SKI Report 2008:10

Research

International Expert Review of SR-Can: Engineered Barrier Issues

External review contribution in support of SKI's and SSI's review of SR-Can

David Savage
David Bennett
Mick Apted
Göran Sällfors
Timo Saario
Peter Segle

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ISSN 1104-1374
ISRN SKI-R-08/10-SE

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David Savage, Quintessa Limted (Chairman)
David Bennett, TerraSalus Limited (Secretary)
Mick Apted, Monitor Scientific LLC
Göran Sällfors, Chalmers University of Technology
Timo Saario, VTT Materials and Building
Peter Segle, Inspecta

March 2008

Foreword

The work presented in this report is part of the Swedish Nuclear Power Inspectorate's (SKI) and the Swedish Radiation Protection Authority's (SSI) SR-Can review project.

The Swedish Nuclear Fuel and Waste Management Co (SKB) plans to submit a license application for the construction of a repository for spent nuclear fuel in Sweden 2010. In support of this application SKB will present a safety report, SR-Site, on the repository's long-term safety and radiological consequences. As a preparation for SR-Site, SKB published the preliminary safety assessment SR-Can in November 2006. The purposes were to document a first evaluation of long-term safety for the two candidate sites at Forsmark and Laxemar and to provide feedback to SKB's future programme of work.

An important objective of the authorities' review of SR-Can is to provide guidance to SKB on the complete safety reporting for the license application. The authorities have engaged external experts for independent modelling, analysis and review, with the aim to provide a range of expert opinions related to the sufficiency and appropriateness of various aspects of SR-Can. This report presents an international expert evaluation of the engineered barrier issues in SKB's SR-Can assessment. It is one of three parallel reviews by international expert teams, which have been undertaken to support the regulatory review by SKI and SSI. In addition to this review, separate teams were established to review SKB's handling of information from the site investigations and the utilised safety assessment methodology.

The conclusions and judgements in this report are those of the authors and may not necessarily coincide with those of SKI and SSI. The authorities own review will be published separately (SKI Report 2008:23, SSI Report 2008:04 E).

Bo Strömberg (project leader SKI)   Björn Dverstorp (project leader SSI)

Förord

Denna rapport är en underlagsrapport till Statens kärnkraftinspektions (SKI) och Statens strålskyddsinstituts (SSI) gemensamma granskning av Svensk Kärnbränslehantering AB:s (SKB) säkerhetsredovisning SR-Can.

SKB planerar att lämna in en ansökan om uppförande av ett slutförvar för använt kärnbränsle i Sverige under 2010. Som underlag till ansökan kommer SKB presentera en säkerhetsrapport, SR-Site, som redovisar slutförvarets långsiktiga säkerhet och radiologiska konsekvenser. Som en förberedelse inför SR-Site publicerade SKB den preliminära säkerhetsanalysen SR-Can i november 2006. Syftena med SR-Can är bl.a. att redovisa en första bedömning av den långsiktiga säkerheten för ett KBS-3-förvar vid SKB:s två kandidatplatser Laxemar och Forsmark och att ge återkoppling till SKB:s fortsatta arbete.

Myndigheternas granskning av SR-Can syftar till att ge SKB vägledning om förväntningarna på säkerhetsredovisningen inför den planerade tillståndsansökan. Myndigheterna har i sin granskning tagit hjälp av externa experter för oberoende modellering, analys och granskning. Denna rapport redovisar en internationell expertgranskning av frågor kring tekniska barriärer i SKB:s säkerhetsredovisning SR-Can. Det är en av tre parallella internationella expertgranskningar som SSI och SKI organiserat som stöd för myndigheternas egen granskning. De två övriga internationella expertgrupperna har granskat SKB:s användning av data från platsundersökningarna respektive metodikfrågor för säkerhetsanalys.

Slutsatserna i denna rapport är författarnas egna och överensstämmer inte nödvändigtvis med SKI:s eller SSI:s ställningstaganden. Myndigheternas egen granskning publiceras i en annan rapport (SKI Rapport 2008:19; SSI Rapport 2008:04).

Bo Strömberg (projektledare SKI) Björn Dverstorp (projektledare SSI)

Summary

The Swedish Nuclear Fuel and Waste Management Company (SKB) has recently submitted a license application for the construction of a spent fuel encapsulation plant. SKB plans to submit a further license application in 2009 for the construction of a repository for the disposal spent nuclear fuel. In connection with the first of these applications, SKB published a safety report, known as SR-Can, which assessed the safety of a spent-fuel repository. A further safety report, SR-Site, will be published as an essential component of the license application for the spent fuel repository.

The Swedish Nuclear Power Inspectorate (SKI) and the Swedish Radiation Protection Authority (SSI) (the Authorities) will make formal reviews of the licence applications, and have, therefore, jointly commissioned a team of independent experts to assess and provide comments on SKB's safety reports. The Authorities will consider the views of the independent review team in completing their own reviews. The first task of the independent expert team is to review SR-Can and, in so doing, prepare for the review of SR-Site.

The independent expert team comprises three review groups:

- The Safety Assessment Methodology review group.
- The Site Investigations review group.
- The Engineered Barrier System review group.

This document presents the comments and findings of the Engineered Barrier System (EBS) review group on SR-Can.

The SR-Can safety report includes an examination of EBS design and performance for a range of scenarios, including expected repository evolution and possible variant scenarios, that together address processes and events that might result in the loss of certain repository safety functions. Furthermore, a series of sensitivity analyses is also presented that provides helpful insights into the relative importance of many key parameters and processes related to the EBS.

In general, the explanatory text of the SR-Can safety report is clear, and the cited references provide adequate technical justifications for the assumptions, models, and data that are abstracted into the SR-Can safety report. The review group considers, therefore, that SKB's development of SR-Can has been a very valuable exercise, and that SKB should be congratulated on the breadth, depth and general clarity of its research and development and safety assessment programmes.

Notwithstanding these successes, the EBS review group has identified a range of uncertainties in SKB's programme and safety reports, some of which relate to issues that appear to be of sufficient significance that they will need to be thoroughly addressed in the SR-Site safety report in time for the repository licence application. Other less urgent issues might be identified in SR-Can as uncertainties to be addressed through an appropriate performance confirmation programme. Performance confirmation may be defined as the programme of tests, experiments and analyses,

conducted to evaluate the adequacy of the information used to demonstrate compliance with long-term safety standards for a geological repository.

The most significant of the issues identified by the EBS review group include:

- **Demonstration of the feasibility of EBS emplacement**. SKB will need to present more details on the reference EBS design, on its reference repository construction method, and on the specifications for the EBS materials. In particular, SKB still needs to demonstrate satisfactorily that the EBS can be successfully fabricated and emplaced in the appropriate configuration under repository conditions and at the rates that are projected to be required during waste disposal. SKB needs to develop and test quality assurance and quality control procedures for repository construction and operation, including EBS emplacement. SKB also needs to conduct further tests of EBS emplacement, and to characterise the as-emplaced EBS components. More generally, SKB should describe and explain in more detail how its schedule for developing plans and procedures and for conducting laboratory experiments and underground tests relates to the schedules for safety assessment and licensing.
- **Canister manufacture and integrity.** The view of the review group is that SKB should consider a number of issues in greater detail to build further confidence in the proposed approach for canister manufacture and in the assessments of canister integrity and performance. For example, SKB could improve its canister stress analysis and should conduct further investigations on re-welding of the canister lids.
- **Stress corrosion cracking of copper.** In the opinion of the review group SKB has not completely eliminated the possibility of stress corrosion cracking (SCC) of the copper canister and, that because further experimentation may be required (e.g. to investigate SCC under anoxic conditions), SKB is unlikely to be able to do so in time for the SR-Site safety report.
- **Piping and colloid generation in the buffer and backfill.** SKB has identified piping and colloid generation in the buffer and backfill as processes that could have significant effects on the practicality of EBS emplacement and on the long-term performance of the disposal system. SKB has suggested that the uncertainties associated with piping are limited, but that the uncertainties associated with colloid generation are large. The review group considers that significant uncertainties remain in the understanding of both of these processes and that SKB needs to conduct further work to improve assessments of their effects and plans for their mitigation.
- **Geochemical Modelling and Radionuclide Release.** The review group considers that SKB could do more to improve the consistency and transparency of its modelling of the evolving geochemical environment within the EBS. SKB might also seek to refine its models of radionuclide release by furthering its consideration of processes affecting the rate of spent fuel dissolution and radionuclide co-precipitation.

Finally, it should be noted that there are many relationships and some overlaps amongst the issues considered by the three review groups (e.g. rock spalling may influence processes in both the geosphere and the EBS) and the reader is, therefore, encouraged to consider the other review reports in this series in order to gain a full perspective of the review team’s views.

Contents

1 Introduction

The Swedish Nuclear Fuel and Waste Management Company (SKB) plans to submit license applications for the construction of an encapsulation plant and a final repository for spent nuclear fuel. In connection with these submissions, SKB will publish two safety reports for a KBS-3 type repository. These will be based on the ongoing site investigations in the Oskarshamn and Östhammar municipalities, as well as full-scale manufacturing tests and in situ experiments with different repository components.

The first safety report, SR-Can, was published in the autumn of 2006. SR-Can may be regarded as an early version of SR-Site, which will be submitted in 2009 as an essential component of the license application for construction of a KBS-3 spent fuel repository. SR-Can is not formally a part of the encapsulation plant application. However, the publication of SR-Can still provides a critical opportunity to review and comment on SKB's approaches prior to SR-Site.

The Swedish Nuclear Power Inspectorate (SKI) and the Swedish Radiation Protection Authority (SSI) (the Authorities) will make formal reviews of the licence applications, and have jointly commissioned a team of independent experts to assess and provide comments on SKB's safety reports that the Authorities will consider in completing their own reviews. The first task of the independent expert team is to review SR-Can and, in doing so, prepare for the review of SR-Site. The independent expert team comprises three review groups:

- The Safety Assessment Methodology review group.
- The Site Investigations review group.
- The Engineered Barrier System review group.

This document presents the comments and findings of the Engineered Barrier System (EBS) review group on SR-Can. The members of the EBS review group have previously acquired detailed knowledge of SKB's proposed engineered barrier system through participation in a series of workshops organised between the Authorities and SKB, and are also all experts in their own right having conducted a long record of detailed research and safety assessment studies in various national radioactive waste disposal programmes.

The terms of reference provided by the Authorities to the EBS review group for the review of SR-Can included addressing the following key questions:

- Is the available information on *manufacturing, testing and demonstration of EBS components* accurately represented and fully utilised in SR-Can?
- Is there a good *scientific understanding of key processes* related to the degradation of the engineered barriers?
- If the answer to any of the former two questions is no, what improvements will be needed?
- Are there any *critical issues related to EBS performance that need to be resolved before SR-Site,* which have not been identified by SKB in SR Can?

In coming to its comments and findings on SR-Can, the EBS Review Group has reviewed the 'SR-Can Main Report' and relevant parts of a considerable number of the 'Main References' and 'Other References' that support the SR-Can Safety Report (SKB, 2006f, Figure 2.2). The EBS Review Group has also taken into account information provided by SKB in response to an initial set of written review questions that were provided to SKB by the review groups in early March 2007 (Appendix 3), and discussions with SKB staff during a series of hearings that were held during 20-22 March 2007.

Following this introduction, Section 2 sets out the EBS Review Group's main comments and findings on the SR-Can Safety Report. Key review findings are then summarised in Section 3 together with recommendations that SKB could consider in the near-term (i.e. prior to SR-Site) and in the longer term (i.e. during repository construction prior to repository operation).

2 Review Comments

2.1 EBS Design Decisions and Evolution

2.1.1 SKB's Approach to EBS design

SKB's approach to EBS design was identified as a key area for the review group to address, given both the information presented in the SR-Can safety reports and SKB's responses to some of the review group's initial questions, which point to the existence of several, apparently considerable, design uncertainties at this stage in SKB's programme. For example, there is currently uncertainty over which materials will be used for the backfill (e.g. SKB, 2006f, page 548), particularly for excavations other than the waste deposition tunnels, and over the compositions of the low-pH cementitious materials to be used for shotcreting and grouting (e.g. SKB, 2006f, pages 271-273).

There is also some uncertainty over the types of wastes to be disposed of (e.g. existing MOX fuel and the MOX fuel that may/will be used in BWRs in the future was not included in the SR-Can assessment - SKB, 2006f, page 83), and SKB has described an approach to repository design that allows for repository layout modifications during construction (SKB, 2006f, Section 4.4).

In addition, in its responses to the review group's initial questions, SKB confirmed that it has not yet made a choice between MX-80 and Deponit-CaN bentonites for use as the buffer material (see SKB, 2006f, page 86) and, indeed, SKB suggested that it may not make such a choice. Instead, SKB intends in SR-Site to provide and assess the performance of a specific reference EBS design and to specify the requirements to be fulfilled by the final EBS design.

The review group notes that while various different materials might offer the prospect of meeting the safety functions that SKB has identified (*Figure 1*), this alone may not provide a sufficient test of materials suitability. For example, although various clays might be able to fulfil the safety functions identified by SKB for the buffer (*Figure 1*), different clays are likely to contain different amounts of minor phases (e.g. sulphides, carbonates), some of which might influence canister corrosion and which would need to be addressed in safety assessment. SKB has made some analyses of such effects and will need to continue to take account of material properties other than those directly related to safety function indicators when updating the safety assessment.

Furthermore, in order for the components of the EBS to be able to fulfil their safety functions, their fabrication and emplacement must be feasible and, for some components (e.g. the cementitious grouts), this may be affected by the choice of materials and their compositions (e.g. the inclusion of superplasticisers). Again, the presence of such materials and the detailed compositions of the EBS materials will need to be addressed in the safety assessment that supports SR-Site.

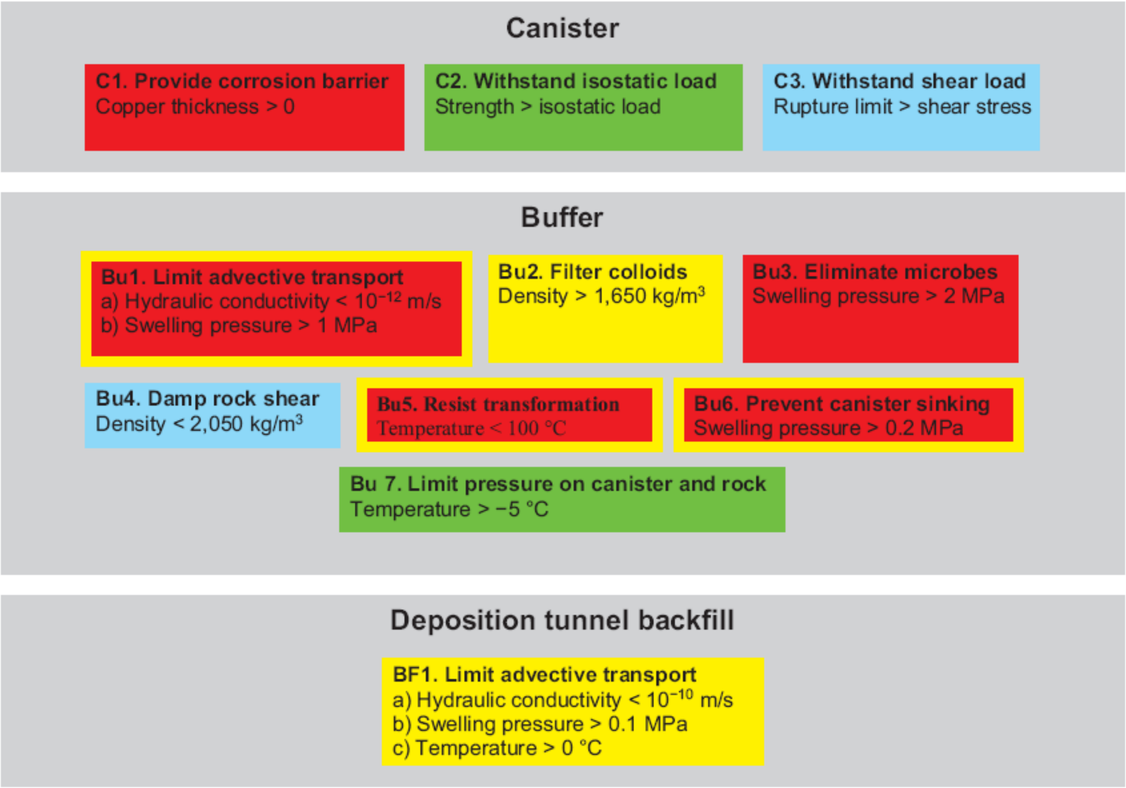

Figure 1: SKB's Safety functions (bold), safety function indicators and safety function indicator criteria for the EBS (from SKB, 2006f). The colour coding shows how the functions contribute to the canister safety functions C1 (red), C2 (green), C3 (blue) or to retardation (yellow). Many functions contribute to both C1 and retardation (red box with yellow board).

The review group understands SKB's approach to EBS design and acknowledges that, up to a point, it is sensible to preserve programmatic flexibility to use different materials for EBS fabrication in the future, as the repository is constructed and waste is emplaced. This may offer some protection from changes in the market for supply of available materials.

However, the review group also considers that as a licence application is approached, there ought to be increasing certainty over the design of the EBS and the inventory of wastes to be disposed of. SKB has presented a high-level schedule for its programme of spent nuclear fuel disposal (*Figure 2*), but although this is very helpful in some respects, it is not detailed enough to allow an understanding of, for example, when decisions will be made on the choice of repository construction method. The choice of repository construction method (i.e., either using drill and blast methods or mechanical excavation using a tunnel boring machine - SKB, 2006f, page 88) could, for example, affect decisions on the method of backfilling and the backfill materials to be used (see below).

The review group considers that SR-Site will need to include a clear and unambiguous description of the reference repository construction method and EBS design, and to specify and assess the waste inventory as comprehensively as possible.

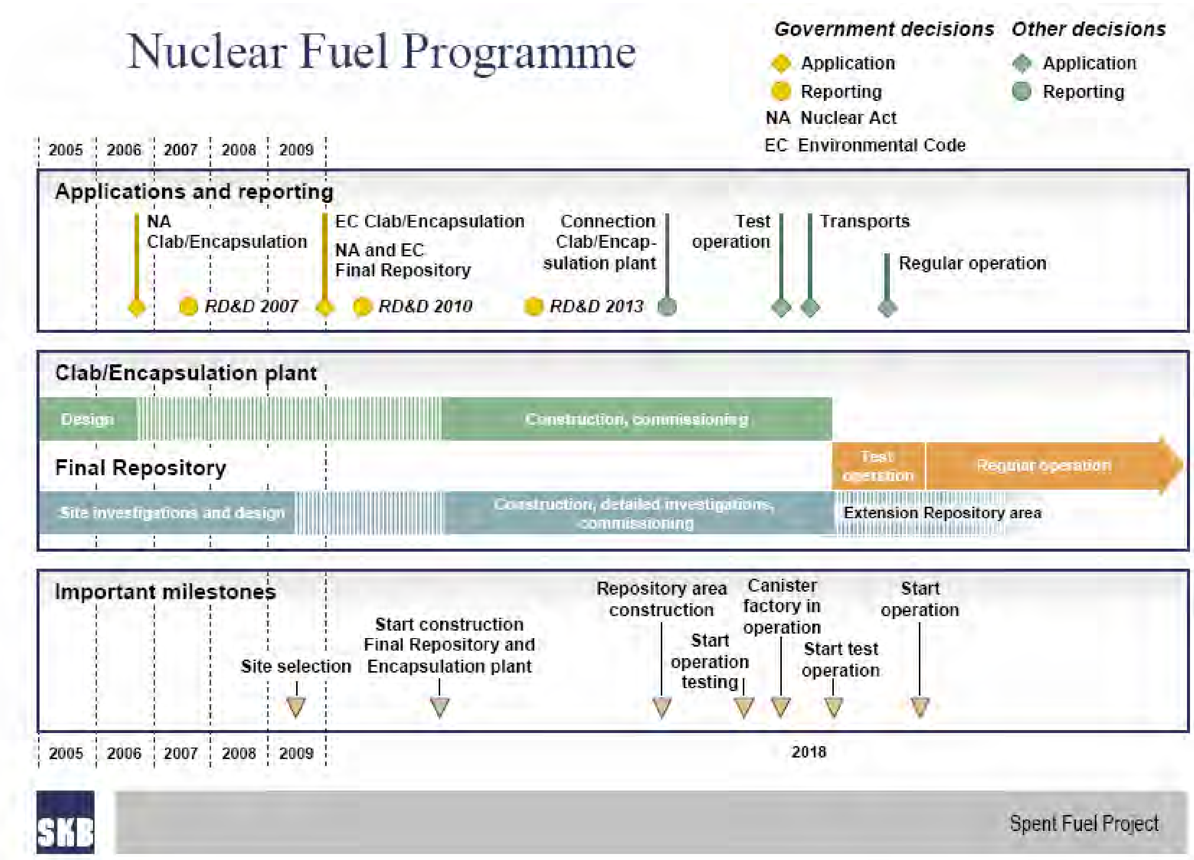

Figure 2: Planned schedule for SKB's Nuclear Fuel Programme.

