

The authorities note that it has not been possible in the site-descriptive modelling for Laxemar (version 1.2) to obtain a good agreement between model results, fracture intensity data from exposed rock surfaces and fracture intensity data from bore holes (SKB TR-06-09, page 123). The authorities consider that SKB should shed further light on this matter since the fracture network models are very important for flow calculations in the safety assessment.

7.2 Rock mechanics

The mechanical characteristics of the rock affect both the isolating and the retarding functions of the repository and are also important for the design and construction of the repository as well as the choice of its depth. Preliminary measurement data indicate that rock stress is relatively high at greater depth at Forsmark, and generally lower at Laxemar although with considerable variations in different rock volumes. It is the case at both places that the greatest horizontal rock stress is in the NW-SE direction. Rock stress is high at Forsmark and it has been difficult to carry out a sufficient number of reliable rock stress measurements. However, SKB makes the assessment that data collected including quantified uncertainties are sufficient for the purpose in SR-Can.

The authorities consider that the reliability of the stress levels at Forsmark is limited due to few initially successful measurements. The situation is similar at Laxemar although in this case, it is because a relatively small number of measurements have been made within the chosen repository area. According to the authorities, SKB should consider a new assessment of rock stress data and possibly carry out additional measurements before completing the site investigations.

7.3 The thermal characteristics of the rock

According to the authorities, SKB has developed a good method for dealing with the thermal characteristics of the rock (SKB R-03-10) which is mainly based on laboratory measurements, but also verified field measurements to support the site-descriptive models. The authorities also consider that SKB has suitable methods to describe the up-scaling, variability and anisotropy of the thermal characteristics. It is a deficiency that the site-descriptive models version 1.2 (SKB R-05-18, SKB-06-10) only discuss laboratory measurements as a basis for temperature modelling. The authorities note, however, that such initiatives are described in a later version of the site-descriptive model (SKB R-06-110, page 113).

7.4 Hydrogeology and near-surface hydrology

SKB's report
In SR-Can, SKB has carried out hydrogeological and near-surface hydrological modelling for a number of different purposes. In the safety assessment, the hydromodelling provides input data for calculations of radionuclide transport and supporting information for the analysis of geochemistry and copper corrosion. Furthermore, the hydromodelling contributes to the supporting information for calculations of possible erosion of the buffer and backfill. Further analyses include lowering of the groundwater level during the construction and operating phase, resaturation of the repository and calculation of the inflow to the deposition holes during the construction and operation phases. Within the framework of the site-descriptive modelling, the hydromodelling constitutes an important part of the overall understanding of the sites. Other important purposes of the site modelling which have not been considered in this review are the support for the repository layout and design.

The flow on a regional scale has been modelled within SR-Can with the focus on predicting the future hydrological evolution of the sites under temperate conditions. On a scale that describes the surroundings of the repository, the flow has been modelled with the objective to calculate flow paths from canister positions in the repository to the biosphere and other input data for calculation of radionuclide transport. The hydrogeological calculations specific for SR-Can are reported for Forsmark in SKB R-06-98 and for Laxemar in SKB R-06-99.

Two types of models have been used on the regional scale for Forsmark. In one of them, the flow is modelled in a continuous porous medium ("Continuous Porous Media", CPM) which has homogenous characteristics in the different rock volumes. In the other model, the flow is also modelled in a porous medium although the characteristics have then been calculated from a description of a discrete fracture network ("Equivalent Continuous Porous Media", ECPM). The fracture networks consist of larger fractures/fracture zones which are defined deterministically and smaller fractures which are defined stochastically. The ECPM model has a more detailed spatial resolution than the CPM model and deals with heterogeneity in the defined rock volumes. For both model types, density effects linked to the salt content of the water have been included in the calculations. These calculations have been carried out from 8000 BC to AD 9000 with a 20-year time step.

The detailed modelling for Forsmark consists of three different model types. The first model type describes the flow through the backfilled repository with a CPM model and the flow through the surrounding rock with a discrete fracture network model ("Discrete Fracture Network", DFN). The fracture networks consist of larger fracture and fracture zones which are defined deterministically and smaller fractures which are defined stochastically. The second type of model describes flow both through the backfilled repository and through the surrounding rock with CPM models. Due to limitations in calculation capacity, a smaller model domain than what is needed for the longest flow paths from the canister positions to the surface has been used in both model types. Flow paths which reach the model boundaries are transferred to the regional ECPM model which is described above. In the third model type, the surroundings of the repository have been modelled with a DFN model which is embedded in an ECPM model. The DFN model describes the repository but not with a level of detail that reaches down to individual emplacement positions. For all three model types, effects of the water's density, which can be linked with the salt content of the water and thus its origin, have been included in the calculations. The calculations have been made for AD 2020, 3000 and 9000.

SKB has modelled a number of different cases on the regional scale for Forsmark, for example variations of the occurrence and characteristics of the deterministic fracture zones, and the importance of variations of the characteristics of the stochastic fracture network. Several stochastic realisations have been calculated. A selection of these cases has been transferred to the more detailed modelling of the repository's surroundings.

For Laxemar, SKB has carried out the corresponding simulations on the regional scale with ECPM models although not with the CPM model. On the scale for the surroundings of the repository, CPM models of the backfilled repository have been linked to detailed DFN models of the surrounding rock. SKB has also linked a less detailed DFN model to a regional ECPM model.

In SR-Can, SKB has also carried out calculations of the flows for the time when the repository is covered by an ice sheet (SKB R-06-100; see section 12.3) and modelled the hydrogeology during the design and operating phase (SKB P-06-249, SKB R-05-57, SKB R-06-57). Modelling of the inflows to deposition holes for the two sites is described in SKB R-06-102.

The site-descriptive modelling of the hydrogeology is reported in SKB R-05-18 Chapter 8 for Forsmark and in SKB R-06-10 Chapter 8 for Laxemar. Two modelling groups have carried out modelling, which includes analysis of data and the hydrogeological characteristics of the sites as well as numerical modelling of the paleo-hydrological and current hydrogeological situation on a regional scale. Considerable effort has been put on the study of the hydrogeological fracture networks. Site modelling of the hydrogeology is based on information reported in the site-descriptive models. The main references are SKB R-05-32 and SKB R-05-60 for Forsmark and SKB R-06-23 and SKB R-06-24 for Laxemar, and a large number of site investigation (P) reports for the respective site.

The site-descriptive modelling of the near-surface hydrology is reported in parts of Chapter 4 in SKB R-05-18 for Forsmark and in SKB R-06-10 for Laxemar. Main references are SKB R-05-06 for Forsmark and SKB R-05-61 for Laxemar.

The structure of the analyses
The authorities regard it as positive that the analyses for site-descriptive models have been carried out by two modelling groups using different methods and models. The authorities consider that the parallel use of both DFN and CPM models is good.

Understanding of the hydrogeology in SR-Can is based on modelling which is reported in the safety assessment, in the site-descriptive modelling and its supporting material. Bearing in mind, the extent of the material and its complexity, it is important that the analyses have a clear structure. In the case of Forsmark, Figure 2-11 in SKB R-06-98 together with Figure 8-24 in SKB R-05-18 (and the corresponding figures for Laxemar respectively) contribute to clarifying the structure to a certain extent. However, the authorities consider that the overall picture is difficult to overview with the large number of calculation cases for the different model types and the large amount of supporting data. It is not either always clear which of the modellings carried out which have been chosen and integrated into the site-descriptive models and how the result then obtained have been transferred to the calculations on which the safety assessment is based. SKB should consider improvements in these respects prior to SR-Site.

Table 8-11 in SKB R-05-18 summarises the DFN modelling of the two groups. However, the table does not include all cases which have been modelled and there is no discussion about how the cases have been selected. Some of these cases have been transferred to the modelling for the safety assessment (SKB R-06-98, Table 3-4). Here as well, the selection has not been clearly justified and there is no indication which of the cases agrees with the modelling for the safety assessment (SKB R-06-98) and the site-descriptive models (SKB R-05-18). The justification of which calculation cases and results are relevant for onward transfer is central to be able to assess whether the identified uncertainties have been taken into account (see also SIG, Chapter 6). For the needs of the safety assessment, for instance, a modified version of the CPM model is created compared with the version in the site-descriptive model, which gives results for salt contents that resemble the ECPM model ("Equivalent Porous Medium", compare SKB R-06-98 Figure 3-35 with SKB R-05-18 Figures 8-55 and 8-56). The site-descriptive model is thus not transferred onwards in its entirety in the safety assessment but only in a version with reduced conceptual uncertainty. This should have been justified better.

Integration of models and their result
The authorities take a positive view of the considerable efforts made in SR-Can to integrate hydrogeology with structural geology and geochemistry. With an expanded basis of data, there should be good prospects for improving the links between these areas. The link between hydromodelling and rock mechanical modelling is an example of an area where integration has not come as far. It may be mentioned that questions concerning the effect of inland ice on the hydraulic properties of the rock are studied in SKB R-06-88 Chapter 8 but that this effect is explicitly neglected in the groundwater modelling for glacial conditions (SKB R-06-100, page 9). In SR-Can, the link between hydrogeology, near-surface hydrology and coast water is insufficiently reported.

The authorities consider that SKB in the site-descriptive models should strive for a more detailed integration of results from different modelling groups. There are, for example, clear differences between the results from hydromodelling when compared with measurement data in section 8.6.3 in SKB R-05-18. The significance of the differences is not discussed, however, neither for hydraulic conductivity, salt contents, major ions nor environmental isotopes. Another example is modelling of surface hydrology at Forsmark for which not all the models produced in the supporting documentation for the site-descriptive models (SKB R-05-06 Chapter 5) are discussed in the site-descriptive model (SKB R-05-18, section 4.4.2).

The review of SR-Can has shown that there are examples of issues that need a more integrated approach in the description of the candidate areas at Laxemar and Forsmark. This problem is exemplified below with questions liked to modelling of the salt content of the groundwater:

- In the case of Forsmark, it is stated that the modelled salt contents at a depth of less than 200m are lower than those measured (SKB R-05-18, page 400), which may be a conceptual problem according to SKB.
- SKB further consider that the almost complete flushing of salt in hydromodelling of glacial conditions in Simpevarp is probably an unrealistic characteristic of the model (SKB TR-06-09, page 340).

- SKB is also uncertain about the interpretation of the result from the modelling of salt contents during the design phase for a repository for Laxemar. However, the preliminary conclusion is that the upconing of salt water to the repository depth is not particularly prominent (SKB R-06-57, page 33).
- The question of how long a period of time the front of the ice-sheet is over the repository (SKB TR-06-09, page 341) can also be linked to the question of the salt content.

Utilisation of site data in the hydromodelling
There is no direct comparison in SR-Can between site-specific pressure data or flow data and the respective modelled values for the scale which is relevant for radionuclide transport from the repository depth to the surface. It is thus difficult to assess how well the model reflects the site-specific situation and how large uncertainties that need to be transferred to subsequent modelling.

The authorities consider that SKB should clearly describe the strategy on which utilisation of site data in parameterisation of hydromodelling is based, for example, how data is used in the different phases of modelling to support the site-descriptive models.
In SR-Site, calibration of hydromodels should be described clearly and be accompanied by a discussion on handling uncertainties, for example the effect of the combination of data uncertainty, use of initial conditions, and conceptual uncertainties. The agreement between measured data and model results should be assessed with quantitative measures to make it clear how different aspects of a good fit are weighted in the calibration. The authorities consider moreover that SKB should clearly describe how the site-descriptive models are used for parameterisation of the hydromodelling used directly within the safety assessment.

Discrete fracture models and flow modelling
The authorities take a positive view of the efforts in SR-Can to produce discrete fracture network models for flow calculations which are linked to the geological fracture network models. It is good that a number of modelling groups have used differing methods and studied different cases.

The authorities consider like SIG that SKB should discuss in more detail uncertainties linked to the choice of relation between the size of the fractures and their transmissivity. Other questions that might need to be further clarified are:
- spatial heterogeneity of hydraulic conductivity or fracture intensity
- anisotropy of rock domains and fracture domains
- spatial correlations of the characteristics of the deformation zones
- hierarchical structures
- differences in parameters that result from adaptation to geological and hydrogeological DFN models (SKB R-05-18, page 380)
- additional factors that affect the fracture connectivity (see SIG report section 6.1).

The authorities' consultant Geier (2008) has carried out independent fracture network modelling of flow and flow paths on a regional scale based on data from the two sites. In the model, the fracture networks have been represented on m-scale closest to the repository. At a greater distance from the repository, fractures are represented partly explicitly and partly with equivalent discrete elements, depending on the size of the fractures and the distance from the repository. The results of this study indicate, inter alia, that the proportion of deposition holes with an insignificant flow at Forsmark is around 5 % and thus much lower than the results in

SR-Can indicate (Geier, 2008). These differences may be caused by details in the application of finite domains in combination with "power-law" fracture size distributions. Another possible cause may be effects of ad hoc assumptions in DFN modelling to make the calculations more effective.

The independent discrete fracture network modelling indicates for Forsmark (Geier, 2008, Figure 4.4 and Table 4.5) shorter travel times to the surface compared with the results in SR-Can (SKB TR-06-25, section 6.6.8). Part of the explanation for this difference is the choice of the relation between the fracture aperture and its transmissivity of the fracture. Geier (2008) uses the "cubic law" while the calculations in SR-Can are based on the "Doe law". In the case of Laxemar, SKB has investigated how this choice affects the sensitivity of the travel times. In SKB TR-06-25 (page 164), SKB argues that the "Doe law" is conservative compared with the "cubic law". There may, however, be other aspects of how conservative the two models can be assumed to be, for example, linked to buffer erosion and complex fractures.

SKB should in SR-Site deal with the numerical problems in SR-Can which have arisen in particle tracking calculations and which lead to transport through the near-field of the repository not continuing to the far-field (SKB TR-06-09 page 252).

SKB states in the main report (SKB TR-06-09, page 251) and in the data report (SKB TR-06-25, page 163) that one pessimistically reduces the F factor by a factor of 10 to account for chanelling in the fractures with reference to SKB R-06-25. The authorities consider that SKB should provide a clearer justification as to why this is a pessimistic assumption. Dverstorp et al. (1996; page 56), show that the F factor can differ by two and a half orders-of-magnitude between a flat parallel fracture and a pipe-shaped channel with corresponding conductivity.

The authorities note that SKB plans experimental studies to verify models for mass transfers between the buffer and the flowing water in the surrounding fractured rock, which are dealt with in SR-Can by the Q_{eq} concept (SKB TR-06-25, page 561). The authorities consider that this is very important since the Q_{eq}-concept has a central role in the safety assessment.

7.5 Geochemistry, microbiology and fracture-filling minerals

SKB has carried out an extensive characterisation of the composition of the groundwater during the site investigations at Laxemar and Forsmark. Data from both the sites have been used to produce conceptual models for geochemical conditions. The modelling of the sites' hydrogeochemical evolution is greatly dependent on understanding and modelling of the site-specific hydrology. SKB considers that the contents of the groundwaters' dominant constituents are best explained by mixing calculations based on end-member water types of different origins such as seawater, water from precipitation, glacial meltwater and deep salt groundwater. Certain components of the groundwater are moreover controlled to a varying extent by reactions with minerals in the bedrock and microbial processes. Besides the analysis of the main components of the groundwater, SKB has carried out a characterisation of, inter alia, environmental isotopes, trace substances, dissolved organic matter, microbes, colloids and fracture filling mineral. There is a brief description of the knowledge obtained about the candidate areas in Chapter 4 in the main report for SR-Can, which is a summary of the information in the site-descriptive models version 1.2 for Laxemar and Forsmark (SKB R-06-10, SKB R-05-18).

The authorities provide in this section some general points of view on SKB's characterisation of geochemical conditions. Additional points of view on geochemistry are reported in later sections on the evolution of the repository after sealing (section 11.6).

The authorities consider in general that SKB has a high level of ambition in its geochemical programme and high demands on the quality and representativeness of the groundwater samples. However, one problem has been that it has proven more difficult than expected to obtain representative samples from different parts of the bedrock. This has led to the number of samples, in particular in the environment which is most representative for the repository environment, i.e. near the repository depth, being relatively few. SIG is concerned about this but expects that more detailed databases will be presented in connection with later versions of site-descriptive models.

SKB needs to show that basic demands for the suitability of the candidate areas are complied with (SKB TR-00-12), e.g. the occurrence of reducing conditions and lack of oxygen at the repository depth. The authorities consider that SKB's databases should be sufficient for a reconciliation of this kind. However, this is not the only use of geochemical information. Data need also to provide supporting evidence for assessment of especially important chemical processes in the near-field of a repository and to contribute to the understanding of the geochemical and hydrological evolution during long time scales.

The authorities consider that it should be possible prior to SR-Site and the final site-descriptive models to considerably extend the site-specific interpretation of geochemical data. An example of an important question is the conceptual understanding of the distribution of groundwater types with different chemical composition and how these are linked to the hydrological evolution of the sites. In the case of Forsmark, a concept is indicated, for example, based on a hydraulic cage where precipitation water is prevented from reaching a greater depth due to surface horizontal zones. A situation of this kind, if it can be confirmed, could be an important component in the understanding of the site-specific hydrological situation.

Another important example of the use of geochemical information is for studies of solubility conditions and the occurrence of sulphides. In SR-Can, it is shown that sulphides are crucial for the lifetime of the canisters. The authorities consider therefore that SKB should more clearly identify and analyse factors in the bedrock that affect sulphide contents, and as far as possible investigate the variability in the bedrock of factors linked to the sulphide contents. The link between microbiology and geochemistry is important for the understanding of sulphide mass balances, which should therefore be developed.

Close to hydrochemistry is the characterisation of the fracture filling mineral which may provide important information about radionuclide transport and supplementary clues for understanding of the geochemical evolution of the sites. There is some description of the characterisation in the site-descriptive models. However, the authorities consider that the interpretation of fracture filling minerals should be given greater scope in SR-Site to show how the results from these studies contribute to the site-specific understanding.

7.6 Transport properties

To be able to calculate transport of radionuclides from a damaged canister through the geosphere to the ground surface, a quantification of the rock's transport characteristics is needed. In SR-Can, calculations of radionuclide transport have been carried out by using the FARF31 model and a simplified analytical model (Hedin, 2002). In the models, the rock's transport characteristics are represented by matrix diffusion and sorption. The quantification of the parameters for matrix diffusion is reported in SKB R-06-111 and for sorption in SKB R-06-75.

The authorities consider that SKB should link better the conceptual model for matrix diffusion and sorption to the characteristics of the rock. SKB has, for instance, not studied issues related to different types of microfractures, the degree of mineral transformations and accessibility of the rock matrix for diffusion (SIG, sections 6.3 and 10.6). The authorities consider further that SKB should be able to better use the result from tracer migration experiments for an assessment of parameterisation of the rock's transport characteristics (SIG, section 6.3).

SKB should in connection with matrix diffusion investigate and handle issues around in-situ measurements for electrical resistance and supplementary laboratory measurements. It needs to be shown that the measurements reflect diffusion of ions in pore water and are not affected by electrically conducting mineral in the rock (Stenhouse et al, 2008, section 4.1.8). In addition, the authorities consider that SKB should improve the understanding of the difference between in-situ and laboratory measurements of the formation factor, as well as analyse the impact of measurement uncertainties.

In the data report for SR-Can (SKB TR-06-25), a triangular distribution of the matrix diffusion depth is suggested with a modal and maximum value of 10 m. The authorities consider that SKB should justify this choice in more detail and deal with important uncertainties, for instance through sensitivity analyses (Stenhouse et al, 2008, section 4.1.7).

Generic sorption data has been used in SR-Can to a great extent. The authorities consider that SKB should have a clearer method for the parallel use of site-specific and generic K_d data (SKB R-06-75, Chapter 7). Moreover, the choice of K_d values should be linked to results from studies of the rock matrix and the mineralogy of the fracture fillings. Bearing in mind the empirical nature of K_d and its sensitivity for local conditions, Stenhouse et al. (2008, section 4.2) consider that the uncertainty interval proposed in SKB R-06-75 appears too small bearing in mind the existing supporting material.

8. Design of the repository

In this chapter, critical issues relating to the design and layout of the repository are discussed. Light is shed on the location and characteristics of the deposition hole, the respect distance, the layout of the repository as well as injection methods.

8.1 The location and characteristics of the deposition holes

Criteria are described in SR-Can to ensure a choice of emplacement positions which are beneficial for safety. SKB points out that these criteria are preliminary and that at present it is neither certain that they are needed nor that they are sufficient to achieve a safe repository (SKB TR-06-09, page 139). Two types of criteria are investigated in SR-Can, partly flow criteria and partly criteria that affect the intersection of deposition holes by large fractures. These are defined in SR-Can by the "Full Perimeter Intersection Criterion" (FPC, SKB R-06-54, SKB R-06-115). An expanded variant "Extended Full Perimeter Intersection Criterion" (EFPC) is also discussed in SR-Can (SKB TR-06-09, page 332). The ability to detect deformation zones with a radius greater than 50 m is discussed in SKB R-06-39. Flow criteria are defined in SR-Can as transmissivity requirements which are applied per se or together with FPC (SKB TR-06-09, page 256). However, they have not been developed as much as FPC. Aspects concerning how flow criteria can be applied in practice and the effectiveness of flow criteria are not either assessed in SR-Can (SKB TR-06-09, page 140).

The results in SR-Can show that the location and characteristics of the deposition holes are very important for the safety of the repository. The exact location of the deposition hole affects, for example, any fracture movements which may affect the integrity of the canister and the water flow around the holes. The location and characteristics are accordingly important for canister corrosion, buffer erosion and transport of radionuclides. The authorities consider therefore that an integrated strategy is needed which aims to choose suitable locations for the deposition holes. This should include methods for investigating the rock when preparing deposition holes, criteria and procedures which are applied when drilling deposition holes as well as quality assurance of the whole procedure. The possibility of affecting the long-term safety of the repository by choice of deposition holes should be discussed in detail. The importance of technique for rock excavation should also be reported better. MILKAS (SKI ref. no. 2006/985) wishes to have an explanation why rock excavation with a tunnel boring machine (TBM) is not considered in SR-Can.

The authorities have carried out calculations of the fraction of approved emplacement positions when applying FPC, which indicate considerably lower degree of utilisation (Geier, 2008) than the results in SR-Can (SKB TR-06-09, Table 9-6). One difference in the assumptions is that Geier includes the dimensions of the deposition holes in the calculations while the report in SKB R-06-54 calculates on the basis of the axis of the holes. Bearing in mind the economic considerations which SKB must take and the available rock volumes, the authorities consider that SKB should investigate whether the results from analysis of the degree of utilisation may have been overestimated.

The authorities note that according to SKB, detection of deformation zones with a radius greater than 50 m put high requirements on planning, methods and implementation which are adapted to site-specific conditions (SKB R-06-39). SKB should prior to SR-Site be able to show that they have access to good methods for detection of fractures. The authorities also consider that control methods for verifying the characteristics of the deposition holes need to be specified.

SKB's calculations indicate that about 20 % of the deposition holes at Laxemar have an inflow greater than 0.1 l/min during the construction and operating phase (SKB R-06-102). This result applies to all investigated hydraulic conductivities which the assumed injection results in. In SR-Can, the requirement for inflow of less than 0.1 l/min has been set to avoid "piping erosion" (SKB TR-06-09, page 218). The FPC criterion leads at Laxemar to 10 % rejection of emplacement positions (SKB TR-06-09, Table 9-6). The authorities consider that SKB should clarify its assessment of possible flow criteria for acceptance of deposition holes and their relation to the FPC criteria.

8.2 Repository layout

SKB report two possible repository depths for Laxemar, 500 m (reference alternative) and 600 m. Based on SKB R-05-71, SKB states that the risk of spalling at the 500 m level is negligible at Laxemar so that the direction of the deposition tunnels has been optimised in relation to the degree of utilisation without taking into consideration rock stresses (SKB TR-06-09, section 4.4.3). In SKB R-06-88, it is stated, however, that spalling can be avoided during the construction and operating phase at Forsmark although probably not at Laxemar. Independent calculations by Rutqvist and Tsang (2008) confirm these results and show moreover that tensile stresses along the side walls of the deposition tunnels could thus lead to increased permeability. In case different EDZ zones are linked to an integrated network, the prerequisites for radionuclide transport increase. At Laxemar, increased stress conditions in the tunnels could arise already during the construction phase. Rutqvist and Tsang (2008) therefore consider that SKB should also take into account the rock stress situation at Laxemar in the orientation of the deposition tunnels.

The authorities share SIG's opinion that a detailed report and justification of the selected repository depth are required prior to SR-Site. The question needs to be clarified from a BAT and optimisation perspective. MKG (SKI ref. no.2006/985) considers that it should be investigated whether a KBS-3 repository can be located at a depth of around 1,000 m. The authorities also consider that SKB should report in more detail the effects of the shaft, ramp and other backfilled tunnels on the repository.

8.3 Injection methods

The authorities consider that SKB has not convincingly shown that low-pH cement can be used for all applications. EBS points out that low-pH cement can lead to an extended period of bentonite transformations with formation of zeolites and this review group suggests that SKB has not taken sufficient account of mechanisms and kinetics for mineral transformations. Moreover, SKB has still not specified a composition of low-pH cement (an example of a specified composition is given, however, in SKB TR-06-21 Table 7-7). In accordance with the requirement for BAT, the authorities consider that SKB should report the breadth of conditions that may occur depending on choice of cement type.

With reference to the newly-obtained knowledge about piping/erosion (see section 11.4), buffer erosion (see section 12.6) and reaction between cement and bentonite (see section 11.7), the authorities consider that SKB needs to investigate whether the methods for plugging of investigation holes with bentonite need to be updated. SKB should also investigate here the question of whether a respect distance is needed between investigation holes and deposition holes.

SKB states in SR-Can that the lowering of the groundwater table (drawdown) at Laxemar during the design and operating phase can be handled if the injection gives a hydraulic conductivity lower than 10^{-9} m/s. In another part of the report, it is stated, however, that such a low conductivity is difficult to achieve with cement injection (SKB TR-06-09, page 212). The authorities consider that SKB should more clearly report how the lowering of the groundwater table during the design and operating phase at Laxemar should be handled.

9. The biosphere and its evolution

In previous safety assessments, SKB has not reported the future effect on the environment of the repository. The review of SR-Can is the first chance for the authorities to give points of view on SKB's treatment of these questions. This chapter discusses the extent to which SKB has reported process understanding for the turnover of radionuclides in the biosphere and how this is reflected in the ecosystem models which SKB developed for analyses of the environmental impact and consequences for human health.

9.1 Reporting of conceptual understanding

During the review, no process report (or corresponding documentation) has been available for the biosphere. The authorities, SIG and SAM consider that this has made the review more difficult. The initial state and the continued evolution in the biosphere are summarised in the main report for SR-Can in sections 4.3 and 9.3.3, 9.4.2 and 9.6.2. The description of the geosphere in section 4.3 is focused on factors which are relevant for a repository, e.g. the strength of the rock and transport characteristics. However, there is no corresponding review of the factors that may be crucial for radionuclide enrichment and exposure in the biosphere.

An analysis of exposure pathways is a prerequisite for risk assessment and serves as a basis for the dose estimates. In SSI's General Guidelines (SSI FS 2005:5), it is stated that the risk analysis should include exposure pathways to organisms in agricultural land, forest, wetland, lakes, sea or other relevant ecosystems. Organisms should be selected on the basis of their importance in the ecosystems, but also taking into consideration other values, for example, the importance they may have for hunting and fishing or if the species is in particular need of protection (7 § SSI FS 1998:1). SKB reports exposure scenarios for humans. In a corresponding way, scenarios should be reported for exposure of organisms, at least in the environments where radioactive substances may accumulate.

On the basis of the identified exposure pathways and calculated activity concentrations, SKB should engage in a discussion on the types of organisms which may be exposed to the highest exposures and which factors are considered most crucial for exposure at population level. Examples of such factors are the geographical extent of the contaminated area in combination with the habitat and migration area of a population. SKB should also report on whether there is any scientifically proven effect correlation for the calculated doses to biota.

The authorities consider like SIG that SKB should make an assessment of the importance that different accumulation processes may have with respect to activity concentrations and the organisms that could have the highest exposure. The experience of the surrounding control programme around the nuclear power plants (Wallberg and Moberg, 2002) and of the consequences of the fallout after the Chernobyl accident (SSI, 1998) show that it is not the direct emission/fallout but the redistribution processes in the environment that lead to the highest activity concentrations. Identification of relevant exposure pathways requires good knowledge of these processes. The authorities consider that SKB has not described the accumulation processes in the biosphere sufficiently well in SR-Can. SKB states for example that the flat topography at Forsmark may mean that wetlands to streams will overflow regularly and that significant accumulation of material can take place in such areas (SKB R-06-82, section 5.3.1). However, SKB does not make any direct link to this material possibly containing radionuclides and what this could mean for biota. Stark et al. (2006) have, for example, in studies after the Chernobyl accident shown that an increased exposure to organisms from Cs-137 may occur during a relatively long time in a temporary wetland which only floods during the spring by a stream that is largely dried up during the rest of the year. The result from a mass balance calculation indicates that the decay of Cs-137 in wetlands is still balanced by the annual surplus from the spring floods 17 years after the initial fallout.

SKB should also report on the importance of geochemical boundary layers in soil and quaternary deposits for accumulation of radionuclides, e.g. redox changes. The exchange of water in the hyporheic zone in waterways and sedimentation in river mouths due to changes in the salt content or flow rate are other examples of transport processes whose importance should be better clarified.

To sum up, the authorities consider that SKB prior to SR-Site should produce a better conceptual description of the turnover of radionuclides in different ecosystems to show convincingly that human beings and the environment are protected. It is important that SKB identifies in a systematic way processes of importance for accumulation of radioactive substances and the exposure paths that are most important for human beings and biota.

9.2 Models

SKB has previously reported model descriptions for how radionuclides are circulated in the biosphere for individual biosphere objects (SKB TR-99-14). Models for irrigation, wells, lakes, running water, coast, agricultural land and bogs were described in the report. Ecosystem specific dose conversion factors (EDF) were reported for every radionuclide. Since then, SKB has produced a dose model for the forest ecosystem (SKB TR-06-08) and further developed "aggregated transfer factor" (TFagg) which in a given ecosystem describes the relationship between the radionuclide concentration in food and in water or soil respectively (SKB R-06-81). In SR-Can, EDF is replaced by landscape factors (LDF, see description in section 13.9 in this review and in SKB TR-06-15). In the biosphere reports for Forsmark and Laxemar (SKB R-06-82, SKB R-06-83) three different models are reported schematically: carbon flow models for sea and lakes, radionuclide transport models for a number of different ecosystems (sea, lake, running water, cultivated land, forest, well), and the landscape model that links the radionuclide transport models in time and space.

The authorities consider that it is a deficiency that there is no integrated description of the different models for biosphere transport with justifications of assumptions and simplifications. This has made the authorities' review more difficult. The authorities consider, as SIG, SAM and Stark (2008), that it is difficult to understand the connection between carbon flow models and the landscape model. The assumptions on which the radionuclide transport models and the landscape models are based are also unclear.

It is not clear what importance carbon flow models have for the description of radionuclide transport processes. SKB states "…carbon can also be used as a proxy for organic matter and energy" (Chapin et al, 2002). Further it is stated "*This approach may be useful to describe the behaviour of a wide range of bioavailable radionuclides assimilating into living tissue*" (SKB R-06-82, page 37, second paragraph). SKB also states "*The estimated residence time for carbon roughly sets limits for possible periods for the accumulation of radionuclides or other pollutants in the area*" (SKB R-06-82, page 39, first paragraph). However, there is no reference which confirms the claims in italics above and it is also unclear how these claims are applied in the modelling.

SIG considers that, based on the information contained in the main report (SKB TR-06-09) and underlying reports (SKB R-06-82, SKB R-06-83), it is difficult to understand how site data is used in the safety assessment and whether this data has been collected in a relevant way. SIG considers, for example, that relatively few measurement points have been used to measure flow rate. SKB should ensure a sufficient resolution of flow measurements in time and space to be able to build up an understanding for, for example, transient flow courses (spring floods) and their importance for transport modelling.

With respect to the radionuclide models in the LDF concept (which are called simple radionuclide models in SKB R-06-82 and SKB R-06-83 but ecosystem models in SKB TR-06-15 and SKB R-06-81), there are a number of simplifications and assumptions that do not seem to be realistic and which are not justified either. They lead to conservative dose estimates in certain cases but not in others which makes an overall assessment difficult. To describe the transition from geosphere to biosphere there is a box called "water in top sediment" in the sea and lake models. In the modelling, SKB has disregarded that radionuclides from a repository are transported through the whole bottom sediment but assumes instead that the inflow takes place directly to "water in the top sediment". Another example is that the water retention time in wetlands is calculated by assuming that the water flow from the whole drainage area passes through the wetlands. SKB's own study (SKB R-06-46) shows that a large flow from a drainage area upstream creates a large watercourse which has a low residence time. However, wetlands develop around large watercourses, where the water flow has a very low rate, which means that the water's residence time in the wetlands cannot be calculated with the whole of the drainage area's water inflow to the wetlands. The authorities consider that SKB should report a better validation of these models. The models should be based on a more thorough process understanding and a more detailed hydrological understanding supported by field data (e.g. tracer tests).

The authorities consider that the large number of model parameters, and the large number of interlinked objects, makes the landscape models complex and difficult to overview. It is therefore difficult to assess whether the calculations and analyses of the environmental impact reported in SR-Can are robust. SKB should rely on more robust model descriptions based on a documented understanding of which processes are important for dose consequences. These models can then be further developed to incorporate greater complexity, for example, taking into consideration isostatic uplift. In order to obtain better insight into which landscape objects make the greatest contribution to the risk analysis, it would be of value to have an analysis of dose rates from unit emissions to individual landscape objects in the linked landscape model. To the extent that this can be justified on the basis of the hydrogeological calculations, the contributions from different objects can then be weighted with probabilities. SKB should also illustrate how the model resolution (the size of the different landscape objects) affects the dose and risk calculations. Additional comments on the LDF model are contained in section 13.5.

