Strål
säkerhets
myndigheten
Swedish Radiation Safety Authority

Authors: Michael J. Apted
David G. Bennet
Timo Saario
David Savage
Peter Segle
Göran Sällfors

2009:35

Evaluation of SKB/Posiva's report on the horizontal alternative of the KBS-3 method

Report number: 2009:35 **ISSN:** 2000-0456
Available at www.stralsakerhetsmyndigheten.se

Title: Evaluation of SKB/Posiva's report on the horizontal alternative of the KBS-3 method
Report number: 2009:35
Author/Authors: LMichael J. Apted, David G. Bennet, Timo Saario, David Savage, Peter Segle and Göran Sällfors
Date: October 2009

This report concerns a study which has been conducted for the Swedish Radiation Safety Authority, SSM. The conclusions and viewpoints presented in the report are those of the author/authors and do not necessarily coincide with those of the SSM.

Background

The KBS-3 method, based on multiple barriers, is the proposed spent fuel disposal method both in Sweden and Finland. The method has two design alternatives: the vertical (KBS-3V) and the horizontal (KBS-3H). SKB and Posiva have conducted a joint research, development and demonstration (RD&D) programme in 2002-2007 with the overall aim of establishing whether the KBS-3H represents a feasible alternative to the reference alternative KBS-3V. The objectives have been to demonstrate that the horizontal deposition alternative is technically feasible and that it fulfils the same long-term safety requirement as the KBS-3V.

Swedish Radiation Safety Authority (SSM) considers that it is a proper time to evaluate the work carried by SKB and Posiva when this period of joint research is ended and a relatively complete set of reporting is available. SSM therefore required its external expert group BRITE (the Barrier Review, Integration, Tracking and Evaluation) to evaluate the reporting.

Objectives of the project

The aims of the evaluation are to investigate the differences between the horizontal and vertical design alternatives with respect to:

- Completeness: has SKB/Posiva identified the full set of key topics, and if not, what additional specific key topics should be evaluated;
- Depth-of-treatment: has SKB/Posiva analysed the key topics in sufficient depth, and if not, on what specific aspects in more detailed consideration required;
- Status of information: has SKB/ Posiva provided enough information on the current status of knowledge and uncertainties that impact the understanding of each key topic, and if not, what further information should be cited;
- Feasibility and practicality: for key issues related to the fabrication and emplacement of the two different designs, has SKB/ Posiva provided sufficient demonstration (or detailed plans for demonstration) of engineering feasibility and practicability to allow confident evaluations to be made regarding the likelihood of resolving these issues;
- Impact on long-term safety: for key issues that are resolved, would the differences in the design have significant impact on the long-term safety;

- Resolution strategy: for key issues that are not yet resolved, has SKB/Posiva identified a feasible work programme and schedule for resolving each issue. Will these key issues have possible significant impact on the long-term safety if possibly be resolved?

Results

The initial reporting on the KBS-3H conceptual design made by SKB and Posiva presents only preliminary information and analyses, and considerable uncertainties remain that limit the ability to fully assess the feasibility and long-term safety of the KBS-3H design concept. Only preliminary comparisons can be made between the KBS-3H and KBS-3V design alternatives in this report.

The preliminary comparisons indicate that there are processes and design specifications that are rather different in the two design alternatives and they may have important impact on the long-term safety. Further RD&D work is needed for SKB and Posiva to fully resolve the issues.

Content

1. Purpose

The BRITE group supports the Strålsäkerhetsmyndigheten (SSM, the Swedish Radiation Safety Authority) in providing independent evaluations of topics and issues associated with the engineered barrier system (EBS) of the planned deep geological repository for the disposal of Swedish spent nuclear fuel (SNF). As part of this independent support to SSM, the BRITE group was requested to evaluate the recent series of reports produced by SKB in Sweden and Posiva in Finland on the so-called "KBS-3H" concept design.

In the KBS-3H concept, copper canisters loaded with SNF are encased in a compacted bentonite buffer with an outer supporting supercontainer composed of a mild steel basket, and the entire supercontainer is emplaced horizontally in long emplacement drifts (Figure 1-1).

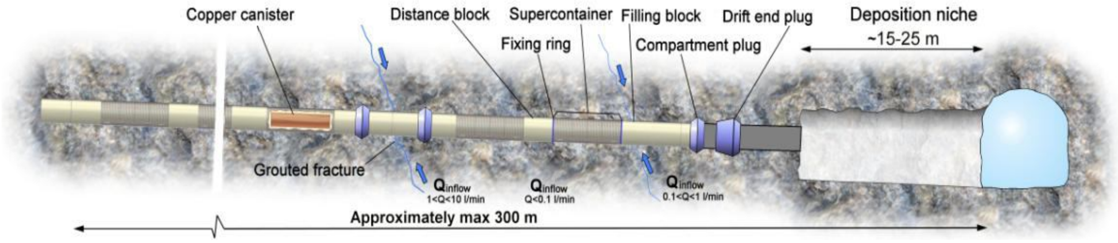

Figure 1-1 The Basic Design for KBS-3H (SKB, 2008, TR-08-03).

The SKB/Posiva reports cover a wide range of topics, including:

- design variants under consideration,
- field demonstration of emplacement techniques,
- laboratory tests examining behavior of EBS components under simulated repository conditions,
- computer-aided analysis of EBS behavior under changes in repository conditions,
- scoping analyses using performance assessment models to estimate impacts on long-term radionuclide release rates for various speculative 'what if?" scenarios,
- identification of remaining uncertainties in assessing the feasibility and safety of the KBS-3H concept, and
- plans to further address and resolve these remaining uncertainties.

The SKB/Posiva reports also present and contrast differences between the KBS-3H conceptual design and the reference KBS-3V design in which essentially the same EBS components of bentonite buffer, copper canister and spent nuclear fuel (SNF) are emplaced vertically, but without a steel basket.

The aims of BRITE's evaluation of the KBS-3H reports have been to investigate the information presented by SKB and Posiva on the KBS-3H conceptual design with respect to:

- completeness: have SKB/Posiva identified the full set of issues that need to be considered when assessing the feasibility and safety of the KBS-3H design, and if not, what additional specific key topics should be evaluated?
- impacts: what are the impacts of these issues on feasibility and long-term safety.
- resolution strategy: for key issues that are not yet resolved, have SKB/Posiva identified an appropriate, feasible work programme and schedule for resolving each issue?
- differences between the KBS-3H and the KBS-3V designs: do these differences have significant impact on operational feasibility and/ or long-term safety of the repository?

The BRITE group was requested to address certain key topics in their evaluation of the KBS-3H concept and supporting reports (Table 1-1).

The following sections of the report contain the collected evaluations by the BRITE group on the topics identified in Table 1-1. A final summary section presents a collective evaluation of the status and remaining key areas of concern with respect to demonstrating the feasibility and long-term safety of the KBS-3H conceptual design.

Table 1-1 KBS-3H evaluation topics.

	Topic Descriptions
1	Assessment of the feasibility of repository and EBS construction and implementation (e.g., including the accuracy of deposition drift construction, supercontainer assembly and emplacement, and drift/ access tunnel sealing). Demonstration of reproducible, quality assured waste and EBS emplacement technologies
2	Rock spalling and effects
3	Water inflow to the deposition drifts from fractures in the host rock and the ability to seal such fractures
4	Piping and erosion of the bentonite buffer
5	Sealing of deposition drifts (seals, buffer and distance blocks)
6	Corrosion of steel components external to the canister
7	Effects of steel corrosion on bentonite and radionuclide transport.
8	Impact of gas from the corrosion of steel components external to the canister, gas flow and implications
9	Impact of leachates from cementitious components
10	Processes within horizontal failed canisters. (e.g., expulsion of water and dissolved radionuclides from a defective canister interior by gas)
11	Implications of the horizontal arrangement with respect to potential for earthquake shear
12	Long-term performance differences, based on integration of evaluation of Topics 1 to 11

2. Assessment of the feasibility of repository and EBS construction and implementation

2.1 Issue description

Many of the safety issues identified by SKB/Posiva are based on the assumption that a KBS-3H repository can be constructed and operated safely. Conversely, many of the other safety issues considered in later sections of this report could adversely impact the feasibility of constructing and safely operating a KBS-3H repository, for example inflow of groundwater and potential rock spalling. As described in Topic 3 on control of inflow groundwater, for example, it is already evident that the initial Basic Design (BD) is probably not suitable, and that alternative design variants are under active evaluation.

2.2 SKB/Posiva's perspective

SKB/Posiva acknowledge that there remain a number of design issues outstanding that will have to be addressed in future studies. Should these studies result in significant changes to the Basic Design (BD) and greater reliance on either the Drainage, Artificial Watering and air Evacuation (DAWE) or Semi-Tight Compartment (STC) variant designs, then these changes could have implications for the key safety issues considered in the present evaluation. Specific uncertainties identified by SKB/Posiva regarding design, operational and emplacement developments are summarized in Section 4.7, SKB, 2008.

2.3 BRITE comments

Issues regarding operational and construction feasibility are among the most difficult for SKB/Posiva to convincingly show resolution because they should involve large-scale and reproducible demonstrations of technology under *in situ* conditions and with actual EBS materials. Furthermore, application of bounding analyses (see Smith et al., 2008) to resolve an issue are generally not suitable for design, construction and operational questions because relevant and defensible "bounds" of parameters often cannot be identified without demonstration at relevant scales and working conditions.

For these reasons, SKB and Posiva have identified a further set of studies on the KBS-3H conceptual design through at least 2012 (SKB, 2008). While it is premature to judge the viability of the KBS-3H concept at this preliminary stage, it is important to note that SKB/Posiva have shown excellent progress in underground demonstrations of the prototype KBS-3H emplacement technology at full scale. Based on considerable underground demonstrations and laboratory testing by SKB/Posiva, there are no indications of any "show-stoppers" that would imply the KBS-3H concept is not viable. However, tests and trials have not been completed for all of the proposed EBS components, and further work is certainly required.

SKB/Posiva intend to carry out a number of further studies addressing design issues, including: 1) avoidance of distance block displacement and deformations; 2) avoidance or limitation of thermally induced rock spalling; 3) alternative supercontainer materials; and 4) layout to avoid potentially problematic fractures (see Smith et al., 2008). Certain design features, such as the nature of materials used in filling blocks, and operational features, such as the use of mega-packers to inject grouts into fractures, also appear to be in a state of continuing development. Details regarding future studies in these areas are not provided in the reviewed documentation, so it is not possible to evaluate the likelihood or timeliness of possible successful resolution to these issues.