The reference EBS design and the specifications for the EBS components and materials should be detailed enough to allow an independent assessment of the processes and effects that may occur and influence the performance of the EBS and the disposal system. To allow this, SKB's materials specifications will need to include more detail than issues solely relating to the safety function indicator criteria identified so far.

2.1.2 Decision-Making for Selection of EBS Concepts and Materials

This section discusses decision-making for the selection of EBS concepts and materials and, in doing so, uses an example related to the backfill. The discussion of the processes that can be used for concept or materials selection is not specific to the backfill, however, and could apply equally to the choice of other EBS concepts, designs or materials.

SKB has recently adopted a revised concept for backfilling of the repository tunnels, which involves the emplacement of pre-formed rectangular clay blocks and the use of bentonite pellets to fill any remaining voids around the tunnel periphery (SKB, 2006f, page 88) (*Figure 3*).

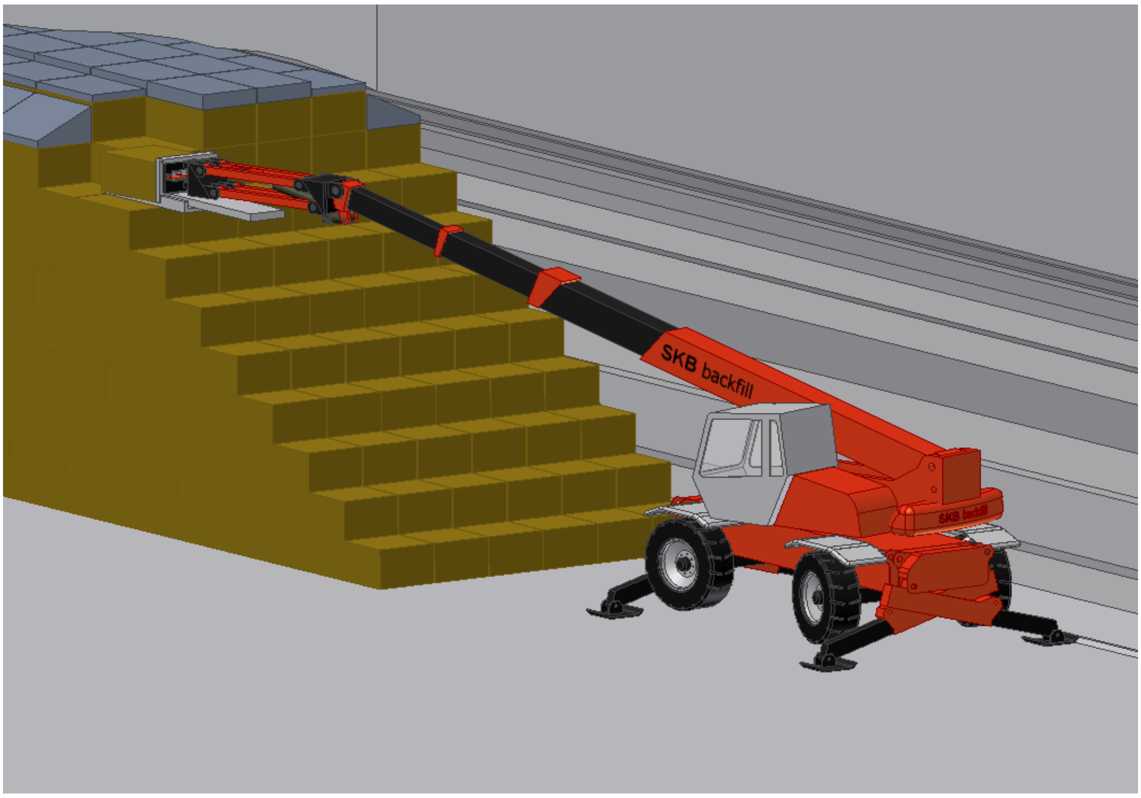

Figure 3: Illustration of SKB's revised concept for backfilling of waste deposition tunnels. From Gunnarsson (2007).

The clay blocks would be pre-formed by re-wetting dried, ground clay at a suitable water to clay ratio. In arriving at its revised backfilling concept, SKB assessed several alternative backfilling concepts (Gunnarsson et al., 2004) against the ability to meet the function indicator criteria for the backfill (see *Figure 1*), engineering feasibility, and cost.

The review group has two types of observations on SKB's revised backfilling concept relating first to the process used by SKB to identify the revised backfilling concept, and second to details of the preferred backfilling concept and its potential implications.

First, with regards to process, the type of options appraisal undertaken by SKB to assess alternative backfilling concepts has many commendable aspects and the review group considers that such structured comparative assessments, or options appraisals, can help to provide confidence that an optimised engineering solution has been devised. Additional confidence may be built into such processes if it is possible to obtain some degree of stakeholder (and/or regulatory) involvement and, where possible, agreement on the set of options to be considered. Confidence is also enhanced if the options are then assessed against a well-defined set of objectives and using independent criteria in a transparent, traceable and reproducible way.

SKB will have to make a series of further decisions on various aspects of EBS design as the disposal programme develops over the next few years, and the review group suggests that, contrary to the indications given by SKB at the hearings, it would be beneficial for SKB to extend its use of such options appraisals (possibly to include use of multi-attribute decision analysis techniques to aid decision-making), in a fashion similar to that being followed in some other radioactive waste disposal programmes outside Sweden (e.g. Belgium, Japan, UK). Such techniques could also provide one route to addressing the SSI's requirement to take account of best available technique (BAT).

Second, with regard to the details of the preferred backfilling concept (pre-formed clay blocks and bentonite pellets), the review group notes that the concept was developed for use with drill and blast tunnel excavation techniques (SKB, 2002) and that it may have to be redesigned (e.g. in terms of block geometry, stacking pattern and installation equipment) if a decision was made to use a tunnel boring machine. The review group also notes that SKB has not yet defined or proposed in detail how it would go about backfilling other repository cavities such as shafts (see SKB, 2006f, page 93).

The topics of demonstrating the feasibility of EBS fabrication and emplacement, and erosion of backfill are addressed in more detail below, but the review group considers that it will be essential for SKB to demonstrate that the backfill can be emplaced successfully at the rates of emplacement that will be required in the repository and given realistic groundwater inflow rates through fractures. One concern is that piping of backfill by inflowing groundwaters during the operational period could slow backfill emplacement operations and possibly result in a backfill with a final density lower than required.

2.1.3 Data Sufficiency

This section summarises the review group's view on the sufficiency of data for possible alternative EBS materials, and considers the status and possible forward programme of R&D on EBS materials for the backfill, buffer and cementitious grouts.

Backfill

SKB (2006f) suggests that SKB will select Friedland Clay for the backfill material in preference to the 30/70 bentonite - crushed rock mix (SKB, 2006f, page 381). The EBS review group had concerns regarding the sufficiency of characterisation data for the Friedland Clay, and whether another demonstration of backfill emplacement would be conducted.

SKB responded that characterisation data are best presented in the (as yet unpublished) TR-06-30 report. SKB took pains to stress that the Friedland Clay is an example of a suitable clay that meets the requirements and that more investigations on candidate backfill materials would be made.

Regarding testing, SKB has stated that full scale, above-ground tests to simulate backfilling using concrete blocks and bentonite pellets will be made during 2007 and that further tests at small scale using Friedland Clay blocks and bentonite pellets are on-going to understand the role of water inflow. SKB has also indicated that further plans to test and demonstrate the entire backfilling system at the rates needed in the repository, will be described in SKB's RD&D Programme for 2007.

The review group is satisfied that its concerns will be addressed by the forthcoming tests but will, of course, have to await the results of the tests to assess the level of confidence that can be placed in the new backfill concept.

Buffer

The review group notes that most of the experimental work on buffer materials has been performed using MX 80 bentonite. SKB believes that there is sufficient data for both MX-80 bentonite and Deponit CA-N bentonite to justify their selection as reference materials in SR-Can. SKB acknowledges, however, that this does not necessarily mean that enough data are available to justify Deponit CA-N as a candidate for the repository, and has recently installed a new long-term test of different clay materials in the Äspö laboratory.

It is clear that there is a larger data set on the potential buffer materials than exists for the potential backfill materials, but the review group remains somewhat uncomfortable with the idea that SKB could apply for a licence without specifying clearly which buffer materials would be used and without providing data to support that selection, unless a clear performance confirmation programme is defined and implemented[1].

Cement Grouts

SKB envisages using low-pH cement for grouting and shotcreting because of concerns regarding the interaction of high-pH pore fluids from conventional Ordinary Portland Cements (OPC) cements with buffer and backfill materials (SKB, 2006f, pages 94, 220-221, 271 and 548). The review team has concerns regarding:

- The rationale and justification for the choice of pH 11 as an upper limit of acceptability for the pore fluids of cements.
- The current status of research and development aimed at establishing suitable compositions for the cementitious EBS materials, and the uncertainty over at what point in the disposal programme a decision would be made regarding compositions.
- The precise details of how SKB carries out modelling of the evolution of the chemical composition of pore fluids in low pH cements (the report by Luna et al., 2006 describing SKB's actions in this area ignores the incongruently-dissolving nature of the CSH gel phase of cement *inter alia*).
- How the high silica-content pore fluids in low-pH cement will be redistributed during the thermal period and whether the bentonite may be destabilised as a result of reaction with dissolved silica.

With regard to the rationale for the choice of pH limit, SKB has stated in its response to the review group's initial questions that "*the limit pH 11 has been selected because there is no evidence known to the SR-Can team indicating that such pore waters would*

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[1] Performance confirmation may be defined as the programme of tests, experiments and analyses, conducted to evaluate the adequacy of the information used to demonstrate compliance with long-term safety standards for a geological repository (SKI, 2004).

damage the performance of the buffer", and also that: "*further experimental studies might show that higher pH values are acceptable, but given the short time span for any experiments their applicability in estimating repository conditions far in the future would require also a very good understanding of the processes involved*".

Regarding the status of the grout development programme, SKB has stated in its response to the review group's initial questions that cementitious grouts are being tested by Posiva, that SKB is planning a test of silica sol grouting at Äspö, and that several studies have already been performed in collaboration with Posiva and Numo. SKB considers that premature decisions on compositions might be detrimental, as it would be reasonable to expect that supplies of materials may change, given the relatively long period of repository operation.

A preliminary evaluation of the reactivity of bentonite with low-pH cement pore fluids has been reported (Karnland and Birgersson, 2006). Since the silica gradient would be from hotter to cooler parts of the repository system, SKB believes that silica in the cement pore fluids will not pose a problem during the thermal period. However, SKB also suggests that this issue might be further addressed in SR-Site.

The review team considers that further work in this area is necessary and welcomes SKB's plans to address the review team's concerns.

2.1.4 Implications for Oversight of SKB's EBS Programme

Particularly when considered alongside the proposed schedule for repository licensing and waste disposal, there are several possible implications of SKB's approach to repository design, EBS materials selection and testing.

First, there is an understandable tension between the desire to maintain programmatic flexibility and the need to provide sufficient information on the EBS and its performance in the SR-Site Safety Report that will support the license application for the repository. It will, for example, be important to determine if SR-Site provides sufficiently detailed materials specifications. It will also be necessary to judge whether there are sufficient data with which to make a reliable assessment of the performance of the EBS and the degree to which any further necessary data gathering may be made through a performance confirmation programme.

Second, it will be necessary to consider carefully and establish what is actually required of SKB in terms of demonstrating the feasibility of EBS fabrication and emplacement before the licence application, and in the longer period, before waste disposal commences.

2.2 Initial States and Early Evolution of the EBS

2.2.1 EBS Emplacement and QA/QC

In SKB's assessments of the KBS-3 concept, it is generally assumed that the buffer and backfill materials eventually fill all of the voids and become homogenously distributed. To accomplish this in practice, satisfactory procedures must be developed that specify in detail how the buffer and backfill materials are to be emplaced, that detail the standards that shall be achieved, and that identify how the emplaced barrier materials should be tested to demonstrate compliance with the requirements of the procedures. These procedures should also allow for worker protection during EBS installation.

While the review group acknowledges the progress made with the considerable experiments that have been conducted in the underground laboratory at Äspö, it also notes that SKB (2006f) contains relatively little information on the engineering feasibility of the KBS-3 concept. Although SKB's description of the initial state of the repository does discuss the EBS installation process (SKB, 2006f, page 77), procedures (QA and QC plans) for emplacement for the EBS, or a schedule that specifies acceptable times between different events in the EBS emplacement sequence are missing. The review group has concerns that even though some experience has been gained in buffer emplacement during the non-radioactive Prototype Repository experiment, questions remain over whether the buffer rings and waste canisters can be installed with accuracy at the rate that will be necessary in the repository. Also, it is questionable whether the drain tubes and plastic liners can be used as intended to control water inflow to the deposition holes during operations, and can then be removed successfully and reliably under repository conditions. SKB has acknowledged that the SR-Site Safety Report will need to contain more information on feasibility than did SR-Can.

Regarding the *backfill* material, procedures are required describing how the blocks should be formed and the patterns for their emplacement. Procedures will also be required describing the emplacement of pellets to fill the irregular voids between the blocks and the rock tunnel walls. The correct use of the emplacement procedures and the resulting state of the EBS materials (e.g. in terms of homogeneity) must also be tested and the standard of EBS emplacement should be shown to be within acceptable ranges. The backfilling concept has been partly reported in SKB (2002) and in Gunnarsson et al., (2004), but the review group considers that it needs further attention. According to SKB, plans for further testing and demonstration of the backfilling system will be included in the RD&D-program 2007, including a test to ensure adequate backfill emplacement at the rates that will be required in the repository.

More generally, the review group considers that SKB should describe and explain in more detail how its schedule for experiments and tests relates to the schedules for safety assessment and licensing.

2.2.2 Extraneous Materials

The presence of extraneous materials (e.g. organic additives in cement grouts) has the potential to influence the solubility and sorption of radionuclides in the near-field. The use of low-pH cements will necessitate the use of organic additives such as superplasticisers to maintain workability and other physical properties.

SKB considers that such organic materials "*will be accessible*" for biodegradation before canister penetration and radionuclide release (SKB, 2006f, page 273). Moreover, SKB has started a collaboration project together with Posiva, Numo and Nagra to study the release of organics from cement samples containing superplasticisers, as well as the influence of both superplasticisers as well as released organics from cement on radionuclide sorption under 'normal' geosphere conditions.

The review group considers that further work to address the issues of the potential availability and effects of cement additives on radionuclide complexation in groundwater would be highly desirable.

2.2.3 Initial and Boundary Conditions

All assessments of EBS behaviour are based on assumptions, ranging from material properties, initial and boundary conditions, idealizations, and simplifications of governing processes. All of these parts of the assessment must be justified and supported by experimental evidence or other lines of reasoning.

Of particular interest here is the relationship between SKB's assessment assumptions regarding the initial state of the disposal system and the actual state of the repository. As noted above it will be essential for SKB to develop procedures and QA/QC plans for EBS emplacement. It is also important that the properties assumed in the post-closure assessment reflect in a reasonable way the actual design and emplacement, and any effects that may occur during the operational phase.

For example, the humidity in the tunnels may need to be regulated in such a way that the water content of the bentonite for the backfill does not change significantly from the conditions assumed in the assessment. Such effects are also relevant for the buffer bentonite, especially regarding the use of water protection measures in the wetter deposition holes.

SKB has stated that it will include the development of procedures and QA/QC plans in the RD&D-program for 2007. SKB will also need to keep consistency between the plans for EBS emplacement and the assumptions regarding the initial conditions for safety assessment.

2.2.4 Thermo-Hydraulic (TH) Evolution

Modelling of the transient processes involving temperature and water content, including flow of water and vapour transport, is complicated, but indirectly extremely important for the long term behaviour of the EBS.

Temperatures that are too high might harm the swelling capacity of the bentonite and, therefore, restrictions on temperature should be strictly enforced. SKB has made numerous thermo-hydraulic simulations and has found that the current repository design meets the relevant thermal criteria by a reasonable margin (Börgesson et al., 2006).

SKB's simulations have been made using finite element methods which require appropriate calibration and verification, for example, against benchmark test cases. SKB claims that such verification tests have been conducted using analytical solutions and that the accuracy of the finite element models used for the simulations is excellent.

Re-saturation of the bentonite is, as pointed out above, important to the stability and performance of the bentonite buffer. Buffer re-saturation will depend on the properties of the bentonite and the availability of water. A gradual and fairly homogenous re-saturation, will result in an homogenous bentonite buffer with properties closely similar to those previously assumed in SKB's finite element analyses. However, uneven re-saturation, due to uneven flow of water into the tunnel and deposition holes, may actually be a more realistic scenario than that of homogeneous re-saturation and bentonite swelling. SKB suggests that buffer re-saturation times are likely to vary from a few years, to a hundred years or so, in different parts of the repository. However, SKB also suggests that saturation time is not a critical issue for repository performance.

The review group considers that further analyses, simulations, verification testing and demonstrations are needed to address the probable consequences of heterogeneous re-saturation.

2.2.5 Thermo-Hydraulic-Mechanical-Chemical (THMC) Evolution

Chemical species with temperature-dependent solubilities (which may either increase or decrease with increasing temperature) may be re-distributed during the thermal period due to gradients in temperature. Some solutes (e.g. Ca^{2+}, SO_4^{2-}) may migrate closer to the canister, and some further away (e.g. H_4SiO_4). This may lead to dissolution / precipitation of solid phases, with attendant changes in porosity and/or cementation of clay particles in the buffer.

It is not clear that SKB has adequately addressed these chemical effects in its modelling studies and, indeed, chemical effects during the repository thermal period are apparently ignored (SKB, 2006f, pages 230-258). The review group considers that the emphasis of SKB's modelling work for the thermal phase appears to be firmly on thermal-hydraulic-mechanical (THM) issues, and very little related to chemical factors. In response, SKB has argued that because the coupling of chemistry with mechanical processes is poorly understood, there is little value in attempting to model these couplings.

The review group acknowledge SKB's concerns regarding fully coupled THMC models, but feels that more could be done to demonstrate that the chemical processes really are of minor significance to long-term safety. Indeed, SKB's statements about the level of uncertainty associated with coupled chemistry effects is all the more compelling a reason for such effects to become a priority for further studies. These studies could begin with coupled TC and HC modelling, and the review group considers that it ought to be possible to make some progress with such studies for inclusion in the SR-Site safety report.

2.3 Near-Field Geochemistry

2.3.1 Consistency of Models for Clay Behaviour

SKB uses several seemingly independent and unconnected geochemical modelling approaches to address various aspects of the chemical evolution of the clay and clay pore fluids in the repository system. For example, SKB utilises at least three geochemical models to describe clay behaviour:

- An osmotic model is used to describe smectite clay swelling behaviour (e.g. Karnland and Birgersson, 2006; Hedin, 2004).
- Ion-exchange and clay surface site protonation / deprotonation models are used to describe long-term pore fluid evolution and interaction with groundwater (e.g. Hedin, 2004).
- An empirical kinetic expression is used to describe the conversion of montmorillonite to illite (e.g. SKB, 2006f, pages 285-286; Karnland and Birgersson, 2006).

In addition, SKB is considering use of a fourth model to describe the conversion of montmorillonite to non-swelling berthierine, as a result of interactions between the clay and the corroding cast iron insert (Karnland and Birgersson, 2006).

SKB considers that a number of different models are required for different geochemical processes so that the most appropriate can be chosen. SKB recognises that this introduces a problem with consistency between the models, but argues that there is no 'universal' model available that could be used for all applications. Consequently, SKB's overall strategy in SR-Can has been to focus on the merits of the individual models.

Although the review group recognises SKB's position on this issue, it is felt that more could be done to improve consistency and transparency in SKB's geochemical modelling studies. Confidence in the consistency between different geochemical models can be enhanced by the use of a single internally-consistent thermodynamic database across the disposal programme and standard procedures for the adoption of other relevant (e.g. kinetic) data.

2.3.2 pH and Redox Conditions

Radionuclide solubility and transport behaviour are significantly affected by the pH and redox conditions of near-field pore fluids. Redox conditions in the buffer and backfill will be established through heterogeneous reactions between solutes in groundwater, and major and minor solid phases in the bentonite / clay. The degree to which pH is buffered and redox poised by the solid phases will depend on mass balance (are there enough buffering minerals present?), mass action (is the solubility of buffering minerals high enough?), and kinetics (is the reaction rate of buffering minerals fast enough?).

Without making any apparent assessment of the contributing roles of mass balance, mass action and kinetics, SKB suggests that calcite dissolution and precipitation (driven by ion exchange reactions involving montmorillonite) will be more important than mechanisms involving protonation-deprotonation reactions in montmorillonite, and montmorillonite dissolution-precipitation reactions (SKB, 2006a, pages 102-104 and 179).