Distribution coefficients (K_d- values) are a conventionally used concept in dose and risk analyses for a repository. This applies in particular to analysis of long time periods when detailed physical-chemical processes may have considerable sources of uncertainty. Most summaries of K_d values indicate, however, that the ranges are large. This entails that only the best estimated values or intervals of K_d values either from literature sources or site-specific investigations (experimental or on-site collection) should be used. In SR-Can, SKB uses K_d data from previous safety assessments (SKB R-02-28) despite site investigations taking place for several years. The authorities consider like SIG and Xu et al (2008) that SKB should report in more detail for underlying documentation and justify the selection of K_d values as well as using site-specific K_d values at least for the nuclides which are assumed to produce the highest dose contributions in the biosphere.

10. Engineered barriers and spent fuel

10.1 Spent fuel and radionuclide chemistry

SR-Can has been based on a total of 9,300 tonnes of spent fuel being taken care of in the repository, of which 7200 tonnes is BWR fuel and 2300 tonnes PWR fuel. Moreover, there are smaller quantities of odd fuel types such as MOX fuel, fuel residues from Studsvik and Ågesta fuel, which, however, has not specially been taken into account in SR-Can. The burnup of existing fuel varies between 15 and 60 MWd/kgU. The calculations in SR-Can have been based on an assumed average burnup of 38 MWd/kg U, although SKB considers that the variations in the inventory do not significantly affect the result of the safety assessment.

The data for fuel which is directly linked with the safety assessment is the inventory when placing the fuel in the repository, radioactive half-lives, the proportion of the instantly released radionuclides and the long-term fuel alteration rate. Moreover, a method is included for selection of the nuclides which are of interest to include in the safety assessment.

Increase of burnup rate for spent fuel
Figure 1-3 in SKB TR-04-19 shows that a predominant part of the spent fuel accumulated between June 1998 and April 2003 has a burnup averaging around 40 MWd/kg U. It has moreover been forecast that the Swedish nuclear power plants can increase the burnup rate (up to 60 MWd/kg U, SKB personal communication). The authorities consider that this should lead SKB prior to SR-Site to carry out a more detailed analysis which sheds light on the effects of final disposal of fuel with a high burnup in a KBS-3 repository.

With an increased burnup, the radioactivity of the fuel also increases (SKB R-99-74). Although the differences in the nuclide inventory for fuel with different burnups are not especially large at the time of emplacement, radioactivity decreases more slowly for fuel with a higher burnup as well as the residual effect. The calculations in SKB R-99-74 show that the total activity in BWR fuel with a burnup of 38 and 55 MWd/kg U respectively differs by 18 % after 1,000 years. However, the difference increases to 38 % after 300,000 years. The increase in burnup also affects the radial distribution of radionuclides within the fuel, for example, effects of an increased content of actinides in the rim zone need to be taking into account.

The authorities' consultants Stenhouse et al (2008) consider that SKB should take into account international validation work that is taking place within OECD to increase the credibility of its inventory calculations. There is, inter alia, a need to evaluate uncertainties in the nuclide inventory for fuel with higher burnup.

The municipality of Östhammar (SKI dnr. 2006/985) points out that SKB has assumed an average burnup of 39 MWd/kg U, which is lower than the planned burnup of over 50 MWd/kg U. According to the municipality, this needs to be taken into consideration both in the safety assessment and in planning of cooling in CLAB.

The instant release fractions
SKB has presented instant release fractions for a number of radionuclides such as ^{14}C, ^{36}Cl, ^{79}Se, ^{90}Sr, ^{99}Tc, ^{107}Pd, ^{126}Sn, ^{129}I, ^{135}Cs and ^{137}Cs (SKB TR-04-19). Two of these (^{90}Sr and ^{137}Cs) have, however, no long-term importance due to their relatively short radioactive half-

lives. The instant release fractions consist of radionuclides in the gap between the fuel and the zirkaloy encapsulation (the gap inventory) and radionuclides segregated to the grain boundaries. However, SKB considers that the contribution from grain boundary inventory is very small. To estimate the total instant release fractions, the correlation with release of fission gases has been used for certain nuclides such as ^{36}Cl, ^{129}I and ^{135}Cs. Uncertainties about the instant release fractions are dealt with by establishing triangle distributions for all important nuclides through expert judgement based on available fuel leaching experiments and correlation with release of fission gases. Uncertainties are due, among other things, to the fuel's varying burnup but also other factors are important such as irradiation history and linear power ratings.

Stenhouse et al. (2008) point out that there is only a small amount of experimental data for SKB's method of defining the instant release fractions and that this data partly refer to CANDU fuel instead of PWR/BWR fuel. This limits the possibilities of obtaining statistics and distributions which are strongly based on experimental data. Johnson et al (2005) suggest an alternative and more conservative method where all nuclides which could eventually be available for the water phase without matrix transformation would be included in the instant release fractions. One reason to consider this more conservative approach is that it cannot be excluded that the nuclides accumulated in the rim zone could be released more quickly than what would correspond to the matrix transformation rate.

In a previous review of SKB's fuel programme, it was noted that the difference between the two methods for definition of the proportion of instant release fractions is relatively small if it is a matter of fuel with the burnup anticipated in SR-Can (SKI, 2007). However, the difference increases with increased burnup. The authorities consider that SKB should again analyse the experimental basis and assess how representative it may be assumed to be for an expected fuel from the whole Swedish nuclear power programme. According to the authorities, the forecast increase of burnup entails a need for more experimental studies focused on high burn-up fuel. Further studies of the instant release fractions should be considered in this context. The low instant releases for ^{76}Se and ^{126}Sn which SKB has used in SR-Can (based on leaching experiments) need to be better justified (SKI, 2007). SKB also needs to justify in some way the fractions of instant release for the limited quantities of MOX-fuel which is included in the Swedish programme.

Migration of fission products with non-thermal diffusion
Spent fuel which has been finally disposed of in a KBS-3 repository would probably not come in contact with groundwater until after very long periods of time. Radionuclides within the fuel matrix will during this period wander out towards the grain boundaries by diffusion. For this reason, experimentally measured instant release fractions are only valid if it can be show that migration processes produce a negligible contribution to the instant release fractions during periods of time of hundreds of thousand years. It has, for example, been suggested that radionuclides within the fuel matrix can diffuse more quickly with mechanisms such as alpha self-irradiation (Poinssot et al, 2002). According to Johnson et al (2005), the instant release fractions may need to be increased to 5 % for the period after 10,000 years if an upper limit for diffusivity is assumed (10^{-25} m^2/s). Stenhouse et al (2008) consider, however, that the improved state of knowledge today enables use of a less conservative value. The authors suggest 10^{-28} m^2/s as a reasonable conservative value, which means that the instant release fractions suggested by Johnson et al (2005) should be adjusted downwards. SKB dismisses completely the effect of migration processes within the fuel matrix based on a model of Olander (SKB TR-04-17). In this study, a diffusivity of 10^{-30} m^2/s is proposed on the basis of

an analysis of local thermal activation from alfa recoil. The authorities consider that SKB's report around this question is too brief and does not report to a sufficient extent the importance of conceptual uncertainties. A more transparent sensitivity analysis is also needed which provides justifications for cases in which migration processes can be completely excluded. The extensive work which has been made within the French programme, e.g. the PRECCI project (Poinssot et al 2001) can be a valuable complement to SKB's own studies.

Formation of helium gas
Formation of helium gas inside the fuel matrix or in existing fission gas bubbles may eventually cause an embrittlement of the fuel. Depending on the strength of the material and the existing porosity, this formation may entail a decomposition of the fuel which increases the size of the contact area between fuel and groundwater. The development of the size of the surface area needs to be taken into consideration when instant release fractions and matrix transformation rates are established. A number of studies of helium implantation have been carried out (SKB TR-04-19) and on the basis of this, SKB draws the conclusion that formation of helium gas does not affect the mechanical stability of the fuel. In the NF-PRO project, a model has been produced which shows that the effect of helium is small during a period of time of 10,000 years for a fuel with an average burnup of 47 MWd/kg U (Ferry et al, 2007). Stenhouse et al (2008) point out, however that the rim zone, which may be of special importance for high burnup fuel, has not been taken into account in this study. Radionuclides in closed porosity in the boundary zone should therefore according to the authors be counted as instant release. Further evidence should be obtained for SKB's conclusion that helium accumulation does not affect the fuel characteristics.

Matrix dissolution rate
SKB assumes that the release of radionuclides from the fuel after the instant release is proportional to the dissolution rate for the fuel matrix and the total inventory of the fuel. SKB suggests a constant dissolution rate throughout the whole time period for the safety assessment, based on a number of tests with dissolution of spent fuel and UO_2(s) doped with U-233 under reducing conditions. The rate described by a triangle distribution between a dissolution rate of 10^{-6} fractions per year to 10^{-8} fractions per year with 10^{-7} fractions per year as the most probable value. To support this, reference is also made to an electrochemical model which describes how H_2 formed affects the dissolution rate (SKB TR-04-20). Consequences of higher and lower fuel dissolution rates for advection/the corrosion outcome are reported in SKB TR-06-09 (page 440; from 10^{-4} to. 10^{-8} fractions per year).

The authorities' consultants Stenhouse et al (2008) consider that SKB's proposed matrix dissolution rates are reasonable and realistic. However, it is pointed out in the review that the justification of the rate distribution and handling of uncertainties are weak. According to the consultants, there needs to be further evidence in addition to an extrapolation of experimental data to show that the chosen rates are valid for the whole time period that the safety assessment covers. The authorities' consultants suggest that available conceptual and mathematical models should be evaluated and utilised to a greater extent, including models produced within the framework of EU projects. EBS notes also the great importance of the fuel dissolution parameter and recommends additional work in this area.

The authorities consider that SKB's research within the area is fit for the purpose and of a high scientific quality. Further research initiatives should be given high priority bearing in mind that the fuel dissolution rate is important especially if buffer erosion cannot be excluded in the future. The justification of the assumptions and handling of uncertainties should be addressed in a more complete way in SR-Site. It is important that there is a documented process understanding in the form of one or more specially identified models, which provide a sufficient basis for extrapolation of experimental results for long time scales. Expected time dependencies for dissolution processes should also be included in the analysis. Effects of burnup need to be further investigated bearing in mind the forecast gradual increase of burnup. Some form of model also needs to be produced for dissolution of MOX-fuel.

The structure and characteristics of the fuel can change due to the impact of dissolution and precipitation processes (see also formation of helium gas above). Even if the extent of these processes is small, this could lead to a structural decomposition of the fuel which provides a considerably greater contact surface between fuel and groundwater. SKB should describe the consequences of this.

Since the fuel parameter is to apply for very long time scales (up to a million years), it cannot be excluded that an extensive decomposition of the insert and shell will take place during this long period and that the buffer will perhaps no longer exist. Evolution of chemical and hydrological parameters may therefore deviate from the prerequisites that SKB's model has been based on, e.g. hydrogen gas from the insert's corrosion may have disappeared and a larger groundwater flow may be close to the fuel in certain deposition holes. The authorities consider that it should be stated more clearly in SR-Site than in SR-Can that a relevant connection has been made between the analysis of the evolution of the repository and the assessment of the fuel matrix dissolution in different time scales.

As pointed out by Stenhouse et al (2008), radiolysis may after tens of thousands of years have completely ceased to play a role as a driving force for dissolution. The authorities consider therefore that other slower dissolution processes which may provide a contribution to release of radionuclides should be identified, analysed and discussed in SR-Site. Other minerals which contain U(IV) can be formed from the fuel (coffinite formation, recrystallisation), and U(IV) may be sorbed in the near-field (e.g. on corrosion products). In SKB R-06-76, there is a short discussion on modelling of this case, although it seems otherwise not to have been implemented or taken into account in SR-Can.

To conclude, the authorities consider that a more transparent model structure is needed in SR-Site which shows that relevant FEP which can affect the fuel evolution in different scenarios have been taken into account and dealt with. It also needs to be shown more clearly for different time scales how the fuel dissolution rate which is used relates to controlling processes and the evolution of the repository environment.

Analysis of the risk of criticality
SKB has conducted calculations of neutron multiplication factors (K_{eff}) for different configurations of the fuel to determine the risk of criticality. Criticality is excluded for an intact canister by a wide margin. A water-filled BWR canister is sub-critical also for fresh fuel while a water-filled PWR canister with fresh fuel does not comply with SKB's criticality criterion (K_{eff}<0.95). However, if the burnup crediting is taken into account, the criterion is also met for sufficient burnt-up PWR fuel. Exactly which burnup is needed depends on the fuel's enrichment and the nuclides taken into account in burnup crediting. In the first place, the existence of U, Pu isotopes and ^{241}Am is taken into account. Additional margins are obtained if other actinides and fission products are included. Certain uncertainty analyses have also been carried out to ensure a particular safety margin in relation to the criticality criterion. The risk of criticality in connection with a redistribution of nuclides after a canister

failure is not discussed in more detail in SR-Can. However, there are references to previous studies (Behrenz and Hannerz, 1978; Oversby, 1998) where it is noted that the risk of criticality outside a canister is negligible. To sum up, SKB considers that the risk of criticality is negligible. However, SKB intends to study how the risk of criticality is affected by major defects in the insert's partitions (SKB R-06-02).

In SKI's regulations SKIFS 2004:1 (Section 2, Chapter 6), it is evident that measures shall be undertaken to prevent criticality in connection with handling and storage of nuclear material (for the time before sealing of the repository). For the time after sealing, it should be shown that criticality cannot arise in the original configuration and that criticality due to redistribution is very improbable (SKIFS 2002:1).

The authorities consider that SKB has carried out a good investigation around the risk of criticality in a damaged canister (SKB TR-02-17), but notes at the same time that there is no approved method for burnup crediting. However, work is in progress and a continued dialogue is therefore motivated on the demands that can be made on reporting in SR-Site. According to the authorities, a continued dialogue can aim at clarifying the method for showing compliance with requirements, e.g. which nuclides that can be taken into account in burnup crediting and the possible need for a higher degree of traceability for handling uncertainty. A special scenario where consequences of criticality are described would be needed if it is not possible to show a margin when uncertainties are taken into account. SKB should in its analyses, in addition to existing fuel in CLAB, also take into account spent fuel which is generated during continued operations in the Swedish programme. This includes the odd fuel types such as spent fuel from a permanently closed reactor, more reactive fuel, damaged fuel and use of fuel with a higher degree of enrichment.

Regarding the risk for criticality due to altered geometry and redistribution of fissile material, the authorities consider that future accounts need to be more explicit and pedagogic. The most important arguments need to be summarised in the SR-Site report. One possibility is to hypothetically analyse what would be required to reach criticality in different time scales and thereafter, based on understanding of solubilities, transport processes etc., assess the realism of such a case. The account should reflect as realistic conditions as possible regarding e.g. the properties of the fuel, the canister geometry and new findings regarding buffer erosion.

Solubility limits
There is a solubility limit for radionuclides released from the fuel matrix since components with sufficiently low solubility will form new solid phases. SKB has carried out solubility calculations based on four different types of groundwater (SKB TR-06-32). SKB has evaluated solubilities close to the fuel surface based on a thermodynamic database (SKB TR-06-17) and groundwater chemical parameters. SKB has identified possible solubility-limiting phases and has made a conservative selection based on expert judgement. The results from calculations have been compared with concentrations in natural groundwater and concentrations in tests of spent fuel. There is also a summary of other studies of radionuclide solubilities, which have been produced in other countries' nuclear waste programmes. SKB has established distributions for the solubility limits, which have subsequently been implemented in radionuclide transport calculations.

EBS calls into question whether uncertainties in groundwater chemistry are more important than uncertainties in thermodynamic data or uncertainties on which solubility-limiting phase that can be expected to form.

The authorities' consultant Stenhouse et al (2008) consider that SKB should make a more complete uncertainty/sensitivity analysis which involves an evaluation of the importance of uncertainties in thermodynamic data. The consultants also consider that a more detailed discussion is needed on the importance of uncertainties in deriving solubility limits. Statistical methods should to a greater extent be used as a complement to expert judgement in the assessment of uncertainties. The consultants' independent calculations (which are reported in an annex to Stenhouse et al, 2008) show that uncertainties in thermodynamic data have greater importance than the variation of the groundwater chemical parameters which SKB assessed in its model study. However, it is emphasised that the uncertainty intervals used by the consultants in the independent study are preliminary and that more realistic uncertainty intervals could change the situation. The consultants have through calculations assessed the importance of uncertainties in groundwater chemistry for the solubilities of americium and neptunium and the results are very close to those estimated by SKB.

Stenhouse et al (2008) also note certain problems in the supporting thermodynamic database for thorium and plutonium. The consultants have, for example, noted that the importance of hydroxicarbonate complexes for thorium and phosphate complexes for plutonium is uncertain. The consultants point out that the analogy between americium and plutonium must be regarded as uncertain since data for americium phosphate complex is also very limited. Another deficiency is that the formation of colloids caused by a polymerisation of plutonium has not been discussed. The authors also consider that the handling of solubilities at higher temperatures needs more work.

The authorities consider that SKB has substantially carried out good studies of radionuclide solubilities in the repository environment (SKB TR-06-17, SKB TR-06-32). It is positive that previous review comments from the authorities have been followed up and largely responded to. The comparisons made with measurements of natural groundwater systems and fuel experiments are also positive elements contributing to the credibility of the calculation results, even if additional measures may be needed to explain the cases where there are large differences between observations and calculation results. The authorities agree with Stenhouse et al (2008) that it would be of value if SKB had access to a method for explicitly analysing the importance of uncertainties in thermodynamic data. Exactly how much input are needed for uncertainty and sensitivity analysis for different nuclides can, however, to a certain extent be adapted depending on how important a specific solubility limit is for the result of the safety assessment.

The authorities consider that SKB should update and develop the thermodynamic database so that it at important times represents a current picture of the state of knowledge in radionuclide chemistry. The database with reporting of solubilities for sulphur compounds must be regarded as insufficient in particular as it directly affects the analysis of the canister integrity (see also sections 11.9 and 12.4). Since the sulphur redox chemistry is important in many other contexts, there should be a considerable number of published scientific studies available. The authorities find it difficult to assess the need of studies of radionuclide chemistry at higher temperatures than 15°C, but the studied temperature interval and the extent of the effort should at any rate be adjusted according to the estimated probability for canister failure during periods of increased temperature.

Co-precipitation of radionuclides
Co-precipitation of a radionuclide means that radionuclide retardation can take place at lower concentrations than those corresponding to the radionuclide's own solubility limit. This would be determined by interaction with other solid phases apart from the pure phases that incorporate the specific radionuclide. SKB considers in feedback from SR-Can that co-precipitation of radium and barium need to be further investigated. A calculation example is reported in SKB TR-04-11 which shows that co-precipitation of ^{226}Ra has a potential to considerably reduce the doses. However, it does not have to be conservative in all cases to exclude co-precipitation. One calculation case is reported for advection/corrosion case (SKB TR-06-09, page 438) which shows that the doses would be higher if thorium plays a part in a co-precipitation process within the canister.

EBS considers that co-precipitation is a well-known process in natural systems and it is therefore probable that it occurs in the near-field of a repository for spent nuclear fuel. A more detailed report is therefore needed of SKB's reasons for including or excluding this process in future safety assessment.

The authorities' consultants Stenhouse et al (2008) consider that it is well established that amorphous mixed phases of alkaline earth metals exist and that these will also probably be formed close to a repository for spent nuclear fuel. Even if radium will probably be undersaturated with respect to $RaSO_4$(s) with up to several orders of magnitude, these authors consider that it is good that SKB conservatively has used the pure sulphate phase for radium in SR-Can. An important question for the stability of mixed sulphate phases of alkaline earth metals is whether the sulphate-reducing bacteria can reduce the sulphate contents and increase the solubility.

The authorities consider that SKB should describe co-precipitation processes in a better way prior to SR-Site and consider a more detailed treatment of this type of processes. The case with co-precipitation of thorium shows that it is not conservative in all cases to neglect this process. It should be clear that identification of such cases is a result of a structured process. Even if it can be shown with a high level of certainty that co-precipitation can be neglected conservatively, this process should not be excluded without investigation of whether there is a potential to substantially affect the dose. To be able to assess the importance of different measures to reduce the dose load in very long time scales as well, great conservatism in the analysis needs to be identified and discussed. An excessively large element of pessimistic assumptions in the safety assessment may make it difficult to assess different measures to optimise the repository.

10.2 The canister

The canister consists of an inner insert of cast iron and a surrounding copper shell. In SR-Can, it is described in most detail in the report on the initial state (SKB TR-06-21, Chapter 4). Certain additional information is also available in the data report (SKB TR-06-25), for example, concerning the initial copper coverage. SKB has also produced a preliminary technical documentation of the canister in the Dokap project which takes up, inter alia, design prerequisites, manufacture, welding and sealing, non-destructive testing and programmes for qualification of manufacture and sealing (SKB R-06-01 up to and including SKB R-06-07).

In this section, the authorities comment on certain particularly important aspects for the safety assessment of the canister's expected characteristics at the time of emplacement in the repository. Processes linked to the evolution of the repository after emplacement is commented on in Chapters 11 and 12 on the initial and long-term evolution of the repository (e.g. creep and corrosion characteristics).

Canister manufacturing
SKB reports on manufacture of canister components in SKB R-06-03. As reference method for manufacture of copper pipes, SKB has chosen extrusion, but also pierce and draw as well as forging have been developed. These methods are based on cast copper ingots. The copper lid and base have been manufactured by forging. The inserts are manufactured from cast iron and three different foundries have been used. Since the insert is pressure-bearing, high demands have been made on good knowledge of the strength characteristics.

The authorities' consultant Bowyer (2008) points out that uncertainty concerning the composition and microstructure is greater for the insert than for the copper shell. Casting of the insert is regarded as a sensitive procedure which may have a great impact on quality. Segregation of different alloy substances can entail that ductility varies within broad limits, which has also to be noted in SKB's programme. Bowyer (2008) considers that this effect has not been investigated sufficiently. According to Bowyer (2008) it is not possible to rely solely on additional manufacturing experience to solve this problem. More work is therefore required to investigate whether the variation of strength characteristics is acceptable and if it also represents blocks with the poorest characteristics. Acceptance criteria for manufacturing defects also need to be produced.

The authorities' consultants Hicks and Baldwin (2008) point out that SKB in the data report only discuss defects in the sealing welding and not other defects from manufacture. In the data report, it is evident that standard handbooks are used to obtain data for the basic characteristics of copper. However, it should always be clear for reasons of traceability which sources have been used.

The authorities have monitored SKB's development work with the canister for a number of years and can note that there are now methods to manufacture canister components. The choice of material for canister components is also considered to be appropriate for its purpose. Specification of grain size intervals for copper is based on too limited basis, however, and needs to be verified by more tests. SKB has been successively informed about various problems identified during the review work of the authorities, which has been largely documented in an SKI investigation report (SKI dnr. 2006/109/20070105).

According to the authorities the reliability of the manufacturing methods in series fabrication needs to be specially investigated bearing in mind the considerable importance for safety of the canister and the narrow tolerances specified. While SKB has already today manufactured a considerable number of canister components, it is still not possible to obtain information about reliability in the form of the proportion that complies with pre-defined quality requirements. Effects of handling damage and cold working which may occur also need to be further investigated.

Sealing of the canister
SKB reports on the sealing methods, which have been developed for welding of the lid and the base (SKB R-06-04). SKB has chosen FSW ("Friction Stir Welding") as its reference method for sealing of canisters since this method is very reliable. EBW ("Electron Beam

Welding”) is also being further developed to have, if possible, two usable methods for sealing. SKB also reports on how the sealing method is to be qualified.

The authorities consider that FSW is a robust method with good repeatability in series fabrication. With respect to EBW, quite a lot of development work remains to be done before the same degree of robustness is achieved as for FSW. EBW functions in very narrow parameter intervals, which means that small changes may lead to major deteriorations in welding quality. The authorities consider that further development is also required for FSW, inter alia, to obtain a better lifetime for the welding tool and to automate the process and improve its efficiency.

EBS considers that SKB should produce a better basis for rewelding defective weld joints. It is not evident that rewelding of defective weld joints produces the same result as two consecutive weldings for one segment of the canister.

The authorities’ consultant Pettersson (2008) considers that SKB should investigate the effect of very fine-grained sections of the FSW weld if this cannot be excluded by some margin.

The municipality of Oskarshamn (SKI dnr. 2006/985) considers that it is crucially important that SKB shows that welding can be carried out in such a way as to comply with the requirements for sealing and strength.

SKB includes in the data report (SKB TR-06-25) a predicted initial copper coverage for the 4500 canisters which are to be emplaced in the repository. This prediction is based as far as the authorities understand it on welding results obtained to date and on the extreme value distribution “(”Generalised Extreme Value Distribution”), the application of which is exemplified in Appendix 2 of SKB R-04-56. However, it is evident in the main report for SR-Can that SR-Can was based on 6,000 canisters to cover uncertainties in the Swedish nuclear power programme. The authorities have not been able to identify any report containing documentation of the calculations referred to.

Experiences from FSW show that five types of welding faults have occurred to date, which are joint line curvature in the weld root, internal cavities, pore accumulations, oxide inclusions and metal inclusion. The authorities consider that SKB in SR-Site should clarify for each of the welding faults which may occur how the development of the canister could be affected and how the welding faults have been treated in the analyses. Conceivable effects on the safety functions C1-C3 should be discussed.

The authorities consider that there are prerequisites for SKB to develop the FSW welding method to a level which is acceptable for future licence applications. Studies of the characteristics of the weld joint, weld quality with respect to any defects and comparison of the characteristics of the joint with the basic material are, however, necessary to provide sufficient input data for the safety assessment.

Design basis
SKB has reported a design basis for the canister which specifies the requirements that the canister is to meet (SKB R-06-02).

EBS points out that SKB’s design basis for the canister (SKB R-06-02) lack requirements for safety margins in relation to load cases and rupture mechanisms for the canister. The group further considers that a damage tolerance analysis of the canister should be carried out which may have both deterministic and probabilistic elements. The damage tolerance analysis should include embrittlement of the copper shell, different sizes and locations of defects, residual stresses in the weld as well as different shear load cases. A similar damage tolerance analysis should also be carried out for the insert.

The authorities consider that the design basis presented by SKB to date is incomplete. The design basis should normally include information on loads and load combinations both during normal operating conditions and expected disturbances, which should be specified in the main scenario of the safety assessment as well as the less probable scenarios. It needs also to be roughly specified what occurrence frequency the various scenarios account for. Load cases are to be included which relate to handling of the canister, e.g. if the canister is dropped during lifting or transport. The design basis shall also include acceptance criteria for different variables where different safety margins are defined. The design basis may include both deterministic and probabilistic criteria.

Moreover, certain remaining requirements for the different materials of the canister as well as certain detailed geometric tolerances which are important for the manufacture of the canister are lacking. Information is also lacking on the largest permitted defects in different parts of the canister which are important for production inspection.

It should also be pointed out that there is lacking of a complete design analysis of the canister containing a dimensioning of the canister and a summary of the structural integrity analyses which have been carried out with reference to the current design basis. SKB should produce an integrated design analysis of the canister including safety margins that supports long-term safety as an important basis for the application to build the repository. At present, the structural integrity analyses are spread over a number of reports and it is not clear which analyses that SKB considers apply and which analyses are considered to be outdated.

Non-destructive testing of welds and canister components

SKB has reported a programme for non-destructive testing (NDT) of canister components (SKB R-06-05) and welds (SKB R-06-06). SKB describes, inter alia, the NDT methods that are to be developed, reliability studies, and programmes for qualification. There is equipment in the canister laboratory at Oskarshamn for testing the sealing welds by X-ray and ultrasonics. Experiments have also been made with several testing methods for testing of the copper pipe, the cast iron insert, and copper lids and bases.

The municipality of Oskarshamn (SKI dnr. 2006/985) considers that non-destructive testing is of crucial importance to ensure that the requirements on the canister are met. The municipality of Östhammar (SKI dnr. 2006/985) also put forwards similar points of view and especially underlines the importance of a strategy to ensure continuity for procedures and equipment over more than 60 years.

The authorities have continuously monitored SKB's work and informed about their view on inspection arrangements, qualification and independent inspection in the form of third-party inspection, which is documented in an investigation report (SKI ref. no. 2006/109; 2006-07-05). The authorities wish particularly to emphasise the importance of connecting the detection requirements and qualification targets of the NDT systems to the basis for the design with choice of materials, load supporting documentation and strength analyses as well as the possible defects and damage that can occur during manufacture.

In the investigation report (SKI dnr. 2006/109; 2006-07-05), it is proposed that the authorities should review the basis for testing qualification. The authorities wish to make this more exact by specifying the following points in the areas which SKB needs to further develop or clarify in its report on qualification order. These areas apply both for systems for testing of the sealing weld and for systems for testing of other canister components.

1. A qualification process needs to be developed where the parts and elements involved are defined. The process needs to include how system qualification is planned with respect to qualification of technology, equipment and personnel as well as how this is to be done (premises, secrecy, etc.) and which main documents will serve as the basis for qualification (procedures and technical justifications). This process also needs to describe how re-qualification is handled, for example, to which extent the system is reviewed and re-qualified and how often this is intended to take place. SKB needs to clarify its role in building up and maintaining expertise at the qualification body.
2. The importance of 60 years of operation and the wear and tear that may arise and system verifications which need to be done and the variables that are involved and affected by this.
3. An analysis of the number of defects and test blocks and which type of simulated defects which may be needed in a qualification as well as how the defects need to be configured in the test blocks (type, size, inclination, turning) for the qualification to be able to show the reliability/detection probability of testing with sufficient confidence (the detection probability and confidence need to be higher than present qualifications at nuclear power plants for recurrent inspection). One way of showing this is to define a "worst case" defect which a qualification shows that the system can detect at, e.g. POD=0.9 at 95 % confidence. Reasoning about which detection probability and which confidence the detection systems can cope with needs to be included in the account.
4. To what extent will the models be used as a complement to the practical experiments in the technical justification and how these models are validated.
5. Further analyses of defects that may arise in manufacturing processes and welding in order, together with other analyses, to arrive at a minimum defect size which the respective testing system is to cope with.
6. A clearer reasoning on how surface testing is to be used and which testing methods are intended to be used for this purpose.
7. Analysis of Man Technology Organisation factors and their effect on detection probability as well as the role of these factors in a qualification.
8. A reasoning on how often periodic inspections (calibrations) need to be made of the respective NDT system.
9. A reasoning and a description of requirements on the non-destructive testing systems at the respective sub-contractor if this testing is also to be credited
10. How surrounding world monitoring and feedback of experience with respect to technical development is intended to function during the period of operation of other NDT systems and how such information can entail updates of the systems.

10.3 Buffer/backfill – manufacture, initial state

Choice of material and specification of requirements for the buffer and backfill
SR-Can has been based on two types of bentonite as reference material for the buffer, partly MX-80 which is a natural sodium bentonite from Wyoming, USA, and partly Deponit CA-N which is a natural calcium bentonite from Milos, Greece. Two different concepts for backfill have been assessed, pre-compacted blocks of Friedland clay, and pre-compacted blocks of a mixture of 70 % crushed rock and 30 % bentonite of buffer quality. Friedland clay is a natural swelling clay which has a lower fraction of expanding clay mineral. During SKB's presentation of SR-Can, it emerged in the analysis that the 30/70 mixture has significant disadvantages compared with Friedland clay and that this alternative is therefore not fully taken into consideration. The function indicators specify requirements for buffer and backfill (SKB TR-06-09, page 191). Examples of requirements are maximum hydraulic conductivity, minimum swelling pressure, maximum and minimum density respectively (the latter only for the buffer). In SKB TR-06-21, the mineralogical composition of the buffer material is specified, which, however, is not formulated as a requirement.

MKG (SKI dnr. 2006/985) considers that more development work is needed to test the bentonite buffer before the final choice of bentonite clay is made.

The authorities consider that the report on which the choice of material is based is brief and limited. However, there is an understanding that the gaps in knowledge relating to buffer erosion, which have been drawn to attention by SKB, have made complete reporting impossible already at the time of SR-Can. However, the effects of the rather large differences in mineralogical and chemical composition between MX-80 and Deponit CA-N should be clarified prior to SR-Site. Some examples that differences may have an effect are: abundance of Ca^{2+} should be able to reduce the risk of buffer erosion, the presence of pyrite and siderite provides a higher capacity to consume intrusive oxygen, a high sulphide quantity is possibly a disadvantage from the point of view of corrosion, and abundant access of Fe^{2+} from siderite may possibly during a period entail reduced concentrations of dissolved sulphide. SKB should formulate concrete requirements on the mineral and chemical composition of the buffer material and possibly state whether there are maximum permitted quantities for components which may have a negative effect on the buffer (i.e. impurities). Moreover, it may come into question to investigate and assess more materials. Relatively extensive efforts are needed, however, for new material for characterisation and long-term tests to achieve the same level of knowledge available for MX-80 which has been SKB's reference material for a long time.

It is evident in SKB TR-06-21 that the state of knowledge for backfill is poorer than for the buffer. The authorities consider that considerable work related to material characterisation will also be needed if Friedland clay or other materials which significantly differs from MX-80 will be chosen. SKB should state which analyses and tests that need to be done to show that the material complies with all applicable requirements. The advantages and disadvantages of alternative materials need to be reported as part of showing compliance with BAT and optimisation requirements.