There are certain key operational steps that are of particular interest at this time. First, the fabrication, handling, transportation and emplacement of the assembled supercontainer into the underground emplacement drift are yet to be fully integrated and demonstrated. Successful demonstrations of emplacing equivalent weight cement supercontainers need to be extended to emplacement of actual bentonite-based supercontainers, which could prove to be less durable and inert (with respect to hydration and expansion) compared to the previous cement proxy. Second, the megapacker with silica sol gel has been shown to successfully seal high-flow fractures (Topic 3). The durability of this sealing compared to the necessary timeframe for overall emplacement of multiple supercontainers in a 300-m long drift, however, has not yet been confirmed. Third, the potential for spalling (Topic 2), especially in the relatively dry and high stress host rock at Forsmark, and potential design/operational countermeasures (induced saturation of buffer) remain to be reliably demonstrated. Lastly, additional design concerns, possibly affecting construction and operations, are articulated in other sections of this report.

In summary, the various KBS-3H reports present a reasonably complete documentation of the progress-to-date for the KBS-3H conceptual design, and associated issues. Inability to eventually resolve remaining aspects of construction, operations and emplacement of supercontainers would probably prevent the viability of the KBS-3H design concept. As noted above, "bounding analyses" are unlikely to be suitable for resolving outstanding construction, operations and emplacement issues; only eventual full-scale, reproducible demonstration under *in situ* conditions can fulfil the necessary requirements for confidence in the KBS-3H design concept.

3. Rock spalling and effects

3.1 Issue description

If the local stress field in a deposition hole diverges from the stress field assumed based on regional measurements, excavation-induced rock spalling may occur and the deposition tunnel may be damaged and lose its circular shape. Thermally induced stresses from emplaced supercontainers could further exacerbate stress anisotropy in the rock, leading to enhanced spalling. Furthermore, where the host rocks are relatively “dry”, the delay in resaturation of the buffer would act to prevent the buffer from swelling, and this, in turn, would mean that the buffer would not act to prevent further spalling of the rock. This could possibly cause enhanced spalling, a greater depth of spalling, and circumferential extension in the borehole wall.

The potential for rock spalling has several implications:

- First, spalling may adversely impact the feasibility of emplacement of supercontainers over the targeted 300-m length of a deposition drift.
- Second, in wetter host rock regions, a high groundwater pressure difference could develop rapidly in the void volume created by the rock spall, resulting in enhanced piping and erosion of the bentonite, and a reduction in swelling pressure that might lead to enhanced thermally-induced spalling and generally adverse conditions.
- Third, spalling could result in changed groundwater-flow conditions at the buffer - host rock interface. Enhanced flow at this boundary could affect radionuclide transport rates.

3.2 SKB/Posiva’s perspective

Smith et al. (2008, Section 7, pages 97-98) approaches the potential impacts of thermal spalling of rock by setting up a sensitivity case, PD-SPALL, where a thermally induced spalling region is treated as a highly conductive mixing tank boundary condition to an initially failed canister. PD-SPALL assumes that spalling occurs in a region of relatively hydraulically tight rock, with groundwater flow lower than that assumed in cases assuming mechanical disruption by other factors such as effects of steel corrosion products. SKB/Posiva do acknowledge that thermally induced spalling could occur in less tight sections, although calculations with higher groundwater flow were not made. The results of PD-SPALL show a slight decrease in peak release rate compared to the base case (see Figure 9-10, Smith et al., 2008).

3.3 BRITE comments

Scoping calculations in Smith et al. (2008) only address one of the several possible performance and feasibility impacts of rock spalling. The impact on operational feasibility (i.e., emplacing supercontainers along 300-m lengths of the emplacement drift that might be experiencing spalling), and the potential for enhanced piping and erosion during both the operational and the far-future glacial periods are not addressed directly.

In order to avoid/minimize spalling of the KBS-3H emplacement drifts, SKB/Posiva would have to attempt orient the deposition drifts parallel with the direction of the maximum horizontal principal stress, which may vary spatially. If deposition drifts in the KBS-3H concept are oriented incorrectly with respect to the maximum principal stress, major spalling of the deposition holes would likely result. Furthermore, the most adverse situation of spalling would likely develop in case of dry sections of deposition drifts where there is no early counter-pressure arising from the resaturation and swelling of the buffer. It is noted that the recently selected Forsmark site is believed to be characterized by dry conditions and possibly by relatively high anisotropic stresses.

If spalling occurs before supercontainer emplacement and this is observed or detected, SKB/Posiva have then to decide either to abandon the deposition hole and fill the opening with buffer material, or to develop a technique to install the supercontainer and fill the gap from the spalling with buffer material. If the spalling causes a volume loss, it must not be so large that it leads to an unacceptable loss of density of the bentonite due to swelling and filling of the void. No method for possibly compensating the volume loss has been proposed or discussed, nor has a critical volume loss been determined for when the standard procedure is insufficient.

There are some other difficulties that might arise, depending on whether BD, DAWE or STC design variants will be used. For BD the tolerances are small and even minor events of spalling might jeopardize the placing (or retrieval) of the supercontainer if the spalling is not dealt with.

The gap between the supercontainer and the rock wall for the DAWE case is large enough so that spalling might not necessary jeopardize the transport of the supercontainer. However, if spalling occurs before the pipes for the artificial wetting are withdrawn, such spalling might severely complicate the procedure of withdrawal.

In conclusion, spalling appears to be a potentially significant issue that has not yet been fully assessed, and for which engineering solutions are still under development.

4. Water inflow to the deposition drifts

4.1 Issue description

Water inflows to the repository drifts may, amongst other things, affect:

- The feasibility of waste emplacement.
- The locations that can be used for waste emplacement.
- The requirements for flow controls and sealing of fractures.
- The rate of bentonite hydration and swelling.
- Piping and erosion (see Topic 4), and the generation and transport of colloids.
- The transport of dissolved substances to the supercontainer and the canister, and, therefore, their corrosion rates and the rate of gas production (see Topic 5).
- The transport of radionuclides.

Water inflows depend on rock hydraulic conductivities and, in tighter drift sections, on gas pressures possibly developed by corrosion of engineered barrier system components.

There may be significant spatial heterogeneity along each drift and between drifts.

4.2 SKB/Posiva's perspective

SKB/Posiva's approach is to manage water inflows by designing and implementing a suitable engineered barrier system.

In their assessments SKB/Posiva distinguish three host rock water-inflow regimes (Table 4-1):

Table 4-1 Three Host-rock water-inflow regimes considered for the KBS-3H conceptual design.

	Host rock hydraulic conductivity (m/s)	Time to full buffer saturation for the KBS-3H Basic Design (years)
‘Less tight sections’	K > 1E-12	10 to 20
‘Tight sections’	1E-13 < K < 1E-12	20 to 200
‘Tightest sections’	K < 1E-13	a few 1,000s to a few 10,000s

Although SKB/Posiva note that distinguishing between the Tight and Tightest sections in the real repository might be difficult in practice.

SKB/Posiva are considering three variants of the KBS-3H design, each with differing arrangements for the management of water inflows:

- The Basic Design (Figure 4-1).
- The DAWE (Drainage, Artificial Watering and air Evacuation) Design (Figure 4-2).
- The STC (Semi-Tight Compartment) Design (Figure 4-3).

Key features of the Basic Design include:

- Pre-excavation and post-excavation grouting using silica sol or low-pH cements in order to seal fractures in the host rock and reduce water inflows. SKB/Posiva have developed and demonstrated use of a ‘Mega-Packer’ tool for the sealing of fractures that intersect the repository drifts. However, because grout penetration and fracture sealing cannot be directly measured during grouting, and the long-term performance of the grouts and fracture seals are uncertain, they are not relied on for long-term performance.
- Compartment plugs will be used to seal off drift sections where water inflows are still >1 l/min over a 10 m length of drift after grouting. The design of the compartment plugs is still in progress and demonstration tests are planned at the Äspö underground research laboratory.
- Filling blocks will be used for other unsuitable sections of rock that are not sealed with compartment plugs. Filling blocks will be used where water inflows are 0.1 to 1.0 l/min over a 10 m length of drift.