According to SKB, the effect of protonation-deprotonation has been tested for MX-80 bentonite with no carbonate minerals present (Arcos et al., 2006, pages 31-47). Arcos et al. (2006) conclude that protonation-deprotonation processes have a role when carbonate minerals are not present, but only have minor effects for the reference case (interaction with present-day groundwater, which does contain appreciable levels of carbonate). In the scenario where ice-melting water can reach the repository level, SKB notes that a stronger buffering of pH is exerted by surface acidity reactions, but that when carbonate minerals (e.g. calcite) are present, the pH buffering is exerted by the equilibrium with this mineral. The effect of montmorillonite dissolution was not taken into account by SKB due to experimental evidence concerning the slow rate of this process (e.g. Cama et al., 2000).

Regarding redox buffering, SKB refers to the roles potentially played by siderite and pyrite, and concludes that siderite dominates redox behaviour (SKB, 2006a, pages102-103). The presence of sulphate/sulphide in groundwater and iron in montmorillonite is apparently ignored, again seemingly without consideration of mass balance, mass action, and kinetic constraints. SKB believes that sulphate/sulphide will not be relevant due to the non-viability of sulphate reducing bacteria in highly compacted bentonite. The other possible redox couple acting in the system, Fe(II)/Fe(III) has been tested by SKB (Arcos et al., 2006), but the conditions expected in the system do not reach the Fe(II)/Fe(III) boundary. Therefore, SKB concludes that the equilibrium with pyrite and siderite (as occurs with present-day groundwater in Forsmark, (Arcos et al., 2006 pages 36-38) is the principal control of redox in the near-field.

Notwithstanding SKB's responses to its initial questions, the review group considers that SKB's assessment of the relative importance of different buffering reactions could be more transparent. Emphasis needs to be transferred from complex numerical modelling of reactions to simpler scoping calculations, assessing the key issues of mass balance, mass action, and kinetics. The review group considers that it ought to be possible to make some progress with such studies for inclusion in the SR-Site safety report.

2.4 Canister Integrity

Maintenance of canister integrity is central to the KBS-3 concept. A number of processes and potential canister damage mechanisms and their impact on the canister integrity are discussed below. Of particular note are those that may influence more than one canister at the same time.

2.4.1 Stress Corrosion Cracking (SCC)

Stress corrosion cracking (SCC) is a process where copper cracks under the combination of high enough stress and an aggressive chemical environment. If it occurs, SCC has the potential to affect many, or possibly all, of the canisters. Stresses sufficient for SCC may well be present in the weld areas of the KBS-3 canister. Aggressive species that are known to induce SCC in copper under certain conditions and are likely to be present in the disposal vault, include acetate (CH_3COO^-) and ammonium (NH_4^+, also produced from nitrite (NO_2^-) and nitrate (NO_3^-)). A rather recent finding, also pertinent to the copper canister, is that CuCl potentially present in the gaseous phase also may induce SCC in copper (e.g. Bianchi and Galvele 1993).

Based on the available data, it has been assumed by SKB that SCC of pure copper only occurs under oxidising conditions, e.g. in the presence of a high enough concentration of oxygen. However, there have been some reports of SCC of pure copper under anoxic conditions (e.g. Bojinov et al. 2003; Saario 2006), and at least two mechanisms for this have been proposed. Moreover, SCC of copper in the presence of CuCl gas takes place under strictly anoxic conditions.

SKB’s approach to the investigation of SCC of copper has been based on a decision tree analysis. They claim that at no point in time do the necessary conditions for SCC of copper, i.e. stress, oxic conditions, and high enough concentrations of aggressive species, occur simultaneously. Therefore, in SKB’s view, SCC can be excluded from safety assessment calculations. The decision tree analysis-based *approach* is in principle acceptable and very transparent. However, a number of additional checks are needed as follows:

- The possibility of SCC occurring after canister emplacement, but before full bentonite saturation, during which time the gap between bentonite and the canister is filled with gas containing some CuCl.
- The possibility of SCC during the long anoxic period, during which sulphide may act as the oxidiser for copper and induce SCC (e.g. through the ‘surface mobility’ mechanism).

In the opinion of the review group SKB has not completely eliminated the possibility of SCC of the copper canister and, because further experimentation may be required (e.g. to investigate SCC under anoxic conditions), SKB is unlikely to be able to do so in time for the SR-Site safety report.

2.4.2 Ductility of Copper

The ductility of the copper material has to be sufficiently high to avoid penetration of the copper canister when subjected to mechanical loading. Major mechanical loads are the bending moment associated with uneven swelling of the bentonite buffer, isostatic pressure, and earthquake shear load. Accumulation of inelastic strain starts as soon as the copper canister is subjected to external pressure from the bentonite clay. Depending on the stress level and temperature, the copper material will either creep, deform by plastic deformation, or a combination of both deformation mechanisms will occur. The temperature of the copper canister will be about 90 °C at the start of the deposition, and will decrease with time as the heat generation from the waste decreases. The accumulation of inelastic strain will vary with location in the copper canister. It is obvious that the location of an earthquake shear has a direct impact, but also the sequence of the different loadings has an influence. Plastic deformation and deformation by creep are intimately related. Both result in accumulation of inelastic strain that has to be less than the ductility of the material in order for the material not to rupture.

In SKB's assessment of copper canister integrity, the two deformation mechanisms outlined above (plastic deformation and creep deformation) are treated separately, as if there was no interaction between them (SKB, 2006f). In SKB (2006e), on the other hand, SKB acknowledges that further investigations are needed on the influence of deformation hardening on long-term canister integrity.

In the opinion of the review group, the interaction between plastic deformation and creep deformation should be taken into account. Results from further experimental testing on copper should be used to test SKB's constitutive model for copper (see Section 2.4.3). Detailed stress analyses considering different loading combinations should then be performed to demonstrate the integrity of the copper canister.

2.4.3 Constitutive Model for Copper

A thorough assessment of copper canister integrity requires a constitutive model describing the behaviour of the copper material. SKB expects that most of the copper canisters will have lifetimes greater than one million years (e.g., SKB, 2006f, Figure 9-103). During this period, the temperature of the copper canister will vary, from about 90 °C to about 18 °C after 10,000 years (SKB, 2006c). During the lifetime of the copper canister, the stress level will vary with location and load combination. In qualifying the constitutive model, considerable extrapolations of experimental results have been made. It is important that the potential change in deformation mechanisms with temperature is considered properly when making this extrapolation.

SKB has been working with two different models, both taking creep and plasticity into account. The first model developed by Kjell Pettersson (Pettersson, 2006) has been implemented into the finite element computer code ABAQUS. Using this model, earthquake-induced rock shear through a deposition hole was analysed (SKB, 2006c). Results from this investigation showed an unexpectedly high amount of creep strain, which SKB could not explain. Based on this, SKB has decided to investigate a second constitutive model developed by Rolf Sandström and Henrik Andersson (Sandström and Andersson, 2007). SKB's work with the second model is on-going.

The view of the review group is that this further research on the behaviour of copper is to be encouraged so that a more reliable model can be developed to support safety assessment.

2.4.4 Canister Stress Analysis

In order to evaluate the structural integrity of the canister, a detailed stress analysis is required. This, in turn, requires qualified constitutive models, knowledge of the geometry of the various engineered components, knowledge of the manufacturing processes, and information about expected loadings.

SKB (2005) presents results from a detailed stress analysis of the cast iron insert. Based on finite element analysis, stresses due to isostatic pressure during glacial loading were determined. Results were used for a probabilistic assessment of initiation of crack growth and local collapse. In the analysis, the model used consisted of one eighth of the insert and plane strain conditions were assumed. Furthermore, no residual stresses from casting were taken into account.

No detailed stress analysis has been performed for the copper canister. In SKB (2006h), the copper canister was included as a part of the model used for analysing earthquake induced rock shear through a deposition hole. The numerical grid or mesh used to represent the copper canister (and particularly the lid) was relatively coarse and creep was not considered. In SKB (2006c), the constitutive model was improved by also taking creep into account. As noted above, however, the results, showed an unexpectedly high amount of creep strain that SKB could not explain.

The view of the review group is that a number of issues need to be considered further for an adequate stress analysis of the canister, including:

- The material models should be based on qualified constitutive equations.
- The geometry of the canister and insert should be represented in sufficient detail.
- The effects of residual stresses from casting and Friction Stir Welding (FSW) need to be investigated and taken into account.
- For some situations simulated, potential defects may have to be modelled.

The review group considers that these issues ought to be addressed prior to SR-Site.

2.4.5 Manufacturing of Copper Canister

SKB has chosen extrusion as their reference method for manufacturing the copper cylinders, but indicates that other manufacturing options will also be available in order to provide programmatic flexibility. The copper lids will be manufactured by forging, and the bottom of the canister will be attached to the copper cylinder by friction stir welding (FSW) with the canister in a horizontal position. Sealing of the canister will be carried out by FSW with the canister in a vertical position. In SKB (2006g), two inspection criteria are suggested for the weld. The first criterion is related to the welding variables such that they are kept within a welding ‘process window’. The second criterion is related to limits for permissible indications during non-destructive testing (NDT). If the criteria are not met, the canister should be identified as a non-conformance. SKB envisages three possible corrective measures for non-conforming canisters; i.e. re-welding, rejection, or NDT approval.

The trial series of FSW has, so far, only been carried out with canisters in the vertical position. The review group considers that a similar trial series should be done with horizontal canisters to allow calibration of appropriate process parameters for welding on the bottom of the canister.

SKB claims that a weld that fails to meet one of the inspection criteria can, after study of the welding system, be re-welded. If the acceptance criteria are met after re-welding, the weld can be approved (SKB, 2006g). This conclusion is based on results from examination of regions of the FSW that have been welded twice, i.e. overlap at start and finish of a single FSW. However, it is not evident that a friction stir weld meeting the inspection criteria and welded twice would show the same characteristics as a weld that did not in the first instance meet the inspection criteria but that was subsequently re-welded.

It is the review group’s view that further investigations should be performed on re-welding before SKB’s suggested approach could be accepted.

2.4.6 Damage Tolerance of Canister Components

In the copper canister, the weld is the region that is most prone to defects. From trials with FSW, two main types of defect have been observed; ‘joint-like hooking’ and ‘wormholes’ (SKB, 2006g). Joint-like hooking tends to occur in the internal part of the weld, while wormholes tend to be found near the outer surface of the canister. Based on results from an assessment of the reliability of the non-destructive testing system and extreme value analysis, SKB has predicted a maximum defect size of 10 mm for the future production of sealing welds (SKB, 2006g). Other parts of the copper canister will also contain defects, but these are expected to be smaller than those in the weld region.

The tolerance of the copper canister to damage has not yet been reported by SKB. The review group considers that SKB’s damage tolerance analysis for the canister should take account of potential embrittlement of the copper material, different locations and sizes of defects, the sequence of loadings, the locations of earthquake shear, and the effects of residual stresses in the weld region.

SKB (2005) describes a probabilistic assessment of initiation of crack growth in the cast iron insert. In this analysis, the canister was subjected to an isostatic pressure and the defect was located between one of the channels and the outer surface of the insert with the crack plane perpendicular to the axial direction of the canister. At an isostatic pressure of 44 MPa, corresponding to the glaciation scenario, the safety margin was shown to be sufficient.

A damage tolerance assessment of the cast iron insert for other loadings and defect locations has not yet been reported by SKB. According to SKB, results achieved so far show satisfactory damage tolerance for the insert. The review group considers that SKB's damage tolerance analysis for the insert should take account of potential embrittlement of the cast material, potential ductility reduction of PWR insert material, different locations and sizes of defects, the locations of earthquake shear, and the effects of residual stresses in the casting.

The review group suggests that deterministic and probabilistic assessment approaches are complementary and that both should be used in demonstrating adequate damage tolerance of the different canister components.

2.4.7 Earthquake Shear Failure Scenario

Earthquake-induced rock shear through a deposition hole represents one of the most significant mechanical loads to which the canister could be subjected. SKB has investigated the possible effects of such loadings, both experimentally and by numerical modelling. Numerical modelling results suggest that the loadings caused by earthquakes of credible size and proximity would lead to significant inelastic deformation of the canister components (SKB, 2004a, 2006c). Comparing results from SKB (2004a) and SKB (2006h) shows that the amount of plastic strain developed in the canister has been reduced by introducing a gap element between the copper canister and the bentonite clay. For some of the parameter combinations, however, the risk for canister failure still cannot be ruled out. Together with the uncertainties in predicting the development of creep strain (SKB, 2006c), this implies that further investigations are needed for an increased understanding of the canister behaviour when subjected to earthquake shear loading.

In order to reduce the probability that canisters will be subjected to earthquake-induced rock shear, only deposition holes that are sufficiently far from potential deformation zones in the bedrock will be utilised (SKB, 2004c). SKB has calculated that if it follows this approach and disposes of 6,000 canisters in total, then the mean number of canister failures from earthquake-induced rock shear in one million years would be less than 0.12 (SKB, 2006f).

Even though the estimated number of canister failures due to earthquake-induced rock shear is low, the review group recommends that SKB should consider undertaking further investigations of such loading scenarios with the objective of enhancing understanding of the mechanical response to earthquake shear loading and if possible defining an approach that would further reduce the risk of such canister failures.

2.4.8 Design Basis for Canister

SKB (2006e) describes the design basis for the canister, provides some background information on the development of the design basis, and summarises the various requirements of the canister. SKB (2006e) also includes an action plan for further improvements to the design basis for the canister.

However, SKB (2006e) does not include detailed requirements in terms of safety margins related to potential failure mechanisms. The review group considers that the final design basis for the canister should include safety margins related to the different failure mechanisms and loadings that may occur.

2.5 Piping & Colloid Generation in Buffer and Backfill

Repository conditions and processes that may disrupt or compromise the safety functions of the buffer (and to a lesser extent, the backfill) are of importance to safety assessment. SKB (2006f) identifies and evaluates two separate cases of conditions that may cause significant removal of buffer and/or backfill:

- Piping / erosion driven by gradients in water pressure during initial repository re-saturation soon after EBS emplacement (see Sections 9.2.4 and 9.3.9 of SKB, 2006f).
- Chemical erosion involving the release of colloidal clay material into fractures as a result of deep circulation of dilute glacial waters during future glaciations (see Sections 9.4.7, 9.4.8, 9.4.9, and 9.5 of SKB, 2006f).

Both of these mechanisms could lead to the removal of buffer material from the deposition holes into fractures and lead to advective flow, enhanced corrosion and earlier-than-expected canister failure. SKB acknowledges that the uncertainties associated with these scenarios are considerable (SKB, 2006f, page 432), and that the consequences could be significant because the safety functions of both the canister and the buffer would be compromised and because radionuclide retention in the host rocks would be low because of high flow rates in the intersecting fractures.

2.5.1 Process Understanding

As the repository re-saturates after waste emplacement and closure, the smectite clay component in the compacted bentonite buffer material will swell and tend to fill voids in and around the deposition hole. Where the smectite clay expands into a fracture intersecting the deposition hole, the swelling pressure and density will tend to be relatively lower. When the friction force between the clay and the walls of the fracture is balanced by the force from swelling and expansion of the clay, it is assumed by SKB (SKB, 2004b) that a stable gel layer is formed. This gel layer is assumed to be incapable of being swept away by flowing water in such fractures because of the balancing forces[2].

There are two situations in which the stability of the gel and, hence, of the buffer or backfill may be overcome:

- Piping, which may occur during the initial post-closure period if there is a sufficiently high gradient in water pressure between fractures in the host rock and the partially saturated buffer or backfill.
- Chemical erosion, which may occur if the intrusion of dilute / fresh water lowers the concentration of divalent cations below the CCC and causes the gel to break down and disperse as colloidal material, either by advection (SKB, 2004b, page 133) or diffusion (SKB, 2006f).

The backfill is likely to be more susceptible to piping than the buffer because of its lower swelling pressure. However, the consequences of backfill piping are projected by SKB to be lower than piping of the buffer because: (1) the cross section of backfill is much larger, and (2) the location of such backfill piping would be far enough removed from the waste canisters and buffer to have minimal effect on buffer density and other safety functions.

For the case of chemical erosion, Arcos et al., (2006) postulates that the deep circulation of relatively dilute water during future glacial cycles will cause Ca^{2+} to diffuse out of the bentonite buffer, and, thus, destabilise the gel layer in the interface region between the buffer (or backfill) and the fracture. Flow rates could be high during such future glacial cycles, and if the duration of high flow rates with dilute water is long, the buffer (or backfill) could lose significant mass in locations with high flow rates. However, a significant amount of the buffer material (~1,200 kg) would have to be removed before water could flow advectively through the deposition hole (Neretnieks, 2006).

2.5.2 Potential Impact on Operations and EBS Emplacement

SKB notes (SKB, 2006f, pages 217-219), that piping and mechanical erosion of the buffer and backfill materials could occur during EBS emplacement and the early post-closure period (until hydrostatic pressure equilibrium is restored). SKB suggests that piping is more *likely* to occur in the backfill, except where the inflow of water is locally extremely low (SKB, 2006f, page 218). Furthermore, SKB notes that it is not known if the mixed 30 % bentonite / 70 % crushed rock backfill will be able to re-seal after the onset of piping, although SKB believes that a Friedland clay backfill would re-seal

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[2] SKB asserts that the stability condition for such a gel depends on a Critical Coagulation Concentration (CCC) for a given set of buffer properties. For groundwater concentrations higher than the CCC, a stable gel is formed, whereas for groundwater concentrations below the CCC, the gel will break up into colloidal particles that can be carried away in intersecting fractures. The concentrations of divalent cations (dominated in repository groundwater by Ca^{2+}) are of particular importance because the CCC is inversely proportional to the square of the ionic charge. SKB (2006f, page 290) notes that the CCC is assumed to be about 1 mM, and that the groundwater concentration of Ca^{2+} is expected to exceed 1 mM under ambient long-term repository conditions.

because of its relatively greater homogeneity and higher swelling pressure (SKB, 2006f, page 219).

As a countermeasure to piping, SKB asserts that emplacement of water-tight plugs in the waste deposition tunnels within an estimated 100-day period after buffer/ backfill emplacement will stop piping. SKB, thus, argues that the total amount of buffer or backfill material that would be removed by piping will be significantly constrained by the relatively short duration of conditions that enable piping to occur. However, SKB's research in this area is still under development, and significant uncertainties are acknowledged, including issues associated with process and conceptual understanding, and methods for appropriate upscaling of results from laboratory-scale tests (Börgesson and Sandén, 2006).

2.5.3 Longer-Term Safety Impacts

SKB has adopted a simplified but not necessarily conservative approach to assess the consequences that might arise from buffer removal from chemical erosion during future glacial cycles (Neretnieks, 2006). Such an approach is a sensible starting point in order to explore some parametric sensitivity, but alternative conceptualisations and parameterisations of how buffer erosion might be manifested within deposition holes will need to be evaluated in order to confirm the appropriateness of these SKB's initial analyses.

Conceptual Model

According to SKB, a loss of more that 1,200 kg of buffer clay per deposition hole (corresponding to the mass of one buffer ring, SKB, 2006f, page 280) cannot be excluded. However, SKB suggests that the fraction of deposition holes in which such a large mass loss would occur is small (see Figures 12-12 and 12-13, SKB, 2006f).

The consequences of a loss of buffer materials equivalent to one buffer ring has been conceptualised in a stylised calculation case as a complete removal of a half-doughnut shaped section of the buffer with a height of 35 cm (SKB, 2006f, based on Neretnieks, 2006). This assumed configuration exposes the copper canister to advective flow of groundwater in the open region.

The review group notes that an alternative calculation case, which could be considered, would assess the consequences for canister corrosion of a more spatially distributed loss of buffer material resulting in a diffuse lowering of buffer bulk density. This would be in some ways be similar to the simulations of the mechanical consequences arising from omitting the emplacement of one buffer ring (Figures 9-53 and 9-54, SKB, 2006f). Such an alternative calculation case for the corrosion consequences of buffer loss does not seem to have been considered in SKB (2006f) or in the most obvious supporting technical reports (e.g. Neretnieks, 2006; Liu and Neretnieks, 2006).

It may be that the assumed removal of a half-doughnut region of buffer with attendant advective flow is judged by SKB to present a conservative bounding case that can be used to assess the maximum likely impacts of buffer mass loss on the long-term containment and release performance of the EBS. It would be useful, however, for SKB to describe and present a modelling analysis of the consequences of what they believe is the reasonably expected evolution for buffer removal.

Effect of Redox Conditions on Containment

SKB has made an analysis of the effect on *general* corrosion of the copper canister of the penetration of oxygenated glacial melt waters to repository depth and indicates that this would have no adverse impacts on performance (SKB, 2006f, page 363). However, the possibility of *localised* stress corrosion cracking under oxidising conditions is not examined in SKB (2006f), and the rates of such localised attack and canister failures would possibly far exceed those attributable to general corrosion. Because localised modes of corrosion potentially have an impact on early canister failure (see Section 2.4.1 of this report), it will be important to re-assess and review SKB's analyses of the potential for deep circulation and persistence of oxygenated glacial melt waters.

Effects on Radionuclide Release

The impact of an eroded buffer on the release rate of radionuclides once the canister fails needs to be considered (SKB, 2006f, Section 10.6). Furthermore, the uncertainties associated with the assumptions, processes and data for radionuclide release and transport calculations must also be considered (SKB, 2006f, pages 496-499).