The authorities consider that there are certain questions about the extent to which SKB's specification of requirements for the buffer is sufficiently detailed concerning the mechanical characteristics. In SR-Can, SKB uses buffer density as a single criterion for shear load. This assumption is based on a model where shear strength of bentonite depends on the bentonite's swelling pressure which in turn depends on the bentonite's void ratio (SKB TR-04-02, equations 3-1 and 3-2, page 12). This simplified model has, however, a limited application and an unclear physical significance (SKB TR-97-31, page 5). In SKB TR-97-31 a number of other models for the bentonite's swelling pressure are reported which show that this is a complex relationship which is controlled by different physical and chemical factors. In SR-Can, SKB has not excluded that cementation of the buffer can take place. This can as far as the authorities understand change the buffer's stiffness without significant changes of the density.

The backfill needs to provide a sufficient counter pressure to counteract the vertical expansion of the buffer in the deposition holes. SKB has previously stated a compressibility condition (M>10 MPa) for a backfill consisting of bentonite and crushed rock (SR-Can interim report TR-04-11, page 124), which, however, is not discussed in the SR-Can main report. The authorities consider that SKB in SR-Site should more clearly report how the requirements for compressibility affect the choice of material and design of the backfill.

Manufacturing of the buffer and the backfill
The authorities' general judgment is that SKB has already demonstrated that a full-scale manufacture of the buffer with block and rings is possible without obvious problems. This manufacture has, however, been based on uniaxial pressing rather than on SKB's reference method isostatic pressing. It also involves relatively few copies which have been manufactured for tests at the Äspö laboratory. The authorities consider therefore that further test manufacture may be needed to show that the requisite quality can be achieved in circumstances that more resemble series fabrication. Geometric tolerances and clear acceptance criteria for bentonite blocks should then be provided and applied.

In the SR-Can initial state report (SKB TR-06-21, page 44), there is a preliminary definition of different elements which needs to be included in a quality assurance programme for the buffer. The authorities consider these descriptions to be a good beginning but they are at present too brief. Further work is needed to produce a quality programme for buffer manufacture. A discussion is also needed on the deviations that may occur in the manufacture and the importance that such deviations may have for the long-term safety, e.g. unintentional heterogeneous conditions in the buffer.

The authorities' view on the buffer to a large extent also applies for backfill although the functional requirements are generally less demanding in the latter case. The authorities consider that SKB refers to a rather untested method for backfill with compacted blocks, which means that there may be unknown problems concerning the full-scale implementation. SKB should in SR-Site develop a more complete method for manufacture of compacted blocks. SR-Can only contains a very brief description of manufacture and control of blocks with 30 % bentonite and 70 % crushed rock, which does not seem to be SKB's first-hand choice.

Installation of the buffer and the backfill in the repository facility
The authorities consider that SKB has shown that installation of a full-size buffer is in principle possible through the tests carried out at the Äspö laboratory. However, this is a matter of limited handling carried out with partly differing prerequisites than in a future operation of a repository. SKB should therefore attend to the difficulty of achieving high quality under the more demanding conditions that exist for routine operation, e.g. remote-operated emplacement at the rate needed for a real emplacement sequence.

MKG (SKI dnr. 2006/985) considers that differences in the characteristics of the rock between the two investigation areas must be assessed in the use of the results from the test emplacements carried out at the Äspö laboratory.

EBS considers that SKB has still not presented a sufficient amount of information to ensure that emplacement of buffer and canisters can take place in an appropriate way in real conditions. The group is not either convinced that measures to protect bentonite blocks during emplacement are sufficiently reliable. More information is also needed about the possible emplacement of bentonite pellets.

The municipality of Oskarshamn (SKI dnr. 2006/985) calls into question whether there is sufficient time to develop and test the bentonite barrier before SR-Site. MKG (SKI dnr. 2006/985) wonders how the tunnel backfill can take place in a safe way and how canisters which have been placed in position can be retrieved bearing in mind the intense radiation environment at the emplacement site. MKG considers further that full-scale tests are needed with backfill of deposition tunnels and access tunnels before the application is submitted.

The authorities consider that the description of the practical handling of the buffer, including routines for quality assurance, is too briefly reported in the initial state report (SKB TR-06-21). In the same way as there is a well-developed programme to ensure that a sealed canister meets the requisite quality requirements, there should be specified methods to verify and ensure that a deposited package with buffer and canister is correctly placed within established geometric tolerances (in the initial state report SKB TR-06-21 only photography is mentioned). It should however be noted that the requirements for verification of the state of the buffer and the backfill to a certain extent can be adapted to the importance for safety which is not yet firmly established. Given that the average density of the buffer is affected by the volume of the deposition hole and the characteristics of backfill, a link is needed to the verification of the backfill and the geometry of the individual deposition holes.

11. The initial evolution of the repository

In this chapter, critical issues are discussed for the initial evolution of the repository during the first thousands of years during the phase when temperate climatic conditions are maintained. The evolution of the repository in connection with major climate changes such as permafrost and glaciations is discussed in Chapter 12.

11.1 Temperature calculations

SKB has calculated maximum temperatures in the near-field with an analytical model and a numerical model, the result of which show good agreement (SKB TR-03-09; SKB R-04-36). Maximum temperatures are affected by the residual heat from the canisters and the distance between deposition holes. The applicable criterion in SR-Can refers to the temperature in the part of the buffer which is closest to the canister (the function indicator Bu5 which should be at most 100°C). At the selected canister distance (6 m for Forsmark and 7.2 m for Laxemar), the maximum temperature will be around 80°C in the normal case. A probabilistic simulation that takes into account variability of the rock's thermal conductivity shows a range between 75-85°C for the inner boundary of the buffer. This entails a safety margin of over 10°C also for the worst canister positions. In SR-Can (SKB TR-06-09), temperature calculations are reported in section 9.3.4. The authorities base their review in the first place on independent calculations to assess maximum temperatures carried out by Rutqvist and Tsang (2008) and Maul et al (2008), which produce similar but not identical results.

A difficulty in the modelling of the thermal evolution is that the temperature close to a particular deposition hole is not only affected by the heat evolution from that canister but also receives contributions from other canisters in the near-field. Maul et al (2008) consider that there are unclear points with respect to how SKB represented the layout of the repository and the contribution from other canisters. The model studies carried out by Maul et al (2008) give approximately 5-10°C higher temperature than SKB's corresponding simulation. The probabilistic calculations that represent variability in the rock's thermal conductivity have also been reproduced. These also indicate higher average temperature although the spread interval is the same as for SKB (around 10°C).

Rutqvist and Tsang (2008) have carried out temperature calculations with the THM-coupled ROCMAS code. These produce a slightly lower temperature for the basic case compared with SKB's corresponding analysis. For a simulated case with a very dry rock, the temperature will be higher than SKB's, however, which is due to the coupled code simulating a drying up of the buffer closest to the canister. Rutqvist and Tsang (2008) therefore consider that SKB should more closely investigate the risk of an extreme drying up of the buffer closest to the canister. If the thermal diffusion coefficient is higher than expected, there is a risk of drying corresponding to a degree of saturation of less than 20% and the temperature will then rise to more than 100°C. The experimental basis for determination of the thermal diffusion coefficient seems to be limited and not wholly representative of field conditions (Rutqvist and Tsang, 2008). Additional experiments to determine this parameter may be justified.

The authorities consider that it is not evident that conservative values on the emissivity of the copper shell have been used for calculation of the transmission of radiation heat in SR-Can, in particular bearing in mind inconsistencies compared with previous reports (SKB TR-03-09;

see Annex B2.4). Emissivity and radiation heat are important for the period before the gap between the buffer and the canister has been sealed due to the swelling of the buffer. This can therefore be an additional important issue for the deposition holes with very slow inflow of groundwater from the surrounding rock. SKB should also review the documentation and adequacy of material data for the buffer and backfill material prior to SR-Site.

The authorities consider that SKB's current method for handling temperature evolution is a good basis for SR-Site as well. However, there are reasons to carry out certain supplements, such as assessing in more detail effects of dry conditions in the rock. Given the fact that the maximum temperature is achieved a relatively short time after emplacement, there is a link to processes such as a possible drying-out of the buffer, transmission of radiation heat and thermal spalling (see section 11.5).

The maximum permitted temperature for the buffer affects the distance between the deposition holes, which is an important variable to optimise bearing in mind requirements for economical and efficient use of resources. The authorities consider therefore that it is important that SKB can show that the calculations have sufficient precision and represent the actual site-specific conditions well. This is particularly relevant for the Laxemar rock bearing in mind its lower thermal conductivity. One possible measure is, for example, more extensive comparisons between analytical and numerical calculations to verify the precision of the calculations (compared with SKB R-04-36).

The authorities consider that SKB should clarify its method relating to use of the temperature criterion including safety margins. A more complete argumentation around the effects of increased temperatures is needed to justify the limit value (see section 5.2 in this report).

11.2 Resaturation of the buffer and backfill and evolution of swelling pressure

SKB has carried out simulations of the resaturation of the buffer and backfill for conditions which are representative for Forsmark and Laxemar (SKB TR-06-14). The calculations have been carried out with ABAQUS code and Code Bright, of which only the latter can handle two-phase flow. If the rock has a relatively high hydraulic conductivity ($K_{rock} > 10^{-12}$ m/s), it is only the characteristics of the buffer and backfill that control the time for resaturation. The time for full resaturation will then be a few years. A more difficult case to analyse is if the rock has a relatively low conductivity ($K_{rock} < 10^{-12}$ m/s), since the more uncertain conditions in the rock will then be controlling. SKB's calculations indicate that the time until full resaturation of the buffer can vary from some tens of years to at most hundreds of years in the latter case. In the case of the deposition holes, which are not linked with a water-conducting fracture, SKB assumes that the matrix water will make a considerable contribution to resaturation. The rock should have a K-value of around 10^{-14} to 10^{-13} m/s, otherwise, the resaturation times will be considerably longer than those stated above. SKB states that the period with unsaturated conditions is not expected to affect the bentonite negatively and points out that this is a normal state for bentonite formations in nature.

The swelling pressure in the buffer develops during the resaturation phase and reaches for a reference case around 8 MPa for both the buffer materials (MX-80 and Deponit-CAN). The swelling pressure in the backfill reaches around 3 MPa at a salt content that corresponds to seawater. When the swelling pressure in the buffer is fully developed, the backfill will be compressed and the buffer may intrude slightly into the deposition tunnels (4-40 cm). The extent is affected by the in-situ density of the materials and friction between the rock and the bentonite. SKB's result indicates, however, that reasonable variations only marginally affect density and swelling pressure in the buffer.

The municipality of Oskarshamn (SKI dnr. 2006/985) points to the need of research on resaturation. MKG (SKI dnr. 2006/985) considers that the very dry rock at Forsmark deviates from the conditions that the KBS-3 method was developed for and this means time-consuming research linked to the swelling of the bentonite.

Independent calculations carried out by Rutqvist and Tsang (2008) with the ROCMAS code produce results that agree with SKB's if the rock has a high hydraulic conductivity. In the case of a rock with low conductivity, the calculated saturation periods are much longer than SKB's (even up to 30,000 years for a rock with an average hydraulic conductivity of 10^{-13} m/s). Rutqvist and Tsang (2008) consider that this discrepancy is linked to SKB's assumption of a boundary condition with constant pressure at the distance 12 m. Rutqvist and Tsang (2008) further point out that the rock's hydraulic retention curve can affect the course of resaturation in an important way. The consultants point out that SKB's analysis does not seem to have taken this uncertainty into account sufficiently.

The design of the backfill may be important to ensure resaturation of the buffer in deposition holes and the deposition tunnels without water-carrying fractures. According to Rutqvist and Tsang's calculations (2008), no complete resaturation of the buffer from backfill water takes place in the case of Friedland clay at the selected initial moisture content. However, for the case of backfill consisting of a 30/70 mixture buffer resaturation was estimated to be completed. A complete resaturation from Friedland clay would, however, be possible at higher initial moisture content.

An additional case that needs to be taken into account is if a buffer is located in a deposition hole with a water-carrying fracture, but if no water carrying fractures cross the adjacent deposition tunnel. This could possibly lead to an unfavourable upward intrusion of the buffer material in the backfill. SKB plans to carry out a large-scale test to study this case.

The authorities consider that SKB should analyse the course of resaturation in more detail for very tight rock types that primarily come into question for Forsmark. SKB should better investigate and justify the handling of boundary conditions as well as justifying its conclusion that matrix water can provide a significant contribution to the resaturation. If a very slow resaturation of the buffer and/or backfill cannot be excluded, this means that the function indicators Bu1, Bu3 and/or BF1b will not be complied with until after a very long time. Conceivable effects of this need to be identified and handled, for instance, that gaps can remain, that certain microbial activity cannot be excluded due to lack of swelling pressure, and that drying of the buffer can take place.

The authorities note that SKB limited its analysis to a maximum of 3.5 % salt content in the surrounding groundwater. It needs to be verified that this limitation is reasonable given the risk of upward movement of groundwater with a very high salt content from great depths.

11.3 Initial load on and deformation of the canister

A swelling pressure is developed when the buffer takes up water during the saturation phase and the hydrostatic pressure also returns during the same period to normal values for the repository depth. The isostatic load on the canister can be estimated as the total of the fully developed swelling pressure and the hydrostatic pressure (around 13 MPa). An uneven pressure on the canister can arise if the swelling pressure is not uniform. These load cases are linked to the safety functions C2 and C3. The authorities consider that the isostatic load during temperate conditions is far below the level that would damage the canister. The isostatic load case is dealt with instead in section 12.7 on glacial conditions since the hydrostatic pressure may then be considerably higher. This section addresses the uneven mechanical load on the canister due to the swelling pressure of the buffer as well as the deformation of the copper shell by creep.

There may be an "inhomogeneous" evolution of pressure around the canister on the swelling of the buffer. An uneven more or less persistent load on the canister may also depend on a density variability of the buffer, an uneven geometry of the deposition hole or if the canister is tilting in the deposition hole. In SR-Can (TR-06-09), these cases are described in section 9.3.12. In SKB R-06-02, a dimensioning swelling pressure case is defined for the copper shell with a swelling pressure of 100 % and 80 % respectively along the canister boundaries. For the insert, one has in SKB R-06-02 defined a dimensioning swelling pressure load case with a pressure of 10 MPa along the length of the canister which is attached in position at one end over a length of one metre. SKB has, however, only taken into account the effect of the load cases of swelling pressure on the cast iron insert. In the older version of the design premises (SKB TR-98-08), several load cases for the canister were defined due to uneven swelling pressure which can apparently produce higher stresses in the copper shell than for the load cases specified in SKB R-06-02. The authorities consider that SKB should clear up among the swelling pressure cases and identify the load cases needed prior to SR-Site.

For the stated dimensioned load case with a swelling pressure of 100 % and 80 % respectively along the length of the canister, this gives rise to an axial stress in the copper shell of 8 and 19 MPa respectively (SKB TR-98-08). However, other load cases (from SKB TR-98-08) are analysed in SKB PM 98-3420-33, which appear to be more limiting for the strength of the copper shell. In PM 98-3420-33, a load case is applied with a swelling pressure on the central parts of the canister while the swelling pressure is zero on the final 500 mm of canister's end surfaces. This load case gives rise to a maximum stress of between 32 and 59 MPa on the copper shell depending on the chosen assumption. For the cast-iron insert, FEM calculations ("Finite Element Method") in PM 98-3420-33 provide a result which indicates a satisfactory margin against plastic deformation of the cast iron insert under a relevant swelling pressure. The authorities consider, however, that SKB should make assessments of more relevant swelling pressure load cases and analyse the stresses on the copper shell that these give rise to.

For reasons of manufacture, there is a gap between the copper shell and the cast iron insert which is gradually sealed by creeping of copper as the pressure builds up in the buffer. This process is listed in Table 6-3 in SR-Can main report (SKB TR-06-09) and is briefly mentioned in the canister process report (SKB TR-06-22). In the design prerequisites for canister (SKB R-06-02), there is some more information. Based on the support of series of creep tests of phosphorous-containing copper material, SKB considers that sulphur contents in the interval 6-12 ppm and grain sizes in the interval 100-800 μm do not result in any measurable effect on creep ductility. However, SKB sees a need to produce a validated creep model and to investigate the long-term stability of the phosphorus. Additional investigations of the characteristics of the FSW weld joint, and studies with an extremely slow increase in load and a multi-axle tension state will also be implemented.

EBS points out that strain from plastic deformation and creep are not independent of one another. Already utilised strain should be taken into consideration in assessment of creep and possible plastic deformation in connection with future shear loads from future earthquakes. EBS also points out that a number of experimental results are needed to test the constitutive model for copper and show that it is sufficient for applications in safety assessment.

Pettersson (2008) has also reviewed creep-related issues in SR-Can and considers that further studies are needed to show that the copper has sufficient creep ductility. This conclusion is based on an analysis of mechanisms for creep, in which it is suggested that SKB should report better arguments to be able to exclude a brittle creep mechanism. Pettersson assesses, however, that this case probably has insignificant relevance for the evolution of the canister during the temperate phase. A more difficult question that is discussed in the review is, however, whether a rupture in the shell can be caused by time-dependent mechanisms some time after a post-glacial earthquake. This case is also discussed in section 12.8.

The authorities consider that SKB's basis for assessment of creep characteristics is far too limited with regard to the number of test rods of different grain sizes and with different compositions. SKB should therefore make more tests which include varying grain size and conditions relevant for repository conditions. It needs to be shown that such tests are carried out in such a way as to study the representative creep mechanism.

In SR-Can (SKB TR-06-09, Table 6-3) and in SKB R-06-02, it is shown that in the creep of cast iron will be studied to assess the long-term integrity of the insert. The authorities await SKB's report on the results of these tests.

11.4 Erosion of the buffer and backfill

Erosion processes can take place in the buffer and backfill during a relatively short time after emplacement. This is due to the possibility that flow channels will arise before sufficient swelling pressure has developed, during which particles can be conveyed. This process could affect the safety functions Bu1, Bu2, Bu3, Bu6, and BF1. This case is described in section 9.2.2 in SR-Can. Deleruyelle and Serres (2008) have reviewed this issue on behalf of the authorities. The review of long-term erosion associated with glacial meltwater is described in section 12.5.

SKB has investigated buffer erosion on a laboratory scale (test size 5 x 10 cm), and on a larger scale (diameter 0.8 m). SKB states that the knowledge about "piping/erosion" in the buffer and the backfill needs to be developed but the preliminary conclusions in SR-Can are (SKB TR-06-09; SKB R-06-80):

- Besides swelling characteristics, the process is affected by geometry, water inflow rate, and the rate of increase of the water pressure.

- Piping probably does not occur when the water inflow into to a deposition hole is less than 0.01 l/min, but may occur when the water inflow exceeds 0.1 l/min. When the water flow exceeds 1 l/min, the eroded quantity is unacceptable.
- "Piping/erosion" will very probably occur in the backfill unless the water flow is extremely low.
- The duration of "piping/erosion" is estimated to be around 100 days depending on the water flow.
- Erosion may be high initially but decrease over time. Higher salt content entails more extensive erosion. Observed concentrations of bentonite in the erosion water are 1- 10 g/dm^3.

SKB assumes that "piping/erosion" of the buffer occurs if the water flow is higher than 0.01 l/min, but many other factors such as the composition of the groundwater can affect the process. SKB's analysis of "piping/erosion" is based on the bentonite concentration in the water not being higher than 10 g/dm^3. This value is based on a limited number of tests, however (Deleruyelle and Serres, 2008). The authorities consider that SKB should obtain more support for this value at, for example, different groundwater compositions, and if possible establish it on theoretical bases.

SKB's estimate of the effect of "piping/erosion" has been based on a rather "ideal" resaturation process (Deleruyelle and Serres, 2008). The duration of "piping/erosion" has been determined taking into consideration the time for restoration of the natural hydraulic pressure in the deposition tunnel. This time has been assumed to be 100 days (SKB TR-06-09, section 9.2.4). However, the time may be longer if the resaturation of the buffer or backfill is slow and takes over a hundred years (Deleruyelle and Serres, 2008). The authorities consider therefore that SKB should better justify the estimate of the duration of "piping/erosion".

In SKB TR-06-13, it is specified that it would take 12 weeks before a hole in the buffer, which has been eroded by water inflow from a fracture, is closed. Thereafter, it takes 2.2 years until the buffer's swelling pressure is 2 MPa. However, SKB has not taken into consideration the mechanism for intrusion of bentonite into the gap, but assumes that the erosion can be stopped after 12 weeks when the hydraulic gradient has been restored (Deleruyelle and Serres, 2008). Another uncertainty is that the threshold value for shear stress of bentonite gel (Bingham flow) can vary within broad limits (20 to 1700 Pa; SKB TR-83-04; Buzzi, 2004) depending on the character of the bentonite, the composition of the groundwater and the quantity of water in the gel (Deleruyelle and Serres, 2008). The authorities consider that SKB should analyse in more detail the mechanism involved in "piping/erosion" to reduce the uncertainties in the assessment of its consequences.

The authorities consider in conclusion that SKB has produced a good approach for "piping/erosion", but at the same time it is apparent that maximum concentrations, duration, and mechanisms need to be further investigated.

11.5 Rock mechanical evolution in the near-field

SKB has with the aid of the 3DEC code made a rock mechanics analysis of the effect linked to the design of tunnels and deposition holes as well as to thermal load on the rock after emplacement of canisters. The rock mechanical evolution can create new fractures, and affect the transmissivity of existing fractures (safety functions R2a and R2b). Seismic activity of tectonic origin or linked to isostatic uplift has also been analysed (SKB R-06-48). Earthquakes are the only process that has been identified which could entail movements in the rock sufficiently large to cause direct damage to the copper canisters (safety function R3a). In SR-Can, rock mechanic evolution is reported in sections 9.2.2 and 9.3.5.

According to SKB, the most important conclusion from the rock mechanics analysis is that thermal spalling around the deposition holes cannot be excluded. This applies for both candidate sites. A contributory cause of this is that thermal stresses are expected to reach their maximum before a counterpressure from the swelling of the buffer has had time to become established. This spalling increases the permeability of the rock, which affects both copper corrosion and radionuclide transport. SKB notes that it has not been possible in SR-Can to calculate the depth and geometry of the fraction of the rock affected by spalling.

Changes of the characteristics of existing fractures caused by thermal load, and swelling pressure are possible locally close to the deposition holes. At greater distances, some impact can take place when a larger part of the rock volume is heated up. SKB's calculation results indicate, however, that this effect is less important.

The authorities' consultants Rutqvist and Tsang (2008) have simulated rock-mechanics conditions in the near-field and the results in the form of the evolution of rock stresses largely agree with SKB's (SKB R-06-88). However, there are some significant differences. The modelling results indicate a risk of spalling already during the design phase, which are generally greater in the case of Laxemar. This is due to the lower strength of the rock, the orientation of the tunnels and a higher degree of anisotropy for horizontal stresses. Rutqvist and Tsang (2008) have calculated for a special case with deposition tunnels at Laxemar oriented according to the main stress direction of the rock and the results from these simulations indicate that the problem would then significantly decrease.

Independent modelling of the base case with rapid resaturation indicates that no further spalling takes place during the thermal phase due to the build-up of the buffer's swelling pressure (Rutqvist and Tsang, 2008). In the case of very dry rock and slow resaturation, the potential for spalling around the deposition holes is, however, greatest after around 100 years, since no counterpressure from the buffer's swelling builds up before then. The independent modelling indicates that tensile stresses are expected to arise in the deposition tunnel walls under the effect of the thermal load from the canisters, which has not been discussed in SKB's corresponding analysis. These tensile stresses may cause a transmissive zone around the tunnels even if the blasting damage is slight. The authorities consider that SKB should take this case into account unless it can clearly be shown that it can be excluded. SIG points out, for example, that a transmissive zone close to the tunnels can be more significant during glacial periods with high hydraulic gradients.

SIG considers that SKB should develop a method to better estimate the extent of thermal spalling. An especially important implication of the spalling may be less effective heat transfer from the deposition holes. SIG considers that SKB should consider carrying out experiments on the thermal characteristics of the zone around a deposition hole affected by spalling. The current lack of knowledge also makes it difficult to parameterize the disturbed zone's hydraulic characteristics (SKB TR-06-25 page 143).

Rutqvist and Tsang (2008) further point out that SKB does not seem to have taken into account a possible reduction of the long-term strength of the rock. Sub-critical fracture growth and chemical alterations close to deposition holes and deposition tunnels can eventually reduce the strength in comparison with original conditions. With respect to the evolution of the permeability of the rock, the consultants consider that SKB should take into account the risk of shearing of shallowly dipping fractures close to the deposition holes. This shearing may for certain fractures entail a greatly increased permeability. Steeply dipping fractures are expected to have reduced permeability, however.

Rock mechanics issues extend over a broad spectrum which includes conditions during construction of the facility, conditions during the thermal phase after sealing of the repository, as well as the special impact during periods with future glaciations. Rock mechanic conditions during construction can affect the need for reinforcement measures and the quantity of cement that has to be used in the repository. SIG points out that early reinforcement measures with shortcrete can deteriorate the possibilities of detecting large fractures in the tunnel walls. However, there are generally prerequisites for obtaining information about damage during construction. Uncertainties linked to changes during the thermal phase are therefore probably greater. The authorities consider like SIG that SKB should assess and report on methods which may be used to reduce the risk of thermal spalling in the near-field of deposition holes and deposition tunnels. To conclude, the authorities consider that SKB should consider complementing its rock mechanics analysis to take new data into account which has emerged during the final phase of the site investigations and to address the above mentioned issues.

The authorities have still not made any independent rock mechanics studies of their own linked to future glaciations and seismic activity as a preparation for the review of SR-Can. These questions have therefore not been addressed in detail in the review, which does not mean that they can be considered as being less important. Questions relating to earthquake frequencies, use of respect distance and any damage to canisters and the buffer are commented on elsewhere in this review (see section 12.8).

11.6 Chemical evolution in the near-field

Chemical conditions which have been analysed during the site characterisation stage will change during the construction and operating phase as well as during the coming thousands of years after the sealing of a repository. Changes caused by large climate changes are commented on in sections 12.5 and 12.6. Changes are caused partly due to material added in the construction of access tunnels and deposition tunnels, and partly by inflow of groundwater of meteoric origin. In SR-Can (SKB TR-06-09), the general chemical evolution is commented on in section 9.3.7.

The authorities consider that SKB during the years with studies at the Äspö laboratory and the site investigation phase has made great progress in the understanding of geochemical conditions at repository depth and that this is reflected in SR-Can. An improved understanding of processes affecting the repository evolution has, however, changed the safety-related importance of chemical variables compared with previous safety analyses. The authorities consider therefore that SKB needs to review the data requirements and consider if any chemical processes may need additional in-depth knowledge and data.

SKB reports modelling results in SR-Can that show that the salt content of the groundwater will decrease radically due to the gradual addition of groundwater of meteoric origin during a period of time of thousands of years. When the existing groundwater with high ion strength is gradually replaced, the calcium contents will also decrease. In SR-Can, it is stated that calcium concentrations already during the temperate phase will approach the limit value for the stability of the buffer (safety function R1c). The authorities consider that in-depth studies may be needed of both hydrological and geochemical factors for availability of Ca^{2+} and Mg^{2+}. A more certain prediction should be made concerning whether chemical buffer erosion is a phenomenon only associated with glacial meltwater or if it can also occur during temperate conditions (see section 12.5).

During the operational phase, it is possible that water with very high salt contents will intrude into the tunnels (linked to the safety function R1b). This may affect the buffer's swelling pressure as well as the risk of "piping/erosion". Hydrological simulations reported in SR-Can shows that only a very small flow can be expected. However, the authorities consider that SKB in SR-Site should also report a maximum expected salt content during operational phase of the repository. This content is a starting point in the analysis supporting the design of the buffer and the backfill.

The authorities consider that it is well established that reducing conditions after an initial period of oxidising conditions will be resumed and continue under temperate conditions (safety function R1a). The result from the REX-project (SKB TR-01-05), the site investigations, etc. provide support for the rock having a considerable capacity to consume oxygen due to the access to organic carbon, iron(II), sulphide, methane and hydrogen (redox conditions during glacial conditions are commented on in more detail in section 12.5). The relative importance of processes that control the redox potential and how these are linked to the measured redox potentials are, however, a topic which is still discussed. In, for example, SKB TR-06-31 it is pointed out that redox potential in a general sense is difficult to define due to different redox pairs not always being coupled with one another. This question may need an in-depth discussion in connection with the safety function R1a and in establishing of an appurtenant limit value in SR-Site. SIG points out that interpretation of redox measurements would be made easier if there was knowledge about the locally available redox affecting minerals.

The chemical variable that probably has the greatest importance in the risk analysis is the sulphide content of the groundwater (safety function R1d). The highest measured concentrations are around 10^{-4} M although more typical values are rather around or below 10^{-6} M. An analysis of the processes that control the access such as microbial sulphate reduction are reported in SR-Can, but should be dealt with in greater depth bearing in mind the importance of general corrosion of copper. The authorities expect that a stronger link to site data can be made after the complete site investigation phase has been completed. It should be noted that an in-depth interpretation of sulphide contents assumes that data is available for other groundwater components such as dissolved iron, sulphate, methane, hydrogen gas and organic material.

11.7 The chemical evolution of the buffer and backfill

The engineered barriers in the repository will be affected by chemical processes starting directly after emplacement during the operational phase of the repository. This is commented on in SR-Can in section 9.2.5. (SKB TR-06-09). The chemical effect continues then in a similar way during the subsequent temperate phase, which is described in SR-Can in sections 9.3.7, 9.3.10 and 9.3.12 (SKB TR-06-09). Issues relating to the buffer's temperature-dependent transformation (safety function Bu5), and the effect of cement (safety function R1e) are reviewed in this section. Review issues linked to the chemical evolution in the buffer in the long term are commented on later in section 12.6 of this report.

SKB has made calculations of how the early phase with a thermal gradient affects the buffer chemistry (SKB TR-06-16). A redistribution of accessory minerals takes place due to the effect of temperatures on the solubilities of certain minerals (with precipitation of calcite and anhydrite in the warm part and silica phases in the cold part). SKB draws the conclusion that these processes are not important for the chemical composition of the buffer. The authorities have also carried out similar simulations, which largely confirm SKB's result (Arthur and Zhou, 2005). However, it is pointed out in the independent study that it is not known to what extent precipitation reactions need to take place to cause a cementation. In an unfavourable case, even less extensive precipitations will increase the stiffness of the buffer. The authorities consider that this question needs to be further analysed. The question is also linked to whether a period with relatively dry conditions in the buffer or a high pH from cement can have a more extensive effect on the buffer. The municipality of Oskarshamn, the municipality of Östhammar and MKG (SKI dnr. 2006/985) point to the risk of the buffer being affected by high temperature.

Even if there are considerable uncertainties about the effects of cementation, SKB has made laudable attempts to deal with these. In SKB TR-06-43, calculations are reported that assume that a part of the buffer has the same characteristics as ordinary cement. If it is assumed that a 9 cm thick layer closest to the canister has been transformed into cement, shearing of the buffer and canister (from an earthquake; see section 12.8) will produce a 20-60% greater deformation of the canister. The authorities consider that this type of calculations can be of great value to assess effects of cementation processes if these cannot be excluded. Further work needs to be done, however, to better justify the calculation case.

Use of ordinary Portland cement (pH ~ 12.5) can entail a significant impact on bentonite and other materials in the repository. SKB has therefore decided to use low pH cement (pH~ 11) which affects pH conditions in the surroundings considerably less. However, it is clear in SR-Can that there is not yet any reference material with a specified composition, which means that it has not either been possible to carry out any complete analysis. It is simply noted that the recipe for cement must be chosen in such a way as not to jeopardise the characteristics of the buffer (SKB TR-06-09, page 290). Benbow and Savage (2008) have carried out a review of SKB's handling of cement issues in SR-Can based on their own model studies (Watson et al, 2007; Benbow et al, 2007) and a literature study on low pH cement (Benbow and Savage, 2007). It is noted in this review that the use of low-pH-cement requires additives whose effect is important to take into account. Furthermore, it is noted that the Ca-Si ratio in the CSH gel has a great effect on the chemical evolution of cement without free portlandite. Benbow and Savage (2008) point out that SKB's model for cement modelling of the interaction of cement and bentonite (SKB R-06-107) is representative for around 1000 year old cement rather than fresh cement.

The authorities note that work remains to be done on the impact of cement that assumes that there are recipes for a well-defined reference material. Effects of cement used in the vicinity of the deposition holes need a more detailed assessment. SKB should report whether deposition holes need to be sealed with cement to avoid "piping/erosion", since this can mean that cement leachwater becomes more important.

11.8 Mechanisms for local copper corrosion

Stress corrosion cracking of copper is in principle possible given the existence of tensile stresses and an aggressive chemical environment. Published studies show that the mechanism is linked to sufficiently high concentrations of ammonium, acetate or nitrate. According to Table 6-3 in SR-Can (SKB TR-06-09), stress corrosion cracking has been excluded based on argument of very small access to these substances in the repository environment and an insufficient quantity of oxidising agents. In the canister process report (SKB TR-06-22), it is indicated, however, that stress corrosion cracking can be excluded since there are no tensile stresses in the canister particularly during the period of oxidising conditions. In the canister process report, stress corrosion cracking is linked to the presence of a Cu_2O/CuO duplex film (SKB TR-06-22, page 106). At a workshop on the mechanical properties of the canister (SKI, 2007a), SKB maintained, however, that the duplex film is not necessarily involved and that empirical observations are only linked to the redox potential not the actual presence of the film.

The authorities' consultant Pettersson (2008) points out that stress corrosion cracking has arisen in unexpected contexts in the nuclear industry and that the process therefore needs to be carefully taken into account in safety assessments on final disposal of spent nuclear fuel. It is stated in the review that the short time for oxidising conditions in the repository is an argument for excluding mechanisms which depend on an oxide film. Pettersson considers, however, that SKB's argumentation around mechanisms which could operate in the event of reducing conditions is not satisfactory, inter alia, due to the difficult of showing absolute limit values for elimination of stress corrosion cracking risk. Recently published experimental results indicate that stress corrosion cracking could occur in a sulphidic environment (Taniguchi and Kawasaki, 2007). EBS also considers that the risk of stress corrosion cracking during reducing conditions cannot be considered to be eliminated and that additional experimental studies need to be carried out.