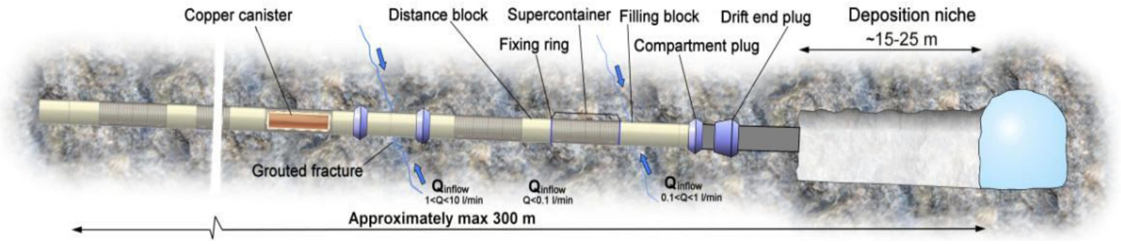

Figure 4-1 The Basic Design

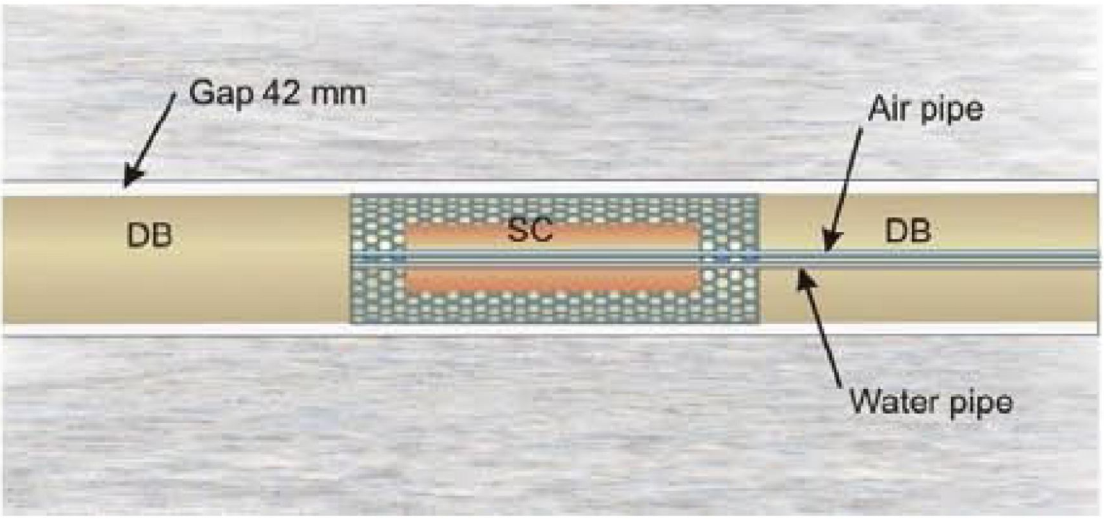

Figure 4-2 The DAWE Design

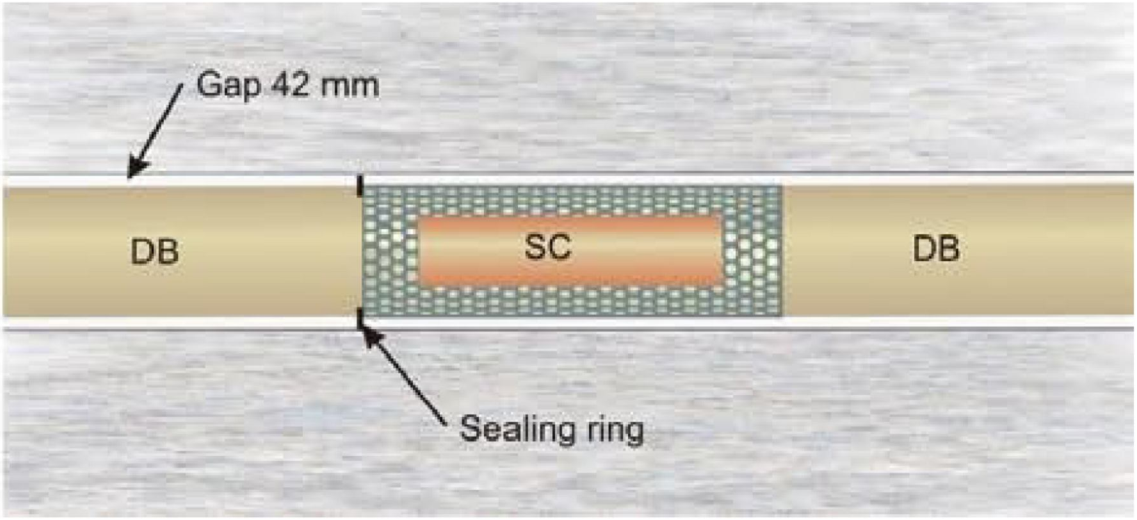

Figure 4-3 The STC Design

- Distance blocks will be used to prevent flow between adjacent supercontainers. Distance blocks will be used for flows of up to 0.1 l/min over a 10 m length of drift.

Key features of the DAWE Design include:

- A system of removable steel pipes with watering nozzles, which would be used to actively drain the drifts during the operational phase, and then, after plugging of the drift, would be used to wet the bentonite components, with the aim of ensuring a more homogeneous buffer saturation. Other 'air' pipes would be used to remove the air from the drift as the wetting proceeds, so that the drift and bentonite components are fully wetted. All of the pipes would be removed after use.
- A slightly inclined drift. Slightly larger, 42 mm, gaps around the distance blocks. Bentonite with a higher initial water saturation to prevent buffer cracking and/or disintegration during the longer period of partially saturated conditions.

The STC design is only at the conceptual stage. In the STC Design, each supercontainer section would be sealed with distance blocks and sealing rings that temporarily prevent water from flowing from one supercontainer section to another before the section is filled with inflowing water. Once the section is filled with water, the water flows into the next section. Since there are no demands on the distance blocks and sealing rings except to provide a seal for hydrostatic water pressure of a few metres, the blocks can be made with the same gap between rock and block as the supercontainer (SKB 2008).

SKB/Posiva note that (at least for the Basic Design) it is possible that some of the buffer will not saturate fully for thousands of years where the host rock has low hydraulic conductivity and water inflows are slow.

4.3 BRITE comments

SKB/Posiva seem to have identified the issues and processes relating to water inflow that might occur and there are no obvious gaps. SKB/Posiva have presented some scoping calculations of flows into and within the drifts (Gribi et al., 2008, Section 4.5). Further, more detailed calculations would be needed in future iterations of the safety assessment for the Swedish context, particularly to take account of site-specific conditions and water flows.

It is clear that the control and management of water inflows is very important to the feasibility and practicality of repository and EBS design and implementation, and waste disposal. Water inflows will affect where canisters can be disposed of, and will influence the choice of EBS design and the size and layout of the repository.

Some ‘uncomfortable’ cases that have the potential to make the use of a drift for disposal difficult are possible, and these may need to be considered further on a site-specific basis. Such cases include the effects of fairly regularly spaced flowing fractures that intersect a horizontal drift, and the effects of sub-horizontal fractures at the drift level. Another issue is that successful identification and management of regions with higher flows may be made more difficult because grouting may cause diversion of water flows to neighbouring fractures, possibly in what appear at first sight to be drier regions.

As noted above, water inflows may have a potentially important effect on long-term safety, but SKB/Posiva’s approach is to ensure adequate safety by developing a suitable design. That is, SKB/Posiva assume that a technical solution will ensure that acceptable long-term safety will be provided. However, formal links between repository design and long-term safety have not been made. No safety functions have been defined for KBS-3H specific EBS components.

In terms of SKB/Posiva’s strategy for addressing the remaining uncertainties, BRITE considers that further demonstration and long-term testing will be essential to assess whether the concept for the different sealing components is feasible. SKB/Posiva should provide more details on their future programme for testing and demonstrating feasibility, and for strengthening links between repository design and long-term safety.

With respect to completeness, the various KBS-3H reports indicate that SKB/Posiva understand the range of effects and processes related to water inflows, and have presented some initial assessments of their impacts on safety and feasibility. Further, more detailed assessments and testing will be needed to support future engineering design work, safety assessments, and safety cases.

Regarding potential impacts, water inflows have the potential to significantly affect safety and feasibility, and their successful control and management will be key to any safety case for disposal by the KBS-3H method. SKB/Posiva are still actively working on the KBS-3H design. It appears that the Basic Design (BD) has been superseded, and that the DAWE design is currently the main candidate for deployment. However, further design and testing work is on-going and it may be expected that the details of the design will change as the KBS-3H programme matures over the coming years. Some of the engineering techniques (e.g., grouting and EBS installation) are also at the research stage and are not yet available for deployment.

Finally, SKB/Posiva have conducted some useful trials and demonstrations of drift boring, and of fracture grouting using the Mega-Packer to begin to address and to resolve these issues. However, they recognise that further testing and research is necessary. SKB/Posiva should provide more details on their future programme for testing and demonstrating feasibility, and for strengthening links between repository design and long-term safety.

5. Piping and erosion of the bentonite buffer

5.1 Issue description

Severe piping and erosion of the buffer could cause the buffer not to fulfil its safety functions. For example, the bulk hydraulic conductivity of the buffer could increase. This could allow increased sulphide transport to the canister, which could cause more rapid canister corrosion, leading to canister failure.

The KBS-3H design may be more vulnerable than KBS-3V because piping and erosion could connect between canisters and cause multiple canister failures.

The key driving forces for bentonite piping and erosion are water inflow rates and hydraulic (water and gas) pressure gradients along the drifts.

5.2 SKB/Posiva's perspective

SKB/Posiva believe that piping and erosion of distance blocks are unlikely, as long as water inflows are < 0.1 litre/minute (Smith et al., 2008), but this depends on:

- Successful identification and management of regions with higher flows (see Topic 3).
- An assumption that hydraulic pressure gradients do not cause mechanical displacement or deformation of the distance blocks.

Poor placement, minor movement, or deformation of the distance blocks could cause the hydrostatic pressures to overcome the steel fixing rings, and this could lead to piping and loss of buffer material (Figure 5.1). SKB/Posiva suggest that this may be a 'critical' issue affecting the Basic Design. Further design developments are being considered to improve the robustness of the engineered barrier system with respect to possible distance block deformation and displacement by hydraulic pressure differences.

SKB/Posiva (Smith et al., 2008) argue that, *"Even if piping were to occur, the limited duration of flow before the downstream void spaces became water filled would limit its potential to cause redistribution of buffer mass (at least once a compartment had been plugged). Assuming rapid homogenisation of any local density reductions, the scoping calculations presented in Appendix B.4 of the Evolution Report indicate that redistribution of buffer mass is unlikely to lead to buffer densities, swelling pressures or hydraulic* *conductivities outside the ranges set by the safety function indicator criteria. Thus, transport of dissolved species within the buffer is expected to remain diffusion dominated, although the diffusion coefficient of the buffer could conceivably be increased to some extent, as assumed when evaluating the potential impact of piping and erosion on canister lifetime and on radionuclide release and transport.*

It should also be noted that there are significant uncertainties in the degree to which the buffer would homogenise following significant localised erosion. Homogenisation will be resisted by internal friction within the buffer and friction between the buffer and fixed surfaces. Börgesson and Hernelind (2006) carried out a modelling study of the homogenisation of a KBS-3V buffer, including the resealing of pipes and buffer swelling following a local loss of buffer mass, e.g. due to piping. The calculations showed that, due to friction, locally decreased densities and swelling pressures and increased hydraulic conductivities will persist indefinitely. Thus, avoidance of significant piping remains a critical issue in repository design."