Even though there may be a hole in the copper canister the characteristics of the hole may still provide some resistance to mass-transfer that could limit the rate of radionuclide release (Neretnieks, 2006). Any initial pinhole through the canister may be expected to grow over time and this is treated explicitly in Section 10.5 of SKB (2006f). SKB accepts that the production of iron corrosion products from general corrosion of the cast iron insert is likely to cause rather rapid expansion of any initial penetration through the mechanically weak copper canister.

Significant mass loss would compromise the ability of the buffer to filter colloids. The removal of colloidal clay particles from the buffer into fractures could also cause the transport of radionuclides as colloids. The formation and migration of buffer colloids with sorbed radionuclides was not modelled in SR-Can, although SKB has suggested that the inclusion of radionuclide sorption on buffer colloids would affect the results only marginally. The review group considers that SKB has not provided a sufficient demonstration that colloidal transport of radionuclides is unimportant for all relevant conditions and alternative scenarios.

2.6 Radionuclide Behaviour and Release

Section 10.4.1 of SKB (2006f) presents SKB's approach to near-field release and transport modelling, and considers the illustrative calculation case of an assumed 'growing pinhole failure' in the canister (SKB, 2006f, Section 10.5). This latter case is presented because it is, "*...suitable for addressing important aspects of the internal evolution of the canister... ... and for exploring uncertainties*" (SKB, 2006f, page 383).

For the ‘growing pinhole failure’ case, SKB (2006f) states that “*… as a continuous pathway has formed [assuming a penetrated canister], the instant release fraction of the inventory dissolves in the water in the canister… … the release of nuclides embedded in the fuel is determined by the fuel dissolution rate. Also in this case, the solubilities of the nuclides limit the concentrations that can occur in the water*” (SKB, 2006f, page 408). Therefore, the instant release fraction, radioelement solubilities, and the spent fuel dissolution rate are all key inputs to models of radionuclide release and transport through the EBS. The following subsections briefly discuss each of these data and identify issues for continuing discussion between SKB and the Authorities.

2.6.1 Instant Release Fraction

The instant release fraction (IRF) is the inventory of radionuclides generated by fission processes in nuclear fuel that migrate to the relatively cooler fuel-cladding gap because of their relative volatility under reactor conditions. Upon failure of the canister, nuclides in the IRF are assumed to dissolve immediately into intruding water (SKB, 2006f, page 408).

Table 10-3 of SKB (2006f) summarises a triangular distribution of assumed IRF for various radionuclides. The source for this distribution and ranges of values are contained in the Data Report (SKB, 2006b). The EBS review group has not conducted a formal, detailed review of SKB’s work underlying these data, but the relatively high dose-importance of I-129, a fraction of which inventory resides in the IRF, would indicate that the data and modelling of the IRF should be a topic for further discussion with SKB.

2.6.2 Radionuclide Solubility Limits

SKB briefly summarises uncertainties associated with the radionuclide solubility limits used in SR-Can (SKB, 2006f, page 407; SKB, 2006b). SKB asserts that uncertainties in the future composition of groundwater, rather than uncertainties in thermodynamic databases or conceptual understanding, have the dominant impact on solubility values used in SR-Can (Duro et al., 2006).

For extreme changes in redox conditions (e.g. changing from ambient reducing conditions to conditions with oxygenated glacial melt waters at repository depths), this assertion might be credible. For the more likely case of a restricted range of reducing redox conditions with variations in salinity, however, it is not clear that uncertainties in groundwater composition will be the dominant overall uncertainty factor. Uncertainties with respect to the type of radionuclide-bearing solubility-limiting phases, and/or the degree of crystallinity of these solids could also be significant. Non-equilibrium, metastability is typical of geochemical systems below 100 ˚C, and the standard equilibrium geochemical codes such as PHREEQC are unable to identify a unique and demonstrably correct set of metastable solubility-limiting phases. As acknowledged in SKB (2006f, page 407), expert judgement must be used to remove unrealistic phases from the modelling simulations. This judgement can only be defended on the basis of laboratory tests or natural analogue studies, which means that the uncertainty in such tests and studies should also be explicitly recognised and considered by SKB.

2.6.3 Co-Precipitation of Radionuclides

A further issue relevant to the uncertainties associated with radioelement concentration limits is the potential importance of radionuclide co-precipitation (see SKB 2006f, pages 422 and 441). SKB explicitly identifies the possibility of co-precipitation of Ra-226, one of the two nuclides that dominate calculated doses in SR-Can safety assessment calculations (SKB, 2006f, Figures 10-19 and 10-31), and this suggests that SKB may include such concentration-limiting phenomena in future safety assessments. Co-precipitation is a well-recognised process in natural systems and, hence, is likely to occur within the EBS of a deep geological repository. The review group suggests that SKB should explain its rationale for including or excluding co-precipitation processes in safety assessment more comprehensively. For example, why was co-precipitation only considered for radium?

One implication of including co-precipitation in future safety assessment calculations is that results from future calculations of the EBS source-term and peak repository doses could depend very largely on:

- Uncertainties in which phases will form co-precipitates with which radionuclides.
- Uncertainties in the relative fractionation of dissolved radionuclides into co-precipitates.

A review of the treatment of radionuclide co-precipitation in SKB's (and possibly in other disposal organisation's) safety assessments and supporting research should, therefore, be maintained.

2.6.4 Spent Fuel Dissolution Rate

Tests on spent fuel dissolution by SKB (King et al., 1999; Spahiu et al., 2000; Rollin et al., 2000) and independent researchers (Sunder et al., 1990; Broczkowski et al., 2007) demonstrate the suppression of spent fuel dissolution under reducing conditions (moderate partial pressure of H_2) similar to those expected in a repository. Possible explanations for this behaviour include scavenging of radiolytic oxidants by H_2 or a reductive influence of hydrogen radicals produced by a catalytic effect of the fuel surface. Whatever the mechanism, the measured dissolution rates for spent fuel under such conditions are on the order of 10^{-8}/year, or lower.

For the case of an intact buffer and a 'growing pinhole failure', the two key dose-contributing nuclides, Ra-226 and I-129, are assumed to have extremely high solubility limits (exclusive of co-precipitation considerations) that are never obtained within the EBS. The release of such non-solubility limited radionuclides would, therefore, be limited by the dissolution rate of the UO_2 matrix of spent fuel (plus any instant fraction release, such as for I-129).

Apparently, SKB did evaluate the effect of different spent fuel dissolution rates in the range from 10^{-6} to 10^{-8}/year on the 'growing pinhole failure' calculation case (SKB, 2006f, Table 10-3), but no results of such sensitivity calculations are reported in the SR-Can documentation. However, the sensitivity of calculated near-field EBS and repository dose rates to spent fuel dissolution rate are reported for the case of buffer loss and the 'advection/corrosion failure mode' (SKB, 2006f, Figure 10-44)[3]. The review group notes that, over the range of dissolution rates adopted for the "advection/ corrosion failure" case (Table 10-10, log-triangular distribution of 10^{-6}, 10^{-7} and 10^{-8}/year), the dose rate curves for both the near-field EBS and overall repository are directly proportional to the spent fuel dissolution rate. Indeed, it is stated in SKB (2006f, page 496) that for the case of an eroded buffer, "*the fuel dissolution rate is the most important controlling factor of the releases from the near field*", and based on Figure 10-44 in SKB (2006f), the spent fuel dissolution rate would also be the factor controlling release from the overall repository.

Furthermore, for extremely low spent fuel dissolution rates (e.g. of ~10^{-6}/year or maybe much lower), it might be that the release of radionuclides other than just Ra-226 and Th-230 would be limited by the extremely low dissolution rate. The effect may depend on whether the buffer is intact ('growing pinhole failure') or not ('advection/ canister failure'), as well as the actual low long-term dissolution rate itself.

This dissolution rate effect has the potential to be extremely important because the concentrations of all radionuclides (other than those in the IRF) within a failed canister would be controlled by:

- The (extremely low) solubility of the UO2 spent fuel matrix (which can be assessed with relatively high certainty).

- The time-dependent mass-fraction of each nuclide present in the UO2 matrix (which can also be assessed with extremely high certainty).

The review group suggests, therefore, that the effects of spent fuel matrix dissolution should be considered further in future safety assessments.

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[3] SKB provided results from additional sensitivity analyses of the pinhole case in response to a written question from the Site Investigation review group during their review of SR-Can. SKB's response confirms that the fuel dissolution rate is an influential parameter.

3 Conclusions and Recommendations

In general, the explanatory text of the SR-Can safety report is clear, and the cited references provide adequate technical justifications for the assumptions, models, and data that are abstracted into the SR-Can safety report. The review group considers, therefore, that SKB's development of SR-Can has been a very valuable exercise, and that SKB should be congratulated on the breadth, depth and general clarity of its research and development and safety assessment programmes.

Notwithstanding these successes, the EBS review group has identified a range of uncertainties in SKB's programme and safety reports, some of which relate to issues that appear to be of sufficient significance that they will need to be thoroughly addressed in the SR-Site safety report in time for the repository licence application. Other less urgent issues might be identified in SR-Can as uncertainties to be addressed through research and development in an appropriate performance confirmation programme.

The review group's view of the relative importance to the Swedish radioactive waste disposal programme of the more significant of these is indicated in Table 1. For the assessment presented in Table 1, importance has been gauged by expert judgement, taking into account several broad factors, including (in no particular order) assessed post-closure dose and risk and identified uncertainties, demonstration of understanding of the disposal system, engineering design and feasibility, and programmatic risk and credibility.

The most significant of the issues identified by the EBS review group include:

- **Demonstration of the feasibility of EBS emplacement**. SKB will need to present more details on the reference EBS design, on its reference repository construction method, and on the specifications for the EBS materials. In particular, SKB still needs to demonstrate satisfactorily that the EBS can be successfully fabricated and emplaced in the appropriate configuration under repository conditions and at the rates that are projected to be required during waste disposal. SKB needs to develop and test quality assurance and quality control procedures for repository construction and operation, including EBS emplacement. SKB also needs to conduct further tests of EBS emplacement, and to characterise the as-emplaced EBS components. More generally, SKB should describe and explain in more detail how its schedule for developing plans and procedures and for conducting laboratory experiments and underground tests relates to the schedules for safety assessment and licensing.
- **Canister manufacture and integrity.** The view of the review group is that SKB should consider a number of issues in greater detail to build further confidence in the proposed approach for canister manufacture and in the assessments of canister integrity and performance. For example, SKB could improve its canister stress analysis and should conduct further investigations on re-welding of the canister lids.
- **Stress corrosion cracking of copper.** In the opinion of the review group SKB has not completely eliminated the possibility of stress corrosion cracking (SCC)

of the copper canister and, that because further experimentation may be required (e.g. to investigate SCC under anoxic conditions), SKB is unlikely to be able to do so in time for the SR-Site safety report.

- **Piping and colloid generation in the buffer and backfill.** SKB has identified piping and colloid generation in the buffer and backfill as processes that could have significant effects on the practicality of EBS emplacement and on the long-term performance of the disposal system. SKB has suggested that the uncertainties associated with piping are limited, but that the uncertainties associated with colloid generation are large. The review group considers that significant uncertainties remain in the understanding of both of these processes and that SKB needs to conduct further work to improve assessments of their effects and plans for their mitigation.
- **Geochemical Modelling and Radionuclide Release.** The review group considers that SKB could do more to improve the consistency and transparency of its modelling of the evolving geochemical environment within the EBS. SKB might also seek to refine its models of radionuclide release by furthering its consideration of processes affecting the rate of spent fuel dissolution and radionuclide co-precipitation.

Finally, it should be noted that there are many relationships and some overlaps amongst the issues considered by the three review groups (e.g. rock spalling may influence processes in both the geosphere and the EBS) and the reader is, therefore, encouraged to consider the other review reports in this series in order to gain a full perspective of the review team's views.

Table 1: Assessment of the relative importance to the Swedish spent fuel disposal programme of selected key topics. Importance is shown on a scale of 1 to 5, with 5 being the most important. The notation that an issue is "Essential to be thoroughly addressed in SR-Site" does not imply that the issue necessarily needs to be completely resolved by the time of the SR-Site safety report - the SR-Site safety report should resolve the issue if this is possible but if this is not the case, then the report should present clear and detailed information on SKB's approaches and plans to resolve the issue.

Topic	**Report Section**	**Importance**	**Essential to be thoroughly addressed in SR-Site?**	**Comment**
Clear description of the reference repository construction method, EBS design and materials specifications	2.1.1, 2.1.5	5	Yes	-
Progress of EBS design optimisation with respect to: fabrication; operations; emplacement; and long-term safety	2.1.2	5	Yes	SR-Site should summarise the design optimisation studies conducted to date. Further optimisation studies could continue until the times of fabrication, handling and emplacement, and repository closure, as appropriate
Identification of how BAT might be considered and applied	2.1.2	5	Yes	-
Demonstration of EBS emplacement at realistic rates	2.1.3	5	Yes	Further demonstrations would be needed if significant design changes were made
Development of procedures and QA/QC plans for repository construction, operation, and EBS emplacement	2.1.3, 2.2.1	5	Yes	These procedures and plans will need revision to reflect any design changes
Assessment of the chemical effects of cements and additives	2.2.2	2	No	Possible topics for performance confirmation programme
Further assessment of heterogeneous swelling of the buffer	2.2.4	4	No	
Assessment of THMC effects during early post-closure phase	2.2.6	2	No	
Demonstration of consistency among geochemical models	2.3.1	3	No	
Further analysis of pH and redox controls in the near field	2.3.2	4	No	
Stress corrosion cracking	2.4.1	5	Yes	-
Ductility of copper	2.4.2	4	Yes	-
Constitutive model for copper	2.4.3	3	Yes	-
Canister stress analysis	2.4.4	4	Yes	-
Canister manufacture	2.4.5	5	Yes	Acceptance criteria for the re-welding of canister lids need to be reviewed
Canister damage tolerance	2.4.6	4	Yes	-
Further development of measures to reduce the likelihood and/or assessed consequences of earthquake shear failure	2.4.7	5	Yes	-
Canister design basis	2.4.8	4	Yes	-
Piping and colloid generation in buffer and backfill	2.5.2	4	Yes	Should be investigated as part of the demonstration of EBS emplacement
Assessment of alternative conceptual models for buffer erosion	2.5.3	4	Yes	A less conservative approach might lead to lower calculates doses and risks
Re-assessment of penetration of oxidising water to repository depth and effects on localised corrosion	2.5.3	4	Yes	-
Assessment of formation and transport of buffer-based radionuclide-bearing colloids for conditions of buffer loss.	2.5.3	3	No	Possible topic for performance confirmation programme
Reassessment of spent fuel dissolution rates (IRF and matrix)	2.5.3, 2.6.1, 2.6.4	4	No	If it were possible to take more account of recent experiments indicating slow dissolution of the spent fuel matrix this could lower assessed doses and risks
Solubility limits and co-precipitation	2.6.2 & 2.6.3	3	No	If it were possible to account for co-precipitation effects this could lower assessed doses and risks

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Appendix 1: Terms of Reference

SKI's and SSI's guidelines for this review were as follows:

- Is the available information on manufacturing, testing and demonstration of EBS components accurately represented and fully utilised in SR-Can?
- Is there a good scientific understanding of key processes related to the degradation of the engineered barriers?
- If the answer to any of the former two questions is no what improvements will be needed?
- Are there any critical issues related to EBS performance that need to be resolved before SR-Site, which have not been identified by SKB in SR-Can?

The following areas are of particular interest:

- Justification of assumed properties of engineered barriers in relation to:
  - Methods for non-destructive testing and quality assurance
  - Procedures for manufacturing, handling and deposition of EBS components including the backfill
  - Selection of acceptance criteria for EBS components
  - Consideration of manufacturing imperfections and mishaps
- Sufficiency of the understanding and modelling of FEPs related to long-term barrier degradation
- Account of SKB's scientific basis for EBS performance:
  - Use the performance confirmation programme at e.g. the Äspö HRL in SR- Can?
  - Sufficiency of the planned performance confirmation programme to resolve critical uncertainties as identified in SR-Can for future stages in the SKB programme?
  - Use of data from laboratory experiments in SR-Can?
- Abstraction of data and simplified PA models in the evaluation of barrier degradation (simplification of results from detailed process models). Examples are
  - Corrosion model for the copper shell
  - Long-term stability of buffer and performance, e.g. swelling, erosion, chemical transformation
  - Evolution of a defect canister and the relation to eventual radionuclide releases
- The handling of the early evolution of EBS components in SR-Can (i.e. less than a few thousand years), e.g.
  - Thermal development and its influence on the chemical and physical properties of the bentonite buffer
  - Resaturation of buffer and backfill, e.g. influence of very long resaturation times
  - Consumption of oxidants and its performance implications
- Is there a reason to reconsider some aspect of the KBS-3 EBS design considering SR-Can results?

Appendix 2: Review Group Members

The EBS review team consisted of the following members:

- David Savage, Chairman (davidsavage@quintessa.org) Quintessa Limited, UK.
- David Bennett, Secretary (davidbennett@TerraSalus.co.uk) TerraSalus Limited, UK.
- Mick Apted (mapted@monitorsci.com) Monitor Scientific LLC, USA.
- Göran Sällfors (sallfors@chalmers.se) Chalmers University of Technology, Sweden.
- Timo Saario (timo.saario@vtt.fi) VTT Materials and Building, Finland.
- Peter Segle (peter.segle@inspecta.com) Inspecta, Sweden.

Appendix 3: EBS Review Group Initial Questions on SR-Can January 2007

Answers added by SKB February 2007

Introduction

The Swedish Nuclear Power Inspectorate (SKI) has commissioned an independent expert review of SKB's SR-Can Safety Report. The review is being conducted principally by three review groups. This document presents a series of initial questions on the SR-Can Safety Report that have been identified by the EBS (Engineered Barrier System) Review Group[4].

The EBS Review Group is at an early stage in its review of the SR-Can Safety Report, and will continue to identify and document questions and comments on the Safety Report over the coming months. However, the Group's initial reaction is that it is impressed at the breadth and complexity of SKB's work.

The EBS Review Group's initial questions are presented under the following headings:

1) Insert and Canister Types and Manufacture.
2) Ductility of Copper.
3) Stress Corrosion Cracking of Copper.
4) Backfill Concept and Materials Selection, Emplacement, Testing and Performance Criteria.
5) Buffer Concept, Materials Selection, Emplacement, Testing and Performance Criteria.
6) pH and Redox Conditions in Buffer and Backfill.
7) Piping and Erosion Processes in Buffer and Backfill.
8) Cement Grouts – Selection and Modelling.
9) Thermo-Hydro-Mechanical Modelling.
10) Geochemical Modelling.
11) Spent Fuel.
12) Assessment of the EBS in the Advection-Corrosion Failure Scenario.
13) Assessment of the EBS in the Pinhole Scenario.
14) Assessment of the EBS in the Earthquake Scenario.
15) Influence of Safety Assessment on Repository Implementation.
16) Influence of Safety Assessment on the RD&D Programme and EBS Design.
17) Others.

The questions themselves are presented in the following.

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[4] The EBS Review Group comprises Dr Dave Savage (Chairman), Dr David Bennett (Secretary), Dr Mick Apted, Prof. Göran Sällfors, Dr Timo Saario, and Dr Peter Segle.

1 Insert and Canister Types and Manufacture

Insert Manufacture

In order to maintain the correct distance between the steel tubes when manufacturing the cast iron insert, the tubes are attached to each other.

a) **How are the attachments designed?**

There are 7 sets of attachments along the full length of the cassette. Their design and positions are shown in the design drawing attached at the end of this document.

b) **Where are the attachments located?**

See above.

c) **Could the presence of the tube attachments introduce defects in the cast iron insert?**

It is possible that the attachments can interfere with the flow of the cast iron and give rise to defects. Ongoing work, however, has shown that the insert has a high damage tolerance and will be able to withstand the design loads even with relatively large defects in this part of the structure.

d) **How will SKB inspect and certify such attachments?**

The attachments themselves serve no purpose once the insert has been cast. Their function is to maintain the dimensions of the tube cassette during the casting process. The volumes between the tubes can be inspected ultrasonically in transmission (see R-06-05). There are, however, limited regions that will be obscured by the attachments. As mentioned above, with the high damage tolerance it will be able to withstand the design loads even with relatively large defects in this part of the structure. We are also currently investigating the possibilities of using radiographic methods for the inspection of these volumes.

Waste Packages for BWR and PWR Spent Fuels

Although SKB plans to use the same design of copper canister for Boiling Water Reactor (BWR) and Pressurised Water Reactor (PWR) spent fuels, the fuel, fuel cladding, cast iron insert and steel lids within the BWR and PWR waste packages will differ. SKB's assessments of waste package integrity have focused on the package for BWR spent fuel because the cast iron insert for BWR spent fuel is more complicated to manufacture (R-06-03, page 27). Given that SKB has less experience with, and understanding of, the waste package for PWR spent fuel:

e) **Is there a risk that the PWR insert will not meet the ductility requirements? (SKB indicates that the PWR insert has lower ductility than the BWR insert).**

The relatively few PWR inserts that we have manufactured to date (4 inserts) have all met the required ductility (7 %) although the ductility was in general lower than for the "state of the art" BWR inserts. We do not believe that is an inherent property of the PWR insert, but rather a result of less experience with casting PWR inserts. During the next two years, we will concentrate on casting PWR inserts. For 2007, 3 inserts are planned and for 2008 5 inserts.

f) Are there other characteristics of the waste package for PWR spent fuel that might lead it to perform more poorly than the package for BWR spent fuel?