Experimental studies show that a very limited form of local corrosion may occur, which only takes the form of unevenness in relation to general corrosion. According to SKB, this mechanism only gives a constant additional corrosion depth of 30-50 µm. A pure pitting with a permanent separation of anodic and cathodic reactions has, however, been excluded in SR-Can. It may be noted that SKB's approach for pitting has been based only on empirical observations (SKB TR-06-22, page 100-101) reported as a limited corrosion depth, a pitting factor or a distribution of probabilities for different corrosion depths. However, there are experiences of pitting of copper from other contexts which lead to a need for understanding of the mechanisms and controlling environmental factors (contribution by Pourbaix in SKI, 2006). Understanding of this kind should serve as the basis for discussion and assessment around the relevance for the repository. In the same way as discussed above for stress corrosion cracking, there is a remaining uncertainty about whether there are sufficiently detailed experimental studies of local corrosion in a sulphidic environment (contribution by Pourbaix in SKI, 2006).

To conclude, the authorities consider that it should be a high priority for SKB to produce a better basis for the understanding of local corrosion mechanisms such as stress corrosion cracking. Handling these processes should be based on a consistent and well-defined strategy as well as a relevant and a more extensive experimental basis. The authorities consider that SKB should produce a more detailed report in SR-Site where all known mechanisms are analysed and discussed separately.

11.9 General copper corrosion during the initial and temperate phase

Some corrosion of copper is expected to take place already during the emplacement and handling phase as well as the initial temperate phase. The preceding mechanism is due to oxygen and is dealt with in SR-Can in section 9.2.5 (SKB TR-06-09) and the latter which is caused by sulphide is described in section 9.3.12. The copper corrosion processes affect the safety function C1.

SKB has calculated the extent of copper corrosion during the initial evolution of the copper. If all the maximum retained oxygen (560 mol per deposition hole) reacts with the copper, this would produce a corrosion depth of 840 µm. However, SKB points out that almost all the oxygen is consumed by microbial processes and that the corrosion depth is in reality expected to be much smaller. Maul et al (2008) have repeated SKB's calculations and consider that they are correct, but point out that the assumed quantity of oxygen has not been justified (e.g. SKB TR-06-22, page 100). The fact that corrosion does not have to be wholly homogeneously distributed, as well as that copper can be corroded before sealing are other points of view that SKB should take into account. The authorities agree with SKB that is seems extremely improbable that all remaining oxygen would react with the copper. However, the authorities consider that other oxygen-consuming processes may need to be reported better in SR-Site to justify this.

SKB has estimated and analysed the remaining organic material (residues from operation of the repository) in SKB R-06-104 and found that the maximum quantity for every deposition hole could theoretically generate 10 mol sulphides in the event of microbial sulphate reduction. If this sulphide were then to react with copper, the depth of corrosion would be less than 10 µm. The authorities' consultant Hallberg (2008) points out, however, that bentonite in its natural form contains considerable quantities of organic material which does not seem to have been taken into account in SR-Can.

Copper corrosion may also take place with sulphide which is present in bentonite and surrounding groundwater. SKB estimates that corrosion by sulphite consumes less than 35 µm of the copper coverage during the first thousand years. If temperate conditions are hypothetically maintained in the very long term as well, corrosion would according to SKB be less than 1 mm per 100,000 years (corrosion after glaciation is commented on in section 12.4). SKB's analysis is based, however, on the sulphide content under all circumstances being controlled by the low solubility which is given by the equilibrium with pyrite. Stenhouse et al (2008) point out that there are studies that show that sulphide solubility can be controlled by other phases, for example, mackinawit, which in certain cases can also be formed even if pyrite is available (Sinclair et al, 2005). How corrosion might be affected by such alternative sulphur compounds is not mentioned in SR-Can. SKB does not either discuss the effects of microbial sulphate reduction in the backfill or in the fractures close to the deposition holes (Liu 2005; Sidborn and Neretnieks, 2006), which could provide an additional contribution to copper corrosion even if the buffer remains intact. The authorities consider that SKB should either deal with or exclude these two alternative courses on good grounds in SR-Site. Analysis of solubility conditions for sulphide in and around the buffer should address reasonable variations of chemical variables such as pH, salinity, concentration of dissolved iron etc.

SKB has carried out studies of microbial activity in compacted bentonite and found that sulphate-reducing bacteria (SRB) have very low activity (Masurat, 2006). There are several reasons suggested for the absence of microbes at such low water activity and high swelling pressure. In SR-Can, the microbial corrosion is considered to be so low that it only provides a contribution of 4 µm per 1000 years for the case with an intact buffer. However, Hallberg (2008) points out that there are microbes with considerable resistance to unfavourably dry conditions. A conclusion from Hallberg´s review is that it cannot be assumed without further analysis that microbes lack importance, even if tests show that activity has been eliminated in the short term. Microbes can namely adapt to severe conditions after a time. SKB should therefore analyse in more detail and discuss which factors control microbial activity in compacted bentonite. The prerequisites for a slow adaptation of microbes in the buffer could, for example, be studied with the type of long-term tests already being carried out at the Äspö laboratory. When planning additional long-term tests, consideration should be taken to the types of results that are needed at the time of important decision-making points in the Swedish programme.

The authorities recommend SKB to report and document calculations justifying corrosion depth in a more systematic way. Contributions from different mechanisms for local and general copper corrosion can, for example, be added together when assessing the safety function C1 for different times in the evolution of the repository. The most significant aspect is the sealing requirement (safety function C1) which is only affected by very extensive corrosion. The fracture strain of the shell may also be affected if a significant part of the goods has been corroded away. A link of this kind between corrosion and mechanical effect may need to be investigated for the relatively large deformations that may occur close to the canister lid (calculations in SKB-TR-06-43).

The authorities have themselves analysed radiation induced corrosion and found that this process provides very little contribution to corrosion of the copper canister (Liu et al, 2008). The municipality of Oskarshamn (SKI dnr. 2006/985) has, inter alia, pointed out the importance of this process. Liu et al (2008) suggest that SKB should produce a more complete photoenergy spectrum of the canister surface and a more detailed report of the consequences in the form of canister corrosion.

It should finally be noted that it is suggested in a newly published article that copper may corrode in oxygen-free water with the evolution of hydrogen (Szakálos et al., 2007). The authorities have not examined these results more closely and intend therefore to return to this question.

11.10 Evolution of a damaged canister

In SR-Can, the evolution of a damaged canister with an initial defect has been analysed (a penetrating pinhole with a radius of 2 mm) (SKB TR-06-09, page 403; SKB TR-06-25, page 55). SKB has assumed a time period of 1,000 years before any transport of radionuclides take place from the canister. This time period without radionuclide transport can be related to: 1) a slow supply of water, 2) gradual build-up of a counterpressure from hydrogen gas generation within the canister interior, 3) the barrier function of iron insert and 4) the barrier function of the fuel's encapsulation. SKB states that each of these processes will probably produce at least 1,000 years' delay. This case provides a basis for assessing a barrier system with a single defect in one of the barriers (7 § SKIFS 2002:1). This case can also be linked to very improbable events; such as if a throughgoing defect were unexpectedly to exist in the copper shell from manufacture.

When radionuclide transport has been initiated, the canister still has a considerable transport resistance, however and thus provides an important barrier function. After continued corrosion of the insert, the defect may, however, expand and the transport resistance will decrease. In SKB TR-06-25 (page 58) different scenarios are reported for this evolution. The probability of the time until the canister loses its transport resistance, has assumed to be triangularly distributed between 1,000 and 10^5 years, where the most probable value coincides with the upper time limit. Two previous modelling studies are very important as a background to the understanding of interacting processes in the evolution of the canister (SKB TR-97-19, SKB TR-99-34) in combination with studies of the corrosion mechanisms for the insert (e.g. Smart et al, 2002).

The authorities consider that a period of 1,000 years between a minor penetrating defect in the copper shell and initiated radionuclide transport is very probably conservative. However, it can be noted that there is no direct support in SR-Can for the safety functions of a defective canister that SKB refers to (see above). Bearing in mind the need to show robust multiple barrier functions for the initial period of the safety assessment, SKB should prior to SR-Site produce a basis to justify at least one or several of these safety functions (see also Chapter 14.).

The authorities also consider that SKB should better justify the distribution of the time interval between an initially started radionuclide transport and the time when large canister damage arises. The four different scenarios reported by SKB in SKB TR-06-25 (page 58) would need more detailed reports to make possible an assessment of whether the time estimates are reasonable. A sufficiently verified creep model is needed, for example, for evaluation of how large a deformation the copper shell may be considered to bear due to the formation of corrosion products from the insert (see section 11.3). For the assumed distribution of the time until large canister damage, it is difficult to understand why the maximum period is considered to be the most probable.

12. The long-term evolution of the repository

This chapter discusses critical issues concerning the long-term evolution of the repository during and after periods of major climate change such as permafrost and glaciation.

12.1 General climate issues

Climate issues in SR-Can are dealt with in the form of studies of the three most important domains for climate evolutions: glacial, temperate and permafrost. SKB indicates that if repository safety is maintained during all three phases, including transitional periods, the exact extent of these domains in terms of time and space is not of crucial importance. The first glaciation cycle after sealing the repository facility is based on a reconstruction of the Weichsel ice age. Subsequent glaciation cycles are repetitions of this period over a period of one million years. In addition, a greenhouse variant has been analysed in which it is assumed that a period of temperate conditions will continue for 50,000 years.

In SR-Can (SKB TR-06-09), climate developments are summarised within a reference development in Section 9.4.1, which is based on the special climate report (SKB TR-06-23). In the following, the authorities present their views on the way in which specific climate issues have been taken into account in the evaluation of the safety functions of the repository. The link between climate issues and the choice of scenarios is also discussed in Chapter 14.

The municipality of Östhammar (SKI Reg. No. 2006/985) considers that the earth model for estimation of land elevation and ice modelling needs to be improved. As regards the advanced three-dimensional models, discussion of their potential and limitations is requested. SKB is urged to investigate which model of the lithosphere complies best with seismological data.

MILKAS (SKI Reg. No. 2006/985) emphasises the importance of issues involving methane ice explosions. MKG (SKI Reg. No. 2006/985) asks what the impact on the safety assessment would be if it was assumed that the order of the three glaciations in the main scenario changed places so that the greatest glaciation occurred first. MKG also points out that there are theories that imply that a stronger greenhouse effect might result in more rapid glaciation.

SIG considers that SKB has made considerable progress in achieving an understanding of the way in which climate changes affect a repository, particularly as regards future glaciations. However, there continues to be scope for improvements, particularly as regards an understanding of permafrost, and also groundwater chemistry and hydrology during periods of climate change. Greater use of information from natural analogies may be one possibility in this context.

The authorities' consultant Holmlund (2008) considers that SKB has made considerable progress in dealing with the climate-related issues since the SR-97 report (cf. Holmlund, 2000). The numerical ice modelling, which also lays the foundation for other types of climate modelling, is now considered to be well-established and of good quality. According to Holmlund, SKB's choice of base variant, which takes Weichsel as its starting point, is highly appropriate for evaluation of the climate impact on the long-term safety for a repository. The use of climate data from Greenland (GRIP or North Grip) is the best possible input data for modelling of Weichsel, although in the future SKB may need to make a detailed analysis of the transfer from Greenland to Sweden in estimating temperatures. Holmlund (2008) considers that SKB should analyse the uncertainties further, and report them in clearer terms, for example as regards the presentation of temperature evolutions over the past 120,000 years (e.g. Figure 9-64 in SKB TR-06-09).

According to Holmlund (2008), SKB's estimates of maximum ice thickness provide results that appear to be reasonable and as expected, in view of observations in Greenland and the Antarctic. There may, however, be justification for a better description by SKB of the model and the simplifications on which it is based.

According to Holmlund (2008), the greenhouse variant is a good supplement to the basic variant. Questions may be raised, however, as to whether the land elevation can offset the sea-level changes corresponding to the melting of the Greenland and Antarctic ice cover. In addition, there is the thermal expansion of the oceans as a result of a higher average temperature. A higher water level in the Baltic Sea might result in a higher salt concentration, and possibly greater sea-water penetration into the repository.

Holmlund (2008) considers that SKB has not sufficiently discussed the risk of substantial glacial erosion in both the candidate areas. In view of the fact that the analysis covers a period of a million years, this factor cannot be excluded without a more detailed explanation. The extent of the erosion depth for the entire period depends on the erosion potential, and the time factor for glacial erosion during each cycle. Holmlund (2008) does not exclude erosion rates of about 1 mm/year during erosion phases of 20,000-30,000 years. This would result in erosion depths which might considerably affect the permafrost estimates and the possibility of avoiding freezing of the buffer towards the end of the period covered by the safety assessment.

Like Holmlund (2008) and SIG, the authorities consider that, for the most part, SKB has a sound basis for an understanding of most aspects of future climate changes. SR-Can is the first SKB safety assessment in which the impact of climate changes has been integrated in a detailed manner into an analysis of repository and the development of the barrier. This has resulted, however, in the identification of new questions, and tackling them may lead to additional requirements for the design of the repository and engineered barriers. As a result, SKB should aim at a continued analysis that specifically reduces uncertainties regarding changes in the groundwater chemistry and hydrology at the repository depth. The authorities agree with Holmlund (2008) and SIG that SKB should consider what information field studies and natural analogies may contribute in order to reduce the uncertainties. As regards glacial erosion, the authorities consider that Holmlund's objections should be taken into account. If substantial glacial erosion cannot be excluded on satisfactory grounds, this should be taken into account in assessing the appropriate repository depth.

The authorities note that SKB itself has stated that certain processes linked to glaciation have not been tackled in SR-Can, for example microbial processes (SKB TR-06-19, Tables 1-3).

12.2 Permafrost changes

SKB describes its treatment of the long-term thermal evolution of repository facilities in section 9.4.3 of SR-Can (SKB TR-06-09). The most obvious purpose of this analysis is to estimate the risk of freezing of the buffer (safety functions Bu7 and R4), which would create a mechanical loading of both the canister and the surrounding rock. Furthermore, the functioning of the buffer is regarded as uncertain after a period in a frozen condition. Permafrost also has a considerable impact on rock mechanics, hydrology and geochemical factors at repository depth.

Freezing of the buffer is not taken into account in SR-Can since permafrost in the basic variant does not reach repository depth in any of the candidate areas. There is an additional safety margin since it is not anticipated that the buffer will freeze until a temperature of less than -5^0 C is reached (SKB TR-06-18, page 35). More conservative cases have also been analysed that imply that permafrost might reach the repository depth at Forsmark, but not the -5^0 C isotherm which is considered to determine freezing of the buffer.

SIG considers that SKB should evaluate the geochemical and hydrological changes in permafrost conditions in more detail, and also the uncertainties associated with such changes. The significance of the permafrost period is stressed, since it is expected to be longer than the glacial period and will occur at an earlier stage in the repository development.

MKG (SKI Reg. No. 2006/985) considers that SKB needs to study the indirect impact of permafrost on groundwater chemistry in a repository.

Holmlund (2008) considers that SKB's estimates of permafrost involve some uncertain factors that are not reported in a clear manner, both as regards models and input data. One of the key uncertainty factors is that air temperatures in central Greenland probably cannot be estimated to a greater degree of precision than with an uncertainty of 10° C. A difference of this nature would affect the permafrost depth to a considerable extent if it continued for thousands of years, as confirmed by SKB's estimates (SKB TR-06-09, page 480). As a result, further details of uncertainties in the presentation of modelling results may be justified. Holmlund (2008) indicates that glacial erosion might increase the risk of permafrost reaching the repository depth to a significant extent.

The authorities agree with Holmlund (2008) that SKB should improve its reporting and evaluation of uncertain factors in connection with the permafrost estimates. This is required, for example, in order to simplify assessment of the considerable safety margins in SKB's current analysis. In addition, the authorities consider that SKB should analyse and report the consequences if freezing of the buffer zone and/or backfill nonetheless occurs. Experiments may need to be carried out. SKB has already made a good start by its analysis of freezing in a partially eroded buffer (SKB TR-06-09, page 484). It may be reasonably expected that the level of detail for an analysis of buffer freezing is affected by the safety margin that SKB ultimately considers to be achievable (depending, for example on the repository depth, the buffer freezing point and the temperature evolution).

The authorities note that SKB has not considered certain processes for the permafrost phase in SR-Can, for example methane ice formation (SKB TR-06-19, Tables 1-3).

12.3 Hydrological evolution during the glaciation and permafrost phases

Extensive climate changes are expected to result in considerable impact on the pressure conditions and groundwater flow (safety function R2c). The maximum hydrostatic pressure at the repository depth may be almost 10 times greater in a glaciation period (safety function C2), which means greater demands on the design of the canister. The hydrological evolution also affects the geochemical conditions at the repository depth (safety function R1). These issues are covered in SR-Can in section 9.4.6.

Holmlund (2008) suggests that the issue of glacial hydrology needs to be explained more fully and integrated in greater detail with the treatment of other climate issues. Critical questions such as the way the hydrology changes during a glaciation and how this affects the candidate locations have not yet been evaluated. SKB's handling of this question is inevitably on a very general level since there is very little measurement data. As a result, Holmlund concludes that more research is required. One key question is the way in which glacial meltwater reaches the bottom of a glacier and then penetrates down to the repository depth. It should be taken into account that massive cold glaciers are much less permeable than temperate glaciers.

The authorities note that SKB is planning to implement extensive modelling of groundwater flows for the glacial phase in the next safety assessment SR-Site. For this more fully developed modelling, the authorities consider that SKB should take into account the location-specific circumstances and establish a more detailed basis for assumptions and boundary conditions than in SR-Can, for example incoming flows under the glacier, the influence of the Baltic Sea, the impact of an inland ice load on the rock's hydraulic characteristics and the impact of the excavation damaged zone (EDZ) on groundwater flows. Furthermore, the authorities consider that SKB should tackle the uncertainties that are due to the fact that most of the process studies have been carried out on relatively small glaciers, while most of the models involve inland ice formations (SKB TR-06-34, page 125). The differences in assumptions between the calculations for glacial hydrology and calculations for the inland ice development should be elucidated (Holmlund, 2008).

SKB is also planning to present a more complete study of groundwater flows in a permafrost situation (SKB TR-06-09, page 335). The questions that will be elucidated in more detail are the volume of groundwater flows at repository depth, dilution effects on the surface, and flow patterns and outflow points into the biosphere when hydraulic conductivity close to the surface is reduced, due to permafrost. The authorities consider that it is important to conduct these analyses in the light of the protracted period of the potential hydrogeological and geochemical impact of permafrost and the generally limited understanding of the processes that apply during this period. In addition, the authorities and SIG (Chapter 8) consider that SKB should take into account the possibility of taliks beneath lakes with a concentrated outflow from great depth.

The authorities and SIG (Chapter 8) consider that there are limited possibilities of utilising published information to support the assumptions on which the modelling of hydrology and geochemistry during the glacial period is based. For this reason, it is important that SKB explains its handling of these issues in a detailed manner, and possibly applies more conservative estimates for the periods for infiltration by melted water (which, in case B, is estimated to be 1,300 years in SKB TR-06-09, page 341).

In SR-Can, estimates of oxygen penetration to repository depth have not been fully integrated with the hydrogeological calculations that have been carried out. For example, it is not clear how the transport time for water from the repository depth to the ground surface that has been estimated in SKB R-06-100 is related to the transport time assumed from the bottom of the glacier to the repository depth (these estimates are reported in SKB TR-06-09, p 350). In SR-Site, SKB should integrate the hydrogeology calculations with the oxygen penetration estimates so as to make it clear which transport paths (and the associated transport times) have formed the basis for the estimates for oxygen penetration.

12.4 Corrosion of copper canisters

Canister corrosion with sulphide in the groundwater is expected to take place throughout the entire development of the repository for up to one million years. SKB reports one case with an intact buffer throughout the period, and one case with a partially eroded buffer (reported in SKB TR-06-09, Section 9.4.9). The estimated result is of decisive importance for evaluation of safety function C1.

In the case of an intact buffer, SKB notes that sulphide corrosion is virtually negligible. In the case of partial erosion of the buffer, however, a number of canisters may be fully penetrated in the course of a million years. In addition, a hypothetical case of corrosion due to the penetration of oxygen is reported, as commented on by the authorities in Section 12.5.

Copper corrosion for a partially eroded buffer is the most significant case in SR-Can as regards the estimated dose/risk. This case is linked with the handling of buffer erosion, which is regarded as highly uncertain (see Section 12.6). If more than 1,200 kg is eroded, advective conditions in the buffer cannot be excluded. This means that sulphide may be transported more rapidly to the canister surface and, in this case, the Bu1 safety function will not be fulfilled. Furthermore, in the event of lower density and swelling pressure, the buffer will be unable to filter colloids or eliminate microbes. (safety functions Bu2 and Bu3). In the event of very extensive buffer erosion, the canister will sink to the bottom of the deposition hole. (safety function Bu6).

SKB assumes that a cavity will be developed in the buffer (a semi-cylindrical section with the same height as the thickness of the buffer) which will also provide a surface in which more rapid copper corrosion can take place. It is assumed that microbial sulphate reduction may take place in this cavity to the extent permitted by the methane introduced. It is assumed that the methane concentrations are limited for copper corrosion rather than sulphate concentrations. The estimated results indicate that the time required to totally erode the buffer are short compared with the time for rupture of the canister as a result of general corrosion. The number of canister failures after a million years will be from zero to more than 200, depending on which criteria that are employed for the selection of deposition holes, the choice of site and the choice of hydrological model. Another variable that has considerable impact is the concentrations of sulphide and methane, whose significance is only reported in connection with the evaluation of scenarios in SR-Can (TR-06-09, section 12.7). It is considered that the presence of canister defects would not significantly affect the containment time of the canisters.

Bath and Hermansson (2008), the authorities' consultants, consider that SKB should evaluate whether there are scenarios that may mean increased activity for sulphate-reducing bacteria in the repository. In the transition from permafrost, there may be a risk of the release of methane from accumulated methane ice. In addition, these experts consider that SKB has not produced sufficiently strong arguments for the exclusion of the penetration of saline groundwater, and salt exclusion in the event of freezing, which would affect the geochemical processes at repository depth.

The authorities consider that analysis and reporting in SR-Can of the associated advection and corrosion case is insufficient in a safety context. Prior to SR-Site, a greater focus on this case is called for unless new research findings can exclude the risk of buffer erosion. Since the risk of canister failure is as closely linked to the distribution of groundwater flows as it is to the availability of corrosive substances, a more detailed analysis of both these factors is called for. This case may need to be regarded as a decisive factor in the design of the repository (e.g. acceptance criteria for deposition holes and copper coverage), and in this case a reasonably realistic basis for the dimensioning of the engineered barriers is required.

There is considerable uncertainty as regards the geometry of a partially eroded buffer. The authorities do not consider that this question has been sufficiently elucidated or discussed in SR-Can. There should, for example, be sensitivity analyses that provide more exhaustive information regarding the impact of the geometry. SKB's treatment in SR-Can is confined to instantaneous snapshots in two stages of the condition of an eroding buffer, and this cannot provide any deeper insights into the gradual progression of buffer erosion. As EBS points out, there is a contradiction between the buffer erosion case and the case of a of buffer deficiency at the time of emplacement (SKB TR-06-09, Section 9.3.9). This contradiction is probably based on a more conservative treatment of the buffer erosion situation. In any event, SR-Can does not contain any analysis or in-depth discussion of these questions.

A case of more rapid corrosion of a cemented buffer with a fracture is also noted in SKB TR-06-33, although this is not discussed in SR-Can. The authorities consider that SKB should explain the reasons for this in SR-Site.

Factors that govern concentrations of corrosive substances need to be evaluated and reported in more detail in SR-Site. The procedure for selecting the total concentration of sulphide and methane and establishing this entity at three different levels (10^{-4} M, 10^{-5} M, 10^{-6} M) appears to be arbitrary, or is at least reported too briefly. According to the site-specific results, the concentrations of potentially corrosive substances (methane, sulphide, etc.) are distributed heterogeneously in the bedrock, and this also applies to the groundwater flow, which needs to be taken into account along with possible correlations between these factors. SKB's analysis should take into account that these concentrations, and the groundwater flow, will be affected by the different stages in the climate evolution.

The authorities consider that SKB in SR-Site needs to analyse in more detail microbial sulphide reduction, the redox and solubility chemistry of the sulphides, and copper corrosion by sulphide. These processes are linked to other aspects of the evolution of the repository that may also call for further consideration, for example entry paths for sulphate and methane and entry paths for nutrition substances for microbes. A better understanding of the constraining factors for microbial activity is needed since the results of certain site investigations indicate that sulphate is not fully reduced, despite access to methane or hydrogen. MKG (SKI Reg. No. 2006/985) considers that SKB needs to carry out more work to investigate copper corrosion in the presence of sulphides.

Even the case of copper corrosion in an intact buffer may also call for a somewhat more detailed reporting (see section 11.9). The contributions made by various corrosion processes may, for example, be summarised for different stages of the repository evolution in order to facilitate an overview of the expected condition of the canisters. The arguments presented for excluding the impact of canister defects on the containment time of the canister appear to be reasonable, but may need to be supported better in SR-Site, for example by means of estimates and analyses.

Finally, the authorities note that if buffer erosion continues to be a major factor in future safety analyses, SKB should develop a clearer method for handling the risk contribution. A method of this nature should be based on requirements for both the rock and the engineered barriers that are reasonable in terms of resources, and that can also be checked. Comparison may be made with the shear loading case, for which SKB has already developed a method for risk limitation involving requirements for the canister's strength, and acceptance criteria for emplacement areas and deposition holes. In the case of corrosion, the issues to be dealt with include thermal spalling, long-term permeability changes, and correlations between the size of fractures and transmissivity. In SR-Can, it is implied, for example, that high demands for maximum transmissivity for deposition holes might be difficult to handle (SKB TR-06-09, Table 9-6, semi-correlated DFN model).

12.5 Oxygen penetration with glacial meltwater

If oxygen-rich glacial meltwater were to penetrate down to the repository depth, there would be a risk of interference with the normal reducing conditions in the repository. If there are oxidising conditions in the deposition holes, this might affect the corrosion of the copper and the transport of certain redox-sensitive nuclides in the event of a possible leakage from a canister.

SKB presents a modelling of the downward penetration of oxygen in glacial meltwater as part of the documentation for SR-Can (SKB TR-99-19, SKB TR-06-31, SKB R-06-105; Sidborn & Neretnieks, 2007). This issue is covered in Section 9.4.7 of the main SR-Can report (SKB TR-06-09).

In its modelling, SKB has assumed a given oxygen concentration in the glacial meltwater, and that this water may penetrate downwards into a fractured zone and a fracture in the rock due to the considerable hydraulic gradients that occur when the ice-front passes the repository. SKB has evaluated the consumption of oxygen due to reactions with reducing iron (II) minerals which are found both as fracture-filling minerals in fractured zones and in the rock matrix. The models are based on different assumptions about the proportion of different iron minerals, the surface area of the mineral grains and the kinetics for the oxygen reactions.

According to SKB, the flow rate and the duration of the period for penetration by glacial meltwater are the crucial factors as regards whether oxygen can reach the repository depth. SKB's calculations indicate that mineral reactions consume all the oxygen, providing that the advective transport times to the repository depth are more than one year and that the capacity of the fracture-filling mineral to buffer the oxygen suffices for more than 1,000 years. Since SKB's flow simulations indicate that the transport times are more than one year, SKB excludes the occurrence of oxidising conditions. However, SKB has estimated the effects of a hypothetical oxygen penetration on canister corrosion (Section 9.4.10), and notes that the corrosion for a melting period might be 1 mm. This case is not taken into account in the analysis of the containment time of the canisters.

Oxygen concentration in glacial meltwater
The concentration of oxygen in glacial meltwater is an important parameter in SKB's model calculations. When the enclosed air has been compressed by the ice and snow above, a relatively large volume of oxygen may be trapped (e.g. Raynaud & Lebel, 1979). As a result, the glacial meltwater may have a concentration (45 mg/dm^3) that is 3-5 times higher than groundwater in equilibrium with atmospheric oxygen (8-15 mg/dm^3). SKB, however, only uses the lower concentration (8 mg/dm^3) in the calculations cited in SR-Can (SKB TR-06-31, SKB R-06-105). The authorities and Glynn (2008) consider that it is doubtful if there are sufficiently strong arguments for excluding higher oxygen concentrations in the analysis of consequences. It is possible that erosion processes and reactions on particulate materials formed under the ice consume oxygen (SKB R-99-41), but the authorities consider that the evidence presented in the study cited is insufficient to permit assessment of reliance on these processes.

Accessibility of reducing capacity in the rock and reaction kinetics
In SR-Can, SKB has estimated the dissolution rate for iron(II) minerals (mainly biotite) using a kinetics model (SKB R-06-105). A similar model was reported previously in SKB TR-99-19.

The authorities and their consultants consider that there are considerable uncertainties in SKB's model for accessibility of reducing capacity in the rock and reaction kinetics. Bath and Hermansson (2008), the authorities' consultants, have reproduced SKB's estimates for oxygen penetration with identical input data, and the results largely confirm SKB's results. Bath and Hermansson (2008) point out, however, that there are considerable uncertainties as regards the modelling of oxygen consumption, due to the difficulty in determining reactive surfaces, representative rate constants, and the fact that the proportion of Fe(II) minerals in filled fracture zones has not been reported (and has possibly been erroneously assumed to be biotite rather than chlorite). Glynn (2008) considers that the downward adjustment by two orders of magnitude to compensate for differences between laboratory data and realistic field conditions is probably insufficient (SKB R-06-105). The need for a downward adjustment of this nature in order to obtain realistic results from the modelling of weathering processes is well-known (White & Petersen, 1990). Glynn (2008) considers that SKB should take into account chemical affinity, which reduces weathering when reactions approach equilibrium, channel formations in the fractures and the fact that a certain proportion of the iron in relevant minerals is often already in an oxidised form. Furthermore, SKB may need to evaluate how factors other than pH may affect the dissolution kinetics of biotite or chlorite, for example oxygen concentration (Sugimori et al, 2003), temperature (Murakami et al, 2004, and bacteria (Hopf et al, 2007).

In the geosphere process report (SKB TR-06-19, page 161), SKB states that microbial processes in the rock provide a renewable source of organic carbon which results in oxygen reduction capacity throughout the life of the repository. However, only the inorganic processes are discussed in the main report for SR-Can and in SKB R-06-105. Bath and Hermansson (2008) think that it is likely that both systems exist in parallel, but that their relative importance may vary during the functional period for the repository.

Model for infiltration of glacial meltwater
In SR-Can, the flow rate in fractured zones is depicted as a critical uncertainty factor for the assessment of glacial oxygen penetration. SKB's estimates are based on the worst possible case with substantial hydraulic gradients (case A and B) as the ice front passes the repository.

Glynn (2008) maintains, however, that infiltration may occur over an extended area that is much more distant from the ice front. Excess pressure may be formed in a thin layer of meltwater under warm-based ice, and this water may also penetrate down to the bedrock (Provost et al, 1998). This would mean that the period for oxygen penetration might be considerably longer that in the cases specified by SKB. The authorities consider that SKB should either take into account this case, or present arguments for the exclusion of this possibility.

The authorities' summarised assessment
In view of the considerable uncertainties in SKB's modelling discussed above, the authorities do not consider that the information reported in SR-Can provides a sufficient basis for dismissing penetration of glacial oxygen to the repository depth in connection with future glaciations. This assessment is also supported to some extent by experts cited by SKB itself in SR-Can (Sidborn, 2007, page 50).

In the authorities' view, prior to SR-Site, SKB should supplement the supportive modelling by an analysis of the uncertainties both in the rock's reducing capacity and in the models for infiltration of glacial meltwater. The authorities also consider that SKB should develop an integrated description of all the relevant redox processes and, on this basis, justify an appropriate model structure for future handling in the safety assessment. The decisive question as regards canister corrosion is not necessarily whether oxygen can reach the repository depth in a deformation zone, but rather whether oxygen penetration can have any real impact on conditions in the repository. If there continues to be considerable uncertainties, SKB can adapt the analysis on a site basis, utilising its knowledge of fracture networks and flow models for the candidate areas concerned, and the variations between deposition holes in the form of flows and flow-wetted surfaces. SKB should report what significance oxygen consumption in the buffer and backfill may have. If oxygen consumption as a direct result of copper corrosion cannot be excluded, this means that SKB should decide whether there is a risk of local corrosion processes.

12.6 Chemical changes in the buffer and buffer erosion

Long-term geochemical evolution in the buffer and backfill involve ion-exchange reactions and dissolution/precipitation of trace minerals, possible alteration processes of smectite clay and other dominating silicate minerals (for the backfill), and also possible erosion processes. Chemical alterations of the buffer may affect its mechanical and hydraulic characteristics. The chemical conditions in the buffer affect the transport of radionuclides. However, in SR-Can, erosion of the buffer has the greatest safety significance since the reported modelling indicate that penetration of a number of copper canisters as a result of corrosion is possible within a million years. It is stressed, however, that the understanding of mechanisms for buffer erosion is inadequate and that more work is required to arrive at robust estimates of the extent of buffer erosion. In principle, buffer erosion and major chemical alterations might have an impact on all safety functions for the buffer (Bu1-Bu7).

The rate of buffer erosion is estimated by means of the product of colloidal concentrations and the equivalent flow in the immediate near-field (Q_{eq}). It is assumed that erosion takes place during glacial periods when glacial meltwater seeping downwards may have concentrations of divalent cations (primarily Ca^{2+}) that are less than 1 mM. However, TR-06-18 indicates that the impact of mechanical erosion has not been investigated. The colloid concentration during an erosion phase has been assumed, on a very preliminary basis, to be 50 g/dm^3. The dependence on groundwater flow rates means that the method for estimating the distribution of groundwater flows at repository depth is of considerable importance. The majority of deposition holes with appreciable buffer erosion are obtained with the semi-correlated DFN method. Possible spalling of the rock near the deposition holes is also relevant since this process has a considerable impact at the local scale on the equivalent flow in the immediate near-field.