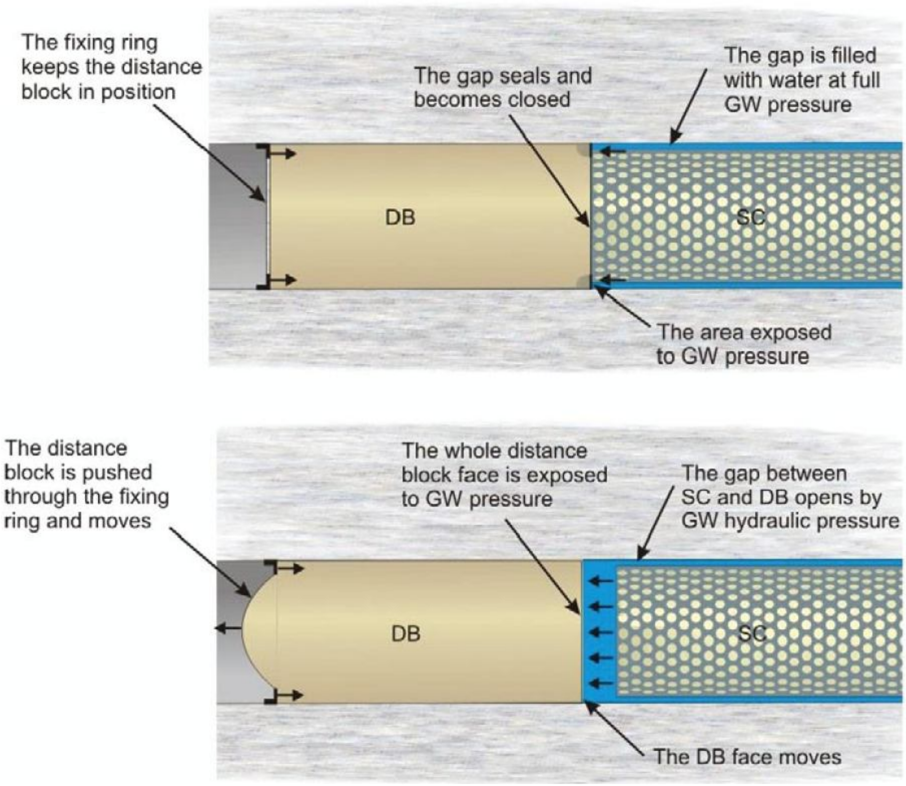

Figure 5.1 Illustration of the potential for movement and deformation of the distance block, DB, if there is a gap between it and the supercontainer, SC, and hydraulic pressure is exerted over the face of the distance block (SKB 2008; TR-08-03).

SKB/Posiva have identified several possible pathways for the transport of water and suspended buffer material (Figure 5.2).

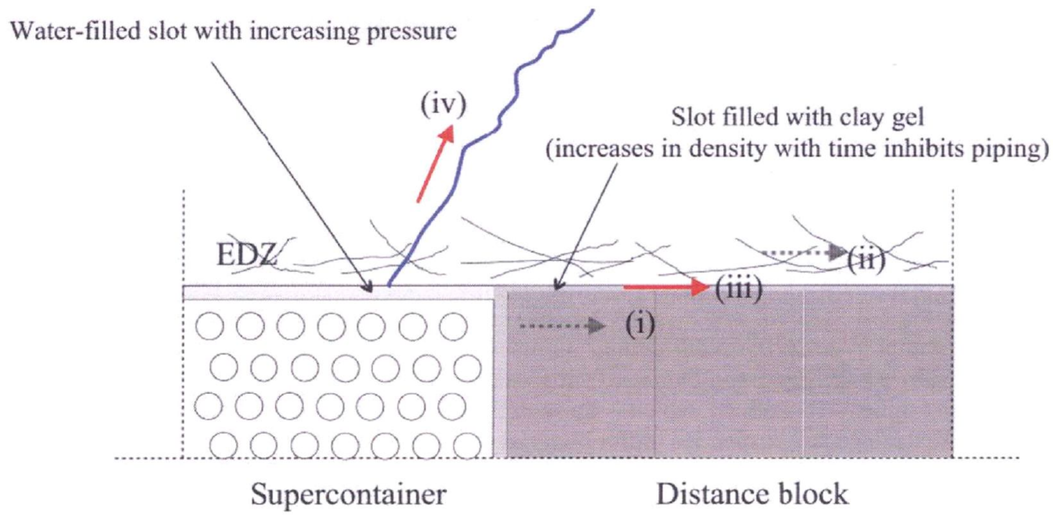

Figure 5.2 Potential paths for the transport of water and suspended buffer material (ii), (iii) and (iv). In the case of path (i), suspended buffer material would be filtered and unable to migrate (SKB 2008, TR-08-03).

5.3 BRITE comments

SKB/Posiva have identified a range of processes and effects related to piping and erosion. However, it is too early to be certain that this is comprehensive.

SKB/Posiva have presented some scoping calculations on the impact of loss and redistribution of buffer (Smith et al., 2007a, pages 89-90 and Appendix B.4). These are scoping calculations, not detailed calculations of the type commonly used for thermo-hydro-mechanical calculations. Also, some processes have not been assessed in any detail (e.g., gas piping). Key uncertainties identified during the scoping calculations include the properties of the excavation-damaged zone (EDZ), the flow paths that may be active, the duration of flows, and how much bentonite can remain in colloidal suspension.

SKB/Posiva recognise that "*it is unclear whether all possibilities regarding piping and erosion can be addressed in such calculations, because of uncertainties associated with some of the assumptions. Therefore, these results are not sufficient to give guidance on the design requirements regarding the avoidance of piping and erosion*."

Overall, SKB/Posiva have provided a reasonable picture of the status of knowledge and uncertainties, but the issue is still one of active research, and the assessment of the effects of piping and erosion is not yet comprehensive or complete. It is notable, however, that the KBS-3H assessment calculations do not assume such large buffer mass losses as in the SR-Can Safety Report.

The impact of piping and erosion on long-term safety has been considered in the KBS-3H assessment by assuming that the amounts of piping, erosion and mass redistribution are minor and that the buffer re-homogenises, and by increasing the diffusion coefficient applied to the buffer.

SKB/Posiva's calculations with an increased buffer diffusion coefficient do not give significantly different results from those of the base case. However, re-homogenisation of the buffer after erosion is a key uncertainty because it may affect buffer densities, swelling pressures, effective diffusivities, canister failure rates and radionuclide transport rates. Further research and assessment calculations would be necessary to support the assumption of buffer re-homogenisation, and to determine the impacts if the buffer does not re-homogenise.

In terms of SKB/Posiva's strategy for addressing the remaining uncertainties, SKB/Posiva note that:

- *"The evolution of the buffer, including the possibility of erosion by transient water flows (piping) during operations and subsequent saturation, drying/wetting, impact of iron saturation and cementation due to silica precipitation are all issues requiring more thorough investigation. Limitation of piping and erosion is discussed further in the context of design issues'*
- *'There is currently no adequate quantitative understanding of chemical erosion of the buffer following the potential penetration of dilute glacial meltwater to repository depth"*

Although SKB/Posiva recognise the need for further work, in the reports reviewed they have not described a detailed systematic programme or plan for resolution of these uncertainties. With respect to completeness, SKB/Posiva have provided a reasonable picture of the status of knowledge and uncertainties, but the issue is still one of active research, and the assessment of the effects of piping and erosion is not yet comprehensive or complete.

Regarding potential impacts, the consequences of piping and erosion on long-term safety has been considered in the assessment in a limited way and assumptions have been made that need further support. Finally, SKB/Posiva recognise that resolution of this topic will need for further work, but in the reports reviewed they have not described a detailed systematic programme or plan for resolution of these uncertainties.

6. Sealing of deposition drifts

6.1 Issue description

The deposition drifts must be sealed to prevent or acceptably minimize the inflow of groundwater from the fractured host rock and thus minimize the potential for piping and erosion of the buffer material. The horizontal orientation of the KBS-3H conceptual design presents both challenges and opportunities for sealing that are similar or could be different than those for the KBS-3V conceptual design.

6.2 SKB/Posiva's perspective

The 300 m long horizontal drift with its supercontainers will be filled and sealed using *Distance Blocks, Filling Blocks,* and *Compartment Plugs*. In addition, *Drift End Plug* closes off the whole drift and separates it from the *Deposition Niche*, which in turn will be filled and closed with *bentonite blocks and pellets*, in the same way as for the KBS-3V.

As described above, three different design concepts are under consideration, namely the basic design, BD, the artificial wetting and air evacuation design, DAWE, and the semi tight compartments design, STC.

All of the designs are preliminary, but the BD design is claimed to be at a more detailed stage of development. However, the BD design was found not to be robust (SKB/Posiva conclude that "*the design is not robust, includes severe functional uncertainties and should not be considered a viable alternative*"). In all cases further experiments are likely to be needed, not least to help select which of the designs will be used.

6.3 BRITE comments

The above-mentioned different key components are each evaluated separately below, following the scheme for evaluation specified in Section 1 of this report.

6.3.1 Distance blocks

These blocks are being placed between supercontainers in sections where the inflow of water is less than 0,1 l/min, with the intention that they shall absorb water, swell and seal the drift between the supercontainers. The requirements and the design differ, depending on whether BD, DAWE or STC will be used. In particular, fixing rings will be used with the DAWE design, and sealing rings with the STC design.

The requirements and functions of the distance blocks are clearly stated (they should be used in tunnel sections where the inflow is less than or equal to 0.1 l/min), but the basis for the derivation of this value of inflow is not very clear.

The placement of the distance blocks is clearly outlined, although, many aspects remain to be addressed and solved. The wetting phase is perhaps the most important and critical issue to be addressed, especially depending on whether BD, DAWE or STC will be used. Also, the emplacement of the sealing/fixing rings is not resolved and needs further testing and development.

Regarding long-term safety, the distance blocks are important for separating the supercontainers so that the temperature is kept within appropriate limits, for inhibiting water flow between supercontainers, and for limiting bentonite piping and erosion.

Currently, SKB/Posiva's overall strategy for resolving these issues is not presented in sufficient detail to allow evaluation of future plans to address these various questions.

6.3.2 Filling blocks

Filling blocks will be used for unsuitable sections of rock that are not sealed with compartment plugs. Filling blocks will be used where water inflows are 0.1 to 1.0 l/min over a 10 m length of drift.

Trial filling blocks have been manufactured and different designs are being considered, mainly related to the size of the gap between their outer surfaces and the host rock, depending on whether the BD, DAWE or STC design will be used.

SKB/Posiva seem to have identified all of the relevant issues, but it is somewhat unclear whether it has been proven that the filling blocks can be manufactured and compressed to the right densities.

Although plans for the manufacturing, transportation and placing of the filling blocks seem to be adequately developed, they have not yet been satisfactory tested and much remains to be proven when it comes to their functioning and ability to fulfill the relevant criteria.

SKB/Posiva have given a comprehensive picture of the problems encountered and the activities needed, although much development remains to be done related to the wetting system, especially the withdrawal of the pipes in the DAWE design.

Overall, the concept of using filling blocks seems to be feasible as well as practically achievable, but the system for wetting of the blocks needs to be resolved.

Regarding long-term safety, the filling blocks have a great impact as they seal off and prevent flow of water between the supercontainers. They also restrict flow of water from the rock into the drift by being so impermeable that flow of water in an intersecting fracture is almost solely confined to the fracture itself.

SKB/Posiva have indicated that further full scale testing will be done, which definitely is needed to prove the functioning of the Filling blocks.

6.3.3 Compartment plugs

Compartment plugs will be used to seal off drift sections where water inflows are still >1 l/min over a 10 m length of drift after grouting. Thus, the performance of this component of the KBS-3H design has important implications with respect to long-term safety.