We have not identified any such characteristics. In general, the PWR insert is stronger than the BWR insert.

g) What investigations of the PWR spent fuel waste package are planned?

See above. The inserts will be characterized in the same way as the previously manufactured BWR inserts.

Canister Manufacture

SKB indicates that different companies may be employed to manufacture different parts of the canister, and that these companies may use different methodologies (TR-06-09, page 84).

h) How will SKB manage the risks to the disposal programme from interactions and possible inconsistencies between the organizations?

Not all of the four tested manufacturing methods will be used in the final production. We foresee that SKB will interact directly with the companies and manage the manufacturing programme (i.e. no, there will be no direct interaction between the companies involved except through SKB), An appropriate quality assurance/quality control programme will of course be implemented.

SKB states (TR-06-09, page 85):

- ***'Defects under normal operation have been observed in a test series of 20 canister lids. Maximum defect sizes are of the order of a few millimetres with the largest being 4.5 mm…'***

- ***'Based on results of statistical analyses of the test series, it is cautiously assumed that all canisters sealed under normal operation will have a minimum copper coverage of 40 mm'***

- ***'A first evaluation of the reliability of the sealing process itself, of its surveillance functions and of the NDT*** **[Non-Destructive Testing]** ***suggests that the likelihood of disturbed operations leading to copper thicknesses below 40 mm is very low. A first crude estimate is that at most one percent of the canisters leaving the encapsulation plant would have such defects.***

> ***These events will lead to a distribution of copper thicknesses that is difficult to determine. A first, pessimistic assumption is that all such canisters have a minimum copper coverage of 35 mm…'***

i) What is the evidence (e.g., laboratory and industrial studies) supporting SKB's claim of zero pinholes in copper canisters welded with the proposed friction stirred welding technique?

This is discussed in R-06-26 (Chapters 8 and 9, in particular).

2 Ductility of Copper

According to SKB, the influence of radiation on the material properties can be neglected (TR-06-22, page 23, Table 1-8, also TR-01-32).

a) **Does this hold for plastic deformation ductility and creep ductility of copper?**

We believe this to be the case based on the results given in TR-01-32.

In early tests with oxygen free copper (with no added phosphorus) creep fracture strains well below 10% were measured. Creep tests with the current oxygen-free phosphorus micro-alloyed copper (OFP Cu) have shown adequate creep fracture strain above 10%. All the experimental tests inevitably have a timescale much shorter than the one spent by the canisters in the real repository.

b) **Is it reasonable to extrapolate results from short-term tests of the creep ductility of copper to the long time scales of interest in the repository?**

Recent modelling show that when the assumed rupture time is increased from 10000 h (1.1 years) to 1000000 h (114 years) the magnitude of the creep ductility minimum is much reduced and vanishes for still longer rupture times for Cu-OFP. The temperature position of the minimum is only marginally affected by the rupture time. Thus, the model predicts that low creep ductility in the temperature range 0 to 100 ºC of technical interest for the canisters can be ruled out even for very long rupture times for Cu-OFP (IM 2007-101, in preparation).

c) **What is the mechanism through which adding 40 to 60 ppm phosphorous to the copper affects the creep process? Does this amount of phosphorous merely slow down the creep process (in which case 'brittle creep fracture' phenomena may appear over the relevant time scale)? It is also not clear whether, especially due to welding procedures, there may be areas where the phosphorus concentration is locally different from the nominal concentration, again resulting in an increased risk of brittle creep fracture. How is this uncertainty taken into account in the safety assessment? What steps are being taken or are planned to reduce this uncertainty?**

Our current understanding is that the phosphorus agglomerates at the grain boundaries (see also SKI Report 2003:6), lock their sliding and thereby reducing the formation and growth of cavities. This is the main reason why extra low creep ductility does not occur in phosphorus alloyed copper. Recent modelling predicts that low creep ductility in the temperature range 0 to 100 ºC of technical interest for the canisters can be ruled out even for very long rupture times for Cu-OFP (IM 2007-101, in preparation). The friction stir welding is not expected to result in a re-dissolution of the phosphorous in the copper and increase the risk for brittle failure. Furthermore, the ductility minimum has been observed and predicted by the model at 250 °C and not at the temperatures relevant for the repository, nor does the model predict low ductility at these temperatures.

d) **Is there a possibility for the bentonite buffer, as a result of swelling, to transfer axial loads to the copper canister resulting in axial tensile stresses in the copper? If so, for how long could such loads last and what stress levels might be reached? Could the copper canister fail by creep rupture?**

Possible bending loads are expected to be too low to cause a deformation of the cast iron insert and, therefore, give rise to axial tensile stresses in the copper. A higher bentonite density at bottom of the canister than at the top (including the tunnel backfill) can lead to a “push” upwards of the canister and a remaining tensile stresses in the copper. A conservative estimate of 20 % difference in swelling pressure between top and bottom of the canister will give rise to tensile stresses of less than 10 MPa in the copper. We do not expect this to lead to creep failure.

e) **In SKB’s assessment of copper canister integrity, plastic deformation ductility and creep ductility were treated separately as if there was no interaction between them. What are the potential effects on the canister of plastic deformation ductility and creep ductility acting together?**

There are no indications that previous cold work (10 %) has had a major influence on the creep ductility.

3 Stress Corrosion Cracking of Copper

SKB's approach to assessing Stress Corrosion Cracking (SCC) of the copper canister is based on a decision tree analysis (TR-01-23) and appears both transparent and, generally, convincing. There are, however, at least three issues regarding SCC of copper under repository conditions on which further clarification may be required.

First, SKB states that tensile stresses are not present throughout the whole thickness of the copper canister (TR-06-22, page 106). However, if there is uneven swelling of the bentonite buffer, the whole canister could be subjected to bending forces. This bending may, in turn, lead to tensile stresses through the whole copper canister thickness.

a) How long can bending stresses due to uneven swelling of the bentonite buffer be present in the canister?

Stresses in the canister caused by uneven wetting will to a large extent cease when the buffer is completely water saturated and homogenised. However, small remaining stress differences may occur due to the inner friction angle of the bentonite that prevents complete homogenisation. Similar stresses may occur from the possible upwards swelling of the buffer on the backfill. These stresses (which are small) will remain during the life time of the repository although they will decrease slowly due to creep in the clay.

b) Assuming sufficient tensile stress for SCC to occur, can the risk of SCC be ruled out on other grounds?

Sufficient tensile stress is only one of the factors required for SCC to occur. There must also be sufficient amounts of species that promote SCC at the Cu surface and a potential high enough to stabilize Cu^{2+} (and the absence of species that impede SCC as well as a temperature at which SCC can occur). If not all of these requirements are fulfilled, SCC will not occur.

Second, the canister is expected to experience a long period of reducing chemical conditions with low groundwater sulphide concentrations. Although cases of SCC in copper under such conditions have not been identified, this does not necessarily mean that, in the long-term, SCC of copper will not occur by mechanisms such as those described by the Surface Enhanced Mobility Model or the Film-induced Cleavage Model.

c) How does SKB justify its position that SCC of copper in reducing sulphide-bearing groundwaters is not a threat to canister integrity?

Regarding SMM, the criterion based on Cu/Cu2+ equilibrium potential threshold potential has been shown not to be met for the container

Regarding FICM:

- Nano-porous surface layer necessary to initiate brittle crack by film-induced cleavage mechanism could only be produced at extremely high dissolution rates (equivalent to corrosion rates >350 mm/yr)
- No cracking observed at lower dissolution rates, regardless of strain rate
- Such high rates of dissolution are not possible for a canister

Third, pure copper has been found to be susceptible to SCC in presence of gaseous CuCl (Bianchi, G. and Galvele, J., 1993. ***Stress Corrosion, Cracking of Pure Copper and Pure Silver in Gaseous Environments*****, Corrosion Science, vol. 34, pp. 1411-1422). It is conceivable that before and/or during the repository re-saturation period, the gap between the copper canister and the bentonite could contain gas that includes CuCl.**

d) Has SKB considered or assessed the possible effects of gaseous CuCl on the possibility of SCC of copper?

No. We shall look into this, but we suspect that the vapour pressure of CuCl will be too low at 373 K for sufficient amounts of CuCl vapour to be present in the gas phase. An extrapolation from literature data indicates that we can expect a vapour pressure of about 10^{-7} torr. (Possibly, however, such an extrapolation is not justified.)

4 Backfill Concept and Materials Selection, Emplacement, Testing and Performance Criteria

Backfill Concept

SKB's new backfilling concept for the deposition tunnels involves the emplacement of pre-formed rectangular blocks (TR-06-09, page 88).

a) How compatible is this concept with the circular cross-section tunnels that would be produced using a tunnel boring machine (TBM)? At what point in the programme will a decision on the tunnel excavation method (drill and blast or TBM) be made?

The development of this backfilling concept has had drilled and blast tunnels as described in R-02-18 as design base. If the backfilling concept would be used for TBM tunnels, a redesign of block geometry, stacking pattern and installation equipment would have to be made. This has not been investigated in detail.

b) How suitable is the backfilling concept for filling other repository cavities such as shafts (see TR-06-09, page 93)?

The concept is suitable but design of block geometry, stacking pattern, installation method and installation equipment will have to be made. The concept will have to be developed and tested for the specific application. The requirements on the backfilling of shafts will have to be defined in more detail. This may be dependent on the hydrogeology of the site.

Backfill Material Selection

The SR-Can Report suggests that SKB will select Friedland Clay for the backfill material in preference to the 30/70 bentonite - crushed rock mix (TR-06-09, page 381).

c) What characterization data is available for the Friedland Clay? Are these data considered sufficient or will further investigations be undertaken?

Characterisation data are best presented in TR-06-30. It should however be stressed that Friedland is an example of a suitable clay that meets the requirements. More investigations on candidate backfill materials will be made.

d) What steps are taken in preparing the backfill blocks – is the Friedland Clay processed?

The clay is excavated, dried and ground in a few steps. Before the blocks are compacted the water ratio may be adjusted to get the desired block properties.

e) How much spatial variability could be present in the emplaced backfill?

Approximately 80% of the cross section will be backfilled with pre-compacted blocks and the remaining volume with pellets. The geometry of the cross-section varies along the length of the tunnel and this will mean that the width of the pellet filled slot will vary. This will give a variation in average density over the cross-section.

f) In detail, what plans are there for a demonstration of backfill emplacement?

Tests with simulated backfilling above ground in full scale (concrete blocks and bentonite pellets) will be made during 2007. Backfilling tests in small scale with Friedland blocks and bentonite pellets to understand the role of water inflow is ongoing. The further plans to test and demonstrate the entire backfilling system will be described in RD&D-programme 2007.

g) Will a demonstration be made of emplacing the backfill at the rates needed in the repository?

This will be made. The development of the method and equipment will be made in a stepwise manner. This will be described in RD&D-programme 2007

h) How do expected rates of backfill re-saturation relate to fractures in the host rock, how variable might backfill re-saturation be? What factors, including potentially adverse impacts, determine the amount of variation in re-saturation that can be accommodated and how much variation can be accommodated?

This is presented in SR-Can and in more detail in /Börgesson et al SKB TR-06-14/. Figure **1** shows the saturation time for the Friedland backfill as a function of fracture spacing and transmissivity. The saturation time will most likely vary from a few years to a few hundred years in different parts of the repository. Backfill saturation time is not seen as a critical issue for repository performance.

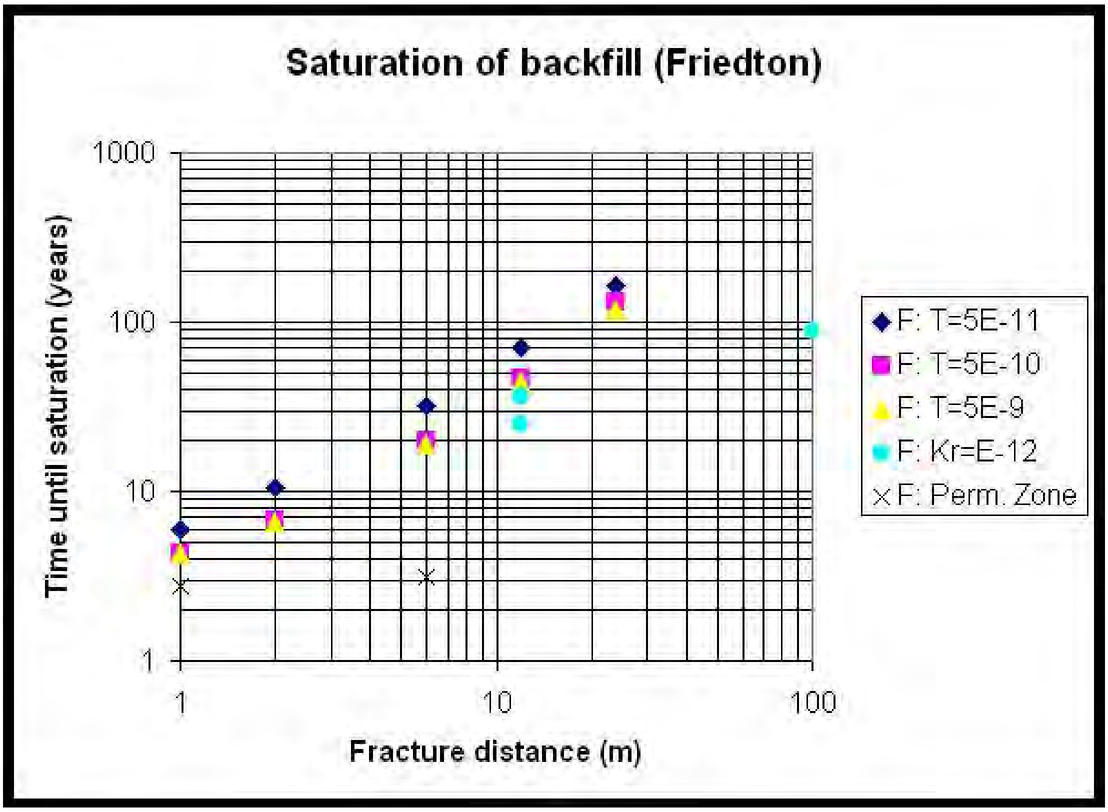


Figure 1 Saturation time of Friedland backfill as a function of fracture spacing and transmissivity

Backfill Emplacement

SKB's description of the initial state of the repository provides a description of the EBS installation process (TR-06-09, page 77).

i) **Does SKB have a time schedule for EBS emplacement that specifies acceptable times between different events?**

Work that will give the bases for describing the installation sequence in more detail and thereby also addressing acceptable times for different operations is ongoing. This will be presented in the bases for the application for the final repository. A brief description of how this will be presented in the application is shown in the recently issued System's analysis report (SKB R-06-117, in Swedish).

j) **Have assessments been made of cases where the planned schedule for engineered barrier system (EBS) emplacement is delayed (see TR-06-09, page 77)? For example, what would happen if the buffer is installed but then canister emplacement is delayed? What would be the effect if the buffer and canister were emplaced but backfill emplacement was delayed?**

For the buffer and canister deposition sequence used in the prototype repository the buffer was protected from water and changes in air humidity awaiting the emplacement of the canister. This method will probably also be used in the operation of the repository. When this type of method is used the buffer is not sensitive to delay. The whole sequence of installing the engineered barriers will be designed to ensure that the initial state used in the safety assessments is fulfilled.

SKB suggests that samples of the backfill will be taken after its emplacement in the tunnels to ensure homogeneity (TR-06-09, page 88).

k) What size would the samples be and what would be the frequency of sampling?

The sampling in the deposition tunnels are mainly needed for the concept where mixtures are compacted in the tunnel and this is no longer considered as an actual alternative. For the block emplacement alternative the quality control in the tunnel will rely on the weight of the installed backfill and the filled volume. This will give the average density in the backfilled tunnel section. After water saturation the backfill material swells and homogenises.

l) How will SKB ensure that this sampling does not have any detrimental effect on long-term performance?

See answer to question 4k)

SKB quotes an average density for the backfill (TR-06-09, page 273) but this average incorporates both the regions filled using pellets and blocks.

m) Does the area filled with pellets have a lower density and what is the minimum density of the backfill in each of the two regions formed using pellets and blocks?

The pellet filling will have a lower density than the blocks. The important factor is that the average density is high enough to ensure that the backfill homogenises after water saturation so that the requirement set on hydraulic conductivity is fulfilled.

Backfill Performance Criteria

SKB states that the amount of canister-corroding agents in the backfill should be low (TR-06-09, page 187).

n) Is there a need to establish a Safety Function Indicator Criterion for the amount of pyrite (or other potentially corrosive substances) in the backfill, and if not, why not?

The amount of pyrite in buffer/backfill that is needed to corrode through the canister can easily be estimated with a mass balance. This would give an upper limit on what is acceptable as an impurity. However, an acceptance criterion would require some approach to safety margin. A low pyrite content in the material is an advantage, but it is not the only factor in the selection of materials.

SKB indicates that the backfill should provide for slow radionuclide transport by limiting advection and providing sorption (TR-06-09, page 189). SKB has

established a Safety Function Indicator Criterion related to advection ($K_{Backfill}$ < 10^{-18} m/s) but not for sorption.

o) Is there a need to establish Safety Function Indicator Criteria related to the sorption properties of the backfill material, and if not, why not?

No, definitely not. Sorption in the backfill is not a barrier function in the KBS-3 concept. In order to make this effective it must be ensured that the backfill is the main path for the radionuclide transport, which will be more or less impossible to claim.

5 Buffer Concept, Materials Selection, Emplacement, Testing and Performance Criteria

Buffer Material Selection

SKB has not yet made a choice between MX-80 and Deponit-CaN bentonites for use as buffer material (TR-06-09, page 86). The choice of clay will affect many properties of the buffer, such as swelling ability, permeability etc., as well as having a fundamental influence upon processes such as redox buffering (e.g., through the presence of pyrite or organics) and ion exchange/pH buffering.

a) When does SKB envisage making the final selection of clay material for the buffer?

Most likely never, the selection will be on the properties on the clay and not the clay itself. The repository will be operated for a period of ~50 years. It is unlikely that the same material will be used during the entire operation.

b) Does SKB consider that enough long-term and *in situ* tests have been performed with Deponit-CaN to justify its potential choice as the reference buffer material?

Deponit CA-N was one reference material for the SR-Can assessment. If SKB did not believe that there was sufficient data to use the material for that purpose, it would not have been selected. This does not necessarily mean that enough data is available to justify Deponit CA-N as a candidate for the repository. However, a long-term test of different clay materials has just been in installed in the Äspö Laboratory.

c) What factors (post-closure safety, cost, ease of emplacement operations, etc.) will SKB consider in making their final selection of buffer material, and how will these factors be weighted?

All of the above + some more as well (availability, reliability of supplier, etc). However, the post closure safety is the key factor. The other factors will only be considered for materials that can be considered to be “equal” in long term performance.

Buffer Emplacement

SKB’s description of the initial state of the repository provides a description of the EBS installation process (TR-06-09, page 77, Section 4). Buffer emplacement, in particular, is critical to the long-term performance of the EBS because of the need to minimise deleterious processes such as buffer erosion, to ensure that the buffer achieves a sufficient density, and to limit spatial heterogeneity of buffer density and swelling (TR-06-09, page 87).

d) Have the proposed buffer emplacement techniques been demonstrated at a large scale, and if so, where are such studies reported?

Yes, the installation was demonstrated for non nuclear operation in the installation of the Prototype Repository reported in IPR-02-23 and IPR 04-13 (not on our website, but will be made available on request).

e) Please will SKB clarify how it intends to use drain tubes and plastic liners to control water inflow to the deposition holes during operations?

This method was used for the installation of the Prototype Repository and worked well. The method will be further developed, tested, demonstrated and implemented. The plans for this will be described in RD&D-programme 2007.

f) Does SKB consider that the drain tubes and plastic liners can be deployed and removed reliably, and that these operations can be undertaken for the emplacement of thousands of waste packages in a way that can be shown to meet appropriate quality control constraints?

Yes, but work remains to further develop, test, demonstrate and implement these solutions. The method will be tested for different possible underground conditions and the consequences of mishaps will be evaluated. Countermeasures for mishaps will be developed and described. The plans for this will be described in RD&D-programme 2007.