SKB has presented a preliminary summary of mechanisms for the formation and stability of bentonite colloids. In SKB R-06-103, it is assumed that gypsum provides the pore water in the buffer with calcium which prevents colloid formation. The modelling results in SKB TR-06-16 indicate, however, that gypsum may be dissolved during the temperate period and that the calcium ions released are instead bound to ion-exchange positions.

In the case of backfill that has a lower swelling pressure and higher concentrations of other minerals apart from smectite, the effect of a filter cake may be greater. In other respects, the treatment in SR-Can is identical with that for the buffer (SKB TR-06-18).

In SR-Can, SKB has systematically analysed the long-term chemical changes in the buffer and the backfill using a model that links chemical processes with groundwater flows in a fracture, and also diffusion/transport in the buffer and backfill (SKB TR-06-16). The chemical processes included are equilibrium with carbonate and sulphate minerals ($CaCO_3$, $FeCO_3$, $CaSO_4$, etc.), proton reactions on mineral surfaces, ion exchange processes (with Ca^{2+}, Mg^{2+}, K^+, Na^+), and redox processes (oxidation/reduction of FeS_2 and $FeCO_3$). The results indicate that pH and redox conditions in the buffer and backfill continue to be stable in the long term. Certain marginal changes in pH may be expected, due to the dissolution of carbonate minerals. In the absence of carbonate minerals, the system's pH is buffered by surface reactions. During the evolution of the buffer and the backfill, the proportion of calcium increases gradually in the solid phase as a result of ion exchange with sodium. During periods of infiltration of glacial meltwater, however, the calcium is leached. The effects of the initial residual heat have also been studied. Certain minerals with temperature-dependent solubility are affected by the temperature evolution in the buffer.

SKB has also analysed the risk of mineral transformations for smectite, which is the main component in the buffer and the basis for the buffer's good isolation characteristics (SKB TR-06-11). The process that has been primarily evaluated is the leaching of silicon and uptake of potassium, resulting in illitisation. The illite mineral does not have smectite's strong interaction with water and development of swelling pressure. The layer charge increases with the loss of silicon and when potassium is fixed, which eliminates the mineral's ability to bind water to it. In a natural sediment layer, the rate-determining step is probably the crystallisation of quartz, which eliminates dissolved silicon from the system. SKB's estimates for repository conditions, which are based on the activation energy of the reaction, indicate, however, that the expected extent of the reaction is much less than would be required to affect the buffer's properties to any appreciable extent. In principle, other silicate minerals with higher layer charges might be formed from smectite without the addition of potassium, but SKB points out that observation of natural sediment layers indicate that these are less common in comparison with illite.

SR-Can contains a residual scenario for buffer transformations, but the hypothetical consequences have not been analysed due to lack of time. However, SKB's preliminary conclusion is that no extensive mineral transformations will occur during the life of the repository, although a number of specific questions call for further study, for example sensitivity to higher pH values since silicon can be more easily transported away, the effects of a combination of high pH and high temperatures and reactions caused by metallic iron. The latter process is only relevant if the canister's insert comes into contact with the buffer after the copper shell has been penetrated.

Arthur and Zhou (2008), the authorities' consultants, consider that the simplified assumptions used to define the limit value for buffer erosion may be questioned. These assumptions are linked to application of the DLVO theory and the Critical Coagulation Concentration (CCC) concept (see SKB TR-06-18, page 121). According to Arthur and Zhou (2008), further work is also required on evaluation of the interaction between ground water/bentonite and the diffusive exchange between the buffer/fractures. Factors that determine the transport of possible bentonite colloids, such as possible filtering, also need to be evaluated, and this also applies to changes in the hydrology and geochemistry.

Marsal et al (2008), who are also the authorities' consultants, consider on the basis of independent estimates that geochemical changes in the buffer will be gradual and limited. The porosity changes will continue to be limited, but increased pH may be considerable (up to pH 10.5) due to the inflow of glacial meltwater (represented by Grimsel water). Results from the independent calculation comply well with the results obtained in SKB's corresponding study (SKB TR-06-16), apart from a greater pH increase in the independent study. This is probably due to the application of an electrostatic correction for the double layer. Another difference between the modelling results concerns the life of the gypsum and dolomite minerals. It is considered that this difference is simply due to the selection of equilibrium constants.

EBS points out that SKB's modelling of buffer evolution is based on several different conceptual models which take into account different aspects – for example an osmotic model for swelling pressure, an ion exchange model for pore water evolution, and an empirical kinetics model for illitisation. A complex approach of this nature, with different models for different processes leads to a need for evaluation of the consistency between both the models and the data. EBS also considers that SKB's reporting concerning the relative importance of different buffering reaction for pH and redox could be more transparent. There should be results from scoping calculations, in addition to the results of complex numerical models.

MKG (SKI Reg. No. 2006/985) considers that additional experimental investigations of the way in which bentonite is affected by iron are required.

MILKAS (SKI Reg. No. 2006/985) is critical of the fact that SKB is planning to dispose nuclear fuel in rock containing groundwater, due to the risks, for example, of buffer losses as a result of ground water with a low salinity, channel formations in the buffer, and fractures with considerable water-conducting characteristics. As a result, MILKAS considers that SKB should investigate alternative repository solutions, for example dry storage above the surface, on the same conditions as KBS-3.

The authorities are positive to SKB's recently commenced research project on buffer erosion. In view of the significance of buffer erosion for evaluation of the buffer's safety function and the analysis of consequences, this work is needed as a basis prior to the completion of SR-Site. One of the goals should be a deeper theoretical understanding of the stability of buffer colloids under various relevant conditions. Since SKB has itself indicated that the existing model in SR-Can has a very preliminary status, it is not meaningful in this context to go into details as regards this approach (SKB TR-06-09, page 356). One question, however, is whether buffer erosion is only linked to glacial meltwater which may only be anticipated in the far-distant future, or whether buffer erosion may also occur in an earlier phase of the repository evolution (due to physical erosion or reduced ion strength under temperate conditions). Estimates of the extent of possible erosion of the backfill are also required, which does not appear to be reported in SR-Can. Measures to minimise erosion of the buffer and backfill need to be reported in order to justify the requirements of optimisation and best available technology.

In the case of chemical changes in the buffer, the authorities note that penetration of glacial meltwater and salt water has been assumed to occur from 10,000 years after sealing, which does not comply with the future climate trends in SR-Can (SKB TR-06-09, page 308). Furthermore, it is not clear whether the changes in the hydraulic gradient during this phase have been taken into account. The authorities consider that, generally speaking, SKB should endeavour to achieve a greater degree of consistency between the various modelling studies, in order to permit straightforward assessment of the relevance of the various processes. In addition, in the authorities' view, SKB should explain more fully why the Grimsel water may be considered to represent the inflow of glacial meltwater at repository depth. The melted water that is not affected probably has much lower ion concentrations (de Mora et al, 1994). There is no doubt that some reactions with geological materials take place before this water reaches repository depth, but Glynn (2008) points out that the geological and mineralogical characteristics of the rock under an alpine glacier differ in comparison with those under a Fenno-Scandinavian ice sheet.

Questions involving the geochemical stability of the smectite clay in the repository environment are of fundamental importance for the functioning of the buffer and backfill in this very protracted time scale. As a result, it is important that the issues identified are addressed in SKB's research programme. It may, however, be noted that this work has advanced considerably more than research concerning possible long-term erosion of the buffer and backfill. The authorities consider that SKB's treatment of illitisation may need to be augmented by arguments other than those based on laboratory studies of the activation energy of the process. It would, for example, be helpful if the importance of limitations on the introduction of potassium could be reported more explicitly.

12.7 Isostatic load as a result of glaciation

The maximum hydrostatic load that can occur at repository depth coincides with the time for future glaciations. An increased hydrostatic pressure and the additional swelling pressure from the buffer results in an isostatic load on the canister which represents a design limiting load case for the canister insert. One of the most crucial requirements for the canister is that it should be able to resist the high pressures applied in this case, which are linked to the safety functions C2 and R3b. There is a description of the isostatic loading in sections 7.3.1 and 9.4.9 in SR-Can (TR-06-09).

The maximum ice thickness determines the maximum possible pressure. SKB's climate report (SKB TR-06-23) discusses the evaluation of changes in the ice thickness for both SKB's candidate areas: Forsmark and Laxemar. In the case of the reference evolution based on a repetition of the Weichsel ice age, the maximum ice thickness would be 2,900 m for Forsmark and 2,400 m for Laxemar. With the aim of investigating the effects of an even greater degree of ice load, the maximum ice thickness for the Saale ice age has been estimated to be 2,600 m for Laxemar and 3,200 m for Forsmark. The maximum ice thickness in an extreme case is estimated to be 3,670 m. In the design premises for the canister (SKB R-06-02), SKB has defined a total hydrostatic pressure in a Saale ice age as 45 MPa for Forsmark and 42 MPa for Laxemar.

Holmlund (2008) considers that SKB's estimates of ice thickness are reasonable. The authorities consider that the uncertainties for estimation of maximum ice thickness are manageable, and that the combination of modelling and geological observations provides a satisfactory documentary basis.

SKB has carried out a characterisation of the material characteristics of the insert, and on this basis, has implemented both a deterministic and a probabilistic analysis of the way the canister would behave under increasing hydrostatic pressure (SKB TR-05-17, SKB TR-05-19). In addition, SKB has also carried out large-scale experiments regarding the way in which the canister would be deformed in the event of external pressures of up to 140 MPa (SKB TR-05-18). In the case of a pressure of up to 50 MPa, the probability of local collapse has been reported, and also the probability of the initiation of crack growth. A defect distribution after casting has been used, derived from microscopic studies of the insert. It is shown that, at a pressure of 44 MPa, the probability of local collapse is extremely small (of the order of 10^{-9}) for a reference case with no eccentricity, a corner radius of 20 mm, and a standard deviation for the yield strength and the ultimate strength of 6 MPa. It is noted, however, that the probability of local collapse is sensitive to small variations in certain parameters. For example, the probability of local collapse according to SKB TR-05-19 is:

- 10^{-4} for a pressure of 50 MPa,
- 1.0 for a pressure of 50 MPa, if eccentricity is 5 mm,
- 1.0 for a pressure of 50 MPa, if the corner radius is 15 mm,
- 0.1 for a pressure of 50 MPa, if the standard deviation for the yield strength and the ultimate strength is 15 MPa.

However, the canister will not fail in the event of a local collapse. In this case, only a local plastic hinge will be formed, and the canister can still support a load with intact geometry. If a global collapse were to occur, with a rupture of the canister – which normally involves deformations – several plastic hinges would of necessity be formed under increasing pressure. Applying a deterministic analysis for a partial canister model (one eighth of the canister cross-section modelled), it has been determined that the global collapse pressure would be 130 MPa. Using a three-dimensional model, POSIVA has estimated that a global collapse pressure of about 90 MPa would apply, with an eccentricity of 5 mm (Ikonen, 2005). These results are supported by full-scale tests (with two canisters of full diameter but with a shorter length). In one case, the test was terminated at a pressure of 130 MPa, when major deformations developed, even if the canister was still leakproof. The second canister fractured at a pressure of 139 MPa, with very considerable deformations and holes in the copper casing. Although these results indicate a considerable margin between the design pressure (45 MPa for the Forsmark site) and the pressure at which the canister breaks, there are uncertainties in the analyses that need to be clarified.

The probabilistic analysis assumes that in most cases the most limiting mechanism is local plastic collapse that does not result in canister failure but leads to very high probability values for a pressure that is only slightly higher than the design pressure, and also for small variations in certain key parameters. This means that the value of the probabilistic analysis carried out is limited in indicating adequate margins for canister rupture. On the other hand, it may provide guidance regarding the tolerance for certain geometrical parameters which are of importance in the manufacturing process. This also means that, as regards the risk of canister rupture, improving the precision of the probabilistic analysis is of little avail with regard to the remaining uncertainties. It is of greater interest to ensure that there is a sufficient margin between the design pressure and the pressure at which rupturing of the canister may be anticipated. In the case of higher pressures than 50 MPa, SKB has hitherto only performed a deterministic elastic-plastic stress analysis with a simplified canister model, and with no consideration of the impact of defects. However, a fracture mechanics analysis conducted by Koyama et al (2006) indicated a small risk of the development of cracks at an external pressure of 44 MPa.

The authorities consider that the structural integrity analyses regarding isostatic pressure have been carried out in a correct manner in the main, and that there are satisfactory prerequisites with continued analyses for demonstrating adequate strength to withstand external pressure during a glaciation period. The authorities have, however, presented the following viewpoints regarding the remaining uncertainties in the structural integrity and their prerequisites:

1. A three dimensional stress analysis of the canister (insert plus copper shell) with a pressure up to the canister rupture point (corresponding to holes in the canister) should be carried out, taking into account the full size of the canister and providing information about the sensitivity to variations both in the materials data and certain key geometrical parameters, such as eccentricity.
2. A fracture mechanics analysis of the canister with a pressure up to the canister rupture-point should be carried out that takes into account the effect of manufacturing defects of various degrees, linked to the manufacturing aspects on the one hand, and, on the other hand, what may well be missed in a non-destructive examination. In the case of the insert, there is a possibility that crack growth might occur prior to the occurrence of global plastic collapse. The analysis should also include defects in the copper shell, which may provide guidance in the assessment of the probability of stress corrosion cracking. The analyses should provide information about the maximum acceptable defect sizes, both in the cast-iron insert and the copper shell, and also an evaluation of whether the extent of such defects can be detected with the NDE methods employed. This study should also include sensitivity analyses for variations in significant parameters, including parameters that are relevant for manufacture, in order to demonstrate the robustness of the results. Residual stresses in the copper shell in connection with welding operations should also be taken into account. In the latter case, SKB should investigate whether large residual stresses can exist after casting and, if so, what impact these residual stresses have on the damage tolerance.

12.8 Shear loads from earthquakes

A well-known risk in connection with a KBS-3 repository is that a canister is damaged by rock movements from an earthquake in the near-field so that the leakproof requirement is no longer fulfilled. The damage occurs as the result of a shearing movement along a fracture plane that intersects a deposition hole containing a canister and buffer material. The extent of the movement depends on the size of the fracture and the distance from the deformation zone in which the primary movement was generated. The buffer cushions the movement in the rock to some extent, but the canister may nonetheless be deformed to a greater or lesser degree. The canister will not fulfil its leakproof requirements if deformation of the casing or the insert exceeds the fracture strain. SKB has established a criterion based numerical modelling for rock movements in which movements may not exceed 10 cm if the integrity of the canister is not to be endangered. The C3, Bu4 and R3a safety functions are geared to this type of load. This situation is described in Section 9.4.5 of SR-Can.

MILKAS (SKI Reg. No. 2006/985) questions whether the repository can be made safe against earthquakes. It is considered that the idea of final emplacement is based on old and erroneous information that assumes that the bedrock is stable. MILKAS points, in particular, to the risk associated with seismic activity after an ice age, and considers that a respect distance is not, in practice, a useful concept for reducing the risk of earthquakes.

MKG (SKI Reg. No. 2006/985) asks whether the entire tectonic lens at Forsmark might fracture. The repository might constitute a defect which would mean that the lens fractured at a low angle through the repository, resulting in the crushing of a large number of canisters (due to the ice load in combination with earthquakes).

The structural integrity of the canister in the event of a shear load
SKB presents calculations for a canister (cast-iron insert, copper cylinder and copper lid) exposed to a shearing movement of 10 cm and 20 cm in SKB TR-04-02 and SKB TR-06-43. The results in SKB TR-06-43 are considered to be more realistic since the FEM model involves contact elements between the rock and the buffer, between the buffer and the copper shell, and between the copper shell and the insert. Only the results of SKB TR-06-43 are used for the evaluation of canister integrity in SR-Can (SKB TR-06-09).

SKB has analysed two types of bentonite for buffer purposes: Na bentonite and Ca bentonite – both with a maximum density of 2,050 kg/m^3 (SKB TR-06-43). The latter type of bentonite gives rise to greater strains in the canister due to the higher stiffness and shearing strength of Ca bentonite, which means that its ability to cushion the rock shearing load on the canister is not as great as for Na bentonite. Ca bentonite constitutes the reference case, since Na bentonite is also gradually transformed into Ca bentonite over time via ion-exchange reactions with calcium in the ground water. SKB has also analysed the effects of an illitised buffer, which is much less rigid and, as a result, such a transformation is not a problem in this context.

The results obtained suggest that the canister can withstand a shearing movement of 10 cm without exceeding the fracture strain, either in the copper shell or in the cast-iron insert (SKB TR-06-43). It is assumed, however, that the fracture strain represents at least 7% for the cast-iron insert and 30% for the copper shell. In several cases, materials testing have indicated lower values for the fracture strain of the insert. SKB TR-05-17 reports fracture strain values of less than 2%, which is assumed to be due to casting defects in the form of slag inclusions. The authorities consider that SKB should present better analyses and investigations that verify that the actual fracture strain is not exceeded for the cast-iron insert in the case of shearing of at least 10 cm. If this proves impossible, the criterion should be reviewed.

In the case of Ca bentonite, relatively large strains in the copper lid is reported (max 19% for shearing, d = 10 cm and max 32% for shearing, d= 20 cm, with a bentonite density of 2,050 kg/m^3). This means relatively large strains in relation to the fracture strain for the copper. A case involving partially cemented bentonite has also been analysed in SKB TR-06-43, which provides greater strains than a normal buffer but still without jeopardizing the integrity of the canister (see also Section 11.7). However, if a cemented buffer was even more rigid, or if a greater proportion of the buffer was cemented, the canister might be damaged in the event of a 10 cm shearing. SKB TR-06-43 points out that the characteristics of Ca bentonite are not as well-known as those for Na bentonite. The characteristics assumed for Ca bentonite in the models in SKB TR-06-43 are primarily based on information about Na bentonite, and only on a limited number of experiments with Ca bentonite.

The effect of creep of the copper material in the event of a shearing load due to earthquakes has been analysed by SKB, using a specific creep model (SKB R-06-87). Relatively high creep strain is obtained in the copper lid and its vicinity, even if the creep-failure limit is not exceeded with a shearing of a maximum of 10 cm. As a result, the authorities, and also Petterson (2008), consider that SKB needs to investigate in more detail the impact of the residual stresses in the copper shell after a shearing load that may result in a creep failure. Pettersson (2008) considers that SKB's analysis of this case (SKB R-06-87) is based on a questionable application of the creep model. In this context, EBS states that SKB has not taken sufficient account of the link between plastic deformation and creep. Yet another aspect of residual tensile stresses in the shell is that they may affect assessment of stress corrosion cracking (Pettersson, 2008).

When modelling the shearing load case (SKB TR-06-43), a shearing rate of 1 m/s is assumed, which, it is anticipated, may correspond to a relatively high value for an earthquake in the near-field of the deposition hole. The higher the shearing rate assumed, the higher is the stiffness of the bentonite in the event of a shearing load. The shearing strength of the buffer is relatively weakly dependent on the shearing rate which reduces the effect of this uncertainty. Of greater importance, perhaps, are the effects of time-dependent plasticity in the copper material and in the cast-iron insert. Even at a shearing rate of 1 m/s, there is a risk that the materials' dependence on the strain rate will become considerable. This might result in increasing yield strength, a reduced fracture strain and more localised plasticity, which means greater propensity to reach the fracture strain than in quasistatic loading (Bowyer, 2008). As a result, the authorities consider that, when undertaking further analyses of shearing deformation, SKB should also investigate the impact of the strain rate on the copper material and the cast-iron insert.

To summarise, the authorities consider that the structural integrity analyses with regard to shearing loads due to earthquakes have been carried out in a correct manner for the most part, and that continued analyses offer satisfactory prerequisites for demonstrating sufficient strength to withstand a limited shearing load as the result of an earthquake. However, the arguments for the 10 cm criterion need to be reinforced in order to demonstrate the validity of SKB's strategy for overall handling of the earthquake problem. The authorities have the following viewpoints as regards the remaining uncertainties in the strength analyses and their prerequisites:

1. The canister's ability to withstand mechanical loads in connection with an earthquake depends greatly on the buffer's characteristics. SKB should perform future studies in order to:

    - demonstrate the necessary procedures to guarantee that the buffer density does not exceed 2050 kg/m^3,
    - investigate and verify the characteristics of Ca bentonite that do not appear to have been studied sufficiently,
    - analyse further the case of a partially cemented buffer, providing that strong arguments cannot be presented for excluding this case.

2. SKB should present improved analyses and investigations which can verify that the actual fracture strain is not exceeded for the cast-iron insert when subjected to a shear load, partly as regards evidence of a considerable scatter in the cast-iron insert's fracture strain, and partly as regards the impact of the strain rate on the copper material and the cast-iron insert, so that such impacts do not mean that the fracture strain in these materials is reached more easily than with quasistatic loads.
3. The calculations indicate relatively large strains in the copper lid in the case of shear loads. SKB should conduct new analyses to further demonstrate sufficient strength in the copper shell (e.g. better analysis methodology, more recent materials data, and possibly redesign of the lid). In this context, SKB should investigate the impact of residual stress in the copper shell after a shearing load, and how this may affect the risk of creep failure and stress corrosion cracking.
4. SKB should study the impact of defects in the cast-iron insert in the case of a shear load.
5. Initial estimates by SKB indicate that creep failure in the copper shell cannot be anticipated for a shearing movement of a maximum of 10 cm, although relatively high creep strains may be predicted. Further studies with other creep models should be carried out in order to make a more reliable assessment of the risk of creep failure in the copper shell after a shear movement.

Combination of shear load and high hydrostatic pressure
SR-Can (SKB TR-06-09) states that the combination of simultaneous shearing as the result of an earthquake and an isostatic load resulting from glaciation does not need to be taken into account. SKB bases its argument primarily on the calculations in SR R-06-88 which, among other things, have determined the effective stress in the rock prior to, during, and after a glaciation. This shows that the effective stress, which is also proportionate to the maximum shear tension, declines during periods of high glaciation loads, which indicates greater stability. A shear movement due to earthquakes may therefore be regarded as less probable during periods of high glaciation loads. However, it should be pointed out that the results in SKB R-06-88 do not exclude the possibility that a shear movement may occur during a glaciation, particularly in cases with high pore pressure, even if it is more likely that shearing occurs after the ice front passes by the repository.

SKB has also (SKB R-06-95) performed analysis of stability during a glaciation, with alternative models of the earth's crust which has different elastic and viscous characteristics and which affects changes in the rock stresses in the repository. Although the results of SKB R-06-95 indicate a general increase in stability during glaciation periods, they also show that there are periods of reduced stability and greater risk of shearing due to earthquakes during a glaciation process. This applies especially to the Oskarshamn case in the initial phases of a glaciation. It should be noted that the impact of pore pressure has been neglected in SKB R-06-95, which has a non-conservative effect on stability.

The municipality of Oskarshamn (SKI Reg. No. 2006/985) asks whether SKB has studied what happens if a canister is first deformed and weakened by an earthquake and is then subsequently affected by the high hydrostatic pressure resulting from a maximum ice load. During the protracted period that needs to be taken into account in the safety assessment, it may, for example, be imagined that a canister that has suffered some damage in a previous ice period is more sensitive to impacts during the next glacial period.

The authorities consider that the analyses presented by SKB are not sufficient to reject the possibility that shearing as the result of an earthquake and an isostatic load from glaciation might occur simultaneously. SKB should conduct further studies to elucidate the way in which such loads may interact. Questions that need to be explained include the selection of models for the earth's crust (e.g. viscoelastic or viscoplastic models and the impact of thickness with different forms) and ice, the impact of pore pressure and cohesion, and possible three-dimensional effects. It may also be worthwhile to carry out an analysis of a canister subjected to shearing and a simultaneous isostatic load from a glaciation in order to study how the structural integrity is affected.

Respect distance and strategy for the selection of suitable deposition holes
SKB's strategy in SR-Can for limiting the risk of damage to canisters is based on information about potentially hazardous structures in the rock obtained in the initial site-investigation phase. Potentially hazardous structures are defined as structures which are sufficiently large to permit the hypothetical occurrence of a movement of 10 cm in the event of an earthquake of magnitude M6 or greater (10 cm is SKB's criterion for a movement that is considered might endanger the integrity of the canister). Such structures are avoided by locating repository areas at a given respect distance from deformation zones. Special criteria for the selection of deposition holes also reduce the risk.

The respect distance is defined as the perpendicular distance from the edge of a deformation zone in which deposition holes for canisters may not be located. Estimates are presented in SKB R-04-17 and SKB R-04-48 which indicate that the size of shear movements declines with increasing respect distances. This also applies to the size (in terms of the fracture radius) of the existing rock fractures which may be found in the near-field of the deformation zone. No deposition tunnels are to be constructed within a respect distance of 100 m, and stricter criteria are applied within a further 100 m to avoid dangerous fractures. Repository holes are located so that fractures that intersect the entire deposition tunnel do not cross deposition holes (the FPC criterion). In addition, there is also a more rigorous criterion under which deposition holes in which the same fracture plane intersects more than five drilled deposition holes are avoided (the EFPC criterion). These criteria are defined in SKB R-06-54. The remaining residual risk after application of these criteria is due to the fact that the horizontal fracture plane cannot be confidently identified at the ends of a deposition tunnel and that more extensive horizontal fracture planes may intersect less that five deposition holes.

The municipality of Östhammar (SKI Reg. No. 2006/985) questions SKB's respect distance modelling with an equal dislocation along a fault, and considers that SKB should take into account the considerable differences that have been observed in seismological studies. In addition, it is considered that further modelling is required to achieve a better understanding of the differences between the movements observed in tunnels and the overall risk of earthquakes.

In SKB R-05-29, SKB reports a method for estimation of a volume fraction, ε, in which randomly located deposition holes would include discriminating structures. The value of these estimates is that they provide an indication of the proportion of canisters that may be damaged if the acceptance criteria for deposition holes (FPC, EFPC) are not employed. The precision of the estimates depends, however, on the quality of the underlying discrete network model (DFN). Geier (2008) considers, for example, that, based on his independent DFN model, that SKB may have overestimated the degree of utilisation. In addition to the purely geometrical issues concerning the representation of discriminating structures, the degree of utilisation also depends on the application of acceptance criteria for deposition holes.

Several parameters affect the model for rock fractures, for example the fracture intensity P_{32} and the exponent *k*. The latter occurs in the frequency function f(*r*) for fractures that are assumed to be proportional to the fracture radius *r* to a power of -(*k*+1). As demonstrated in SKB R-05-29, the calculation results are particularly sensitive to certain parameters, mainly uncertainties as regards the exponent *k*. A change in *k* of 15% corresponds to a change of an order of magnitude for the volume fraction. The parameters in the model are not independent of each other, however, which reduce the sensitivity. In SR-Can (SKB TR-06-09), SKB estimates that the volume fraction ε may, at most, increase by a factor of 2.5 due to uncertainties regarding the parameters in the rock model. It should be noted, however, that the information regarding the fracture network in the rock is based on a limited number of fracture radii, some less than 10 m and others greater than 1,000 m, as clearly demonstrated in the statistical treatment in the site investigations at Laxemar (SKB R-05-45) and Simpevarp (SKB R-05-28). There is no data from the intermediate sizes which are of interest, with fracture dimensions that cause potentially discriminating fractures. A further uncertainty factor may be that short fractures in the documentation have been linked with major fractures which, in this case, would have an impact on *k*. It should be noted, however, that the treatment in SR-Can is only based on a small proportion of the information that is expected to be available prior to SR-Site.

The authorities consider that, prior to SR-Site, SKB needs to improve the accuracy in estimates of the model parameters in the DFN model. SKB also needs to address the remaining uncertainties in the DFN model in a systematic manner, and investigate the impact they have on estimates of the risk of canister failure. According to the authorities, SKB should describe the mapping and investigation of potential deposition tunnels in order to demonstrate the certainty with which discriminating structures may be identified. Factors that limit effectiveness should be taken into account in the same manner as in evaluation of other components in the repository. Furthermore, it should be taken into account that identification of structures is more difficult in tunnels that are blasted than in tunnels that are drilled.

In SR-Can (SKB TR-06-09), SKB reports the average number of damaged canisters as the result of an earthquake (out of a total of 6,000) over a period of 120,000 years. These estimates are based on the DFN model, applying a respect distance of 100 m to avoid hazardous fracture areas. If estimation is confined to the volume fraction ε in which randomly oriented deposition holes intersect a fracture zone and in which shear movements of more than 10 cm may be anticipated, the number of seriously damaged canisters over 120,000 years (a climate cycle) is 0.5 for disposal at Forsmark and 0.9 for Laxemar. This estimate has been based on estimation of the probability of an earthquake of at least M6 within a 5 km radius of the repository that may be expected to occur over a climate cycle ($p = 3x10^{-2}$). This risk may, however, be reduced by application of the acceptance criteria (EFPC) discussed above, which means that positions in the rock that are intersected by discriminating structures are eliminated. This reduces the number of damaged canisters (out of a total of 6,000) over a climate cycle to 0.014 for emplacement at Forsmark and 0.008 at Laxemar. As regards the entire period covered by the safety assessment (10^6 years), the number of damaged canisters is 0.12 for Forsmark and 0.065 for Laxemar.

The authorities consider that SKB has developed an appropriate strategy for limiting and controlling the contribution to risk associated with future earthquakes, based on the estimation methods described above. SKB's plans for application of respect distances and criteria for the selection of emplacement locations should provide satisfactory prerequisites for indications of repository sites for which the risk contribution from earthquakes meets the authorities' requirements. It is clear, however, that the actual results of calculations presented in SR-Can are based on very preliminary information and, as a result, there continues to be a need for a number of measures and further investigations, for example:

1. SKB should carry out continued studies aiming to increase the accuracy of estimation of the model parameters in the DFN model as regards rock fractures, particularly as regards fracture radii in the range 10-1,000 m. This also includes investigation of other aspects of the function f(*r*), which describes the frequency function for fracture sizes in the rock.
2. SKB should report in more detail on procedures prior to and after the construction of the repository facility which provides location-specific information to avoid deposition holes crossed by discriminating structures. This also involves the investigation methods that are to be used in blasted tunnels, where there is a greater risk of missing circumferential cracks in comparison with drilled tunnels. Continued development of procedures for avoiding structures that are discriminating in the case of shear loads also need to be coordinated with a corresponding future development of procedures designed to limit the additional risk resulting from advection and corrosion cases (if buffer erosion continues to be regarded as a significant factor).

Earthquakes – frequencies and magnitudes
The risk of earthquakes of a significant magnitude increases during periods of reduction in glacial loads, and possibly also during increasing glacial loading (the term employed in SR-Can is, however, "post-glacial faulting"). SR-Can assumes general awareness of this phenomenon in the literature in this field and, in particular, studies of the Pärvie fault and other relevant observations in northern Sweden. It should be pointed out that all known cases have involved reactivation of existing rock structures. Field studies of structures in glacial overburden with the aim of identifying traces of fault movements have been carried out (SKB P-04-123, SKB P-05-232). In the case of the Forsmark area, there are no indications from major earthquakes (M<7) since the previous ice age, while traces in the Oskarshamn area are more difficult to interpret.

The estimation methodology in SR-Can is based on an estimated annual probability for earthquakes of a magnitude of 6 or greater, which are normalised to a circular area with a radius of five km around the repository. The total probability is allocated equally between all known deformation zones within the repository area. SKB considers that this is a cautious but nonetheless unrealistic assumption. The probability of greater earthquakes should reasonably be higher for certain zones since there are considerable rock-mechanical and geometrical differences. This question is being investigated in ongoing studies.

The municipality of Östhammar (SKI Reg. No. 2006/985) does not consider that the general earthquake risk, besides the ice-age scenario, has been investigated sufficiently. Improved collation of information on previous earthquakes is required, and also mechanisms such as earthquake risks associated with river outlets and residual stresses in the vicinity of previous earthquakes. According to the municipality of Östhammar, SKB should consider a statistical analysis employing extreme-value distributions.

The authorities note that the independent study by Hora & Jensen (2005) has had a considerable impact in SR-Can. In view of the fact that this study was carried out with relatively limited resources and the primary aim was to develop a methodology for formal expert hearings, it is not impossible that a more ambitious expert hearing might have produced more reliable results. One important question discussed was, for example, the assumption about M7.6 as a nominal value for Dehl's Pärvie earthquake. The authorities consider, however, that SKB needs to balance additional studies for more reliable earthquake frequencies against other measures that can be implemented to reduce the uncertainties. SKB should base an analysis of the prerequisites for strengthening all components in the strategy on minimising and characterising the risk contribution from earthquakes.

SKB should study, and possibly take into account, the fact that probabilities vary with time. One obvious reason for such variations is that the frequency may increase when the ice load from major glaciations disappears. The aim should not merely be to estimate the maximum annual risk, but also to illustrate as realistically as possible how this risk changes over time.

The estimate of the dependence on distance of the aggregate displacement has been based on an M6 earthquake in SR-Can for technical estimation reasons (SKB R-06-48). A larger earthquake has a greater range, however, and higher shearing rates. As a result, confirmation that the conclusions in SR-Can are also valid for larger earthquakes (M7) is needed. The extended range means that it is not obvious that less probable earthquakes of a greater magnitude result in a lower risk factor. The authorities consider, however, that dealing with earthquakes that are highly improbable, even in extreme time scales, may be restricted to discussions in principle.

Attention should also be paid in SR-Site to the incidence and the effects of smaller earthquakes (M5). The lower limit at which an earthquake has the prerequisites to cause significant damage to the barrier system at short distances needs to be identified. SR-Can assumes that this threshold is at M6, without providing any detailed analysis. The impact of small earthquakes may also be relevant since there are still uncertainties about the validity of the 10 cm criterion for shear movements over a deposition hole.