The design of the compartment plugs is still in progress and demonstration tests are planned at the Äspö underground research laboratory. SKB/Posiva seem to have provided adequate information regarding future testing and demonstration for this component. It seems that SKB/Posiva have identified the key issues relating to emplacement and wetting of the compartment plugs and no obvious gaps remain.

However, currently, the limits of groundwater inflow are not decided, nor are the DAWE design pipe removal techniques finalized. Finite-element analyses have been made for the design of the compartment plug, but these do not give sufficiently detailed information on several practical issues to further evaluate this component.

6.3.4 Drift end plug and drip shields

At the end of each drift, a drift end-plug seals the drift from the deposition niche. Different designs consisting of steel, or alternatively a low-pH concrete plug, or a combination of both have been considered by SKB/Posiva. Drip shields will be used to delay wetting of the supercontainers, distance blocks and filling blocks.

The conceptual advantages and disadvantages associated with the different design alternatives for the drift end plugs seem to be well understood. Three different designs of the low pH concrete plug have been considered (frictional, notch and wedge shaped notch) as well as a cement-grouted rock plug.

The different designs of the drift end plugs have been analyzed, and experiences from other manufactured, larger concrete plugs appear positive. The potential need for temporary steel plugs to avoid early wetting and swelling movements is identified.

Although the specific designs for the different alternatives of the compartment plugs have not been tested for the current KBS-3H assessment, tests from larger drifts have been successful and suggest that emplacement should be fairly straightforward.

The design of the drip shields is comparatively simple and straightforward. Their functioning has been tested and found satisfactory, but further development would seem to be necessary for the BD design alternative if this was to be taken forward.

Once the choice between the BD, DAWE and STC designs is made, full-scale manufacturing and testing should be straightforward and the strategy is therefore satisfactory.

6.3.5 Deposition niche

The deposition niche is supposed to be 15 to 25 m long and is expected to be filled with bentonite blocks in the bulk of the niche complemented, with pellets emplaced between the blocks and the tunnel wall. Several major issues remain to be addressed and solved, including:

- a firm horizontal base for the floor of the blocks;
- prevention of wetting and swelling until the full tunnel section is filled with bentonite;
- adequate densities in the pellets for different wetting intensities in different areas of the niche;
- adequate densities of the pellets section.

Regarding completeness, the overall information presented is inadequate at this time and the depth of treatment is unsatisfactory as many problems remain unsolved and need to be addressed.

It is hard to determine the feasibility and practicality of backfilling the deposition niches at this time because of the limited depth of treatment of the problem in the SKB/Posiva reports examined. Consequently feasibility and practicality must be considered to be an open question.

It is obvious that successful closure of the deposition drifts and of the rest of the tunnels is vital to the long-term safety for the whole repository. SKB/Posiva's strategy for resolving these issues is unclear but will apparently be discussed in later reports.

7. Corrosion of steel components external to the canister

7.1 Issue description

The corrosion of mild steel components (e.g., basket, feet) of the KBS-3H design external to the copper canister are of concern because this corrosion process can lead to several different types of impacts, including

- chemical interaction with contacting smectite minerals of the bentonite buffer,
- generation of a separate hydrogen (H_2) gas phase, and
- formation of iron corrosion products having significantly greater molar volume than the initial mild steel components.

Therefore, the reaction mechanism, reaction rate, and specific reaction products from the corrosion of mild steel and potential impacts from such corrosion present obvious differences between the KBS-3H and KBS-3V conceptual designs.

7.2 SKB/Posiva's perspective

A steel supercontainer (or basket) is estimated by SKB/Posiva to corrode within a few thousand years (SKB, 2008, TR-08-03, page 42). Under anaerobic conditions in water the expected corrosion reaction would be

$$3Fe + 4H_2O = Fe_3O_4 + 8H^+ + 8e^- \qquad (7\text{-}1)$$

with further recombination of hydrogen atoms to produce hydrogen gas.

The wall thickness of the supercontainer is set at 8 mm. Figure 7-1 shows the collection of data points by Crossland (2005) on the corrosion rate of iron in different soils. Based on these data, the estimate of a lifetime of a few thousand years is plausible for the supercontainer of the KBS-3H conceptual design.

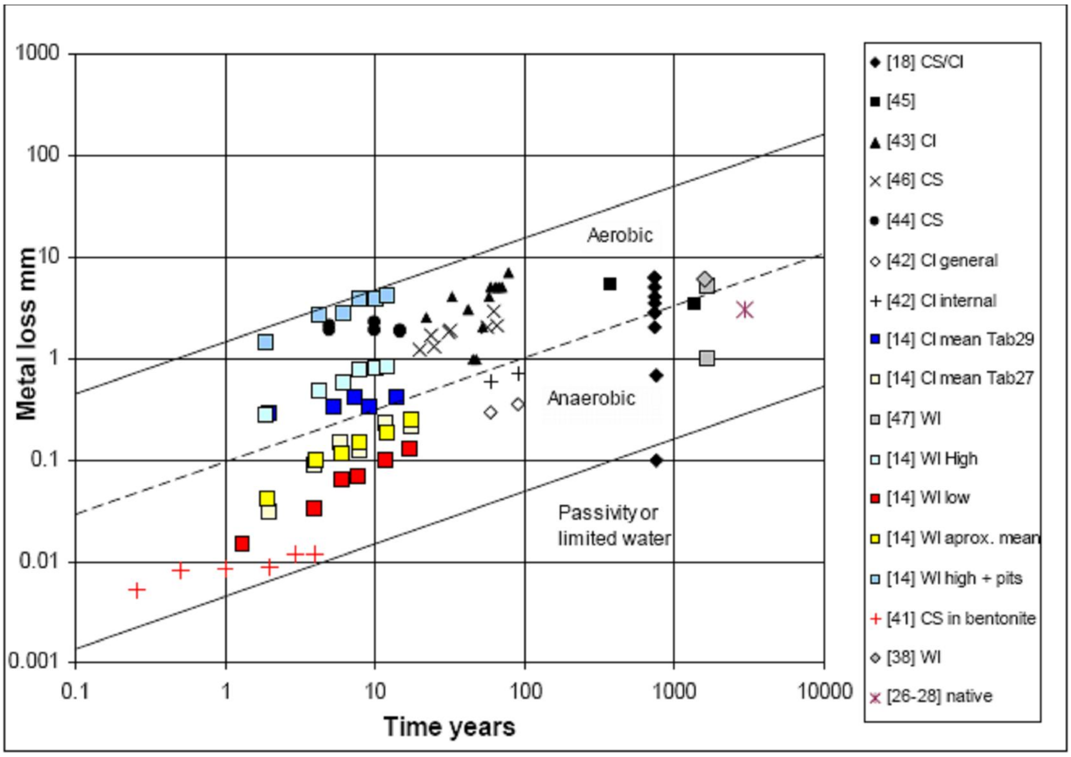

Figure 7-1 Plot of metal-loss measurements vs. test duration for mild steel under different environmental conditions (Crossland, 2005). Dashed straight lines indicate three different constant-corrosion rates.

Two main long-term safety related issues arising as a consequence of super-container corrosion have been identified by SKB. These are:

- the impact of steel corrosion products on mass transport.
- the effects of gas from the corrosion of steel components.

The iron from corrosion is suggested to interact with bentonite forming "iron-bentonite" and, thus, changing bentonite properties at the outer layer of the buffer. The extent of this effect may be evaluated by simple mass balance calculations. Estimates by Wersin et al. (2007) and Wersin and Snellman (2008) using mass balance state that a maximum 10-30% of montmorillonite in bentonite could be transformed. A more advanced reactive transport model predicts that the thickness of a non-swelling layer could be a few centimetres. Although there are uncertainties with regard to the extent of the alteration and its effects on properties of the outer layer of buffer, the measures taken and planned by SKB/Posiva to clarify this area are considered satisfactory. The practical question is whether the alteration of the external layer to the above-mentioned extent will jeopardise the overall functions of the buffer.

The effects of H_2 gas production from steel corrosion would be the following:

- slowing buffer saturation (because of the 2° drift inclination gas may collect at the far end of the drift and/or at the compartment plug location).
- reduction of Fe^{3+} to Fe^{2+} within the bentonite, which would increase the hydraulic conductivity of the buffer dramatically (Carlson et al., 2006).
- alteration of pore water chemistry, e.g., effect on sulphate to sulphide reduction by microbial activity.
- production of gas pathways that may cause or promote affect piping and or erosion of the buffer.

The above-mentioned possible effects of H_2 gas have been noted by SKB/Posiva, but a clear research plan on how to address them is mostly lacking.

If oxygen is available for iron corrosion (e.g., dissolved in the groundwater) the resulting corrosion reaction would not produce hydrogen. This is the expected condition during the early phase of repository development, until the oxygen resources are depleted. The overall corrosion reaction in this phase would be:

$$2Fe + O_2 + 2H_2O = 2Fe(OH)_2 \qquad (7\text{-}2)$$

and thus no hydrogen production would take place. The empty space in the KBS-3H deposition tunnel can be estimated to be less than 100 m^3, with an average 5 cm distance between the supercontainer and the rock. If filled with air, this volume would have roughly 1000 mol of O_2, while if filled with oxygen saturated water, it would contain roughly 150 moles of O (as OH^-). According to reaction (2) one mol of O_2 would consume 2 moles of Fe. One supercontainer weighs roughly 1000 kg, corresponding to about 18000 mol of Fe. Thus it is clear that only a small part of the supercontainer would be corroded via reaction (2), and most of the corrosion would take place via reaction (1), producing hydrogen gas as a reaction product. This applies probably even if one accounts for the oxygen in the air traps left in the other parts of the disposal vault.

To avoid potential problems with the iron/bentonite interactions and gas generation due to corrosion, titanium has been investigated as a substitute metal.

7.3 BRITE comments

SKB/Posiva have presented a full and detailed description of expected iron corrosion processes, and have linked these to the possible consequences in terms of the formation of iron-rich smectite in the buffer, the generation of hydrogen gas, and the formation of volumetrically expansive iron corrosion products.

The effects of corrosion on bentonite are discussed in Section 8, and the effect of gas generation in Section 9. It is also noted that there will be a marked expansion in molar volume in the corrosion of steel supercontainer and cast iron components to form iron corrosion products. How such expansion of solid material might be accommodated within the engineered barrier system and near-field rock has yet to be adequately assessed by SKB/Posiva for the KBS-3H design concept.