6 pH and Redox Conditions in Buffer and Backfill

Radionuclide solubility and transport behaviour are significantly affected by the pH and redox conditions. Redox conditions in the buffer and backfill will be established through heterogeneous reactions between solutes in groundwater, and major and minor solid phases in the bentonite/clay. The degree to which pH is buffered and redox poised by the solid phases will depend on mass balance (is there enough material present?), mass action (is the solubility high enough?), and kinetics (is the reaction rate fast enough?).

a) **SKB suggests that calcite dissolution and precipitation (driven by ion exchange reactions involving montmorillonite) will be the dominant process governing pH in the buffer and backfill (TR-06-18, pages 102-104 and 179). SKB presumably considers that calcite dissolution and precipitation will be more important than mechanisms involving protonation-deprotonation reactions in montmorillonite, and montmorillonite dissolution-precipitation reactions. In view of the comments above concerning the contributions of mass balance, mass action, and kinetics, how was the conclusion concerning pH buffering derived? Did SKB make a quantitative assessment of the various different mechanisms / reactions that may contribute to pH control over the one million year period of the SR-Can safety assessments?**

The effect of protonation-deprotonation has been tested (MX-80 bentonite case with no carbonate minerals) and reported in TR-06-16, pages 31-47. The conclusion is that this process certainly has a role when carbonate minerals are not present, but with minor effects for the reference case (interaction with present-day groundwater). Whereas in the scenario where ice-melting water can reach the repository level, a stronger buffering of pH is exerted by surface acidity reaction. However, when carbonate minerals are present (i.e. calcite) the pH buffering is exerted by the equilibrium with this mineral.

The effect of montmorillonite dissolution is even less relevant, as it will have a slow kinetic dissolution rate, and therefore the effect of faster reactions as calcite dissolution-precipitation or protonation-deprotonation will buffer pH instead. According to this it has been stated in TR-06-16 (page 28) that: *"... due to the low kinetic rate of dissolution of montmorillonite by granitic water under near-neutral pH (Cama et al., 2000; Huertas et al., 2001), the calculations do not include the potential dissolution-precipitation of montmorillonite."*

Finally, the models studies conducted in TR-06-16 where ran for a time period of 60,000 years, as it typically covers several glacial episodes. Moreover, as no major changes occur in this time frame it is not expected that a larger simulation time would result in significant changes, especially assuming that the system will approach equilibrium with regional groundwater.

b) **SKB refers to the roles potentially played by siderite and pyrite in governing redox conditions in the buffer, and concludes that siderite dominates redox behaviour (TR-06-18, pages102-103). The presence of sulphate/sulphide in groundwater and iron in montmorillonite is apparently ignored. In view of the comments above concerning the contributions of**

mass balance, mass action, and kinetics, how was the conclusion concerning buffer redox buffering derived? Did SKB make a quantitative assessment of the various different mechanisms / reactions (including those involving dissolved sulphur and iron species) that may contribute to redox control over the one million year period of the SR-Can safety assessments?

Certainly, sulphate/sulphide should control the redox of the system. However, the impossibility of sulphate reducing bacteria to develop under highly compacted bentonite conditions lead to the disequilibrium of this redox couple once other reactions involving them occur in the bentonite buffer. The other possible redox couple acting in the system, Fe(II)/Fe(III) has been tested (TR-06-16), despite the source of iron (siderite, pyrite or montmorillonite) the expected conditions in the system do not reach the Fe(II)/Fe(III) boundary. Therefore, only the equilibrium with pyrite and siderite (as occurs with present-day groundwater in Forsmark, TR-06-16 pages 36-38) could control the redox of the system.

7 Piping and Erosion Processes in Buffer and Backfill

SKB states that '*Piping or hydraulic fracturing probably only occurs before complete water saturation and homogenisation of the buffer since the swelling pressure of the buffer material is very high as opposed to the situation in the backfill where the swelling pressure is much lower. Erosion can occur in channels caused by piping or hydraulic fracturing.*' (TR-06-09, page 217; see also TR-06-18, page 58).

SKB suggests that piping and erosion of the backfill is expected (TR-06-18, page 160) and may occur both before and after full hydraulic saturation is attained (TR-06-09, page 218). Piping and erosion of the backfill might be most pronounced in the periphery of the backfill, which will be formed using pellets (TR-06-09, page 275; TR-06-18, page 159).

SKB also indicates that colloids may be eroded from the buffer and backfill, and that the backfill may lose its swelling pressure during the later part of the reference glacial cycle (TR-06-09, page 358, Section 9.4.8).

SKB presents some mass-balance type calculations to assess the possible effects of piping and erosion processes in the buffer, but these calculations do not provide a detailed representation of the piping and erosion processes (TR-06-09, pages 217-219, Section 9.2.4).

a) **In detail, what is SKB's approach to developing understanding of, assessing and managing the risks associated with, piping, erosion and colloid formation?**

It should be noted that piping and colloid formation are two entirely different process which both lead to erosion.

The state of the art on piping is reported in /Börgesson and Sandén, SKB R-06-80/. The piping process is rather well understood, but extensive research is still going on, since the process is of critical importance for the development of the backfill methodology as well as for the KBS-3H concept.

The model for colloid formation used in SR-Can on the other hand needs major improvement. SKB has initiated an extensive project to study the issues around colloid formation. The final aim of the project is to develop a quantitative model for buffer loss due to colloid formation to be used in SR-Site.

b) **What plans are there to develop a mechanistic model of piping and erosion? Will there be consideration of the channel morphology that piping and erosion that may lead to?**

For the moment there seems to be little need for additional model development around the piping process. Piping only occurs in the early stage of the repository evolution. The process can be studied in both laboratory and field experiments and the mass balance type approach used in SR-Can should be sufficient in SR-Site as well. Data from new tests will be taken into account.

c) What are SKB's field or laboratory data regarding whether buffer erosion leads to an overall reduction in buffer density (and associated properties and safety functions), or development of a narrow band of complete buffer-removal centred on the intersecting rock fractures?

Bentonite is selected as buffer material mainly due to its self-sealing properties. The mechanical properties of the buffer material are rather well known. A development of a narrow band of buffer removal could only occur if the buffer had lost all its swelling pressure.

/Börgesson and Hernelind 2006, SKB TR-06-13/ have modelled the restoration of the swelling pressure for different losses of buffer mass.

d) In detail, what further experiments are planned on piping and erosion?

The piping process is studied in medium-large scale experiments in the KBS-3H and Baclo projects.

The colloid formation process is studied within the Bentonite Erosion project. This project includes an extensive range of experiments, among them the coffee table type (Figure 2).

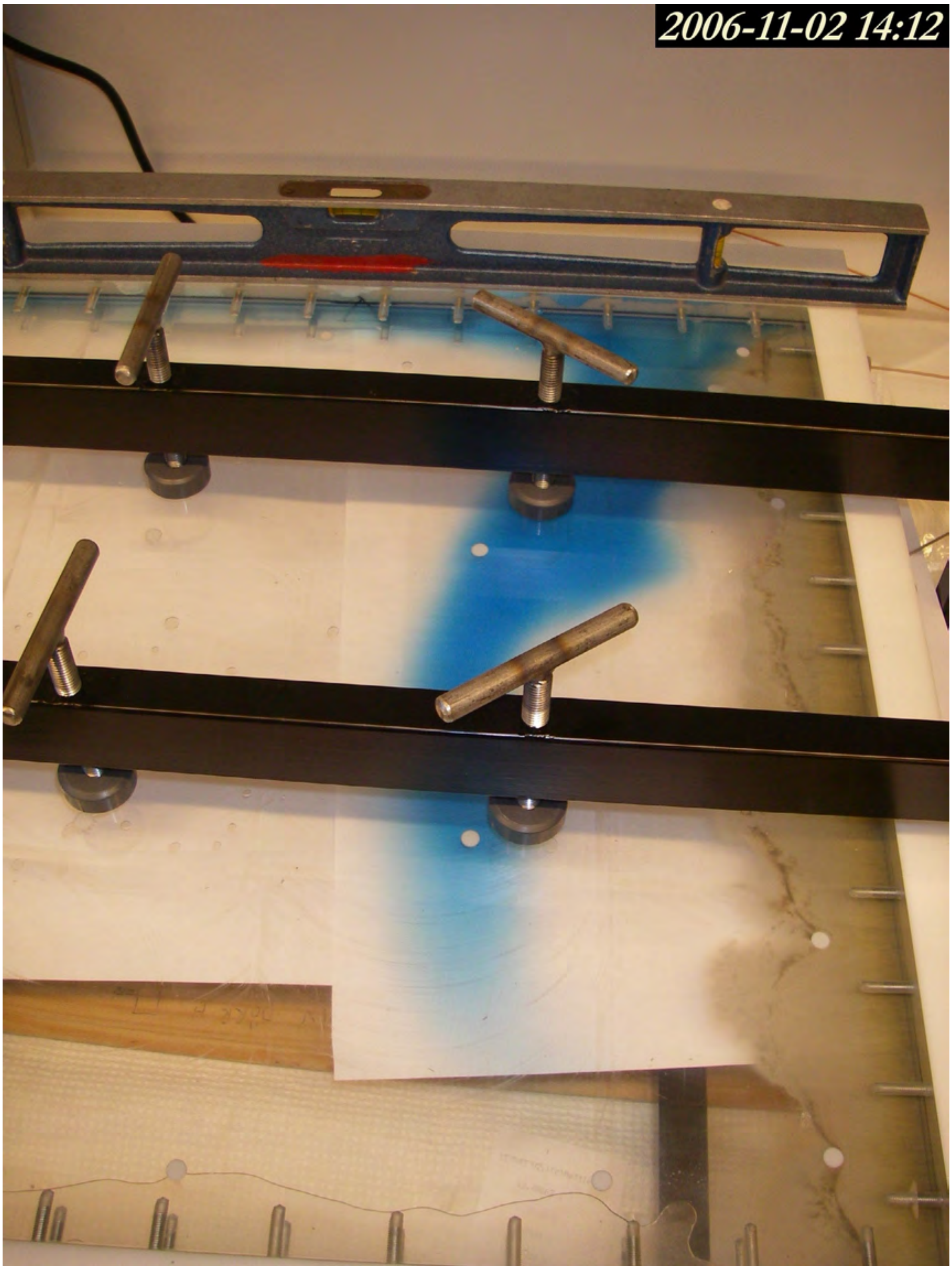


Figure 2 Coffee table experiments, where bentonite is expanding out into a slowly flowing water in a artificial fracture between two plexiglass plates

See also initial questions on Assessment of EBS in Advection-Corrosion Failure Scenario.

8 Cement Grouts – Selection and Modelling

SKB envisages using low-pH cement for grouting and shotcreting because of concerns regarding the interaction of high-pH pore fluids from conventional Ordinary Portland Cements (OPC) cements with buffer and backfill materials (TR-06-09, pages 94, 220-221, 271 and 548).

a) **What is the rationale and justification for the choice of pH 11 as the upper limit of acceptability for the pore fluids of the cements?**

The first occurrence of pH 11 as a limit for clay stability appears to be /Bradbury & Baeyens, 1997/. Both modelling, e.g. /Gaucher et al 2004/, and experimental studies, e.g. /Karnland 1997; Huertas et al 2001, Cuevas et al 2006/ indicate that "ordinary" cement porewaters affect negatively bentonite performance. The rate of transformation appears to increase with pH, but it is also dependent on dissolved silica concentration. Experiments with "low-pH" cements do not evidence negative effects, e.g. /Pusch et al 2003/. The stability of bentonite has also been discussed in /Metcalfe and Walker 2004/. Mass-balance calculations and pH-buffering capacities of bentonite have been used to argue that the bentonite buffer should not be affected by "ordinary" cement grouting /Vieno et al 2003/. The limit pH 11 has been selected because there is no evidence known to the SR-Can team indicating that such porewaters would damage the performance of the buffer. Therefore, the use of low-pH cement reduces the uncertainties in the safety assessment. It is possible that further experimental studies might show that higher pH values are acceptable, but given the short time span for any experiments their applicability in estimating repository conditions far in the future would require also a very good understanding of the processes involved.

References:

Bradbury M H, Baeyens B 1997. Far-field sorption data bases for performance assessment of a L/ILW repository in a disturbed/altered Palfris marl host rock, Nagra-NTB-96-06.

Cuevas J, Vigil de la Villa R, Ramírez S, Sánchez L, Fernández R, Leguey S, 2006. The alkaline reaction of FEBEX bentonite: a contribution to the study of the performance of bentonite/concrete engineered barrier systems. *J. Iberian Geol.* **32**: 151-174.

Gaucher E C, Blanc P, Matray J-M, Michau N 2004. Modeling diffusion of an alkaline plume in a clay barrier. *Appl. Geochem.* **19**: 1505-1515.

Karnland O, 1997. Cement/bentonite interaction. Results from 16 month laboratory tests. SKB-TR-97-32.

Huertas F J, Caballero E, Jiménez de Cisneros C, JHuertas F, Linares J, 2001. Kinetics of montmorillonite dissolution in granitic solutions. *Appl. Geochem.* **16**: 397-407.

Metcalfe R, Walker C, 2004. Proceedings of the international workshop on bentonite-cement interaction in repository environments. 14-16 April 2004, Tokyo, Japan. POSIVA WR-2004-25, NUMO-TR-04-05.

Pusch R, Zwahr H, Gerber R, Schomburg J, 2003. Interaction of cement and smectite clay - theory and practice. *App. Clay Sci.* **23**: 203-210.

Vieno T, Lehikoinen J, Löfman J, Nordman H, Mészáros F, 2003. Assessment of disturbances caused by construction and operation of ONKALO. POSIVA 2003-06.

b) The use of low-pH cements will probably necessitate the use of organic additives such as superplasticisers to maintain workability and other physical properties. What experimental or other evidence does SKB have to suggest that these organic materials will be biodegraded (TR-06-09, page 273) before canister penetration and radionuclide release?

The only claim made in the paragraph is that the concentration of superplasticisers in groundwaters, and the concentration of any possible degradation product, will be negligible when compared to other organics naturally present in groundwater. In the SR-Can report it is in fact stated that superplasticisers "will be accessible" for microbial degradation, not that they will actually be degraded. However, it seems reasonable to assume that, in the long term, microbes would use them as source of energy or organic carbon. No claim is made that, if they are degraded, this would happen before radionuclide release.

SKB has started a collaboration project together with Posiva, Numo and Nagra to study the release of organics from cement samples containing superplasticisers, as well as the influence of both superplasticisers as well as released organics from cement on radionuclide sorption under "normal" geosphere conditions.

c) What is the current status of research and development aimed at establishing suitable compositions for the cementitious EBS materials, and at what point in the programme will a decision be made on the compositions?

Cementitious grouts are being tested by Posiva, and SKB is planning a test of silica sol grouting at Äspö. Several studies have already been performed in collaboration with Posiva and Numo. SKB is studying grout and concrete compositions which limits the pH of emitted fluids to less than 11, which is the prime criterion for grout that will be regularly used in the repository. Premature decisions on compositions might be detrimental, as it would be reasonable to expect that supplies may change. Furthermore, given the relatively long period of repository operation, it is quite probable that the compositions of any cement materials in the repository will change with time.

After repository closure, grout and shotcrete will start reacting with circulating groundwater, and a mildly alkaline plume of pore fluid may interact with the clay and rock barrier materials (TR-06-09, pages 271-273). The degree of interaction will be determined by heterogeneous reactions between solutes in the pore fluids, and major and minor solid phases in the clay and rock, and will depend on mass balance (is there enough material present?), mass action (is the solubility high enough?), and kinetics (is the reaction rate fast enough?).

Since the report that presumably describes these processes in detail (R-06-107) is currently unavailable, the following questions are relevant:

d) **The phase assemblage of low-pH cements is dominated by a complex, incongruently dissolving CSH gel. How does SKB model the dissolution of this phase in detail?**

The report has been ready and in the printing process since the main SR-Can report was released. A pdf file has been available, and still is, if requested before the report is finally printed. In summary, the low-pH grout is assumed to consist of the CSH phase jennite which slowly dissolves to produce secondary CSH phases with lower Ca:Si ratios.

In addition to this report, SKB is supporting other modelling efforts of grout degradation. See for example: Galindez et al, J. Phys. IV France, 136 (2006) 177.

Low-pH cements may contain pore fluids with relatively high concentrations of dissolved silica.

e) **Has SKB evaluated how the silica-bearing cement pore fluids will be redistributed during the thermal period and whether the bentonite may be destabilised as a result of reaction with dissolved silica?**

A preliminary evaluation is reported in /Karnland and Birgersson 2006/, sect. 3.2. Silica concentrations in "low-pH" cements are low (up to 0.4 mM /Vuorinen et al 2005/) when compared with porewaters from "normal" cement, but higher than those of groundwater or bentonite porewater. The silica gradient would be from hotter to cooler volumes of the repository system. It is therefore believed that silica in the cement pore fluids do not pose a problem during the thermal period. After that period, and given the low concentrations of silica in the "low-pH" cement porewaters, silica does not pose a problem either. This question might be further addressed in SR-Site.

Vuorinen U, Lehikoinen J, Imoto H, Yamamoto T, Alonso M C, 2005. Injection grout for deep repositories. Subproject 1: Low-pH cementitious grout for larger fractures, leach testing of grout mixes and evaluation of the long-term safety. POSIVA WR-2004-46.
Karnland O, Birgersson M, 2006. Montmorillonite stability. With special respect to KBS-3 conditions. SKB TR-06-11.

9 Thermo-Hydro-Mechanical Modelling

Correct prediction of heat flow and temperatures in the canister, the buffer and the rock is an essential part of assessing the integrity and performance of the KBS-3 system.

a) **SKB has certainly undertaken a lot of finite element model (FEM) calculations to assess the thermo-hydro-mechanical (THM) behaviour of the repository, but to what extent have the results from these studies been confirmed or verified?**

There are past, ongoing and planned projects that include comparison of modelling results with measurements both regarding laboratory tests and full scale field tests (Tests in Äspö HRL, FEBEX, URL tests, Catsius Clay, Decovalex, Task Force on EBS etc.)

b) **What are the most important simplifications made in the constitutive models that underpin SKB's THM modelling?**

SKB uses several codes for THM modelling the main ones being ABAQUS and Code Bright, which have different advantages and disadvantages.

ABAQUS has some obvious simplifications in the models of water unsaturated bentonite: 1) Vapour flux is simplified since the vapour phase is not modelled. Instead the vapour flux that origins from a temperature gradient is modelled as a diffusion process driven by the thermal gradient and controlled by a diffusion coefficient that is a function of the degree of saturation. 2) The retention curve is only a function of the degree of saturation and cannot be changed with void ratio. 3) The mechanics is modelled with the effective stress theory and with the erroneous behaviour compensated with a function called "moisture swelling" that is a function of the degree of saturation that cannot be made a function of the void ratio.

These simplifications in ABAQUS are the reason for that also Code Bright is used especially at unsaturated stages. ABAQUS model of saturated conditions does not have such obvious simplifications.
Code Bright does not have the obvious simplification regarding the models of water unsaturated bentonite, but of course all models include small simplifications e.g. the retention curve cannot be freely chosen but must obey the equations of Van Genuchten. The mechanics of unsaturated swelling clay is complicated and the model in Code Bright is of course a simplification.

c) **According to SKB, the temperature criterion has been changed from *'100 °C at the outside of the canister'* to '*100 °C at the inside of the buffer'* (TR-06-21, page 40). What is the reason for this change? Is it that earlier predictions of temperatures are now thought to have been underestimates?**

No, this is not the case. The reasons for a temperature limit on the canister surface when in contact with the bentonite buffer were:

- Elevated temperature in conjunction with unfavourable groundwater chemistry can adversely affect the chemical stability of the bentonite buffer. This concern remains.
- The risk for creating a more corrosive environment close to the canister surface if salt deposits are formed on the canister surface. A re-analysis of the risks for enhanced corrosion has shown that it can be neglected (see TR-06-22).

The criterion for maximum allowed temperature in the bentonite buffer when in contact with the canister surface, however, leads to a limit on the canister surface temperature. We do not, therefore, see a need to separately specify a temperature limit for the canister surface.

d) According to SKB, the main uncertainties in the temperature estimates relate to the relatively large uncertainties associated with heat transfer from the canister surface to the surroundings (TR-06-21, page 41). Can these uncertainties be reduced?

The uncertainties relate to how fast the initial clearance between the canister surface and the surrounding bentonite will close as a result of water uptake and swelling. The peak canister surface temperature will be at maximum if this clearance remains. In the safety analysis it is pessimistically assumed that the initial clearance will remain at least as long as it takes to reach the peak temperature (i.e. some 10 -20 years). The uncertainties in the heat transfer properties of the open clearance can and will be reduced by new back-calculations of the temperature evolution in a dry deposition hole (hole #6) in the Prototype Repository

e) Immediately after canister deposition, heat conduction will be more effective at the bottom of the canister than at canister walls because, until the buffer swells, there may be an air gap around the canister walls. What temperatures may be reached in the bentonite at the bottom of the deposition hole? How will this temperature rise influence the bentonite in this region?

The observation made in this question is correct. The temperature curve shown in SR-Can shows the maximum bentonite temperature at the canister mid-height position – whereas the maximum bentonite temperature actually is just below the canister. Revised thermal calculations, carried out after publishing SR-Can shows that at the time of the temperature peak, the bentonite temperature in the top and bottom regions will be about 2 ºC lower than the maximum canister surface temperature (at canister mid-height). The SR-Site repository will be dimensioned such that this temperature will not exceed 100 ºC.