To summarise, the authorities consider that SKB has a satisfactory approach for handling earthquake problems in SR-Can. The methodology is based on dividing up the problem, with well-defined conditions and criteria for sub-areas. The allocation of requirements for the engineered barriers and the rock provides a good starting point for future work. The authorities consider, however, that the analysis in SR-Can has been based on a number of assumptions that are not sufficiently explained, and this aspect needs to be reviewed prior to SR-Site. There is no detailed discussion of the safety impact of earthquakes of different magnitudes, for example.

13. Consequence analysis and radionuclide transport

This chapter reports on the authorities' points of view on radionuclide transport as well as uncertainty and sensitivity analyses for the reference evolution (SKB TR-06-09, Chapter 10). Additional radionuclide calculations reported by SKB in Chapter 12 (Analysis of scenarios) are commented on in section 14 in this report.

As support for the authorities' review, independent calculations of radionuclide transport have been carried out with SSI's own models (Xu et al, 2008) and with the aid of consultants (Maul et al, 2008). Maul et al (2008) have also carried out radionuclide transport calculations based on independent flow calculations (Geier, 2008). However, the results from these calculations were ready too late to be taken into consideration in this review.

SKB has not produced a report within the SR-Can project that describes SKB's radionuclide transport calculations in particular. The authorities have therefore only had access to the relatively brief documentation in the main report. This has made the review difficult and the work of reproducing SKB's calculations, which is reflected in several of the comments made below.

13.1 SKB's report

SKB reports in Chapter 10 of the main report (SKB TR-06-09) calculations of radionuclide transport and dose for four different canister rupture cases which have been identified in the reference evolution for the repository: initial defect (a small hole in the canister), copper corrosion for an eroded buffer, shear rupture cases and isostatic rupture. Moreover, questions are discussed relating to criticality in the canister.

The models for calculations of radionuclide transport include a "compartment" model for the near-field (COMP23) which describes three different leakage points from the near-field (Q1: fracture that runs across the deposition hole, Q2: the disturbed zone along the floor of the deposition tunnel and Q3: a fracture that cuts through the deposition tunnel). Effects of thermal spalling in the deposition hole have been dealt with by adjusting the value of the equivalent flow for transport path Q1. For transport in the rock, FARF31 is used which is a one-dimensional transport model that takes into consideration advection, sorption, matrix diffusion and chain decay. For the probabilistic calculations, SKB has used their own simplified analytical transport model. Dose calculations in the biosphere are made with the aid of dose transformation factors for the whole landscape (LDF). The LDF factors are based on a separate analysis of unit emissions (Bq/year) from the repository during an interglacial period of 20,000 years. For every radionuclide, the highest modelled LDF value during this time period has been selected for the dose calculations. The LDF values have then been used to calculate doses under all climate conditions, i.e. also for periods when the repository site is covered by an inland ice.

For every canister rupture case, a basic case is reported as well as a set of uncertainty and sensitivity analyses which describe the uncertainties in the reference evolution. Moreover, special calculation cases are reported to clarify the barriers' functions in accordance with the authorities' regulations.

13.2 Calculation models

The authorities consider that SKB in SR-Can has considerably improved documentation and the overview of codes with the development of flow diagrams for models (AMF) and the model report (SKB TR-06-26). However, the model report needs to be further improved prior to SR-Site. The authorities have started a review of SKB's quality work with respect to codes (Hicks, 2005) and experiments (Hicks, 2007). Hicks and Baldwin (2008) have also carried out a smaller supplementary review of SR-Can. This material forms an initial starting point for the authorities' view on SKB's quality work connected with long-term safety. The authorities intend to follow these questions up with additional points of view for the production of SR-Site within the framework of consultations during the site investigation phase. Additional points of view on the documentation of the calculation models and the reproducibility of the calculation results are contained in Chapter 4 and in Annex 2 of this report.

The codes have been structured in an appropriate way (classes 1, 2, 3, 4a and 4b) in the model report which also has a suitable structure in other respects. The review of different codes would, however, need to contain a better description of the applicability, use and role of the codes in the safety assessment. The authorities' consultants Hicks and Baldwin (2008) also emphasise that SKB should describe procedures for review and checking that the codes are used in the correct way in the safety assessment. Since certain codes will probably be used for safety analyses for a very long time, it is important that SKB carries out planning of the use of the codes that includes version control and documentation of all modifications, updates and further development. SKB also needs to have control over codes that "are retired" since the results from these may serve as a basis for a certain safety evaluation at a later stage.

The authorities note that SKB's level of ambition for documentation of codes in the model report is uneven. The description of Abaqus is, for example, minimal despite it having an important role in the safety assessment, while the description of Connectflow is more complete. The description of SKB's analytical radionuclide transport code and how it is used in the probabilistic calculations in SR-Can is also insufficient. The new analytical model for advective conditions in the deposition holes should be checked and documented particularly carefully bearing in mind that this case is very important for the assessment of compliance with regulatory requirements. The authorities also consider that SKB should explain and justify the parallel use of numerical and analytical codes for radionuclide transport.

SKB states in SR-Can that the intention is to continue to use analytical models for probabilistic calculations in SR-Site due to technical reasons. The authorities have no objection to this strategy but wish to emphasise that a more extensive verification and validation of the models are required in this case. Maul et al (2008) point out, for example that the analytical solutions should be able to be shown to be applicable for the whole interval of parameter values included in the probabilistic calculations.

The authorities take a positive view to SKB planning to introduce a wholly new code for radionuclide transport for SR-Site, PORSS, which is to be used in parallel with FARF31. There are issues about the handling of transient conditions and chain decay which cannot be handled in the existing calculation models. However, the authorities consider that it is important that SKB sets aside sufficient time to develop, test and document this code before it is introduced in SR-Site. One observation is that SKB already has two parallel tracks for radionuclide transport with COMP23+FARF31 and analytical solutions. With PORSS a third track is introduced. In the event of a clearer strategy for use of these codes not being presented, the authorities see difficulties ahead in understanding their mutual roles in the review of SR-Site.

As mentioned above, SKB does not present any radionuclide transport calculations that include colloid transport in SR-Can. In the event of a new model tool for such calculations being introduced in SR-Site, there is a need to develop, test and document this code. A description of the strategy for use of this code should in this case also be produced. The authorities also note that a couple of codes which are described in the model report do not seem to have been used in SR-Can (FracMan, FARF32, FARF33).

Modelling and other treatment of solubility limits are commented on the by the authorities in section 10.1 of this report.

13.3 Radionuclide transport with colloids

SKB has excluded calculations of the effect of colloid on radionuclide transport in SR-Can. SKB refers instead to rough estimates where the retardation in the geosphere is neglected for glacial periods. The authorities do not consider that this provides sufficient evidence to exclude effects of colloidal transport. While the importance of the rock for retardation is limited for the risk-dominating cases with advective conditions in the deposition holes according to Figures 10-42 and 10-43 (SKB TR-06-09), the rock none the less has some effect. According to the “what-if” calculation in Figure 10-53, it moreover emerges that the rock’s retarding role can affect the calculated risks by several orders of magnitudes, which should be taken into account when assessing the importance of colloids. The authorities consider that the differences between the figures are due to the rock barrier being more important for deposition holes with low flow rates. The authorities consider that SKB in all circumstances should be able to show that it has an understanding in principle of the importance of colloidal transport and can handle it in terms of modelling. An additional reason for a better report concerning colloids is the potential link to buffer erosion, which is a key process in the advection-corrosion scenario. Considerable uncertainties remain concerning the handling of buffer erosion and it cannot be excluded that the studies initiated by SKB may show that buffer erosion can be a problem for deposition holes with lower flows than those assumed in SR-Can.

The municipality of Östhammar (SKI dnr. 2006/985) does not consider that transport of plutonium in colloidal form has been dealt with in SR-Can. MKG (SKI dnr. 2006/985) also takes up the question of transport of radioactive particles with colloids due to results from an study of a polluted lake close to the reprocessing plant at Mayak in Russia.

13.4 Input data and distributions

The authorities consider that SKB’s standardised format for documentation of data has prerequisites to provide good traceability of input data to the analyses. The report of input data to the calculations of radionuclide transport is, however, not complete in SR-Can. As shown in Chapter 4, there are also some quality deficiencies in the documentation. The authorities agree with SAM that SKB should produce routines to internally check that it is possible to trace the assumptions that lie behind the choice of the parameter values.

The authorities consider like SAM and Maul et al (2008) that SKB needs to strengthen its argumentation for important parameter values and distributions used in the consequence analysis, for example, canister failure distribution, time for penetration of the cast iron insert and matrix diffusion depth. The arguments in the data report (SKB TR-06-25, page 193) for the selected triangle distribution (0.01, 10, 10) m for the maximum penetration depth of matrix diffusion are insufficient. Furthermore, other values are stated for Laxemar (0.5 – 1 m) in the analysis of glacial hydrology (SKB TR-06-09, page 338). Another example is the justification of the distribution function for the fuel dissolution rate. According to the data report (SKB TR-06-25, page 45), the project group for SR-Can proposes a log-triangular distribution due to the large spread of data. The project group is supported here on a recommendation from the external experts (SKB TR-04-19), i.e. Werme et al (2004) despite Werme also being included as SKB's fuel expert in the project group. Bearing in mind this parameter's great importance for the risk analysis and that the dose is a factor three times lower when choosing a log-triangular instead of triangular distribution (Maul et al, 2008), the authorities consider that a more detailed justification is needed.

The authorities have noted that certain data used in the calculations of radionuclide transport have been updated since the previous safety assessment. Clear arguments are lacking, however for certain parameter values having been chosen in a less conservative way compared with previous safety assessment. The authorities and their consultants (Xu et al, 2008; Stenhouse et al, 2008) emphasise that the value for the sorption coefficient used (K_d) for Ra-226 in the geosphere is two orders of magnitudes higher compared with SR-97 (SKB TR-99-23). This difference should be better explained. The authorities share the point of view in Stenhouse et al (2008) that SKB may need to review the chosen interval of K_d values taking into consideration that these parameter values have been empirically derived and are affected by the chemical environment. SKB should investigate to a greater extent selected sorption data (including uncertainty intervals) with site-specific laboratory and field measurements. Another example applies to the effective diffusion of the rock matrix where the recommended value of the data report (SKB TR-06-25) is higher for most nuclides and thus less conservative compared with SR-97 (see more details in Stenhouse et al, 2008). Similar differences exist for more nuclides as regards both IRF ("instant release fraction") and solubility limitations (Xu et al, 2008).

13.5 Uncertainty and sensitivity analyses

Uncertainty analysis
The authorities consider that SR-Can contains a set of calculation cases that together provide a good illustration of how uncertainties in the reference evolution affect the calculation results. However, the report is unstructured and an integrated description and justification of the strategy for uncertainty and sensitivity analyses is lacking, which has also been pointed out by SAM. A better explanation is needed prior to SR-Site of the purpose of different analyses and how SKB has selected calculation cases to shed light on critical uncertainties.

The report and discussion of the results from the uncertainty and sensitivity analyses are in some respects too brief to be able to understand the importance of different uncertainties (which could probably be explained by the lack of a dedicated report for the radionuclide transport calculations). A measure put forward by Maul et al (2008) is that all probabilistic calculations of risk should be based on a deterministic calculation case to illustrate critical factors. Another is to produce more complete texts for important figures. Figure 10-53 in SR-

Can main report shed light, inter alia, on the major impact of the rock barriers on calculated doses for the case without canisters and buffer, although it does not make clear which radionuclides are affected during different time periods or how these results relate to the probabilistic calculations for advective conditions (Figure 10-42 and 10-43) where the rock barrier does not have any great importance. SKB's report of geosphere transmission for different nuclides is good although it does not provide sufficient information to interpret Figure 10-53. A more detailed analysis of the realisations which provide high doses is required for the probabilistic calculations to be able to understand which parameter combinations produce major consequences.

The separate analyses of pulse emissions (the advection-corrosion case), gas-induced emissions from the canister (the pin-hole case) and calculation of dose conversion factors for wells are illustrative although it is not clear whether/how these effects are included in the integrated calculation cases and risk summation.

SAM recommends that SKB produces a central register for uncertainties prior to SR-Site. The authorities do not see any evident advantages, however, in compiling such a register bearing in mind that practically all parts of the safety assessment in one or another way are about evaluating and analysing different types of uncertainties, for example, in the data and process reports. The authorities consider that it is more important that methods to handle different uncertainties in the different phases of the safety assessment are justified and explained, and that it is clear where in the safety report the different uncertainty analyses are documented.

Sensitivity analysis

SR-Can does not include any complete sensitivity analyses. Instead, SKB refers to an interim report for SR-Can (SKB TR-04-11) with the justification that the same parameters are used in SR-Can. The authority considers that this is misleading since the value intervals are different in certain cases, although the parameters are approximately the same. For example, the interval of hydrodata to radionuclide transport calculations in SR-Can is based on Forsmark site-descriptive model version 1.2 while SR-Can interim is based on version 1.1. Furthermore, the major focus on the advection-conversion scenario in SR-Can means that the relative importance of transport parameters in the near-field and far-field have been altered, e.g. the importance of corrosion and fuel dissolution has increased. While SKB has supplemented with a separate sensitivity analysis for fuel dissolution rate (TR-06-09, page 440), although there is no analysis available of how important the fuel solution rate is in relation to the transport parameters.

The authorities consider like SAM that SKB should produce a more thorough sensitivity analysis in SR-Site. For critical parameters, such as solubility limits and canister failure distributions, it may be justified to extend the sensitivity analysis and provide a more detailed analysis of the underlying factors and parameters which affects the results. The authorities also share SAM's point of view that SKB should consider other methods apart from the SRRC method ("Standardised Rank Regression Coefficients") to increase the reliability of the results. The software Eios has been used in the sensitivity analysis for the dose calculations in the biosphere (Ekström and Broed, 2005), but also the Morris method to identify parameters with a non-linear effect or interaction between the parameters. Eikos includes several sensitivity analysis methods, for example SRRC and Morris as well.

SKB states in the method chapter (TR-06-09, page 60) that it may be reasonable to use pessimistic assumptions for demonstration of compliance with requirements but that more realistic estimates are needed of uncertainties to provide feedback for continued work with design, R&D and site investigations. The authorities do not consider that it is made clear in a good way how SKB deals with this problem in the sensitivity analyses in SR-Can. SAM emphasises that SKB's sensitivity analyses should be interpreted with caution bearing in mind the mixture of pessimistic and realistic assumptions made during the development of models and choice of parameter values. SAM also wishes to see explicit analyses in support of the assumptions that certain models are pessimistic. It should be clear in the documentation how the pessimism has been assessed, for example through the effect on doses, geosphere transport and radionuclide releases from the near-field.

An important purpose of sensitivity and uncertainty analyses is to assess how the repository can be designed so as to minimise the risk and the consequences of a leakage in accordance with the principles for optimisation and best available technology in SSI's regulations and general guidelines (SSI FS 1998:1 and 2005:5). One question, which is particularly relevant for the advection-corrosion scenario is whether thicker canisters and buffers could improve the protective capacity of the repository. Bearing in mind that it is an explicit aim in SR-Can to provide feedback for the design of the repository and canister manufacture the authorities consider that this type of sensitivity analyses is insufficient in SR-Can.

13.6 Risk dilution

The averaging of consequences from a repository over long times or over large areas may in certain cases lead to a calculated reduction of risks from the repository. This problem is partly a consequence of SSI's risk criterion being expressed as an annual risk in combination with very long time periods which need to be taken into account in the safety assessment. SSI's general guidelines (SSI FS 2005:5) state the effects of risk dilution are to be reported and assessed with a view to improving the understanding of the results from probabilistic dose calculations.

The authorities consider that SKB has described the problems with risk dilution in a correct way in SR-Can. The authorities also consider that SKB has illustrated the effects of risk dilution for the analysed canister failure cases in a credible way and that this approach is also a good starting point for the analyses in SR-Site. One exception applies to the calculation of dose factors for the biosphere (LDF) where it is not clear whether the dilution of radionuclides between different landscape objects can be justified taking into consideration the major uncertainties in the hydrogeological models (see section 13.9).

13.7 "What-if"-calculations

SKB reports in accordance with SKI's regulations (SKI FS 2002:1) special calculation cases to shed light on individual barriers. The authorities consider that the reported calculation cases are good in principle. However, there is, as mentioned above, a need to assess and explain the calculations in a clearer way. It should, for example, be stated how different key nuclides are affected by different barriers and how the relative importance of the barriers changes throughout the whole analysis period, for example taking into consideration decay of certain nuclides.

13.8 Specific comments on reported canister failure modes

The pinhole case
The pinhole case is not included in the risk analysis since SKB asserts that there will not be any canisters with initial perforation defects. SKB chooses none the less to analyse the case to shed light on the inner evolution of the canister and the retention characteristics of the buffer and the rock.

It is good, for several reasons, that SKB reports a case with an initially leaking canister. In the first place, SKI's general guidelines state that it is not sufficient only to assume that all canisters are sealed in the safety assessment (SKI FS 2002: 1). Secondly, certain questions remain on the importance of different defects for the lifetime of the canister (see sections 10.2 and 12.4). There are not either any complete results from series fabrication and testing of canisters and demonstration of the emplacement.

SKB's transport calculations for the pinhole case are relatively well developed compared with the advection/corrosion case. With the aid of independent models, it has been possible to reproduce the main part of SKB's calculation results (Xu et al, 2008; Stenhouse et al, 2008), even if there are certain questions concerning the transport path Q3 in the near-field model. As stated above, the authorities also consider that SKB's report contains good analyses of uncertainties for the pinhole case.

A special question which should be further investigated prior to SR-Site is how thermal spalling affects the equivalent flow (Q_{eq}) in the deposition holes. Maul et al (2008; section 3.2) point out that there are deficiencies and errors in the documentation of how the effects of spalling has been dealt with in the transport calculations. SR-Can contains certain uncertainty analyses to illustrate the importance of spalling. Bearing in mind the potentially great importance of spalling for the calculated doses in SR-Can, the authorities regard it as positive that SKB plans further experimental work to validate the conceptual models both for spalling and equivalent flows in the deposition holes.

The advection/corrosion case
Leakage of radionuclides from corroded canisters in deposition holes with buffer erosion is the wholly predominant case for the risk analysis in SR-Can. The authorities note, like SKB itself, that quite a lot of work remains to be done to obtain an acceptable conceptual understanding of this canister failure case. The analysis in SR-Can is based on a number of more or less preliminary assumptions which need to be better justified in SR-Site, for example, what applies to geometry of the eroded buffer, the applicability of Q_{eq}, the effect of colloids, handling of pulse emissions and co-precipitation of Th-230. The authorities therefore regard it as positive that SKB announces research initiatives to improve the state of knowledge before SR-Site (SKB TR-06-09, Chapter 13).

The calculations of radionuclide transport in SR-Can have been made with analytical models for advective conditions in the deposition hole and for transmission of radionuclides in the geosphere. Maul et al (2008) have, with the exception of Pb-210, succeeded in reproducing the results of SKB's calculations of radionuclide transport, but note that the documentation of the models (SKB TR-06-09, appendix B) is too brief. The authorities wish to emphasise that more complete documentation is needed and considerably more detailed discussion of the applicability of transport models for this canister rupture case in SR-Site.

It is good that SKB reports probabilistic calculations based on fixed times for canister failure. This facilitates the interpretation of the results and eliminates risk dilution in time. However, the authorities consider that SKB should complement with some calculations to illustrate the importance of uncertainties in the canister failure distribution.

With the model for buffer erosion used by SKB in SR-Can, the groundwater flow is, and in particular the proportion of deposition holes with high flow rates, controlling for the results of the radionuclide transport calculations. In the light of this, it is good that SKB propagates the alternative hydrological models to the radionuclide transport calculations. The uncertainties in the flow distribution for the respective model should be assessed in greater detail prior to SR-Site, however (the results from a single realisation are used in SR-Can).

The shear rupture case
The shear rupture case is treated in a very simplified way in the transport calculations in SR-Can. The transport resistance is neglected in both canister and rock, while the thickness of the bentonite buffer is assumed to be reduced from 35 cm to 20 cm. The chosen probabilities for canister rupture due to earthquakes, 0.2 and 0.06 during 1 million years for Forsmark and Laxemar, are commented on by the authorities in section 12.8.

The authorities consider that this canister rupture case needs to be described and justified in more detail prior to SR-Site. Documentation of how the analytical model has been applied for this case is far too brief compared with, for example, the pinhole case. The report of risk dilution due to the discrete canister rupture distribution is, however, illustrative and in accordance with the intentions in SSI's general guidelines (SSI FS 2005:5). The authorities do not exclude that a pessimistically simplified transport model may be acceptable for this canister rupture case, but it should in this case be justified on the basis of a considerably more extensive discussion about conceptual uncertainties in the description of transport processes.

Isostatic collapse
Canister rupture cases due to isostatic collapse are excluded from the risk analysis with reference to a negligible probability. SKB reports none the less the results of postulated isostatic canister breach of one or all canisters at two different times. The transport resistance of the canister is wholly neglected while the buffer and the rock are assumed to have intact retention characteristics. The authorities consider that a simplified description is acceptable if the canister breach case can be shown to have sufficiently low probability not to affect the risk assessment.

13.9 Dose calculations and analysis of environmental impact

Dose calculations
Unlike the previous risk analysis in SR-97, where only one ecosystem at a time was included, SKB uses an integrated landscape model in SR-Can that includes more ecosystems in the succession of landscape due to isostatic uplift (SKB TR-06-09 section 10.2; SKB TR-06-15). This is a step forward in the development of the risk analysis. New elements in the analysis are, for example, ”aggregated transfer factor” (TF_{agg} [Bq/kg C per Bq/l]), lognormal distribution method and Landscape Dose Factor (LDF).

TF_{agg} describes in a given ecosystem the relationship between radionuclide concentration in food, in water and in soil, respectively. The dose contribution from an ecosystem can be estimated by multiplying TF_{agg} with an estimated radionuclide concentration in water or soil, annual intake of carbon through food and a dose transformation factor. The lognormal distribution method is used to identify the most exposed group by adapting the function to dose contributions and the number of people in the different ecosystems.

The LDF concept is based on a continues unit release of each radionuclide which is distributed between different landscape objects in proportion to the probability that the discharge takes place to a specific place at a given time. The calculation of the LDF value is based on the highest dose rate for every radionuclide throughout the whole calculation period (18,000 years), which may be considered as being a conservative assumption. However, the authorities consider that it is difficult to make a holistic assessment since all assumptions in the LDF concept are not obviously conservative for example effect of dilution in the biosphere and insufficient representation of certain retention processes.

The LDF calculations are based on leakages from all canisters in the repository, which leads to the radionuclides being distributed among many landscape objects in the biosphere. This is not consistent with the risk-dominating advection/corrosion scenario where only one or a few canisters can be assumed to leak. The authorities consider furthermore that the averaging of dose calculation for the different landscape objects is not theoretically correct, since a summation step is lacking (see more detailed discussion in Xu et al, 2008). In practice, both these problems may result in an underestimate of the estimated doses. Another weakness is that the radionuclide transport models, which are included in the calculation of the LDF, do not reflect processes such as radionuclide dispersion and accumulation in areas affected by radionuclides, in any great detail. The combination of the above-mentioned effects can produce large consequences for the dose calculation. The authorities' independent modelling has, for example, shown that the inflow of radionuclides to the biosphere may take place in geographically more limited areas, which results in a higher dose rate than the LDF values reported in SR-Can. This difference is due to differences in the resulting extent of the contaminated area and accumulations in quaternary deposits (see discussion in Xu et al, 2008). The authorities consider that SKB should provide more support for the LDF concept in a better way taking into consideration the above issues.

With the justification that ".. several conservative assumptions have been made in dose calculations and for selection of the LDF values" (SKB TR-06-15, page 85), SKB has not reported any probabilistic simulation and has only used one value for LDF in the safety assessment. However, the authorities consider that uncertainties for the LDF values have not been reported to a sufficiently great extent since the values, in comparison with the well scenario, are not conservative for all nuclides. The well scenario is dealt with separately from LDF i.e. SKB assumes that all radionuclides from the geosphere are taken up in drinking water wells before they reach the biosphere, but does not include intake from the water wells in the calculation of LDF. The result from the authorities' independent calculations indicates that the LDF value is most often lower than the corresponding EDF value for the well (see discussion in Xu et al, 2008). The authorities consider that the dose contribution from the drinking water from a well should be included in the calculation of LDF unless SKB can show that the risk contribution is negligible.

SKB states in the main report (section 13.8.9) that a sensitivity analysis is being carried out with respect to different combinations of landscape objects. The authorities consider that SKB should also include alternative descriptions of the sites' future development as part of the uncertainty analysis, for example, different variants of watercourses and wetlands which are in the region at present or which may come into existence at the repository site in the future.

The authorities consider that SKB should make more detailed analyses of uncertainties in the distribution of discharge points from the repository prior to SR-Site. It is insufficient to base LDF calculations on a single realisation of the hydrogeological model as in SR-Can. Independent calculations carried out by the authorities' consultant (Geier, 2008) show differences in discharge points between realisations. The independent hydrological calculations also indicate that the discharge points may be considerably more concentrated, since discharges from several leaking canisters may take place in a single object in the biosphere via larger deformation zones.

The authorities consider that the lognormal distribution method may be used to identify the most exposed group and that it is in principle in agreement with SSI's general guidelines (SSIFS 2005:5). Application of the method in SR-Can is, however, called into question in the light of the inflow of radionuclides to the biosphere being distributed to a large number of landscape objects.

The authorities consider that TF_{agg} can be a good method to translate environmental concentrations to dose. However, the authorities parts SIG's, SAM's and Stark's (2008) opinion that the assumptions on which the estimate TF_{agg} is based are unclear. SKB should justify why certain food substances are excluded and that the human being, for example, only eats fish from aquatic ecosystems (SKB TR-06-15, page 51). SKB has previously reported that consumption of crayfish can give the highest and in certain cases the totally predominant dose contribution for certain radionuclides in the lake model (SKB TR-99-14, page 62 last paragraph). The authorities therefore share Stark's (2008) opinion that SKB should present alternative calculations to support assumptions that exposure via food are conservative. According to SSI FS 2005:5, SKB should base itself on the diversity of human use of environmental and natural resources that occurs today.

The report of the calculations and assumptions on which the estimate of the ecosystems' production is based are unclear. SKB states that it assumes that human beings eat all food produced within an ecosystem (SKB TR-06-15, page 51). This estimate is the basis for the calculation of how many people an ecosystem can support. However, it is close at hand to believe that the selection of intake of food for the calculation of TF_{agg} is the same as the selection for the estimated production within an ecosystem. It is also unclear how the different production parameters for food are used, for example, "*Productivity of food normally consumed"* and "*Productivity of edible products"* (SKB R-06-82, SKB R-06-83), and it is unclear in the case of the aquatic ecosystems which organisms are included in production (compared, for example, SKB R-06-82 and SKB R-06-81, Table 4-1). SKB should also explain why the stated production figures for Laxemar and Forsmark differ to some extent. Production is twice as high for agricultural land and ten times as high for forest ecosystems at Laxemar than at Forsmark (compared SKB R-06-82 and SKB R-06-83). SKB should also report on whether the dose estimates are affected by the productivity of different ecosystems.

Analysis of environmental impact
In SR-Can, SKB uses the ERICA tool to estimate dose for biota. This tool, which has been produced within the framework of the ERICA project in the EU's sixth framework programme, aims at developing a protective system for the environment within the radiation area. A risk estimate is made in the ERICA tool in three steps ("tier 1-3"). Tier 1 aims at very conservatively showing whether there is any risk for populations. This analysis is based on risk quotas (RQ) where the given activity concentrations for radionuclides in soil, water and sediment respectively (so-called "Environmental Media Concentration Limits", EMCL) are compared with maximum measured or modelled activity concentrations in the area which is to

be investigated. The values of EMCL which are suggested in the ERICA project correspond to a dose of 10µGy/h to the most sensitive reference organism in the respective ecosystem. The target value 10 µGy/h is based on an analysis of dose effect correlations which are reported in a database in the ERICA tool (Frederica). If the risk ratio is below 1, the risk of populations is considered to be very low and the assessment can be terminated. If the risk ratio is above 1, the next step is taken in the risk analysis which requires more detailed information about the site.

SKB reports an estimate of risk quotes for the pinhole case and the advection/corrosion case (SKB R-06-82, page 100, and SKB TR-06-09, Chapter 10 sections 10.2.5, 10.5.5 and 10.6.6). Estimated concentrations in soil and water have been tested in tier 1 and the ratios for the different radionuclides have been reported in six tables (SKB R-06-82, Table 8-2 – Table 8-7). Concentrations or calculations for aquatic sediment are not reported, however. For the advection/corrosion case, the screening level is exceeded at the end of the evaluation period for Ra-226 and Po-210. SKB states that it is intended to make a more careful assessment in SR-Site. Based on the data in the report, Stark (2008) has been able to repeat the calculations.

The authorities consider that the ERICA tool can be used to estimate dose to biota, but that the report should be complemented to SR-Site. SKB does not report how great the uncertainty is for estimated activity concentrations in water and soil for different radionuclides and it is unclear why the risk ratios for aquatic sediment have not been calculated. Identification and description of exposure paths for biota, which is a very important part of the risk assessment, are also lacking. SKB has not either completely complied with the instructions on how the method is to be used. SKB does not make, for example, any summation of the risk ratios. According to Stark (2008), this would not have changed the end result (i.e. for the advection/corrosion case, the RQ will be over 1 at the end of the assessment period but not in the pinhole case). However, the authorities consider that justification is needed if the stated method is not complied with.

The method of assessment of effects on the biota is at present an area undergoing considerable development. Databases with the proposed values of transmission factors as well as descriptions of the dose effect correlations are being updated. SKB should therefore state which version of the dose estimate tool for biota that has been used. SKB should also, in accordance with the general guidelines (SSI FS 2005:5), always report an evaluation of the dose tool, for example, if the selection of radionuclides and reference organism databases is relevant for the area in question. SKB should also discuss the assumptions on which the results are based, for example, the dose effect correlations which are documented in the Frederica database, and justify the choice of dose rate on which the calculations of risk quotas are based. SKB has had an active role in the EU projects FASSET and ERICA. The authorities had therefore expected that SKB's report to be more detailed and that the results would be discussed in relation to the development that has taken place internationally within this area. In the discussion of the results, SKB compares activity concentrations for Ra-226, Pb-210 and Po-210 in soil and water with background levels in Sweden and in the world (SKB R-06-82, page 100 and Table 8-8). The authorities and Stark (2008) do not consider that this is a convincing reasoning.

The authorities' overall assessment
The authorities consider that the LDF concept is a big step in the development of the risk analysis. However, the authorities consider that it is important that SKB prior to SR-Site rectifies the deficiencies in the concept which may have large consequences for the dose

calculations, for example, dilution in the biosphere and simplifications in radionuclide transport models. SKB should also endeavour to be clearer in its report in SR-Site both with respect to the LDF concept and the use of dose models for biota, for example, as regards the assumptions on which the models are based, and to discuss the results to a greater extent.

14. Scenarios and risk analysis

14.1 SKB's report

SKB reports in Chapter 11 and 12 in the main report (SKB TR-06-09) on the principles for choice of scenarios and analysis of the chosen scenarios. These scenarios consist of a main scenario which is based on the reference evolution and complementary scenarios. The main scenario is based on the tolerances of the initial state specified in the reference initial state and two variants of the climate evolution (Weichsel and a greenhouse variant). Uncertainties in the hydrogeological interpretation of the site are assessed by propagating the results from several alternative hydrogeological site models.

Additional scenarios are selected to illustrate uncertainties not included in the main scenario. This choice is based on an analysis of factors that can lead to loss of a safety function. In all, three additional scenarios are identified with different failure modes for the buffer and canister respectively, which are categorised as less probable or residual scenarios. On the basis of paired combinations of these scenarios, SKB concluded that only the combination "advective conditions in the deposition hole" and ”canister failure due to general corrosion" as well as the shear rupture case need be included in the risk analysis. Other scenarios or scenario combinations are categorised as residual scenarios

14.2 The authorities' assessment

The authorities consider that the principles for choice of scenarios reported in Chapter 11 in the SR-Can main report comply with SKI's and SSI's regulations. The authorities consider like SAM that SKB's new approach of using safety functions to identify scenarios provides a good focus on the critical safety issues. However, the authorities have identified a number of issues in the application of the method, which should be taken into account prior to SR-Site. It is, for example, difficult to assess the completeness of the derivation of factors or combinations of factors that may affect the different safety functions/scenarios in Chapter 12 of the main report. The authorities also consider that a clearer description is needed of the method for choice of scenarios, including the newly-developed terminology, for example, the distinction between failure modes and scenarios.

Completeness in the choice of scenarios
The function indicators provide a good starting point for choice of scenarios, although since these function indicators do not claim to be complete, other factors may need to be taken into account to convince about the completeness of the choice of scenario, for example,

- alternative sequences and timescales for the climate evolution (see SSI FS 2005:5)
- gradually overlapping failure modes
- deviations in the initial state with respect to manufacture, handling and operation
- the importance of certain processes in the FEP database which have been excluded from further treatment early on

An example of a climate-related uncertainty which should be clarified in more detail is the duration of the temperate climate. In SR-Can, the calculations of landscape dose factors (LDF values) are based on the length of the temperate period being 20,000 years. SKB also reports an alternative calculation for the greenhouse variant of the main scenario, which provides lower or corresponding LDF values. However, the authorities do not consider that this calculation is convincing bearing in mind the deficiencies which have been identified when handling accumulation of radionuclides in the near-surface environment in SKB's biosphere model (see section 13.9).