8. Effects of steel corrosion on bentonite and radionuclide transport

8.1 Issue description

In the KBS-3H design, after a relatively short period during which oxygen in the excavations is consumed and reducing chemical conditions are attained, steel components external to the canister will be subject to anaerobic corrosion and will release Fe(II) to the buffer pore water. The subsequent interactions of Fe(II) with bentonite, could potentially include:

- saturation of ion exchange/sorption sites with Fe^{2+} (Charlet and Tournassat, 2005; Géhin et al., 2007);
- mineral transformation of smectite to non-swelling sheet silicates (Savage et al., in press). Although mineral transformation of the buffer is expected to proceed slowly due to the slow kinetics of the transformation processes, there is evidence from some laboratory experiments that these processes can proceed rapidly, even at relatively low temperatures (Lantenois et al., 2005; Milodowski et al., 2009);
- perturbation of buffer physical properties, such as decreased swelling and/or increased hydraulic conductivity. Experiments investigating the corrosion of steel in compacted bentonite have shown that swelling may be affected (Milodowski et al., 2009) and that hydraulic conductivity may be substantially increased on a relatively short timescale (Carlson et al., 2008).

An essential feature of these interactions is that they are strongly coupled in a non-linear fashion (Figure 8-2):

- anaerobic corrosion of steel supplies ferrous ions and hydrogen gas at the interface with bentonite. Sorption of ferrous ions may act as a 'pump', driving steel corrosion. Migration of pulses of gas through bentonite will provide a pathway for aqueous species such as dissolved iron.

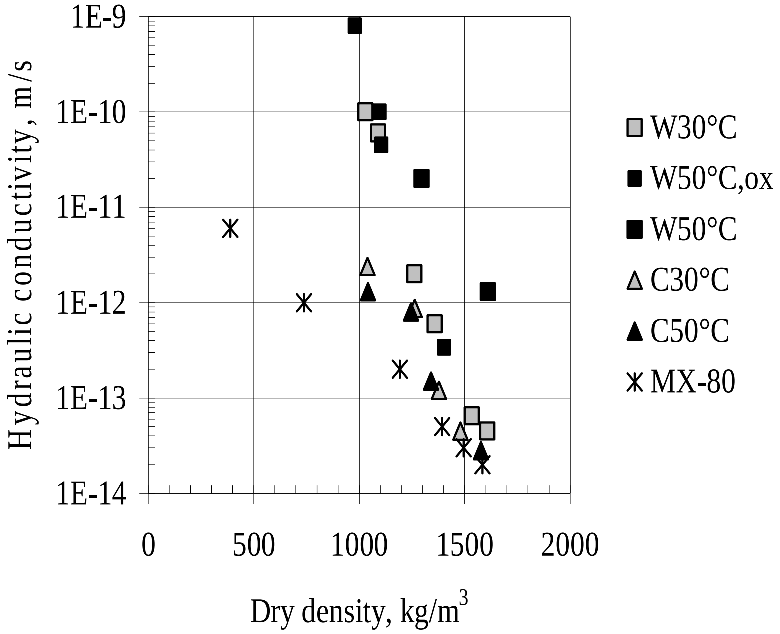

Figure 8-1 Comparison of hydraulic conductivity of unaltered MX-80 bentonite (crosses) with samples altered in corrosion experiments at 30 and 50 °C conducted by Carlson et al. (2008).

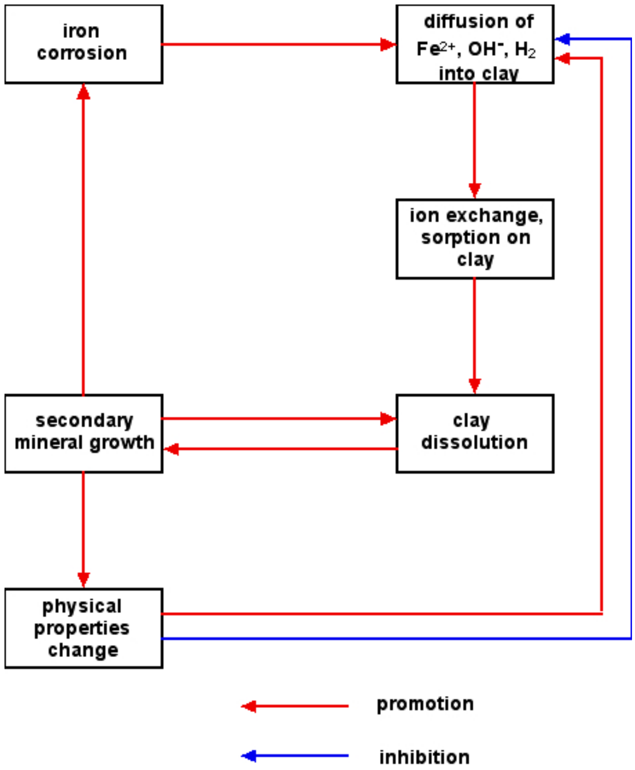

Figure 8-2 Iron-bentonite interactions proceed through a coupled, non-linear process.

- Ion exchange/sorption of Fe^{2+} on clay will retard its migration through the bentonite, but may be linked to long-term mineralogical transformation processes.
- Corrosion of steel may be linked to smectite transformation through chemical reduction of structural Fe^{3+} in the clay (Lantenois et al., 2005; Wersin et al., 2008).
- Anaerobic corrosion of iron, coupled with clay transformation processes serve to increase pore fluid pH, thus accelerating clay dissolution:

$$10Fe + 20H_2O + 6Smectite \Rightarrow$$
$$5Berthierine + 20SiO_2 + 6OH^- + 2Na^+ + 2Mg^{2+} + 10H_2$$

- Transformation of montmorillonite to non-swelling minerals will change the physical properties of the bentonite, potentially further enhancing transport through the clay.

It is, thus, important to incorporate this strong coupling between different processes in modelling of the iron-bentonite system, and moreover, not to focus on individual sub-systems without due regard to process coupling.

8.2 SKB/Posiva's perspective

Overviews of iron-bentonite interactions are described in the Process Report (Gribi et al., 2008) and Summary Report (Smith et al., 2008) and, in more detail, in a number of underlying reports: in a literature review (Marcos, 2003); in a summary of the status of international research (Wersin and Snellman, 2008); as applied to the Olkiluoto Site (Wersin et al., 2008), as linked to gas behaviour (Johnson et al., 2008), and in evidence from steel corrosion experiments in compacted bentonite (Carlson et al., 2008; Milodowski et al., 2009). SKB/Posiva's broad conclusions from these studies are that (Gribi et al., 2008, p. 251):

- *"Chemical alteration may adversely affect swelling, hydraulic and rheological properties of the buffer in the outer region. In particular, enhanced hydraulic conductivity of the outer region of the bentonite may result, which could increase the transport of detrimental solutes to the canister or increase the rate of transport of radionuclides from the canister in case of a release. Significant uncertainties remain in the understanding of the overall impact on the affected region of the buffer, including the extent and nature of neo-mineral formation and the degree of changes in hydraulic conductivity, plasticity and swelling pressure of the affected zone. In addition, a possibly lower density in this region could permit more significant microbial activity, a process that is expected to be of little relevance in denser buffer material. The present treatment of the transport properties of the outer buffer region in safety assessment calculations (represented as a mixing tank rather than a zone of somewhat increased hydraulic conductivity) to deal with these various impacts is very conservative, as explained in the KBS-3H Radionuclide Transport Report.*
- *An additional potential consequence of the iron/bentonite interaction is the high occupation by Fe(II) of sorption sites in the outer part of the buffer, which could reduce sorption of some radionuclides. However, the reduced sorption capacity of bentonite surface is largely compensated by that resulting from the formation of iron corrosion products (mainly Fe_3O_4), which would act as a sink. The long-term evolution of such corrosion products and the fate of the sorbed radionuclides are unclear."*

SKB/Posiva further assess the problem by quantitative analysis with limiting cases based on mass balance and transport considerations (Gribi et al., 2008 based on Wersin et al., 2008). SKB/Posiva conclude that (Gribi et al., 2008, p. 135): "*the reactive transport calculations indicate limited migration of the Fe(II) front, and an even more limited zone of clay alteration even after time periods > 100 000 years. This is mainly due to the low Fe(II) gradient between the iron source and the buffer, the strong sorption of Fe(II) to the clay, and iron precipitation reactions leading to partial clogging. The adverse effects on the swelling buffer material are thus spatially limited to the outermost few cm near the buffer-rock interface for very long periods*". SKB/Posiva continue to state: "*the extent of the altered montmorillonite* *zone remained within a few cm, even for very unfavourable bounding assumptions. The zone of altered montmorillonite for this case extends to about 5 cm into the buffer after 500 000 years*" (Gribi et al., 2008, p. 135).

In the KBS-3H Radionuclide Transport Report (Smith et al., 2007), SKB/Posiva consider that the impact of iron-bentonite interaction is treated in a simplified and conservative manner by considering two different buffer domains: an inner part that is not affected by iron-bentonite interactions; and an outer part treated as a 'mixing tank'. The extent of the bentonite alteration zone in the calculation cases is 0 % (but with altered transfer coefficients), 10 %, and 50 % of bentonite thickness. SKB/Posiva believe that this approach, in which the altered buffer has essentially an infinite hydraulic conductivity, is highly conservative (Gribi et al., 2008, p. 139).

Nevertheless, SKB/Posiva believe that considerable uncertainties exist regarding iron-bentonite interactions (Gribi et al., p140) so that:

- further experimental work should include measurements of swelling pressure and hydraulic properties, including gas transport properties of altered bentonite.
- the potential effect of H_2 on Fe-clay interactions and on reduction of structural iron in smectite should be experimentally investigated.
- from a modelling perspective, it would be useful to include reaction kinetics for smectite transformation in the KBS-3H conceptual model to obtain a more realistic description of the evolution of the iron front.