10 Geochemical Modelling

SKB uses several seemingly independent and unconnected geochemical modelling approaches to address various aspects of the EBS, the repository near-field and the immediately surrounding geosphere. For example, SKB utilises at least three geochemical models to describe clay behaviour:

- **An osmotic model is used to describe smectite clay swelling behaviour (e.g., TR-06-11; R-04-36 Appendix B).**
- **An ion-exchange and protonation / deprotonation model is used to describe long-term pore fluid evolution and interaction with groundwater (e.g., R-04-36, Appendix C).**
- **An empirical expression is used to describe the conversion of montmorillonite to illite (e.g., TR-06-09, pages 285-286; TR-06-11).**

In addition, SKB is considering use of a fourth model to describe the conversion of montmorillonite to non-swelling berthierine, as a result of interactions between the clay and the corroding cast iron insert (TR-06-11).

Elsewhere in the SR-Can assessment, geochemical models are used to describe other processes, including:

- **In-situ, labile reduction-oxidation of octahedral Fe in smectite.**
- **The effect of dissolution / precipitation in bentonite of minor and trace phases such as pyrite, silica and organic carbon.**

There may be defensible reasons why SKB uses certain geochemical models for different materials, processes or time periods. However:

a) **What is SKB's overall approach to ensuring that the individual geochemical modelling studies included in the assessment are appropriate and consistent?**

The reason for using a number of different models for different geochemical process is to always have the most appropriate. This introduces a problem with consistency between the models, since there is no "universal" model for all applications available. The consistency check is difficult since the models are fundamentally different and can not be verified against each other.
The overall strategy in SR-Can has been to focus on the merits of he individual models.

b) **How does SKB integrate its geochemical modelling to provide a coherent evaluation of the geochemical evolution of the repository, from waste emplacement, through the thermal heating period, and thereafter during the long-term return to ambient conditions?**

This is the target of geochemical modelling within the safety assessments. The modelling in SR-Can was an attempt to achieve this.

c) **How does SKB's ion-exchange model of buffer pore-water chemistry account for multiple field studies showing that the long-term compositions of pore waters in clay sediments are buffered by clay minerals?**

This has been accounted for as the selectivity coefficients used in models (i.e. TR-06-16) are based on the experimental data conducted with MX-80 bentonite **at repository conditions** (which is not the case for field studies). However, the control exerted is only on major cation concentrations as it is shown in the modelling results and several studies conducted in many clay formations (Opalinus Clay, COX, Boom Clay, etc). Moreover, when abundant and fast reactive additional minerals are present in these clay rocks (i.e. calcite) the dissolution-precipitation processes exert an additional control on the concentration of some major cations, which is something also observed in field studies and underground laboratory experiments.

11 Spent Fuel

SKB states that spent Mixed Oxide (MOX) spent fuels are not included in the inventory used for the SR Can assessment (TR-06-09, page 83).

a) **How much difference would it make to the risk summation (TR-06-09, Figure 12-20) and to the conclusions from the assessment if the MOX spent fuels were included?**

We don't know this since MOX-fuel was not included in the assessment.

However, if just the different inventory in the MOX-fuel was included the difference would most likely be none or very marginal. The maximum residual of 1700 W/canister puts a restriction on how much radionuclides that can be contained in each canister. The content of Sr/Y-90 and Ba/Cs-137 (and Am-241 in the case of MOX) determines how much fuel that can be emplaced in each canister. Since Ra-226 dominates the risk a defective MOX-canister would actually lead to a lower risk.

Still, the assessment of the spent fuel alteration rates and the instant release fractions may not be valid for the MOX-fuel and this may have an impact on the risk summation.

The SR-Can assessment results suggest that for some radionuclides the calculated release rate is highly dependent on the assumed UO_2 dissolution rate. SKB states (TR-06-09, page 441), *'It is clear that the fuel dissolution is the most important process that limits the release of radionuclides in the advection/corrosion case.'* A considerable body of published data, both from SKB (e.g., TR-05-09 and TR-04-19) and others, indicates that, under reducing conditions, the dissolution rate of UO_2 is extremely slow.

b) **Please will SKB clarify its approach to estimating the quantity of radionuclide in the 'instant release fraction'? The explanation at TR-06-09, Section 10.6.3 seems to suggest that in addition to radionuclides in the fuel-cladding gap, some radionuclides contained in the metal parts of the fuel are also assumed to be instantly released on failure of the cast iron insert.**

That is correct. The radionuclides in all the metal parts of the fuel are assumed to be instantaneously released. This is described in detail in thee SR-Can Data Report TR-06-25.

c) **Why did SKB not cite and use in the SR-Can assessment the data in TR-05-09, TR-04-19 and elsewhere that show low UO_2 dissolution rates? Does SKB plan to use such data in future safety analyses (e.g., SR-Site)?**

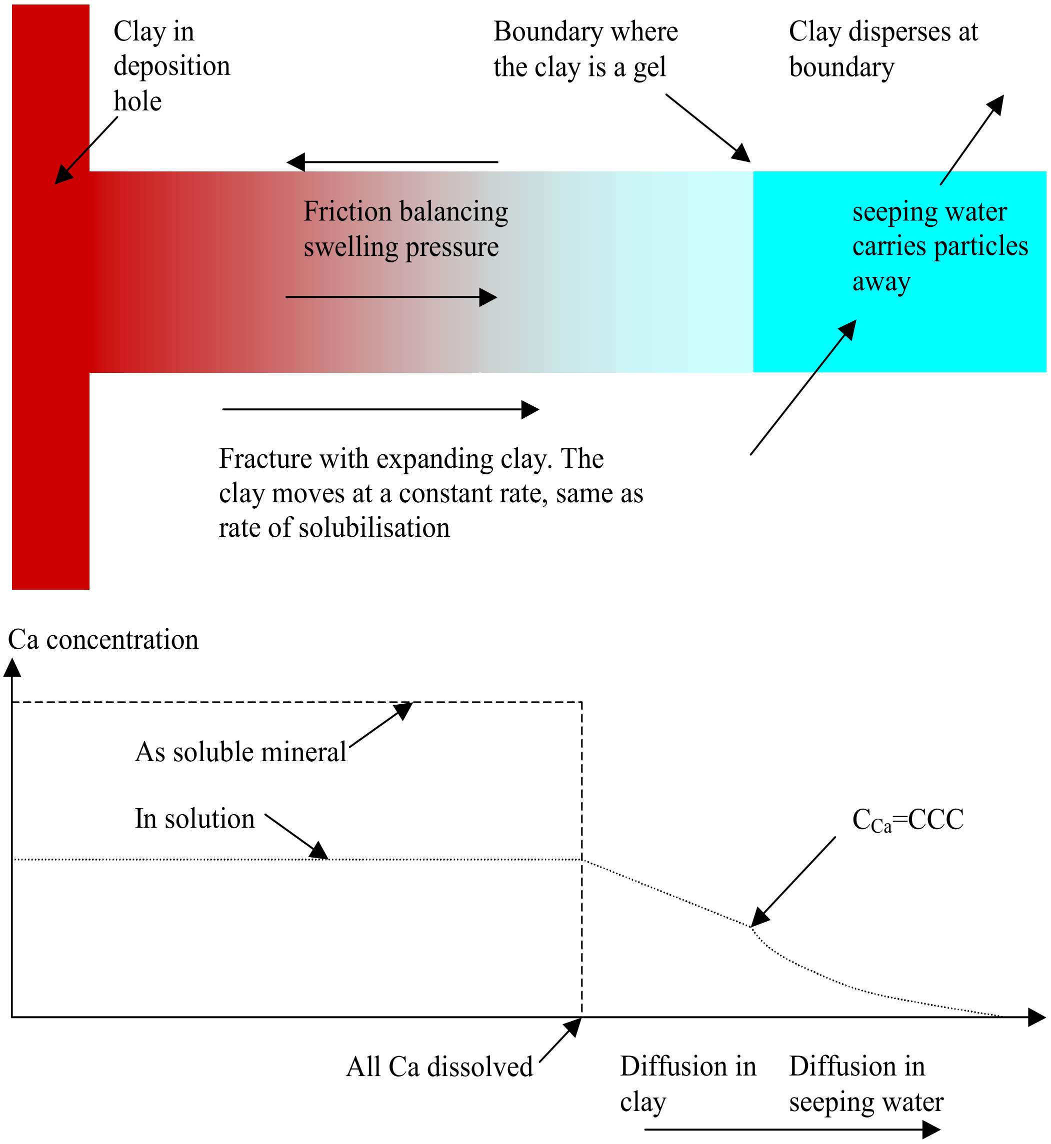
These data are used in the analysis. Relevant dissolution data later published in TR-05-09 are incorporated in the analysis presented in TR-04-19, which is referenced in the SR-Can Data Report TR-06-25.

12 Assessment of the EBS in the Advection-Corrosion Failure Scenario

SKB describes an approach to assessing the Advection Corrosion Failure Mode (TR-06-09, pages 432-438, Section 10.6). SKB's approach includes a conceptual model for buffer erosion and other processes that might lead to corrosion and failure of the copper canister (TR-06-09, page 361).

Model Justification

a) **Please can SKB provide a diagram of the conceptual model of buffer erosion for this scenario, and describe the assumptions made and explain their basis?**



The conceptual model is described in section 9.4.8. The model is based on the description by Liu & Neretnieks 2006, SKB R-06-106 (see figure above). However, in SR-Can no credit is taken for any content of Ca in the buffer. The driving force for the diffusion is instead the concentration of clay in a sol phase. The selected value for this parameter is 50 g/l.

However, not too much attention should be given to this model, since it does not reflect all the mechanisms that are involved in the process (as also stated in section 9.4.8).

b) What is the justification for SKB's assumption that erosion would '*…progress in all directions into the buffer*', instead of forming channels some of which might act to direct most of the water flow (TR-06-09, page 361)?

See answer to question as 7c.

c) Why are '*small releases*' excluded from the Advection Corrosion Failure Mode assessment (TR-06-09, page 432)?

In the pinhole case, there will be a period with small release followed be larger releases as the pinhole grows. There will be no such effect in the advection case. The releases will be large already at the time of the occurrence of the failure.

d) The only justification given for using a different model to simulate the release of activation products from metals in the Advection Corrosion Failure Mode assessment is that otherwise releases of Ni-59 and Nb-94 would be too high. What is the justification for the assumed 1,000-year release period (TR-06-09, page 433)?

Assuming that the radionuclides from the metal parts would be instantaneously released is, of course pessimistic and also unrealistic. The corrosion of the metal parts and the subsequent release of radionuclides will take time. At this time we have no release model (corrosion model) for the metal parts and the 1000 years are only to be seen as a reasonable estimate. This will be elaborated further in SR-Site.

e) What is the justification for spreading pulse releases to the biosphere out over 50 years (TR-06-09, page 433)?

The aim is to calculate an annual average lifetime risk. A certain exposure would yield the same annual average lifetime risk if received as a pulse or spread out as a continuous exposure over a lifetime, assumed to be 50 years. (This is briefly discussed in the paragraph "*Pulse releases in the biosphere*" on p. 433.)

f) What is the basis for the rules for handling pulse releases given on TR-06-09, page 433?

This is explained on page 433 and in the answers to questions d) and e) above. (If several dispersion mechanisms are active, it is pessimistic to use the one that gives the highest dispersion (longest time constant) when assessing the consequences.)

g) What is the justification for assuming canister failure at 100,000 years (TR-06-09, page 437)?

Figures 10-40 and 10-41 show the result of deterministic example calculations constructed to illustrate releases for this failure mode. The actual assessment calculations, page 439, are done with the calculated distribution of failure times given in Table 10-11.

Effects of Loss of Buffer Safety Functions

h) In cases where buffer erosion has led to a reduction in buffer density and swelling pressure, how have the loss of the buffer 'safety functions' for colloid filtration, prevention of microbial activity, and canister sinking have been factored into SR-Can assessment calculations?

There is no evidence that colloid would form from the waste even if the colloid filter was lost. The process was not treated in SR-Can. However, this may require stronger justification in the future.

Microbial sulphate reduction is included in the assessment in the calculation of copper corrosion in the case where the buffer is lost. The groundwater content of hydrogen and methane are considered in the corrosion calculation.

Co-precipitation Behaviour of Radium and Iodine

In several places SKB notes the potentially favourable effect on calculated safety (up to 3 orders of magnitude) of co-precipitation of I-129 and Ra-226 (as well as the Th-230 precursor to Ra-226) (e.g., TR-06-09, pages 437-441, Section 10).

i) Is SKB planning further investigations of the potential occurrence and safety impacts of co-precipitation?

Yes, but only co-precipitation of Ra with $BaSO_4$ will be considered.

13 Assessment of the EBS in the Pinhole Scenario

SKB presents evidence that ductile deformation of copper onto the cast iron insert may occur before re-saturation of the buffer under some site conditions (TR-06-09, Section 10.5).

a) **Given this relatively rapid ductile / creep response of copper, has a variant of the pin hole scenario been analysed, in which water eventually entering through an initial pin hole in the copper canister will only contact a localized portion of the cast iron insert, and that the three-fold volumetric expansion from the iron corrosion products formed will act to relatively rapidly and completely 'unzip' the copper canister (akin to a similar phenomenon observed for pin-holes in Zircaloy cladding of spent fuel)?**

This is included in the pinhole case, the full name of which is "the growing pinhole failure mode". The time to this "unzip" event is assumed to be triangularly distributed between 1,000 and 100,000 years with the peak at 100,000 years, as described in section 10.5.2 of the main report and more thoroughly motivated in the Data report. After the event, all the transport resistance in the canister is assumed to be lost.

14 Assessment of the EBS in the Earthquake Scenario

According to SKB, creep strains within the canister of 7.6% and 11.5% are predicted for shear deformations of 10 cm and 20 cm respectively. The density of the bentonite used in these calculations was 2,000 kg/m^3 (R-06-87, page 23).

a) **Can SKB explain why the creep strains in these the earthquake simulations are so high?**

At this time no. The current model gives these results, but work is in progress with alternative creep models and this will be further elaborated in SR-Site.

Creep relaxation of stresses induced in the copper canister by earthquake shear deformation should not result in more than about 1% creep strain. The remaining creep strain thus has to be a result of some other loading that is present after the earthquake has occurred. One explanation could be the interaction between the canister and the bentonite buffer and the additional loading thereby introduced. If this is the case, the model used for describing the bentonite material will have direct impact on the prediction of creep strain developed in the canister.

b) **Has SKB investigated the influence of different buffer materials and different bentonite models on the creep strain generated in the canister? If the interaction between the canister and the bentonite buffer does not explain the amount of creep strain, what is then the explanation?**

No. No alternative bentonite models have been tested so far. Alternatives have, however, been suggested. At present, we have no explanation for the unexpectedly large creep strain. Testing of alternative models may help us to get a better insight into this.

For the analyses presented in R-06-87 a creep model suggested by Kjell Pettersson has been used.

c) **Will the effect of other creep models be investigated?**

Yes, see above.

According to SKB, no defects larger than 15 mm or, for surface-breaching defects, having a radius larger than 20 mm will be allowed in the copper canister Friction Stir Weld (FSW) region (TR-06-25, page 53).

d) **What is the effect of the presence of such defects on the integrity of copper canisters that undergo shear deformation?**

This has not yet been investigated.

SKB indicates that the cast iron insert will be closed with a steel lid fastened with a bolt (TR-06-09, page 85).

e) **Is it correct that the steel lid is attached to the insert with only one bolt? If so, will this be a 'weak link' during earthquake shear deformation near to the top of the canister?**

This has not yet been investigated.

SKB has considered the possible effects of earthquake-induced shearing on the canister (TR-06-09, Section 9.4.5).

f) **What are the impacts of possible earthquakes on the backfill, plugs and seals?**

Plugs and seals serve no long-term function in the repository. If an earthquake occurs during the operational phase they will be repaired.

The tunnel backfill is selected for its self sealing properties and is expected to maintain its important properties after an earthquake.

15 Influence of Safety Assessment on Repository Implementation

The number of waste packages potentially experiencing buffer erosion (as considered in TR-06-09, Section 10.6) will depend on the number of waste deposition holes intersected by suitably large fractures ($\mathbf{N_{frac}}$).

a) How will SKB's characterisation programme identify such 'erosion-enabling' large fractures?

As discussed in the concluding chapter (section 13.6.4) of the main report:

"A flow rate criterion will be developed, and applied when the repository design for SR-Site is developed. Previous chapters show that applying the FPC criterion, as well as a criterion related to intersecting fracture transmissivity, is highly efficient in reducing the number of deposition holes with high flow rate, but this efficiency reduces dramatically for DFN-model variants with less correlation between fracture size and transmissivity. Furthermore, a simple transmissivity criterion would then also unnecessarily reject a large number of deposition holes with very low flow, just because they were intersected by very short highly transmissive fractures. This means that it is necessary to:

- further explore the possibilities for reaching firmer conclusions on correlations between fracture size and transmissivity (see further section 9.3.6), and
- devise a practically useful flow-rate related criterion that is less sensitive to the details of the hydraulic DFN-model.

It appears likely that a flow-rate criterion related to measured transmissivities in pilot holes drilled along the deposition tunnel or in individual deposition holes positions, or a flow-rate criterion related to measured inflows to deposition holes, would be a more efficient and better discriminating criterion. The measured flow would essentially test the combined transmissivity and connectivity of the fractures connected to the holes. Preliminary analyses by /Svensson 2006b/ suggest a very strong correlation between inflows to an open repository and subsequent flows after closure and resaturation. Before adopting a flow-related acceptance criterion further evaluations are needed, as summarised below.

- The long-term stability of the measured transmissivity needs to be considered. Possibly a robust criterion would need not only to consider currently measured transmissivity (or flow), but also evidence of high flow in the past. /Cosgrove et al. 2006/ point out that if fractures of large magnitude have experienced high flows in the past, this would result in the walls of the fractures having been altered either physically or chemically and/or minerals having been deposited along the fractures. Such features are easily identified from tunnels by direct observation and can be detected in boreholes using geophysical techniques. This, could provide an additional, important criterion for identifying large fractures. The criterion needs to be tested, at least theoretically, in a numerical DFN-model exploring its implications for different assumptions on the correlation of flow with fracture size. Such analyses could build on the preliminary analyses by /Svensson 2006b/ discussed above.
- Its practical applicability needs also be considered, including assessing "skin-effects" and the effects of potential disturbances from grouting before measurements are conducted. It is emphasised that the flow rate criterion will not be independent

of the fracture size criterion, especially when there is a strong correlation between fracture size and transmissivity.

As already noted, the FPC criterion alone is quite effective in removing high flow rate deposition holes for the fully correlated case, and application of the EFPC criterion should improve this effectiveness. Furthermore, /Cosgrove et al. 2006/ point out that there is generally a correlation between fracture size and evidence of strong fluid movement. When estimating the degree-of-utilisation, the correlation between the criteria should be considered, in order not to be overly pessimistic about the required space."

It should also be noted that the detailed mechanism behind the buffer colloid formation/erosion process is not known. Its dependence on fracture properties thus remain to be clarified.

b) How will SKB assess the potential for existing smaller fractures to grow into larger erosion-enabling fractures?

Propagation of existing fractures requires high stresses and high stress anisotropy (cf. SR-Can, Geosphere process report). According to results of 2D calculations, fracture propagation in the near vicinity of deposition holes would be possible if the ratio between the major and minor far-field stresses is larger than 4/1. In particular at sites where the horizontal stresses are high initially, such stress conditions may exist during a period of a few hundred years after deposition.

The relevance and validity of the 2D results in a 3D near-field geometry have not been assessed, which means that there is still uncertainties regarding the scope and extent of fracture propagation in the near-field (or whether fracture propagation will take place at all). The empirical basis for fracture propagation models relevant around openings in large rock masses subject to high thermo-mechanical stresses is very limited.

Results from the AE monitoring of the Prototype Repository rock mass that has been conducted during different stages of the experiment do not indicate any macroscopic growth of existing fractures. Recorded AE events are attributed to movement on pre-existing micro-fractures or to extension or formation of new micro-cracks. During the heated period last reported (i.e. when stresses were high in the Prototype Repository rock mass), the level of activity was much lower than during the excavation stage (SKB, IPR-06-23). Not observing AE patterns that can be associated with macroscopic growth of existing fractures in the Prototype Repository does not necessarily mean that fracture propagation could not occur in another, possibly even more severe, stress environment. Note however that the Prototype Repository canister spacing is smaller than would be allowed in the KBS-3 repository (given the relatively low thermal conductivity of the Prototype Repository rock mass). Additionally, the power of the Prototype Repository heaters is higher than that of KBS-3 canisters. This would give high stresses and high stress gradients. On the other hand, the AE monitoring was not conducted around a central deposition hole, but around the ones closest to the outer tunnel plug, i.e. where stresses, and possibly the potential for fracture growth, may not be at maximum.