SKB bases itself in its choice of scenarios on paired combinations of safety functions (scenarios) which are either on or off. The authorities share SAM's view that SKB should also take into account gradual/overlapping failure modes in a barrier. An example of this might be buffer erosion which could produce a gradual deterioration of swelling pressure, increased diffusivity and microbial activity before advective conditions are achieved. Another example is the combination of canister corrosion and mechanical load, for example, a copper shell weakened by corrosion in combination with shear load.

SR-Can bases itself on specified tolerances in the initial state for the engineered barriers. Prior to SR-Site, these assumptions should be justified more clearly on the basis of procedures for quality assurance of the repository components. SKB should also report a more systematic discussion on potential scenarios linked to deviations from the specified tolerances in the initial state.

The municipality of Oskarshamn (SKI dnr. 2006/985) would like the authorities to comment on assumptions about the sealing of the canisters and the link with choice of scenarios. The municipality points out differences compared with SR-97 when defects were postulated for 0.1 % of the canisters. The authorities consider that SKB's approach in SR-Can is credible given the link to welding results from reasonable realistic conditions. As commented on in section 10.2, work remains to be done, however, to obtain further support for the quality of the weld joint. The case of a perforation defect already at the time of emplacement is important to analyse the multi-barrier system and for redundancy between safety functions (see section 10.10). The municipality of Östhammar (SKI dnr. 2006/985) also requests an analysis of the consequences of an early canister failure and points to the effects of inflowing water becoming steam in contact with the hot fuel.

Finally, the authorities consider that SKB may need to introduce an additional check of the importance of excluded processes in the FEP database, or combinations of these, in the concluding assessment of the completeness of the choice of scenario. An example which has emerged during the authorities' review of SR-Can is that glacial erosion as an example of an excluded process may be important in the very long time perspective for a scenario with permafrost. The authorities are furthermore doubtful that SKB treats buffer transformations as a residual scenario in SR-Can bearing in mind that there are considerable uncertainties about the cementation processes in the buffer. SKB's handling of downward penetration of glacial oxygen-rich meltwater is a third example of an excluded scenario for which there should be a better justification (see section 12.5 in this review).

Scenarios for very early and very late consequences
According to SKB's risk summation, no canister failures will take place before 1,000 years and the risk is extremely small during the first tens of thousands of years (for example, SKB TR-06-09, Figure 12-20). The analysis is then largely focused on how the repository will be affected by extensive climate changes. The initial period should, however, as a foreseeable future and a period with extensive needs of barrier functions be assumed to be of particularly great importance. In SSI FS 1998:1, the first 1,000 years are given a special position with

respect to the need for detailed reasoning. The authorities consider therefore that SKB in SR-Site should clarify and strengthen the argumentation around the risk of early radionuclide releases from the repository. Here, in particular, reasoning should be included on the application of the requirement for multiple barriers for this period (7 § SKI FS 2002:1). Examples of important components may be detailed justification of time scales for evolution of a damaged canister or reporting of other safety functions which is important when the canister's sealing requirements are hypothetically not met.

SAM states that SKB should say something about the evolution of the repository also after the million-year perspective of the safety assessment and at least provide a perspective of what the long-term consequences of the repository could be. SAM considers that comparisons with natural incidence of uranium ore may be illustrative. The authorities consider that reporting of the time period after a million years may be limited to a qualitative discussion about the expected future evolution of the repository, based on the quantitative analyses made for the period up to a million years. Natural analogies in the form of uranium ores may contribute to increased understanding, although there should be a calculation that shows how the hazard of the radioactive substances in the repository decreases over time, also for periods longer than a million years, in accordance with SKI's general guidelines (general guidelines to 10 § SKI FS 2002:1). However, the risk analysis does not need to take into consideration time scales longer than a million years (general guidelines to 10-12 §§ SSI FS 2005:5).

Treatment of the climate
The authorities consider that the most recent glaciation cycle, Weichsel, is a good basis for a main scenario and that the greenhouse variant is also good as a realistic alternative to the early climate evolution. However, the authorities do not consider that the greenhouse variant per se is sufficient to shed light on "reasonable predictable sequences of future climate states", which is sought after in SSI's general guidelines (SSI FS 2005:5). Sensitivity and "what-if" analyses of the scenarios with buffer freezing and isostatic load in connection with glaciation are good examples in SR-Can of how climate uncertainties can be illustrated in more detail. However, the authorities consider that SKB prior to SR-Site should strengthen the discussion of uncertainties on time periods and the extent of future climate changes. An example of the uncertainty in SR-Can is the importance of increased flows in connection with the front of inland ice passing the repository site. In the corrosion scenario, the increased groundwater flows are assessed (case B with 1,300 years of increased flows) for only one of a total of eight expected glaciations during a million years. Another example, which is mentioned above, is how the length of periods with temperate climate affects estimated LDF values.

Risk summation
SKB's principles, as reported in SR-Can, for summing risk contributions from different scenarios complies with SSI's regulations and general guidelines (SSI FS 1998:1, 2005:5). This also applies to SKB's presentation of risk as a function of time and handling of risk dilution. Application of these principles in the final risk summation in SR-Can (section 12.12 in SR-Can main report) is, however, not clearly explained and entails a departure from SKB's own principles (the effects of buffer erosion have been formed by average values over a complete glaciation cycle despite erosion being assumed to begin first in connection with the first glaciation).

Design-basis cases
According to SKI's general guidelines (SKI FS 2002:1), a number of design basis cases should be produced on the basis of risk-dominating scenarios. These scenarios are intended to

provide a support for the producing design premises for the barriers in the repository, for example, with respect to choice of material, dimensioning, tolerances and permitted defects. The authorities consider that SKB has identified relevant mechanical load cases for the canister (isostatic and shear load) in SR-Can. Well-developed design-basis cases for the canister and buffer relevant to the advection/corrosion scenario are still lacking, however, which is partly explained by the great uncertainties concerning the process of buffer erosion. Bearing in mind that the advection/corrosion scenario dominates the risk from the repository in SR-Can, the authorities consider that it is important that SKB in connection with SR-Site specifies the expected functioning of the canister and buffer in this case as well. In order to obtain sufficient information for the design of these barriers, design-basis cases may also be needed for the handling and operational phases. The authorities consider that SKB should produce a more complete and detailed report of the design-basis case prior to SR-Site. The design-basis cases taken into account should be stated when specifying the design premises for the individual repository components. The authorities also wish to draw to attention that SKB in accordance with requirements for the best available technology (BAT) in SSI's regulations (SSI FS 1998:1, 2005:5) is obliged to take into account different measures (for example, alternative canister and buffer designs) which can minimise a future leakage from the repository.

Scenarios for future human actions
According to SSI's regulations (SSI FS 1998:1), the safety report for a repository shall contain a description of the consequences of future unintentional human intrusion, i.e. how the protective capacity of the repository is affected after human disturbance. SSI's general guidelines (SSI FS 2005:5) state that intrusion also includes activities that may lead to a deterioration in the protective capacity of the repository and that scenarios for human impact should not be included in the risk summation. The purpose of these scenarios should instead be to provide a basis for assessing measures that can reduce the risk of human impact in accordance with the requirement for best available technology. SKI's general guidelines (SKI FS 2002:1) state that damage caused to barriers in connection with future human activity should be assessed as less probable scenarios. SKI's guidelines also specify that there should be cases for the residual scenarios that illustrate the injuries to human beings who intrude into the repository and the consequences of an abandoned but not sealed repository.

As shown by the above description, there are certain minor differences in SSI's and SKI's requirements concerning scenarios for human actions, which may be reviewed in connection with the planned merger of SSI and SKI. There may therefore be a need of further guidance from the new radiation safety authority on this issue prior to the licence application for the repository. The authorities' preliminary assessment of SKB's report in SR-Can is, however, that SKB's method to identify scenarios for human intrusion and other human activities is acceptable as a basis also for SR-Site. The authorities consider that the categorisation in THMC categories ("Thermal, Hydraulic, Mechanical, Chemical") is comprehensible. What is important is not the exact chain of events that leads to an intrusion (which is necessarily very speculative) but rather the effects on the repository of different types of activities. The function indicators which are reported in SR-Can are probably also useful as a starting point for assessment of effects of human intrusion and human activities.

However, the authorities consider that the concrete calculation cases reported in SR-Can are too limited. It would, for example, be of interest to include more analyses for drilling of different repository components (canister, buffer, backfill of deposition tunnels), including if prerequisites exist for buffer and backfill to be resealed after drilling. In accordance with

SKI's regulations, there should also be a case which illustrates the consequences of an unsealed repository as well as a stylised calculation of the injuries to human beings who intrude into the repository.

MKG (SKI dnr. 2006/985) state in their points of views on SR-Can that the authorities should request that SKB produces a more detailed analysis of scenarios for intentional intrusion and of the long-term risks for proliferation of nuclear weapons from plutonium from a sealed repository. MILKAS (SKI dnr. 2006/985) considers that the risks of unintentional intrusion due to curiosity are great. This means that people may get into the repository without knowing how dangerous it is. According to MILKAS, it is not probable that information about the hazards of the repository can be kept during the required time.

The authorities' regulations for reporting of safety analyses do not contain any requirements for reporting of scenarios for *intentional* future intrusion into the repository or taking out the spent nuclear fuel. The background to this is that such scenarios would be speculative both as regards probability and any consequences and that it is not part of the intention of the repository to make it impossible for future generations to make their own decisions about what they want to do with the spent fuel. This approach accords with the international guidelines that exist today (see Annex 3).

Finally, it is important to remember that intrusion, either intentional or unintentional, cannot be wholly eliminated. Any disadvantages that this means must therefore be taken into account at a more general level, in connection with comparisons of different methods to handle the spent nuclear fuel. The risks of unintentional intrusion may, however, be limited by suitable measures in connection with location and design of the repository and through measures for preservation of information.

The authorities agree with MKG that the issue of proliferation of nuclear weapons needs additional supporting material, although these contributions are made in other contexts. Work is in process, for example, within an expert group on safeguards which has been established to provide material to IAEA and national authorities to formulate requirements on a repository facility. The question is linked to international demands for safeguards ensuing from Sweden's accession to the non-proliferation treaty. There are also links to measures for physical protection of a repository to hinder unintentional intrusion, sabotage, theft of nuclear waste, etc. These questions need to be dealt with for the different phases of the repository, for example, the construction phase, the operating phase, and the time after sealing. Assessment of the ominous pictures related to a repository and the need for supervision need to be analysed. After sealing, the state is expected to be responsible for supervision and monitoring of the repository rather than SKB (SKI, 2007b).

The intention of the authorities' regulatory requirements associated with human intrusion is to overview the conceivable consequences rather than possible motives and chains of events which in the final analysis could give rise to unintentional intrusion. The authorities do not therefore consider that the example mentioned by MILKAS requires any report in SR-Site, in addition to the examples stated in the regulations (activities which can indirectly lead to a deterioration in the repository's protective capacity, damage caused to the barriers in connection with human activity, injuries to people who intrude into the repository, the consequences of an abandoned but not sealed repository).

In conclusion, the authorities consider that scenarios based on intentional intrusion do not need to be included in SR-Site. They do not provide any additional basis for the authorities' assessment of compliance with the safety and radiation protection requirements in SSI FS 1998:1, SSI FS 2005:5 and SKIFS 2002:1. The authorities consider, however, that SKB should produce more detailed proposals for measures during the period for institutional control, including land use restrictions and discuss how these affect the probability of early unintentional intrusion. SKB should also in its justification of the method of final disposal of spent nuclear fuel discuss both intentional and unintentional intrusion and the prerequisites for retrievability of the nuclear waste.

15. SKB's summary of results and report on compliance evaluation

15.1 SKB's reports

SKB presents in the final chapter of SR-Can main report (SKB TR-06-09, Chapter 13) for the first time an assessment of how a KBS-3-repository complies with the authorities' safety and radiation protection requirements. The reporting is for obvious reasons preliminary, but it provides an indication of the structure of the report that SKB is planning to use in SR-Site. The report includes an overview of the results of the safety assessment and critical safety issues, reconciliation with the requirements in the authorities' regulations (including the detailed reconciliation paragraph by paragraph in SKB TR-06-09, Appendix A) and feedback to the continued work with the repository.

15.2 The authorities' assessment

It is important to emphasise that the authorities cannot take a position in this review on the question of whether the repository is sufficiently safe or provide sufficient radiation protection. SR-Can is a preparatory work of a preliminary nature and is not linked to consideration of a licence. However, the authorities can provide points of view on whether the structure in SKB's report is appropriate for its purpose and may be expected to provide the supporting documentation needed by the authorities to be able to assess a licence application. The planned merger of the authorities (SSI and SKI) means, however, that there may be a need to review the accumulated expectations on the safety and radiation protection reporting. The authorities therefore accept that there will be a continued dialogue with SKB during 2008 within the consultation for the site investigation phase on the structure for reporting compliance with requirements.

Overarching structure
It is good that SKB has provided a summary conclusion relating to long-term safety and radiation protection, summing up the critical safety issues and an assessment of SKB's own reliance on different parts of the analysis. The detailed reconciliation with applicable regulations in Appendix A is a good complement to the more integrated report in Chapter 13 of the main report. The authorities consider that SKB's structure for report of compliance with requirements in SR-Can is a good starting point for SR-Site as well. Certain parts of the argumentation should, however, be further developed or complemented with links to other parts of the repository programme for SR-Site:

- Summary of the safety concept
- Rules and principles controlling the design and construction of the facility
- The link between assumptions about the initial state and other supporting reports, for example, quality routines and plans for demonstration of implementation
- Discussion around critical uncertainties linked to reporting of the risk curve for different time periods
- Argumentation for there not being any early consequences from the repository, including a report on the repository's multiple barrier functions
- Overall reporting of the evolution of the repository after 1 million years
- The role of SKB's own quality assurance of SR-Site

- Depending on how SKB plans to arrange its licence application with regard to alternative breadth, there may be a need to report compliance with requirements in a broader perspective for the alternative designs included in the method applied for.

Reporting of risk
As mentioned previously the authorities consider that SKB's principles for risk summation and analysis of risk dilution comply with the authorities' regulations, which also applies to the division into time periods for reporting of risk. The final risk summation, as presented in Chapter 13 of the main report, is, however, insufficiently explained and does not describe the risk as a function of time in a correct way (the risk curve indicates in conflict with the scenario analysis that canisters will fail already before the next glaciation). The authorities further consider that SKB prior to SR-Site should provide a more detailed description of the risk curve presented in order to better show how different factors contribute to the risk during different time periods. The authorities also consider that SKB should complement the analysis of risk with a discussion about the importance of risk dilution. SKB has in the analysis of radionuclide transport carried out creditable analyses of risk dilution, but it is a deficiency that the results are not discussed in the overall risk assessment in Chapter 13 of the main report.

SKB states correctly that SSI's general guidelines (SSI FS 2005:5) do not require a strict assessment of the risk in relation to the risk criterion after the first glaciation cycle and then draws the conclusion that the calculated risk for the time after the first glaciation complies with the authorities' requirements. The authorities do not take a position on the calculated risks in this review but wish to emphasise that the conclusions on compliance with SSI's risk criterion for long periods (after 100,000 years) should be complemented by a considerably more detailed report on the application of the best available technology. SKB should in a convincing way, for example, by different sensitivity analyses, be able to show that they have taken into consideration possible measures in, for example, the design of the repository, to reduce leakage of radioactive substances from the repository for these long periods.

Environmental impact
SKB uses the ERICA tool to make a risk estimate for biota. The authorities consider that this tool may be used, but better documentation should be presented in SR-Site to convincingly show that SKB's report corresponds to the requirements in the regulations (see section 13.9).

SKB writes in SR-Can (SKB TR-06-09, section 13.3.3) that there is no clear indication in SSI's regulations about the length of time that doses to the biota should be calculated. It is stated in SSI FS 2005:5 that the calculation of radiation doses for people and the environment for the time after a glaciation should be made in a simplified way with respect to climate evolution, biosphere conditions and exposure paths. The assessment of effects for biota can be based on a reasoning on risk quotients (calculated on estimated activity concentrations in the environment) and the size of the contaminated area (see also section 9.1 in this report).

Optimisation and best available technology (BAT)
SKB reasons around the application of optimisation and BAT for different components of a KBS-3 repository. The authorities consider that the report is a good first step but that it should be developed prior to SR-Site with a more systematic documentation of the most important measures in the design and choice of materials etc. which have been assessed in the safety assessment or in another way. The authorities agree with SKB, however, that optimisation and BAT should be seen at this stage as a framework for feedback on further development work with the repository.

SKB's reasoning on the mechanical strength of the canister is a good example of how design alternatives can be assessed in a BAT and optimisation perspective. It is good that SKB states potential improvement measures which would be possible to apply in a later stage of the programme if it proved to be necessary. However, the authorities consider that SKB should produce more quantitative sensitivity analyses to illustrate how alternative designs and choice of materials affect leakage of radioactive substances and calculated risks. As already stated in the discussion on design-basis cases in Chapter 14 in this review, the authorities consider that SKB's reasoning around countermeasures to limit buffer erosion and copper corrosion is too vague in SR-Can. The authorities assume that this reasoning will be further developed for SR-Site when the results from SKB's ongoing research on buffer erosion are available. The authorities consider further that SKB should produce an integrated report of the BAT consideration taken into consideration to reduce the risk related to unintentional human actions.

Design-basis cases
The authorities' points of view on SKB's report of design-basis cases are discussed in this review in Chapter 14. It may be worth noting that SKI's guidance on reporting of design-basis cases (SKI FS 2002:1) and SSI's regulatory requirements on optimisation and BAT (SSI FS1998:1 and SSI FS 2005:5) have partly overlapping intentions. This is an example of a question where the authorities in connection with the planned merger need to produce a higher degree of common approach on expectations on reporting from SKB.

Feedback
The authorities view it as positive that SKB has reported feedback from SR-Can to other parts of SKB's programme in a structured way. The reporting in SR-Can is, however, too brief. The authorities' assessment of how SKB takes care of the identified research and technology development needs will be reported in the review of SKB's programme for research, development and demonstration (R&D programme). However, the authorities can already note here that SKB's own assessment of the safety assessment methodology (section 13.9 in the main report) seems to be too uncritical. The authorities assume that SKB on the basis of this review, as well as the reviews of the international expert groups SAM, SIG and EBS, will make a renewed analysis of development requirements prior to SR-Site. The authorities also consider that the discussion on the development needs for the biosphere analysis (SKB TR-06-09, section 13.8.9) is weak in the perspective of the authorities' criticism in this review. To conclude, the authorities wish to emphasise that a reporting of feedback to further work also needs to be reported in SR-Site in connection with the licence application. In connection with the licence application, feedback will also be required to more detailed plans for how remaining uncertainties and technological development needs will be taken care of. A concrete report is needed, for example, of tests and other measures that can confirm that the repository and its components function in the way expected in the safety assessment.

Timetables
The authorities can after the review of SR-Can note that SKB's own list of remaining work prior to SR-Site is very extensive. The reasonableness of the timetables for the planned licence application is naturally strongly linked to what must be completed by the time of the licence application and what can wait to later occasions. The authorities intend, if it is considered justified, to take up SKB's timetables again in the review of SKB's R&D programme 2007.

The municipality of Oskarshamn (SKI dnr. 2006/985) points out the importance of the timetable not being given higher priority than a complete safety assessment of high quality.

MKG (SKI dnr. 2006/985) considers that SKB prioritises the timetable instead of the quality of the safety assessment, and considers that SR-Can cannot maintain the quality originally promised. MKG wants SKB to complement SR-Can with new data from Laxemar.

16. SKI's and SSI's concluding remarks

SKB has with SR-Can a substantially good starting point for continued work to produce SR-Site and a basis for the application to construct a repository for spent nuclear fuel in Sweden. In comparison with previous safety analyses, SR-Can has been based on a better and more complete methodology. It is also evident that SKB's extensive and concrete research and development work in recent years has created a more realistic and well-founded basis for the safety assessment. This includes, among other things, site investigations at Forsmark and Laxemar, development and manufacture of copper canisters and experiments and demonstrations at the Äspö laboratory. SKB has also compared with previous safety analyses carried out a more complete and more integrated modelling of how the repository is affected by major climatic changes which may be expected in the very long term, for example, future ice ages and periods with permafrost. However, SR-Can has in certain respects gaps and sections of a very preliminary nature. The authorities' review has focused on identifying what needs to be remedied prior to SR-Site, but without forestalling the review that will then be made.

The main conclusions from the review are:

- SKB's methodology for safety assessment mainly complies with the authorities' regulatory requirements, although parts of the methodology need to be further developed prior to a licence application.
- SKB's quality assurance of the safety assessment is insufficient in SR-Can.
- Prior to the licence application, a better knowledge base is needed with respect to certain critical processes with a potentially great impact on the risk from the repository, including erosion of the buffer in deposition holes.
- SKB needs to confirm that the assumed initial state of the repository is realistic and achievable.
- Reporting of the risk of early releases should be strengthened.

Method of safety assessment
SKB's methodology based on 10 steps is good, although a more integrated description and justification of the methodology are needed. This understanding can be obtained in SR-Can only after going through the whole of the report. Since the work with the 10 different steps needs to be implemented in parallel, a final reconciliation of the completeness of the choice of scenarios and the consistency of handling processes and data are needed.

SKB has reported a systematic approach for system description (handling of steps from FEP to modelling and analysis). However, a clearer description is needed of the different process tables and figures and how they are used in the safety assessment. Safety functions and function indicators for different main components, canister, buffer, backfill and rock are an interesting further development of SKB's methodology for safety assessment. These tools can contribute to an increased focus on the critical issues in the safety assessment. However, the methodology needs to be further developed in a number of respects prior to SR-Site. The safety functions and function indicators should also be able to provide some guidance for reporting of optimisation and the best available technology and derivation of design-basis cases.

The models for fuel dissolution are very important if buffer erosion cannot be excluded in the safety assessment. SKB should produce a better basis for justification of the parameter values for fuel dissolution. The fracture network models are of central importance for the assessment of the long-term evolution of the engineered barriers in SR-Can. SKB should further develop and investigate the uncertainties of these models prior to SR-Site. Field data, including hydrogeochemical information, should be used to the greatest possible extent to validate the hydrogeological site models.

SKB's principles for choice of scenarios comply with the applicable regulations. The specified safety functions and function indicators provide good support for less probable scenarios. SKB should, however, provide complementary checks of the completion of the selection of scenarios, for example, taking into consideration deviations in the initial state, gradual and overlapping failure modes and the possible importance of excluded FEP or processes. SKB should further develop the methodology to better shed light on the importance of combinations of potential detrimental processes. Climate evolution has in a suitable way been covered by the scenarios in SR-Can. However, further analysis is needed of uncertainties such as the duration of the different stages of climate evolution. The principles for handling scenarios for human actions and intrusion largely comply with the authorities' regulations, although more calculation cases are needed which provide additional supporting material for assessment of the consequences.

The authorities consider that SKB has access to suitable methods for uncertainty and sensitivity analyses. SKB should, however, produce a clearer strategy for application of these methods. Above all, sensitivity analyses should be used in a more systematic way.

SKB's principles for risk calculation and risk summation are in agreement with the authorities' regulations. SKB's division into time periods for reporting of risk is good. The LDF concept is furthermore a big step in the development of the risk analysis. SKB's handling of dilution and certain transport processes is, however, deficient and can lead to an underestimate of calculated doses. This problem should be investigated prior to SR-Site.

The method (The Erica tool) used by SKB to assess the dose impact on different organisms in the environment is acceptable. However, this report needs to be complemented in certain respects to comply with regulatory requirements, including justification of the applicability of the dose models and the description of the factors affecting exposure of different types of organisms.

It is good that SKB takes up a discussion on optimisation and the best available technology, although SKB should for SR-Site report more quantitative sensitivity analyses to illustrate how alternative designs and choice of materials affect leakage and spreading of radioactive substances and calculated risks from the repository.

Quality assurance
Prior to SR-Site, considerable inputs are needed for SKB's quality assurance work to achieve the high demands made on the licence application. The review shows that work on quality assurance of the safety assessment has started in an appropriate way although the quality plan for SR-Can has not been fully implemented and does not either include sufficiently specific instructions. The structure of reports used for SR-Can is good although documents on a level directly under the main report need to be improved.

The assessment in the process reports need to be made more traceable and consistent. Certain parts should also be made more detailed, for instance, within the canister area. The quality of documentation in the data report varies between different data and it is not evident that this is due to the safety significance of the different data. Documentation of codes has generally made more progress compared with previous safety analyses, although certain complements are also needed here. Despite these deficiencies, the authorities have, with certain complementary information, succeeded in reproducing a selection of calculations in SR-Can.

There is lack of clarity in the data report and to a certain extent also in the process reports concerning the implementation of the expert judgements reported. The division of labour and responsibility between the SR-Can team and other experts is not clear either.

SKB should produce a complete programme for quality assurance of the safety assessment for SR-Site. The authorities consider that it would be good to discuss the content of a quality programme of this kind in the consultations for the site investigation phase. This would improve the prerequisites for being able to address quality problems, which would otherwise make future reviews by the authorities difficult, before completion of SR-Site. Examples of such problems are conflicting assessments, incompletely justified conclusions, concealed prerequisites for the analysis which are not discussed or incomplete handling of important issues. Publication of SKB's own-developed models and theories in scientific journals reinforces the credibility of the safety assessment and should be used if possible.

Critical processes
SR-Can shows that a better knowledge basis is needed for certain processes that are critical in the evolution of the repository. The clearest example which SKB has identified itself is erosion processes for the buffer and backfill. Experiments are needed, a better process understanding as well as well-grounded modelling prior to SR-Site. It is difficult to define the safety context of the buffer and justify its design if there are great uncertainties about buffer erosion. The canister has a key role in the KBS-3 concept, which is further reinforced if buffer erosion cannot be excluded. Mechanisms for corrosion and deformation of the copper canister, particularly stress corrosion cracking and creep, need further experimental work, as well as a more detailed reporting. The downward penetration of glacial meltwater is another example of a potentially critical process for the safety functions of the repository which is insufficiently reported in SR-Can.

Link between implementation and initial state
One important prerequisite for the coming SR-Site analysis to be regarded as a sufficient basis for the licence application is that the description of the initial state of the repository can be regarded as reasonably realistic. A fully realistic description can only take shape when the construction of the repository has been started, but this limitation can be compensated by a reasonably detailed description of the procedures to be used to produce additional information during the design and operating phases. The canister report provides a god basis although additional work is required with well-defined issues such as design premises, inspection arrangements, qualification, and independent checks in the form of third-party controls.

For the buffer and particularly backfill, the supporting material in SR-Can is not as well developed as for the canister. There is, for example, lack of clarity on the characterisation of the selected materials and only a very brief description of manufacturing, handling and quality assurance issues. The requirements for reporting buffer and backfill depend, however, in certain respects on the not yet fully determined safety significance attached to these two components in SR-Site. The authorities are prepared to discuss these issues with SKB in the consultations for the site investigation phase. Finally, SR-Can shows that the selection criteria for the deposition holes have a great impact on the risk analysis. This should lead to an in-depth report on procedures for selection of deposition holes and particularly how any flow restriction is to be applied.

Risk of early consequences
The results in SR-Can show that the annual risk from the repository is very low for the time period up to a thousand or some thousands of years after sealing. SKB should, however, produce a more developed reasoning relating to the risks of early consequences. This should include a discussion of which scenarios could give rise to early consequences in accordance with SSI's general guidelines as well as a discussion on multiple safety functions. An important justification for a report of this kind is that the greatest requirements for robust barrier functions should reasonably be made during the period when the spent fuel is most dangerous.

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Annex 1. External review documentation for SKI's and SSI's review of SR-Can

Complilation of the authorities' external review supporting material in the form of international review groups and other consultants.

Titel / (Review area)	Author	Report number
International review groups		
"International Expert Review of SR-Can: Site Investigation Aspects" (Integration of site investigation data in SR-Can)*	Neil Chapman, Chairman, CH Chin-Fu Tsang , US Ove Stephansson, DE Adrian Bath, UK Joel Geier, US Sven Tirén, SE Roger Wilmot, Secretary, UK Anders Wörman, SE Clifford Voss, US Richard Klos, UK	SKI Report 2008:09 SSI Report 2008:11
"International Expert Review of SR-Can: Engineered Barriers Issues" (Representation of engineered barriers in SR-Can)†	Dave Savage, Chairman, UK. David Bennett, Secretary UK Mick Apted, US Göran Sällfors, SE Timo Saario, FI Peter Segle, SE	SKI Report 2008:10
"International Expert Review of SR-Can: Safety Assessment Methodology" (Safety assessment methodology in SR-Can)+	Budhi Sagar Chairman, US Mike Egan , Secretary UK Klaus-Jürgen Röhlig, DE Neil Chapman, CH Roger Wilmot, UK	SSI Report 2008:05 SKI Report 2008:15
Quality issues		
"Audit of data and code use in the SR-Can safety assessment " (handling of data and documentation of calculation models in SR-Can)	Tim Hicks, UK	SKI Report 2008:16 SSI Report 2008:06
Fuel issues and radionuclide chemistry		
"Evaluation of SKB's handling of spent fuel performance, radionuclide chemistry and geosphere transport parameters" (review of fuel issues and radionuclide chemistry in SR-Can including certain independent chemical modelling)	Mike Stenhouse, US Christophe Jégou, FR Paul Brown, AU Günther Meinrath, DE Heino Nitsche, US Christian Ekberg, SE	SKI Report 2008:17

Canister issues		
”Review of the SR-Can project reports with regard to the long-term structural integrity of the copper shell” (review of the structural integrity of the copper shell)	Kjell Petterson, SE	SKI Report 2008:16 SSI Report 2008:06
”A critical review of issues in the SR-Can report relating to the containment performance of the KBS3-canister” (review of issues linked with the canister’s long-term integrity)	Bill Bowyer, UK	SKI Report 2008:16 SSI Report 2008:06
Buffer and backfill		
”Status of research on chemical erosion of the buffer” (review of issues linked to buffer erosion)	Randy Arthur, US Wei Zhou, US	SKI Report 2008:16 SSI Report 2008:06
”Modelling of long term geochemical evolution of the bentonite buffer of a KBS-3 repository” (independent modelling of the geochemical evolution in the buffer)	F. Marsal, FR L. De Windt, FR D. Pellegrini, FR	SSI Report 2008:07 SKI Report 2008:24
“Mechanical perturbation of the buffer” (loss of the buffer and backfill material after installation)	F. Deleruyelle, FR C. Serres, FR	SSI Report 2008:07 SKI Report 2008:24
Geosphere issues		
”Review of the SR-Can project regarding microbial processes” (Review of the importance of microbes in SR-Can)	Rolf Hallberg, SE	SKI Report 2008:16 SSI Report 2008:06
”Discrete feature modelling of groundwater flow and solute transport for the SR-Can review” (Independent groundwater flow calculations for the SR-Can review with discrete network models)	Joel Geier, US	SKI Report 2008:11
Climate evolution and climate-related modelling		
”SKB’:s klimatscenarier and klimatmodellering SR-Can” (SKB’s climate scenarios and climate modelling SR-Can)	Per Holmlund, SE	SKI Report 2008:16 SSI Report 2008:06
”Impacts of future glaciations on geochemical conditions at repository depth: Review of SKB’s approach” (Review of the effect of future glaciations on geochemical conditions close to a repository)	Adrian Bath, UK Hans-Peter Hermansson, SE	SKI Report 2008:16 SSI Report 2008:06

" Future intrusion of oxygenated glacial meltwaters into the Fennoscandian shield: a possibility to consider in performance assessments for nuclear waste disposal sites?" (Review of SKB's analysis of intrusion of oxygen with glacial meltwater)	Pierre Glynn, US	SKI Report 2008:16 SSI Report 2008:06
Ecosystem and environmental impact		
"Ekosystem and miljöpåverkan: Slutrapport for uppdrag inom SSI:s delprojekt" (Ecosystems and environmental impact for assignments within SSI's sub-projects, in Swedish)	Karolina Stark, SE	SKI Report 2008:16 SSI Report 2008:06
Integrated modelling of the evolution of engineered barriers		
"Independent calculations for the SR-Can assessment" (independent mathematical modelling of thermal processes, resaturation and corrosion)	Philip Maul, UK Peter Robinson, UK Alex Bond, UK Steven Benbow, UK	SKI Report 2008:12
"Review of SKB's work on coupled THM processes within SR-Can" (independent modelling of a repository's thermal, hydrological and rock mechanics evolution)	Jonny Rutqvist, US Chin-Fu Tsang, US	SKI Report 2008:08
"Issues affecting the geochemical evolution of repositories for radioactive waste: Cement and cement-bentonite issues in the SR-Can project" (issues relating to and bentonite in SR-Can)	Steven Benbow, UK Dave Savage, UK	SKI Report 2008:16 SSI Report 2008:06
Radionuclide transport calculations and consequence analysis		
"Independent calculations for the SR-Can assessment" (independent mathematical modelling of radionuclide transport in SR-Can)	Philip Maul, UK Peter Robinson, UK Alex Bond, UK Steven Benbow, UK	SKI Report 2008:12
"SSI's independent consequence calculations in support of the regulatory review of SR-Can" (independent consequence analysis in support of the review of SR-Can)	Shulan Xu, SE Anders Wörman, SE Björn Dverstorp, SE Ryk Klos, UK George Shaw, UK Lars Marklund, SE	SSI Report 2008:08

*) Designated SIG ("Site Investigation group")
†) Designated EBS ("Engineered Barrier System group")
+) Designated SAM ("Safety Assessment Methodology group")

Annex 2. Examples of deficiencies in documentation and quality assurance in SR-Can

This annex reports some examples of deficiencies in documentation and quality assurance. The intention is to investigate the more general points of view reported by the authorities in Chapter 4 of this review report. It is important to point out that the authorities have not made a complete review of quality issues in SR-Can. The reported examples are a sample and a mixture of great and small and do not claim to provide a balanced picture of how deficiencies are distributed between different parts of SR-Can.