8.3 BRITE comments

BRITE concurs with SKB/Posiva's view that there are continuing uncertainties regarding the precise nature and extent of iron-bentonite interaction and associated impacts, but BRITE considers that the quantitative calculations conducted by SKB/Posiva to investigate the possible extent of the effects of this process involve questionable (non-conservative) boundary conditions:

- The choice of Fe solubility-limiting solids at the corroding steel surface (amorphous FeS or siderite) are inconsistent with SKB/Posiva's own recent experimental data where iron oxyhydroxide has been identified as a discrete phase on corroding steel in compacted bentonite (Figure 4-7 in Milodowski et al., 2009). The choice of less soluble FeS/siderite inevitably produces a low concentration gradient across the bentonite to drive diffusion. The selection of iron hydroxide as a model variant would produce an Fe^{2+} concentration at the supercontainer boundary two orders of magnitude greater than those selected by SKB/Posiva and would represent a more conservative (but still realistic) boundary condition.
- There is strong evidence (again, from SKB/Posiva's own experimental work) that the physical properties of compacted ben-

tonite in contact with steel degrade over very short timescales (3 years). For example, samples of bentonite from corrosion experiments (e.g. Carlson et al., 2008) show increased hydraulic conductivity after only 3 years of reaction. Also, new detailed petrographic observations of compacted bentonite from corrosion experiments carried out by SKB/Posiva revealed that bentonite, strongly enriched in Fe close to the corroding steel, displayed increased shrinkage behaviour compared to the lower-Fe bentonite matrix further away from the corroding wires (Milodowski et al., 2009). Although bulk changes in porosity were linked to changes in diffusivity in some of SKB/Posiva's calculations, these model variants are unlikely to have properly captured the effects of increased hydraulic conductivity and decreased swelling measured/observed in laboratory experiments.

- Detailed mineralogical investigations of compacted bentonite from steel corrosion experiments show greatest penetration of Fe into the bentonite matrix along hairline microfractures that radiate outwards from the corroding metal (Figure 8-3). Milodowski et al. (2009, p52) consider that: "*The early formed fractures may have represented potentially important pathways for gas and solute transport during the course of the experiments. The irreversible shrinkage of the bentonite, as a result of interaction with Fe released from corroding iron or steel may therefore be significant in evaluating the long-term behaviour of the bentonite seal and the transport of gas and solutes around corroding waste canisters emplaced in bentonite backfill*". Indeed, the Process Report (p 138) notes that: "*the macroscopic structures of the alteration products are probably more permeable than the remaining montmorillonite, and will function as preferential paths*", and "*while the effect of gas and its penetration of intact buffer is relatively well known, there is little or no understanding of how Fe-saturated or otherwise chemically altered smectite clay lets gas through. It is known, however, that the microstructural constitution of Fe-saturated MX-80 is characterized by channels, meaning that gas can get through at lower pressures*" (Gribi et al., 2008, p 138). Although geometrical properties of the KBS-3H design may prevent gas from creating pathways through the compacted bentonite during corrosion of the supercontainer shell, it is clear that shrinkage cracks in altered bentonite may create preferential pathways for further transport of ferrous ions and a 'feedback loop' for further alteration.

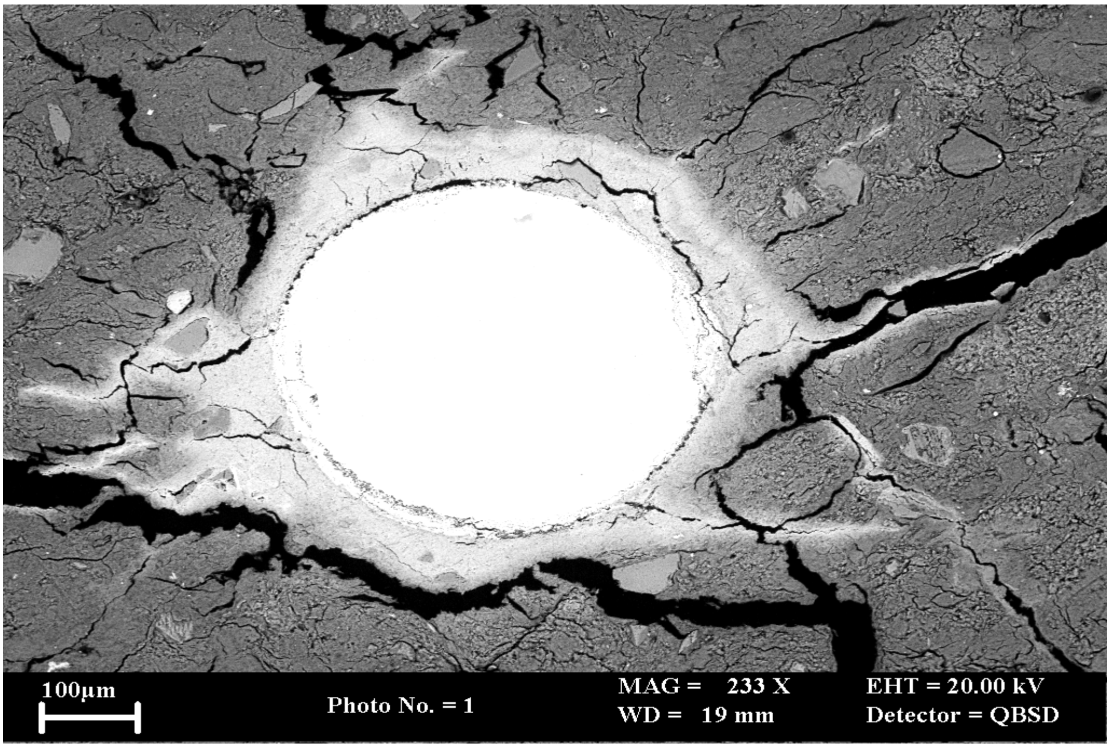

Figure 8-3 Back-scattered electron photomicrograph of a corroded steel wire (white) in compacted bentonite. The bentonite around the wire shows a halo of alteration (light grey) that also penetrates further into the bentonite clay matrix (darker grey) along microfractures. From Milodowski et al. (2009).

- As illustrated in Figure 8-2, iron-bentonite interaction is a strongly coupled process, such that it is relatively uninformative to separate 'sub-systems' for quantitative analysis. For example, Wersin et al. (2008) present several cases examining only diffusion-sorption in bentonite, together with a number of cases incorporating clay hydrolysis reactions plus sorption, but only one case where both iron corrosion and clay hydrolysis reactions were included. The exclusion of the pH-dependency of clay dissolution rates limits the usefulness of this latter simulation.

In summary, although a lot of basic research has been conducted already, further work is necessary including:

- physical properties measurements of altered bentonite;
- more realistic modelling;
- assimilation of recent mineralogical work by Milodowski et al. (2009).

The potential impacts of this process are well recognized by SKB/Posiva. The bounding analyses reported in Smith et al. (2008) provide a useful beginning point for examination and quantification of such impacts, but considerably more realistic assessment of the extent of alteration still need to be conducted. The resolution of the issue may be made with a combination of additional R&D and additional bounding analyses, or consideration could be given to eliminating the issue by using passivating-type metals, such as stainless steels, Ni-alloys, or titanium.

9. Impact of gas from the corrosion of steel components external to the canister, gas flow and implications

9.1 Issue description

Hydrogen gas will be produced by anaerobic corrosion of steel repository components. The gas pressures that will be reached in the drifts strongly depend on the rates of gas generation and the gas transport capacity of fractures in the host rock.

Gas pressures may delay water inflow and prevent the buffer reaching full saturation. If the process of gas evolution lasts longer than the time for canister breach by corrosion, radionuclides might be released into a buffer that is not fully saturated.

Pressures will vary along the drifts and could cause transient flows (e.g., along the buffer-rock interface and through the EDZ), which could cause piping and buffer erosion, loss of swelling pressure and lead to spalling.

Hydrogen gas may also promote microbial sulphate reduction, and this may enhance canister corrosion rates.

The presence of a discrete gas phase may affect water flows in the geosphere, and this could also affect radionuclide transport.

9.2 SKB/Posiva's perspective

The main source of hydrogen gas is the supercontainer shells, but a smaller amount of additional gas will be produced as a result of the corrosion of compartment plugs, fixing rings, spray and drip shields.

Based on the possible range of corrosion rates, SKB/Posiva suggest that gas production will occur for a period of a few thousand years to a few tens of thousands of years.

Significant gas overpressures (p_{gas}>$p_{hydrostatic}$) are possible, particularly in the tightest sections of rock. In accordance with the possible timescales for gas generation, piping and erosion of the bentonite may also occur over a few thousands of years to a few tens of thousands of years.

It is shown in scoping calculations in Appendix B.7 of the Evolution Report (Smith et al., 2007a) that, as long as hydrogen production persists, there is more than enough hydrogen present to facilitate microbial reduction of groundwater sulphate to sulphide, even for a low corrosion rate of 0.1 µm per year. Some of this sulphide will migrate to the canister surface, giving rise to a period of enhanced corrosion. However, SKB/Posiva's scoping calculations also show that, even in the case of a pessimistically modelled perturbed buffer/rock interface, an overall canister lifetime of several hundred thousand years is expected. Only in the case of a high sulphide concentration being maintained at the buffer/rock interface, e.g. by microbial activity, over a period in excess of the period of hydrogen gas generation by steel corrosion is canister lifetime reduced below about 100,000 years.

Methane and hydrogen naturally present in the groundwater could, in principle, play a role in sustaining microbial activity over a longer period. This is an issue for both the KBS-3H and KBS-3V repository alternatives that requires further investigation. The impact of hydrogen gas on the bentonite porewater chemistry, e.g. on the acid-base equilibria, that has not been fully evaluated is noted by SKB/Posiva as another issue for further study.

In the drift sections with an average wall-rock hydraulic conductivity less than approximately $1 \cdot 10^{-13}$ m/s, depending on the rate of steel corrosion, the buffer may remain only partly saturated. The impact on radionuclide release to the geosphere has not as yet been quantified, but releases are expected to be no more than in the case of a fully saturated buffer, and may be somewhat reduced. Any perturbation to groundwater flow in the geosphere due to the gas rising through the fracture network is also likely to have largely ceased by the time most radionuclides are released from failed canisters, except possibly in the tightest drift sections where groundwater flow is in any case virtually zero. Thus, no calculations of radionuclide release and transport dealing with the impact of gas from the corrosion of steel components external to the canister are presented in the current safety assessment.

9.3 BRITE comments

SKB/Posiva have identified the issues and processes that might occur – there are no obvious gaps. However, there are many complex couplings between gas generation and other processes in the near field and far field, and these need to be investigated more fully.

SKB/Posiva's approach to quantifying the amounts of gas seems reasonable, but SKB/Posiva have not yet analysed the impacts of gas in sufficient depth.

In fact, the gaps in knowledge that remain seem to have prevented an assessment of impacts on safety at this stage, and so the impact of gas on long-term safety remains unclear.

SKB/Posiva recognise the need for further work to explore uncertainties associated with the impacts of gas generation resulting from steel corrosion but, in the reports reviewed, they have not described a detailed programme or plan for resolution of these uncertainties.