SKB now intends to analyse the Prototype Repository with regard to the stress evolution and compare the stresses with corresponding stresses predicted around KBS-3 deposition holes (SKB-R-06-89). Possibly it will also be necessary to reassess the fracture propagation process in general.

c) **How will SKB assess the potential for growth of unmapped fractures not intersected by excavation drilling?**

This aspect was not addressed in SR-Can or its references. We anticipate, however, that this issue can be addressed by fine-tuning the FPI criteria. Development of the FPI criteria is on-going.

d) **How will SKB combine the results from a), b) and c) to determine N_{frac} for a specific site?**

See our answer to a)

e) **How does SKB plan to establish a rigorous erosion-related 'respect distance' criterion for the emplacement of waste packages?**

As can be seen from previous answers, we do not suggest a need for a "respect distance", but instead we will work with "acceptance criteria" for deposition holes. The challenge is to formulate both effective (i.e. low probability of erroneously accepting a deposition hole) and efficient (i.e. low probability of discarding a hole that in fact is acceptable) criteria. Absolute rigorous criteria are not needed, as long as the remaining incorrectly accepted holes are few enough not to jeopardise the risk targets and as long as they do not lead to a dramatic loss of canister positions.

In SR-Can we show that just by applying the FPC and EFPC rules we actually will sort out many problems – at a fairly moderate loss of holes. Even for these relatively in-effective criteria regarding the flow situation – we anyway manage to reduce the potential for erosion in deposition holes. For SR-Site we aim at developing improved criteria – with the object of showing feasibility.

However, site specific experiences from the underground will certainly also be developed and applied – both to enhance the probability of discarding deposition holes with high flow and to reduce the probability of discarding acceptable holes.

16 Influence of Safety Assessment on the RD&D Programme and EBS Design

SKB's discussion of influence diagrams for repository processes (TR-06-09, Section 6) presents a reasonable summary of a complex and lengthy process. While SKB seems to focus repeatedly on the *'relevance'* of processes as a criterion in deciding which processes to include and model (and, of course, relevance is a necessary criterion), it would seem sensible that an equal focus be placed on identifying the potential 'importance' or 'significance' of processes in deciding which processes to model.

Perhaps this is simply a matter of definition, and SKB means to include 'importance' within its term of 'relevance'. However, there is little evidence in SR-Can that SKB has considered or applied a 'risk importance' perspective to its overall safety assessment, either at the beginning of the analysis (in terms of screening FEPs), or at the end of the analysis (in terms of identifying key FEPs that are of high importance, or significance, to safety).

In particular, it would be valuable if, at the end of the extensive SR-Can analysis, SKB could identify a set of key FEPs, in areas such as site characterization, material properties, degradation processes, etc., that will require particular emphasis in the future (see TR-06-09, page 453). It would also be valuable for SKB to identify those FEPs that do not have any strong importance or influence on safety.

TR-06-09, Section 10 does report on various sensitivity analyses, but there is no coherent summary that places the results of these analyses into a listing of relative importance to safety.

a) **How does SKB use the results of safety assessment to prioritise and guide its RD&D programme?**

Chapter 13 contains extensive feedback to RD&D, site investigations and repository design. Several key processes are specifically identified in the feedback given to the RD&D programme, section 13.8, e.g. buffer erosion, thermally induced spalling and radium co-precipitation. This feedback is used as input to the RD&D-programme 2007.

Regarding prioritisation between these issues, the buffer erosion process is obviously, and as stated several times in the main report, a highly prioritised matter. This and all other matters are brought up in the feedback and they will also all be addressed in the RD&D-programme, meaning that a strict prioritisation is less relevant.

(This issue is not within the scope of the SR-Can assessment.)

b) **How does SKB use the results of safety assessment to help optimise the design of the repository and the EBS?**

The matter of optimisation and the related issue of BAT are discussed in section 13.3.4. Feedback to canister and repository design is given in sections 13.5 and 13.6, respectively. The latter two sections deal with improvements of the design, rather than optimisation. One important conclusion regarding the further work on optimisation is that the issue of buffer erosion should be resolved since it has a high impact on optimisation.

(This issue is not within the scope of the SR-Can assessment.)

17 Other Comments

Climate

SKB states, '*In the base variant of the reference evolution, the long-term climate trend is assumed to only be affected by natural climate variations, and not by antropogenically* [sic] *enhanced greenhouse warming. Therefore, palaeoclimate data depicting natural climate variability and trends can be used to assess the base case climate during the initial 1,000 years of temperate climate after closure.*' (TR-06-09, page 225).

a) **Given that there is now consensus that anthropogenically-induced climate change is occurring, has SKB excluded from consideration climate data for recent years that might include anthropogenic effects?**

No, on the contrary. A case with a climatic development that also includes anthropogenic warming is analyzed in the dedicated "Greenhouse variant" of the main scenario, see sections 5.2.1, 5.2.3 and 9.1 of the Main report.

b) **Given that there is now consensus that anthropogenically-induced climate change is occurring, the probability of the base variant would seem to be zero. What is SKB's view on the probability of the base variant?**

In SKB's approach on treatment of climate and climate related processes, the base variant is used for two purposes. 1) Since the base variant is one highly relevant example of how climate and climate related conditions may vary during a glacial cycle, the assessment analyses repository safety for this case. 2) Since the base variant is based on a repetition of the glacial cycle, which is the cycle that we have most knowledge about, this case provides essential knowledge on climate related processes of importance for repository safety, including important interactions between them. This knowledge is needed in order to treat and analyse the climate related processes in a realistic and integrated way. With the process knowledge from the last glacial cycle, *the base variant is valuable in the work on defining complementary scenarios that analyze relevant alternative cases not handled in the base variant.*

In the final assessment of risk, climate conditions are selected pessimistically within each scenario, where a scenario is related to a particular failure mode. For the failure modes contributing to risk, it is not essential to establish probabilities to the base variant or the greenhouse variant, but rather to identify the particular climate conditions to which these failure modes are sensitive and to make a cautious assessment of these conditions, building on the knowledge obtained from the analyses of the base and greenhouse variants.

SKB states that it is adequate to assume linear melting of the Greenland Ice sheet over the next 1,000 years (TR-06-09, page 375), but some recent references (e.g., Rignot, E. and Kanagaratnam, P. 2006. *Changes in the Velocity Structure of the Greenland Ice Sheet*, Science, vol. 311. no. 5763, pp. 986-990) suggest that melting may be accelerating and that Greenland could be de-glaciated much more rapidly.

c) **Given the uncertainties in the rates of ice sheet growth and melting, what would the consequences be for the repository of different long-term (e.g., faster) rates of ice sheet melting and sea-level change?**

Our results from the Global Isostatic Modelling for the Greenhouse variant shows that the sites remain above sea-level for a long time in this scenario. We also state that the uncertainties in the GIA modelling are large (including melt rates of Greenland ice sheet, thermal expansion of oceans and a possible collapse of the West Antarctic ice sheet), and furthermore that "for the present day, calculated rebound rates are larger than measured values, and in the early phase of the greenhouse variant, this means that relative sea level cold be constant or even raise" /TR-06-09 p. 375/. We further state that, after an early phase in the Greenhouse variant with these uncertainties, the results of the isostatic modelling suggest that in the long run both sites will be situated above sea level.

A temporary initial transgression in a warming climate, due to a Greenland ice sheet melting faster than in 1000 years, would induce a temporary situation with the sites covered by brackish water and, as a consequence of its infiltration by density effects, the groundwater conditions would become similar to those during the Littorina period. Such a submerged situation also occurs in the analysed scenarios, following a future ice sheet deglaciation. We conclude that such moderate groundwater salinity levels would not affect the repository function.

It is not clear that SKB's consideration of permafrost development under cold, dry conditions (TR-06-09, page 378 and Section 12.4) adequately captures the potential effects of the cooling that could occur as a result of shut-down of the North Atlantic thermohaline circulation.

d) **What is SKB's assessment of the probability of North Atlantic thermohaline circulation shut-down?**

To *adequately captures the potential effects of the cooling that could occur as a result of shut-down of the North Atlantic thermohaline circulation* is in the following interpreted as to show that the repository function is not affected by freezing due to such changes.

/IPCC 2007/ assess that a complete *shut-down* of the thermohaline circulation is not likely to occur, while a 25% reduction of the circulation is very likely. However, IPCC further projects that temperatures in the Atlantic region will increase despite such changes, due to the much larger warming associated with projected increase in greenhouse gases.

In the SR-Can scenario with cold dry conditions, the first permafrost occurs *significantly* earlier than in the base variant of the main scenario (after about 2000 years instead of 8000 years). The lengths of permafrost periods are also longer in the cool and dry climate case. An earlier permafrost development is expected if a regional cooling of Fennoscandia were to occur due to a major reduction of the thermohaline circulation. However, permafrost affect the repository function only if freezing of the buffer were to occur. Buffer freezing would require a very large lowering of the temperature, for example that the temperature curve of the last glacial cycle were to be lowered by more than 10 and 17 degrees for Forsmark and Laxemar, respectively /TR-06-09 p. 482-483/. In the unlikely case of a considerably less variable cooling climate than during the last glacial cycle, it would take 80,000 years for permafrost to reach repository depth if the annual mean temperatures of the Forsmark site were at a level of 15 degrees lower the at present /TR-06-09 p.483/. Such large and long temperature lowering is considered unlikely, even during full glacial conditions.

Based on the above results, and the IPCC 2007 assessment on variations in North Atlantic thermohaline circulation with associated changes in temperature in the North Atlantic region, we conclude that the potential effects of changes in thermohaline circulation can not induce the very severe temperature lowering required for buffer freezing.

In addition, we have initiated a climate modelling study that will provide additional information on the details of a future Fennoscandian climate affected by an increased Greenhouse effect.

Even if permafrost is unlikely at the waste emplacement depth what would the effects of permafrost be on the backfill and other EBS components in the shallower parts of the repository?

This is not assessed in SR-Can. The backfill in the ramp and shaft will most likely freeze during a permafrost period. The consequences of this have yet to be determined. It should, however, be noted that for the canister failure modes contributing to risk, the retention properties of these parts of the repository are irrelevant.

Peak Mean-Annual Dose Rate

In many of the ‘annual dose rate vs. time’ plots (TR-06-09, Section 10), the dose rate is still rising at 1 million years. The time period greater than 100,000 years is beyond SSI’s formal regulatory compliance period. Nevertheless, it might be useful and illuminating for the regulators to know the answers to these questions:

g) What is the peak dose rate for a given scenario/ variant case?

This has been calculated for the Forsmark advection/corrosion base case, i.e. the case presented in Figure 10-42 has been extended, as a response to this question, see the below figure. The peak calculated dose is around 4 mSv, i.e. about four times the background radiation. For the extended calculation, it is simply assumed that canister corrosion and fuel alteration continues at the same rates as in the one million year timeframe and that the transport properties of the host rock are not altered. Probabilistic calculation, 10,000 realisations, analytical model.

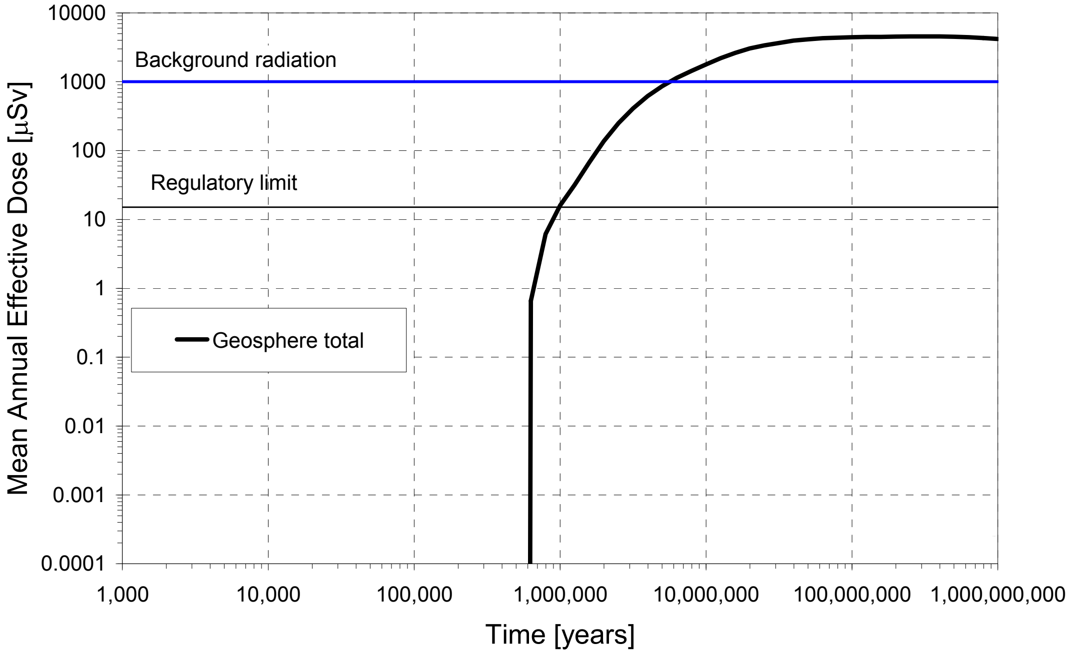


Figure 1. The case in Figure 10-42 of TR-06-09 extended to 10^9 years.

h) When does this peak occur?

In this very hypothetical calculation, it occurs at around 100 million years.

i) What are the primary radionuclides contributing to this dose rate?

As for the one million year period, Ra-226, generated from the decay of U-238 dominates.

Optimisation

SKB notes that there have been many design changes over the course of the repository development programme (TR-06-09, page 78).

j) Is there a centralised project record identifying and explaining the reasons for the various changes that have been made to the original KBS-3 design since it was originally described in 1983?

No, there is no such centralised project record. SKB's triannual RD&D-programmes have described the development over the years. In a recently published so called system's analysis report (SKB R-06-117, in Swedish) there's a summary of the historical development with emphasis on the canister.

Future Human Actions and Biosphere Assumptions

SKB seems to take credit for assumed actions ('*canalisation'*) by future generations in the long-distant future (after 1,000 years post-closure) (TR-06-09, page 229).

k) **What is the justification for the assumption that canalisation will be undertaken in the future?**

l) **What assumptions does SKB make about the effectiveness of canalisation across the potentially contaminated area, and how are these assumptions justified?**

This is a misunderstanding caused by the use of a “Swenglish” word. The meaning is the natural development of a stream network. Thus it is a natural process and no actions of future humans are assumed.

Assessment Model Flowcharts

The various Assessment Model Flowcharts (AMFs) in SR-Can (TR-06-09, Section 6, Figures 6-3 and 6-4) have, of necessity, been simplified and so do not show the full set of Features Events and Processes (FEPs). Although the AMFs may form the basis for model conceptualisation and for technical exchanges on safety analyses, it would seem important that the AMFs capture the relevant and risk-significant processes and their inter-relationships.

m) **What is the meaning or interpretation of boxes in the AMFs (e.g., ‘Early Chemical Alteration’, ‘Hydraulic Conductivity and Swelling Pressure’, etc.) that do not apparently influence the output of the AMFs, (i.e., the lower right-hand box called ‘Doses’)? Does the lack of connectivity between such process boxes and the ‘Doses’ boxes, imply that the processes are not-significant to dose? If these processes significantly affect dose (and it would seem that they might), shouldn’t the AMFs show direct links from such processes to ‘Doses’?**

The results of the early chemical alterations and effects, see section 9.2.5, do actually not influence the dose.

The box ‘Hydraulic Conductivity and Swelling Pressure’ does not affect dose unless a substantial loss of buffer occurs, in which case advective conditions may be created in the buffer. This latter effect is however captured by the boxes ‘Density distribution‘ and ‘Advection?’. The structure of the AMF could be improved on this point.

Monitoring

SKB states that ‘*…monitoring of the engineered barriers may also be considered / see Bäckblom and Almén 2004/.*’ (TR-06-09, page 146). However, Bäckblom and Almén 2004 (R-04-13) state, ‘*There are of course still many open questions to address with respect to monitoring, not the least concerning monitoring of the open repository to collect data to verify barrier performance before closing the repository.*’

n) **What progress has SKB made in defining the monitoring programme, particularly for the EBS, since publication of R-04-13?**

During the last few years SKB has gained considerable experience on the monitoring of the EBS from current experiments at the Äspö HRL, e.g. the Prototype Repository and the Canister retrieval test. The evaluation of these experiments will provide valuable input to SKB's considerations concering possible monitoring of barrier performance during repository operation.

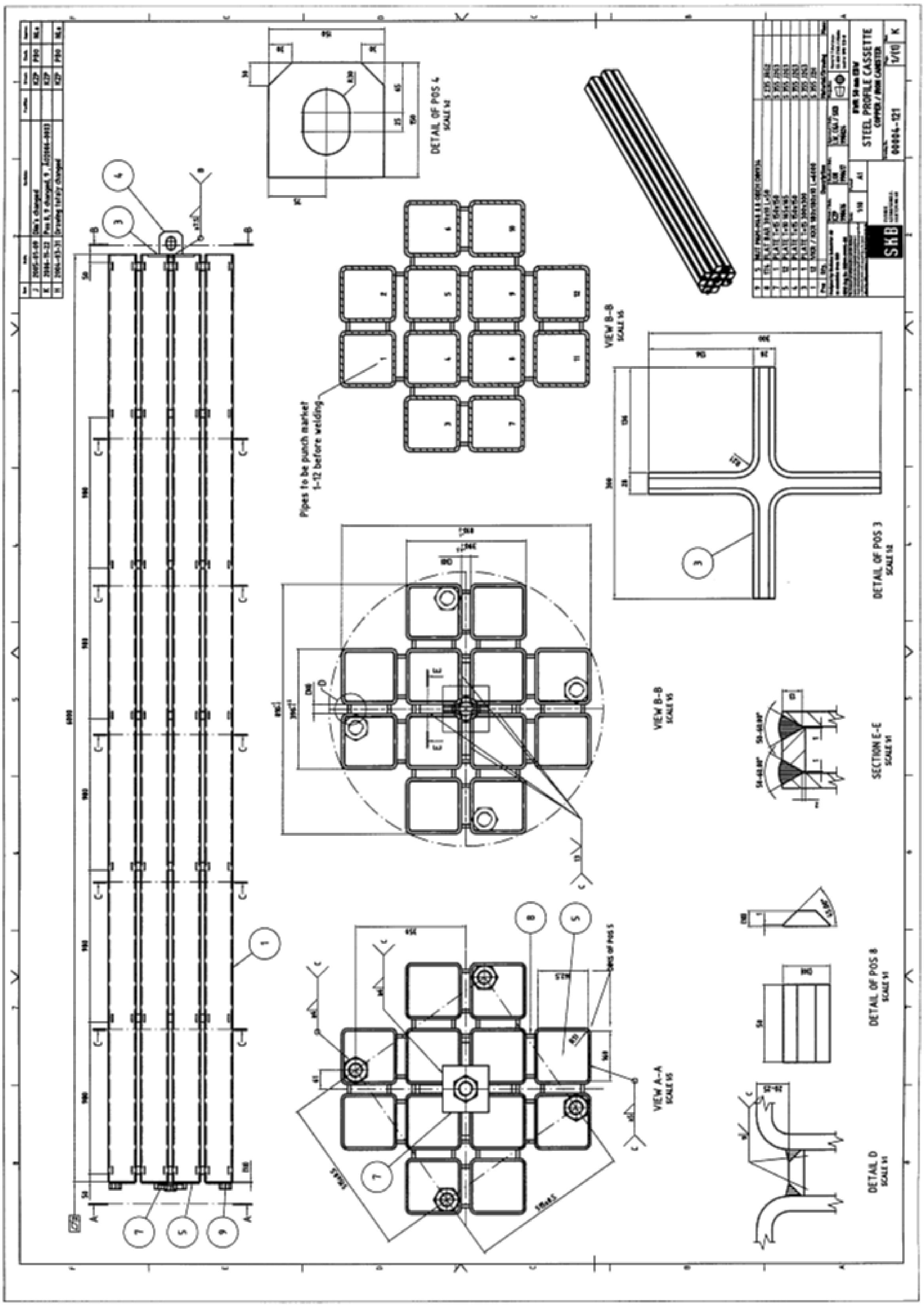
Analogues

SKB states that there is no general account of how natural analogues support the safety arguments in SR-Can (TR-06-09, page 524). (Note added by SKB: Should be p. 542.)

o) In view of SKI/SSI’s emphasis on the importance of providing supporting arguments as well as a quantitative safety assessment, how does SKB justify its approach to the use of analogues?

The amount of material regarding natural analogues is quite substantial, in particular in the Climate report and the Geosphere process report, but also in the process reports for the canister and the buffer. Due to time constraints no general account of how natural analogues support the safety arguments was provided in the SR-Can main report. This could be included in the SR-Site assessment, and would then essentially be a summary of the material already present in the Process reports, i.e. an extension of the examples given on page 542. See also response to second part of question 7 from the safety assessment methodology group.

Design drawing of the canister insert



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STATENS KÄRNKRAFTINSPEKTION
Swedish Nuclear Power Inspectorate

POST/POSTAL ADDRESS SE-106 58 Stockholm
BESÖK/OFFICE Klarabergsviadukten 90
TELEFON/TELEPHONE +46 (0)8 698 84 00
TELEFAX +46 (0)8 661 90 86
E-POST/E-MAIL ski@ski.se
WEBBPLATS/WEB SITE www.ski.se