B2.1 Documentation of data and processes

- In Table 9-4 (SKB TR-06-09, page 232), SKB reports data for temperature calculations in SR-Can. References are lacking to describe how the data has been obtained and selected, for example, emissivity for cast iron and zirkaloy. Reference is made in the data report (SKB TR-06-25, page 31) in turn to SKB TR-05-17 for emissivity data for the cast iron insert. It has, however, not been possible to find this data in this report.
- In section 9.4.7 (SKB TR-06-09, page 348), SKB has discussed whether a lower value of 0-5 mg/l of oxygen concentration in glacial meltwater is reasonable. One of the arguments for this is that the measured relation N_2/O_2 in ice samples indicates a lower oxygen concentration (SKB R-00-17, page 17-19). However, there are scientific publications that show that the change in the relation N_2/O_2 may take place during storage of the ice samples (e.g. Bender et al, 1995; Ikeda-Fukazawa, 2005). SKB does not seem to have taken into account these experimental results in the literature.
- In section 2.5.8 of the fuel and canister process report (SKB TR-06-22), SKB reports on the effects of helium gas formation on the fuel's mechanical stability. SKB takes up intragranular accumulation of helium here and refers to experimental results from injection of helium ions (SKB TR-06-22, page 66). There are scientific publications that indicate other mechanisms such as intragranular accumulation of helium, which do not seem to have been taken into account by SKB. References to relevant publications for this are, for example, Guilbert et al (2003; 2004) and Ferry et al (2006).
- In section 3.5.1 of the fuel and canister process report (SKB TR-06-22, page 94), SKB reports on EQ3/6 calculations for solubility of iron. There does not seem to be any documentation of these calculations.
- In Table 5-11 (SKB TR-06-19, page 184), it is stated that rough calculations have been carried out for quantity of dissolved gas in groundwater. References are lacking to where these are reported.
- According to the geosphere process report (SKB TR-06-19, page 85), there are no conceptual uncertainties relating to shear movements in intact rock. There is a similar formulation in the buffer process report (SKB TR-06-18, page 125) that there are no uncertainties relating to radiation-induced transformations. In neither case is there any justification of these far-reaching conclusions.

- According to the fuel and canister process report (SKB TR-06-22, page 41), assumptions in certain other studies referred to are incorrect (for example, Lovera et al 2003). The question could be raised of whether it would not be simpler to provide a thorough justification of one's one point of view and wholly refrain from referring to studies that include direct errors. This applies especially bearing in mind that the issue in safety assessment most often must be restricted to whether handling of a particular process is sufficiently conservative taking into consideration the uncertainties that have been identified, rather than what is correct or incorrect in a strict sense.
- The distinction between what is reported in the data report, process reports and the initial state report is unclear in some cases. This may make it more difficult to find certain information, for example, questions relating to the minimum initial thickness of the copper shell are reported in the data report (SKB TR-06-25, section 4.2), while other material parameters are reported in the initial state report (SKB TR-06-21). Another example is that corrosion processes for the evolution of a damaged canister are discussed in the data report (SKB TR-06-25, section 4.4.4) rather than in the fuel and canister process report (SKB TR-06-22).
- Reporting of input data for the calculations of radionuclide transport is incomplete in the data report SKB TR-06-25 (see also Xu et al, 2008).
- According to the data report (SKB TR-06-25, page 165): "The variants judged most important from a safety assessment context […] are propagated to the local repository scale analysis. Here only a sub-set of the variants are analysed, using some simplifying modelling approaches." The data report should, however, be as complete as possible.
- Complete derivation, justification and reference management of data for modelling of the resaturation phase are lacking in the data report (SKB TR-06-25, Chapter 5).
- A discussion is lacking in the data report (SKB TR-06-25) on conceptual uncertainties in the derivation of Q_{eq} despite SKB considering that it needs to carry out experimental studies to verify the modelling concept (SKB TR-06-09, page 561).
- Both the data report and the main report lack information about the curve used for the canister residual heat evolution in SR-Can. An equation for residual heat development can be found, however, in SKB TR-06-14 (page 77), although it is stated incorrectly there that the initial heat effect is 1050 W (it is stated in the main report that it is 1,700 W/canister).
- The report on the evolution of a damaged canister in SKB TR-06-25 (section 4.4.) is partly contradictory since it is stated at certain places that the distribution of times is uniform (i.e. the same probability in the whole interval) and at other places triangle distributed.
- The authorities consider that the range for the formation factors proposed in R-06-111 should be better substantiated (Stenhouse et al, 2008, section 4.1.7). In the data report (SKB TR-06-25), the SR-Can team disregards this proposed range and assigns instead the variability of in-situ measurements in the transport calculations. Data presented in Löfgren (2004) Figure 4-19 clarifies that in-situ measurements are not as sensitive as laboratory measurements and do not therefore provide as low minimum values.
- With respect to rate constants for dissolution of biotite, the values on page 27 in SKB TR-95-01 have been quoted by Guimerà et al in SKB R-06-105. A later and more developed publication (Malmström and Banwart, 1997) by the same group of authors as in SKB TR-95-01 has not been cited, however.

B2.2 Documentation of models and reproducibility of calculations

- There are certain deficiencies in the documentation of retention curves and functions for relative permeability used for the rock in SR-Can. In SKB TR-06-14 (page 19), Börgesson et al a reference is made to SKB TR-99-41 (page 25) regarding the retention curve used. However, this report in fact simply states that "the retention curve has not been measured but the values shown in Table 6.1 and fig 5-3 have been used".

Radionuclide transport calculations

- It is not clear in SR-Can which chemical form is assumed for carbon-14 (Maul et al, 2008).
- It is stated in Table 10-3 (SKB TR-06-09) that a triangular distribution has been assumed for sorption coefficients rock, while the data report (SKB TR-06-25, page 193) also discusses a uniform distribution. Maul et al (2008) claim that SKB used a uniform distribution.
- It is stated in SKB TR-06-09 (page 409), SKB that the highest value (10 m) of the matrix diffusion depth was used in the deterministic calculations. However, Maul et al (2008) point out that the value used is 0.02 m.
- There are deficiencies in the SR-Can documentation of the COMP23 calculations, for example, with respect to the advective flow in the deposition tunnel (Maul et al, 2008).
- Information is lacking on the radionuclide solubilities used in the deterministic calculations (Maul et al, 2008).
- Maul et al (2008) point out that data on the correlated hydrological parameters (F, Tw, Qeqv) used in the probabilistic calculations have not been reported in SR-Can (although the data file can be obtained on request from SKB).
- There is lack of clarity in how SKB selected data for the correlated sorption coefficients (Maul et al, 2008).
- SKB states that a high equivalent flow rate (Q_{eq}) has been used for the deterministic case with advective conditions (SKB TR-06-09, page 437). No specific value has been stated, however (Maul et al, 2008).
- It is not clearly stated whether SKB used the alternative model, where Th-230 is retained in the canister, in the probabilistic calculations in Annex B of SKB TR-06-09 (Maul et al, 2008).

Points of view on input data and model descriptions for the biosphere

- Input data for the arable land model differs in different reports with respect to porosity and density (compare Table A-4 in SKB TR-06-15 and SKB R-06-83, Appendix I) despite the same model and results being presented in both reports. The aforesaid data cannot either be traced to the original sources since references are lacking.
- There is no clear description of how objects in the landscape model are connected at different times.
- The values of aggregated transfer factors in Table 3-1 (SKB R-06-81) are incorrect.

- It has not been possible to reproduce the dose transformation factors (DCF) for wells at Laxemar (SKB TR-06-09, page 397, Table 10-2) and these seem to be incorrect (see also Xu et al, 2008).
- It is unclear why the production figures for Laxemar and Forsmark differ to some extent. Production is twice as high for agricultural land and 10 times higher for forest ecosystems at Laxemar than at Forsmark (compare SKB R-06-82 and SKB R-06-83).
- It is reported in SKB R-06-81 (page 17, Table 4-1) how much carbon can be assumed to be produced per surface unit per year. However, it is not clear what type of food is included in this estimate and how these productivity figures have been produced.
- There are errors in the calculation of LDF: SKB spreads a uniform emission (1 Bq/year) to a number of objects. Independent calculation shows, however, that if the whole of the uniform emission takes place to a watercourse, the concentration in the watercourse will be lower compared to SKB's estimations (for more details, see Xu et al, 2008).

B2.3 Reference management and traceability issues

Lack of references

- The quality plan for SR-Can is described (SKB TR-06-09, page 63), although a reference is lacking.
- The reference Börgesson and Hernelind (2006) is referred to in SR-Can (SKB TR-06-09, page 324) although the correct version of this is missing in the list of references (i.e. SKB TR-06-43).
- It is stated (SKB TR-06-09, page 433) that activation products are released over a period of 1,000 years without further justification or reference.
- According to the main report (SKB TR-06-09, page 499), Figure 12-15 (case B for Laxemar), canisters start to leak in the advection corrosion scenario after 30,000 years despite diluted groundwater not appearing before after 50,000 years in the climate model. It is not made clear that the calculation is based on the assumption of average-value created buffer erosion from time zero (after sealing).
- SAM states that supporting arguments are lacking for the claim that rock chambers, tunnels and mining do not affect the functioning of the repository at Forsmark in section 12.10 in SR-Can (SKB TR-06-09).
- In SKB R-06-82 (page 37, second paragraph), the link between the carbon and the radionuclide model is explained as follows "…carbon can also be used as a proxy for organic matter and energy" (Chapin et al 2002). "*This approach may be useful to describe the behaviour of a wide range of bioavailable radionuclides assimilating into living tissue*". SKB also states in the same report (page 39) that "*The estimated residence time for carbon roughly sets limits for possible periods for the accumulation of radionuclides or other pollutants in the area*". References are lacking and it is also unclear how these claims (in italics) are applied in the models.
- According to SKB TR-06-15 (page 82): "*agricultural systems seldom receive direct releases and, when they do will retain a only a very small fraction*". Reference is lacking.

- According to SKB R-06-82 (page 37, last sentence) "…contaminants discharged into the marine environment from the adjacent terrestrial and limnic environments will have a different fate depending on where they enter the marine system." Reference is lacking.
- According to SKB R-06-81 (page 11, section 3.1) "fish were the only component of the diet considered" without any reference. This assumption contrasts moreover with the previously reported conclusion that crayfish for certain radionuclides can provide the predominant dose contribution in marine ecosystems (SKB TR-99-14, page 62 last paragraph).
- According to SKB TR-06-25 (page 153): "The hydraulic conductivity parallel to the axis of the tunnel will be enhanced by about half an order of magnitude over a thickness of 0.3m […]." Reference or alternatively an explanation of why these values are relevant is lacking.
- SKB R-05-18 (page 106): Reference to evaporation and runoff data is lacking.
- SKB R-05-18 (page 107, Table 4-3): "proposed mean values of horizontal saturated hydraulic conductivity, porosity and effective porosity for a simplified 3-layer till profile". References are lacking. It is not clear what kind of average has been used for conductivity.
- SKB R-05-18 (page 107): Reference to the MIKE SHE calculations lacking.
- It is not clear from the data report (SKB TR-06-25, page 15), who has dealt with section 6.5 in the project group for SR-Can.
- SKB TR-06-25 (page 170): reference to calculations is lacking. An explanation is lacking why the total of shares of U_r for different flow paths in Figure a) is less than one.
- SKB TR-06-25 (page 158): "*q*" is defined both as "Darcy velocity" and "Flow rate" on the same page.
- Reference is lacking to the analogy in Dunarobba on page 131 in SKB TR-06-18.

Inexact references

- It is stated in SKB TR-06-15 (section 2.3.1) and SKB R-06-82 (Chap 6 page 71) that a more detailed description of the ecosystem models can be found in SKB R-06-81 which in turn refers to SKB TR-99-14. Certain parts of the assumptions for the models in SKB TR-99-14 have also been changed.
- SKB TR-06-15 states that K_d values can be found in SKB R-06-81, which, however, refers in turn to R-02-28.
- SKB writes in SKB TR-06-15 (section 4.1.1., page 51) SKB that "*For freshwater objects only doses due to ingestion of water and food (fish) were calculated, as previous assessments /SKB 1999, 2004/ have shown that other exposure pathways are unimportant"*. There should be a page reference bearing in mind that a whole safety assessment is being referred to.
- In the SR-Can team's assessment of data uncertainty, spatial and temporal variation (SKB TR-06-25, page 144 section 6.5.6), the team concludes that "The descriptions of data uncertainty and variability as provided in the reports cited above are judged adequate." To refer to the "reports cited above" is not sufficiently specific bearing in mind that reference is made in the aforesaid section to some ten reports, including both the site descriptive reports, the main report and the supporting documentation reports for the site descriptive

reports (for example, SKB R-05-60). Furthermore, it is assessed on page 143 of the same report (which the assessment of the SR-Can team refers to) in connection with data for hydraulic conductivity in EDZ that ”[…] there is still a lack of knowledge when it comes to the question of assigning relevant values in hydro models to be used in the safety assessment.” This can hardly be regarded as an adequate description of data uncertainty and variability.

- SKB TR-06-25 (page 164): "In the DFN simulations, a functional relationship between transmissivity and aperture is assumed. The relation used is *et = 0.46T0.5* where *et* is aperture and *T* transmissivity. The basis for the relationship is empirical evidence from Äspö (Dershowitz et al, 2003). An alternative to this relationship is the cubic law, where $T \sim et^3$." Why is this not taken up under conceptual uncertainties in section 6.5.5?
- SKB TR-06-25 (page 127): No reference is made under groundwater modelling in SR-Can to the reports on which SR-Can is based but to previous models which, for example, served as the basis for SR-Can interim.
- SKB TR-06-09 (page 338): "[…] the 200mm/year value is considered the maximum potential recharge into the rock based on (SKB TR-97-23)." It is not possible to trace the figure 200 mm/year in SKB TR-97-23. In the supporting documentation report for the models (SKB R-06-100), the figure is linked to inflow to hydraulic soil domain and not to the rock.

Incorrect references in the main report

- In SR-Can main report (SKB TR-06-09, page 399), there is an incorrect reference to Wahlund and Hermansson 2006 concerning COMP23.
- Incorrect reference from page 445 in SR-Can main report to Figure 10-40 in comparison of the consequences for shear rupture with advection/corrosion (should be Figure 10-41).
- The value of hydraulic gradient in the front of the inland ice used in Sidborn and Neretnieks (2006) has been incorrectly referred to as 0.01 on page 350 in the main report (SKB TR-06-09). On page 28 of Paper II in Sidborn (2006), Sidborn and Neretnieks have actually modelled two different cases: an inter-glacial scenario and a glacial scenario. In the glacial scenario, the value of 0.2 for the hydraulic gradient is used instead of 0.01 as stated in the main report. Sidborn and Neretnieks assumed a value of 0.01 for the hydraulic gradient only for the inter-glacial scenario.
- The value of emissivity of radiation-transmitted heat on the surface of the copper shell as used in Hökmark and Fälth (2003) has been incorrectly referred to as 0.1 on page 231 in the main report (SKB TR-06-09). Only the values 0.3 and 0.63 have been used in Hökmark and Fälth (2003) (page 33).

B2.4 Inconsistent handling of data, process understanding and supporting arguments

- According to the main report for SR-Can (SKB TR-06-09, page 85), the largest observed defect in the copper canister is 4.5 mm. According to the data report (SKB TR-06-25, page 53): "the best estimate of the maximum defect size after 4,500 produced is 4.8mm with 95% confidence limit at 7.8 mm". This is confusing. Bowyer (2008) considers that it should be "The largest measured defect is 4.5 mm, the defect is 4.8 mm for a 95%

confidence interval for 4,500 canisters, and the largest expected defect in the whole population is 7.8 mm”. Furthermore, the analysis shall really be for 6,000 canisters since this is the starting point for SR-Can.

- According to the SR-Can main report (SKB TR-06-09, page 108): “The analysis suggests that the flow field in the north-western part of the candidate volume is mainly local.” According to the diagram text (Figure 4-26) “Regional groundwater flow simulations strongly suggest that the groundwater flow field in the target volume is local […].” The two assessments differ.
- Handling of criteria for microbial activity in the buffer is not dealt with in a wholly consistent way in SKB TR-06-09. On the one hand, it is stated on page 181 that further studies are required to substantiate that microbial activity stops at 2 MPa swelling pressure. On the other hand, the analyses in SR-Can are based on this criterion being correct, without further analyses or calculation cases to shed light on uncertainties in the criterion. On page 182, SKB further states that the swelling pressure criterion is an example of a criterion where small safety margins can be set since the microbial activity rapidly declines in a narrow swelling pressure interval. Finally, it is not made clear in the link back to the Fud programme (section 13.8 in SKB TR-06-09) that further research is necessary.
- On page 217 in SKB TR-06-09, it is stated that injection needs to be sufficiently efficient to provide a hydraulic conductivity of 10^{-9} m/s to cope with the inflows to repository (for Laxemar). It is evident from page 212 that such a high rate of efficiency is seldom achieved in reality. The significance of this should be better explained.
- On page 231 in the main report, SKB states that the results from the prototype repository show that emissivity in SKB TR-06-09 (important for heat transmission through radiation) is three times higher than the that previously used from laboratory experiments. According to SKB TR-03-09 (page 5), the estimated value of the prototype repository is only half as large as the expected value.
- According to SR-Can (SKB TR-06-09, page 242): “Applying the simplified analysis for Forsmark-like conditions indicates resaturation times between 15 and 50 years, and around six years for Laxemar conditions.” and on page 262: “The modelling discussed briefly in section 9.3.6 above indicates resaturation times between 15 and 150 years for Forsmark.” With careful references, it could be traced whether this is a typing mistake or whether there are results that are not completely consistent.
- On page 252 in SKB TR-06-09, it is explained that SKB pessimistically chooses a plane parallel representation of fracture zones for radionuclide transport and that a less pessimistic model cannot be justified since data is lacking on the internal structure. Despite this, SKB takes credit for the existence of Fe(II)-fracture filling material in the fracture zones in calculations of buffering of downward intrusion of oxygen with glacial meltwater (page 349).
- The methane concentration in groundwater from both the Forsmark and the Simpevarp areas reported in Figure 9-46 on page 267 in SKB TR-06-09 is less than 10^{-4} mol/l for all tests. However, in a previous report (SKB HRL-98-11), it is shown in Figure 1 on page 18 that many tests taken in the Äspö area could have concentrations that exceeded 10^{-4} mol/l (or 100 μM) even at great depths (400 – 450 m).
- On page 348 in SKB TR-06-09, SKB refers to Sidborn and Neretnieks’ 2003, 2004 conclusion that abiotic reactions dominate in the long term in the consumption of oxygen

in the rock. It is stated on page 161 in SKB TR-06-19 that the existence of methanogenesis *guarantees* that microbial oxygen consumption will take place during the lifetime of the repository. A better explanation is required here to understand what applies.

- It is stated on page 404 in SKB TR-06-09 that the time to develop great damage to the canister is stated by the SR-Can team as being triangularly distributed between 1,000 and 100,000 years, despite the experts suggesting uniform distribution in the data report (page 60).
- It is stated on page 498, Figure 12-13 in SKB TR-06-09 that the maximum number of damaged canisters is 120. The text on page 500 states 150 damaged canisters.
- According to the fuel and canister process report (SKB TR-06-22, page 54), there is no proof for there being a mechanism that gives rise to a redox front inside a canister. On page 62 of the same report, it states, however, that such a front will develop.
- It is stated in the fuel and canister process report (SKB TR-06-22, page 63) that solubility limits have been defined for three water compositions while four different groundwater compositions are listed on page 64.
- The value of the oxygen concentration in glacial meltwater used in different models is inconsistent. In SKB R-06-105, the value was 8.76 mg/l (page 19) which was based on Grimsel groundwater in equilibrium with the atmosphere. On page 26 of Paper II in Sidborn (2006), a value of 1.5 mol/m^3 (corresponding to 48 mg/l) has been used for the glacial scenario. The highest possible value has not been used in some of the modelling cases.
- The value of the hydraulic gradient at the glacial is front used in different models is inconsistent. On page 21 in SKB R-06-105, the value was 0.1 while on page 28 in Paper II in Sidborn (2006), it was 0.2. The worst case (with the highest gradient of 0.32 reported on page 341 in SKB TR-06-09) has not been analysed in the two models.
- The reporting of the sensitivity analysis in SKB R-06-81 (Chapter 5) is deficiently explained and assessed. There is, for example, no detailed description of parameters tested in the reports or any reference to where these could exist. The figures are difficult to read, for example, the symbol for the same parameter in comparative figures is different. There is not either any discussion or summary assessment of the results of the sensitivity analysis (neither in SKB R-06-81 nor in the LDF report, SKB TR-06-15).
- The hydraulic conductivities measured in the drill hole KFM01A differs between the figures 8-53 and 8-45, on page 400 and. 401 respectively, in SKB R-05-18 (one of the figures must be incorrect).
- Certain conclusions in the main report (SKB TR-06-09, page 359, Figure 9-101) are based on an extrapolation of measurement data a long way outside the measurement area. Stenhouse et al (2008) point out that purely statistic processing which is only based on linear regression without taking uncertainty into account provides an insufficient basis. Without taking into consideration how critically this specific case may be assumed to be, Figure 9-101 may indicate that SKB routinely applies this type of extrapolation in different contexts in the safety assessment.
- Holmlund (2008) points out that the temperature curve on which the climate evolution is based contains considerable uncertainties. Figure 9-64 (SKB TR-06-09, page 303) does not take these uncertainties into account and therefore provides a misleading picture of the exactness of the temperature calculations. SKB should endeavour to include uncertainty

estimates in the illustration of important results in the safety assessment. When stating the uncertainty intervals, it should also be stated what these are based on and thus can be considered to represent.

- In SR-Can (SKB TR-06-09, page 83), it is stated that 7,200 tonnes of BWR fuel will be generated after 40 years' of operation and also 2,300 tonnes of PWR fuel (i.e. a total of 9500 tonnes). However, it is stated in the previous paragraph that 9,300 tonnes of fuel will be created in total during the same time period. It is not clear what this difference is due to.

B2.5 Lack of clarity in expert judgments

- Ivars Neretnieks is referred to as an external expert in, for example, questions relating to glacial meltwater and is at the same time included in the review group SIERG.
- Lars Werme is referred to as an expert in fuel-related issues (see the data report SKB TR-06-25, section 3.2 and 3.3) and is at the same time a member of the SR-Can team to assess precisely fuel-related issues.
- It is stated in the data report page 15 (SKB TR-06-25) that Rolf Christiansson is included in SR-Can team, while the same expert is stated as a reviewer in the preface of the main report.

B2.6 Legibility issues

- SAM makes proposals for general measures to increase the legibility of the safety report. The authorities wish to particularly emphasise the following recommendations:
    - Include a list of tables and figures in the list of contents
    - Review the legibility of figures (more complete figure texts, legible size, consistent use of symbols, etc.)
    - Ensure that it is clear which data/locations different figures and tables represent
    - Repeat the explanation of technical terms/acronyms which are used in different places in the report
- The terminology for the choice and analysis of scenarios: Bearing in mind that SKB has produced a wholly new concept for choice of scenarios, it would make it easier for the reader if there was a better explanation for how the different concepts, failure modes and calculation cases are related. The authorities consider that it is difficult to follow the argumentation in Chapter 12 on the analysis of scenarios in the main report.
- Certain figures (for example, 4-14, 4-24 and 9-5 in SKB TR-06-09) are too small for all the information to be read.
- Figure 9-61 on page 293 in SKB TR-06-09 should be clarified in order to make it clear what error bars represent.
- The report on combined isostatic load and shear movements on page 332-334 in SKB TR-06-09 is, to put it mildly, not a marvel of clarity. The argumentation that leads to the conclusion that the combination of isostatic load and shear load does not need to be taken into account in the safety assessment would not be sufficient in SR-Site.
- Reporting of the logged values in Table 9-20, page 339 in SKB TR-06-09 makes the tables difficult to read.

- On page 396 in SKB TR-06-09, SKB states with reference to Table 10-1 and 10-2 that the number of individuals in the most exposed group is generally larger for Laxemar. However, it is not evident how the tables provide support for this.
- The conclusions on the results in Figure 10-11 (SKB TR-06-09, page 396, section 10.2.10, second paragraph) should be nuanced. SKB states that *"The greenhouse case yields lower LDFs than the temperate period for almost all nuclides"*. In general, the difference is small in most cases between the two climate periods. The points overlap one another so that it is difficult to see in most cases, although for Laxemar there is no difference of half of the radionuclides and otherwise a very small difference. SKB states in the third paragraph that "*For the interglacial period, the LDF values are consistently higher than the values for Forsmark…*". In this case "*consistently*" should be replaced by "*for almost all radionuclides"*.
- The text that explains the figure symbols in Figure 10-11, page 398, in SKB TR-06-09 is unclear. It is stated there *LDF Lx* and *LDF Fm* respectively instead of *Interglacial Lx,* and *Interglacial Fm* respectively. The figure text should have explained that *Glacial* represents "*glacial ice-margin period"*.
- On page 409 in SKB TR-06-09, Figure 10-14, it is not clearly stated that the deterministic calculations apply for Forsmark.
- The choice of Darcy flows in Table 10-5 on page 410 (SKB TR-06-09) cannot be traced from the data report. It is not either clear which candidate site is referred to.
- Different symbols for the same parameters are used in certain figures, see, for example, Ra-226 in Figure B-1 on page 602 (SKB TR-06-09).
- A model is called an "ecosystem model" in SKB TR-06-15 (section 2.3.1) which is called a "simplified radionuclide model" in SKB R-06-82 and SKB R-06-83 (for example, section 5.1.3).

B2.7 Completeness of argumentation for compliance

In most cases, there is a description in SR-Can of how different types of uncertainties and knowledge gaps, which are important for long-term safety, have been dealt with. However, there are some exceptions (see below). The authorities wish to underline that all important aspects of long-term safety need to be dealt with in some way in SR-Site (for example, by pessimistic assumptions, sensitivity analyses and expert judgements). In the cases where further research and development are needed, there should at least be a reference to the plans for this.

- The impact of temperature on mechanical characteristics for unsaturated Mx-80 bentonite (SKB TR-06-18, page 63)
- The extent and effects of cementation (SKB TR-06-18, page 103 and SKB TR-06-09, page 511)
- Question marks in the table for radiation-induced transformations (SKB TR-06-18, page 124)
- Any existence of microbial activity in the buffer at swelling pressures over 2 MPa (SKB TR-06-09, page 186)

- Consequences of very low hydraulic conductivity in the deposition holes (K< 10^{-13} m/s) for resaturation of the buffer (the problem is mentioned in SKB TR-06-09 page 274 but not dealt with further)
- The importance of the surface structure of bentonite for speciation and mineral reactions (it is stated in the buffer process report, SKB TR-06-18, page 110, that the effect of the surface structure is neglected at the same time as the consequences of this are unclear)

Annex 3. International statements on the handling of human intrusion

The following section takes up excerpts from a number of international documents with guidelines on how intrusion should be dealt with in safety analyses. These extracts have been taken from the OECD Nuclear Energy Agency, the UN International Atomic Energy Agency, the International Commission on Radiological Protection (ICRP), the U.S. Environmental Protection Agency, the U.S. National Research Council and the U.K. Environment Agency (EA). Even if there are no unequivocal guidelines, it is possible to understand from these documents that the required reporting of scenarios linked to human intrusion in a repository only refers to unintentional cases. It is then indirectly stated that deliberate intrusion is not taken into account. None of the examples below contain an explicit recommendation for an analysis of deliberate intrusion. A distinguishing feature is rather if effects are to be analysed only for how the surroundings are affected by intrusion or whether also doses associated with the intrusion as such are to be calculated.

Future Human Actions at Disposal Sites: Safety Assessment of Radioactive Waste Repositories, OECD Nuclear Energy Agency, Paris, 1995:

- "If future generations are aware of the waste and the consequences of disturbing the repository or its barrier system, then their actions are intentional. . . . The Working Group agrees with the principle that the society that creates a radioactive hazard should bear responsibility for developing a safe disposal system that takes into account future societies to the extent possible. The current society cannot, however, protect future societies from their own actions if the latter are forewarned of the consequences." (page19)
- "Human actions leading to the release of radioactivity and committed intentionally, rather than inadvertently, can be considered the responsibility of the society that takes these actions. Intentional disruptive actions should not be considered in safety assessments." (page 47)

The Principles of Radioactive Waste Management: Safety Fundamentals, IAEA, 1995:

- "While it is not possible to ensure total isolation of radioactive waste over extended time scales, the intent is to achieve reasonable assurance that there will be no unacceptable impacts on human health. . . . Account should be taken of possible future exploration for, or exploitation of, valuable natural resources that could potentially result in adverse effects on the isolation capacity of the disposal facility." (section 316, principle no. 4)

ICRP-81: Radiation Protection Recommendations as Applied to the Disposal of Long-lived Solid Radioactive Waste, ICRP, Pergamon Press/Elsevier Science Inc., Oxford, England, 2000:

- "With regard to human intrusion, understood here as inadvertent human intrusion, the consequence from one or more plausible stylized scenarios should be considered in order to evaluate the resilience of the repository to such events. The Commission considers that in circumstances where human intrusion could lead to doses to those living around the site sufficiently high that intervention on current criteria would almost always be justified; reasonable efforts should be made at the repository development stage to reduce the probability of human intrusion or to limit its consequences." (page 1)

- "Human actions in the future may also disrupt a waste disposal system. A human action affecting repository integrity and potentially having radiological consequences is known as human intrusion. The consequences for a deliberate intruder are primarily considered the intruder's responsibility." (section 21, page 7)
- "Optimisation should explore and apply reasonable measures to reduce the probability and/or magnitude of exposures . . . due to inadvertent human intrusions by considering, e.g. presence of natural resources, institutional control measures, selection of repository depth." (section 52, page 16)

Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes : Final Rule, Section 40 Code of Federal Regulations, Part 191, U.S. Environmental Protection Agency, 19 September 1985.

- "The most speculative potential disruptions of a mined geologic repository are those associated with inadvertent human intrusion. Some types of intrusion would have virtually no effect on a repository's containment of waste. On the other hand, it is possible to conceive of intrusions (involving widespread societal loss of knowledge regarding radioactive wastes) that could result in major disruptions that no reasonable repository selection or design precautions could alleviate. The Agency believes that the most productive consideration of inadvertent intrusion concerns those realistic possibilities that may usefully be mitigated by repository design, site selection, or use of passive institutional controls (although passive institutional controls should not be assumed to completely rule out the possibility of intrusion). Therefore, inadvertent and intermittent intrusion by exploratory drilling for resources (other than any provided by the disposal system itself) can be the most severe intrusion scenario assumed by the implementing agencies. Furthermore, the implementing agencies can assume that passive institutional controls or the intruders' own exploratory procedures are adequate for the intruders to soon detect, or be warned of, the incompatibility of the area with their activities." (Appendix C, Guidance for Implementation)

Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada (40 CFR Part 197)—Final Rule: Response to Comments Document, EPA 402-R-01-009, U.S. Environmental Protection Agency, 2001 (http://www.epa.gov/radiation/docs/yucca/402-r-01-009.pdf):

- "This comment also proposes that deliberate intrusion into the repository is possible. The NAS (U.S. National Academy of Sciences) considered this possibility and concluded (NAS Report, page 114) it is unproductive to attempt to determine means to protect against risks from deliberate actions, i.e., if there is a deliberate attempt to intrude, no design measures could assure the intrusion would not occur. . . . We believe that assessing the effect of deliberate intrusions would be fundamentally different than the repository 'resilience test' NAS recommended (and we have adopted) and that analyses would supply no useful information about the repository's performance. " (response to question 5-C, page 5-10)
- "The NAS concluded that there is 'no scientific basis for estimating the probability of inadvertent, wilful, or malicious human action' (NAS Report, page 107), and we agree

with that conclusion. We see no value in attempting to develop exposure limits for deliberate acts that wilfully expose the participants to radionuclide exposure or are intended as malicious acts. Any standard for exposure limits would have no meaning or control over deliberate malicious acts. . . . One comment recommended that EPA should specify that the repository have features to reduce the likelihood of deliberate intrusion. EPA does not believe that repository design features would be effective in reducing the likelihood of deliberate intrusion. The intruder, being aware of these measures or being determined to proceed with the intrusion, would simply use whatever means necessary to complete the deliberate intrusion into the repository. We believe that the institutional controls that will be established for the repository are intended to prevent deliberate intrusion." (response to question 5-D, page 5-16 to 5-17)

Technical Bases for Yucca Mountain Standards: Report of the National Research Council, National Academy Press, Washington, DC, 1995 (http://books.nap.edu/openbook.php?isbn=0309052890&page=R1):

- "There is simply no scientific basis for estimating the probability of inadvertent, wilful, or malicious human action." (page 107)
- "The key performance issue is whether the repository would continue to be able to isolate wastes from the biosphere, or its performance would be substantially degraded as a consequence of an intrusion of the type postulated." (page 111) "The conditional risk would not include risks to the intruder or those arising from the material brought directly to the surface as a result of the intrusion"(page 113)
- "We also considered intentional intrusion for either beneficial or malicious purposes, but concluded that it makes no sense—indeed it is presumptuous—to try to protect against the risks arising from the conscious activities of future human societies." (page 114)

Disposal Facilities on Land for Low and Intermediate Level Radioactive Wastes: Guidance on Requirements for Authorisation, Radioactive Substances Act 1993, Environment Agency, Scottish Environment Protection Agency, Department of the Environment for Northern Ireland.
(http://publications.environment-agency.gov.uk/pdf/GEHO0197BMCZ-e-e.pdf)

- "A range of future human actions can be envisaged having the potential to breach the natural or engineered barriers or significantly impair the performance of the system. These may be deliberate, i.e. taken with knowledge of the location and hazardous nature of the facility, or inadvertent because the location or purpose is unknown. The Agencies consider that it is not necessary to undertake quantitative risk assessments of deliberate human actions, since it is assumed that no such action would be taken without due regard to the safety implications and the economic and environmental values of the time." (section 8.24)

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