In summary, at this time, SKB/Posiva have identified the issues and processes that might occur, there are no obvious gaps. Uncertainties regarding impact of gas on long-term safety remain unclear, and fuller analyses, possibly supported by additional R&D, may be needed. The future R&D plans cited by SKB/Posiva are insufficiently detailed to evaluate if they are likely to lead to timely resolution of current uncertainties. On the other hand, SKB and Posiva are apparently considering substituting passivating metals (e.g., stainless steels, titanium) as a possible alternative to mild steel, which could possibly eliminate the issue entirely.

10. Impact of leachates from cementitious components

10.1 Issue description

Cement and other construction materials will be used in the construction of a spent fuel disposal facility whether constructed to the KBS-3V or KBS-3H design. SKB/Posiva state that the purposes of such materials are to limit the groundwater inflow (grouting), to stabilise the rock (shotcrete, castings of rock bolts), to construct plugs and seals (e.g. drift end plugs, compartment plugs), to fill, for example, anchoring holes and for operational safety purposes (floors, supporting walls etc) (Gribi et al., 2008). Concrete will also be used for temporary construction elements (walls, intermediate floors, doors). Most of the cementitious materials will be removed before the final closure of the repository but, according to the estimates of residual materials in the KBS-3H repository, between 1.2 and 1.8 million kg of cement will be left in the entire repository. Of these, an average of 2,600 to 3,900 kg of cement will be located in each drift (Hagros, 2007).

Three grouting materials are considered for both KBS-3H and KBS-3V in various parts of the repository:

- ordinary (Portland) cement;
- low-pH cement; and
- colloidal silica.

These alternatives may require additives, such as accelerators (i.e. inorganic salts) and organic superplasticisers.

SKB/Posiva believe that shotcreting will not be needed in the deposition drifts because the quality of the rock and inflow rate should be adequate for drift constructability by design (Gribi et al., 2008). However other parts of the repository, including the deposition niche, may require supporting by shotcreting. As in the KBS-3V case, ordinary and low-pH cement are both considered as shotcreting materials. Shotcrete will be removed to the maximum extent practical before closure (Gribi et al., 2008).

10.2 SKB/Posiva's perspective

SKB/Posiva consider that the highly reactive high-pH fluids from cementitious materials could in principle constitute a threat to the long-term stability of the buffer and other bentonite components (Gribi et al., 2008, p140): "*the reaction of the cement-conditioned alkaline water with the buffer will result in mineral dissolution and formation of new phases. Consequently, it is likely that the hydraulic and chemical properties of both the cementitious materials themselves and any bentonite that comes into contact with high-pH fluids will change*". SKB/Posiva's main concerns are:

- montmorillonite dissolution leading to change in swelling pressure, porosity, and hydraulic conductivity;
- bentonite cementation by secondary phases leading to fracturing, with the possibility of advective transport, and;
- formation of alteration products, and their consequences for the properties of altered clay.

A detailed review of likely processes and issues regarding the presence of cementitious materials is contained in Appendix F of the Process report (Gribi et al., 2008). Despite no cement-bearing component being in direct contact with the bentonite in the supercontainer and distance block unit in the KBS-3H design, SKB/Posiva have evaluated the potential effects on the buffer arising through contact of alkaline cementitious pore water transported from a grouted fracture to the supercontainer area. From mass balance calculations, SKB/Posiva show that an outer zone of buffer of 4 cm thickness could be altered over a period of 100,000 years (Gribi et al., 2008). These estimates do not take into account mitigating processes such as the reaction of the alkaline plume with minerals in the host rock; nonetheless, they emphasise the need to minimise the quantities of cement used in the repository. In radionuclide transport calculations, the same approach is used as was used to assess the alteration of bentonite by interaction with iron (Smith et al., 2007). SKB/Posiva intend to minimise the use of cement by using silica sols as a grouting agent for fractures (Gribi et al., 2008). However, according to this source, the use of these materials introduces additional uncertainties:

- *"long-term basic mechanical properties of colloidal silica, such as drying shrinkage, flexural strength, compressive strength, and shear strength;*
- *penetration ability of grouting material in the fractures;*
- *eventual release of colloids;*
- *long-term effect of salt accelerators in Silica Sol on bentonite;*
- *long-term effect of biocide agents such as isothiazols and bromo-nitropropandiols (<1%) present in the Silica Sol mixture to extend its shelf life".*

10.3 BRITE comments

As acknowledged by SKB/Posiva, the use of low-pH cements (instead of ordinary Portland cements) would dramatically reduce the inventory of hydroxyl ions available for reaction with aluminosilicate minerals in the buffer. For example, Savage and Benbow (2007) calculate that low-pH cement contains approximately 50 % less hydroxyl ions than conventional ordinary Portland cement (OPC) for a given volume of cement. BRITE concurs with SKB/Posiva that this would limit the potential amount of buffer alteration. However, it should not be ignored that *concentrations* and activity *ratios* of key aqueous species (Na^+/H^+, $Ca^{2+}/(H^+)^2$, $SiO_{2(aq)}$) and not absolute amounts thereof will control alteration processes (e.g. Figure 10-1).

The analysis seems to focus on the possible effects of cementitious materials and their leachates on the bentonite components of the EBS, but the use of high-pH cements might also affect other components. Highly alkaline leachates, as would be derived from ordinary Portland cements, could, for example, passivate the surfaces of the steel components locally and, thereby, reduce rates of steel corrosion and hydrogen production to very low levels.

In summary, cementitious materials could have several impacts on the EBS, including buffer alteration, particularly if either more cementitious materials are used than are currently planned, or if OPC based systems were used.

Detailed modelling of cases where more than currently anticipated amounts of cement are used would usefully extend current bounding analyses. Similarly, further calculations and assessments may be helpful to build confidence that leachates, silica sols and cement additives will not have significant effects on steels and radionuclide transport.

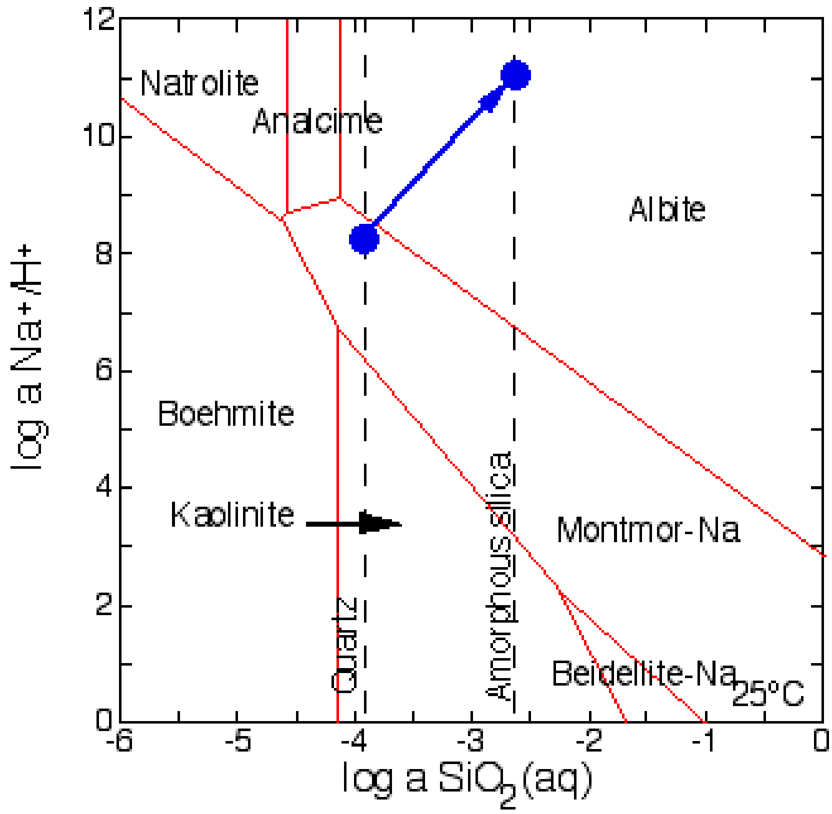

Figure 10-1 The importance of activity ratios and concentrations in determining alteration patterns in the system NaO-MgO-Al_2O_3-SiO_2-H_2O. Mg solubility is defined by Ca-montmorillonite. The transition from ambient bentonite pore fluids saturated with typical low-salinity groundwater (Na = 250 mg/l) and quartz at pH 8.5 to those defined by low-pH cement pore fluids at pH 11 is shown by the blue arrow, defining a shift into a stability region for feldspar. From Savage and Benbow (2007).

11. Processes within horizontal failed canisters

11.1 Issue description

The horizontal orientation of the disposed KBS-3H supercontainer could conceptually lead to a case in which canister with an initial penetrating defect through the weld had a defect that was on the lower part of the canister. This could allow water (or water vapour) from the buffer to come into contact with the iron insert. Corrosion of the insert under anaerobic conditions could generate H_2 gas. SKB/Posiva suggest that the gas may become trapped, allowing the gas pressure within the canister to rise as corrosion continues. Eventually the gas pressure could exceed the breakthrough pressure of the buffer, and a portion of the gas, plus some residual water in contact with the insert, could then be expelled outwards from the canister through buffer. The gas and water inside the canister may include radioactive gases [e.g., $^{14}CO_2(g)$], aqueous solutes and/or colloids released from the spent-fuel waste form. Radionuclides associated with these species could then be transported through the buffer with the expelled gas and liquid phases.

11.2 SKB/Posiva's perspective

SKB/Posiva report (Smith et al., 2008, Section 9.7.3) a bounding analysis of gas-induced displacement of radionuclide-bearing water as case PD-EXPELL. In the PD-EXPELL assessment calculation it is assumed that a gas-driven water pulse, lasting for a period of 1,300 years after its initiation 2,800 years after deposition, causes water to be expelled from the canister and to enter the buffer, and then a fracture in the host rock. The assessment of the displacement of radionuclide-bearing pore water by the formation of a free-hydrogen gas phase is also summarized in Smith et al. (2008, Sections 6.5 and 7.1.7).

The scenario considered in the assessment calculations is predicated on (1) a pin-hole failure of the copper canister located on the lower part of the canister so that the gravitational rise (buoyancy) of the generated hydrogen gas would cause it to be trapped inside the failed canister (Figure 11.1), and (2) that the failed canister remains otherwise sufficiently intact to trap and contain the hydrogen gas.

Scoping calculations by SKB/Posiva (Smith et al., 2008) indicate a significant increase in the release of radionuclides for a canister with such a failure compared to the normal evolution and performance of a failed canister not experiencing this "gas-expulsion" event.

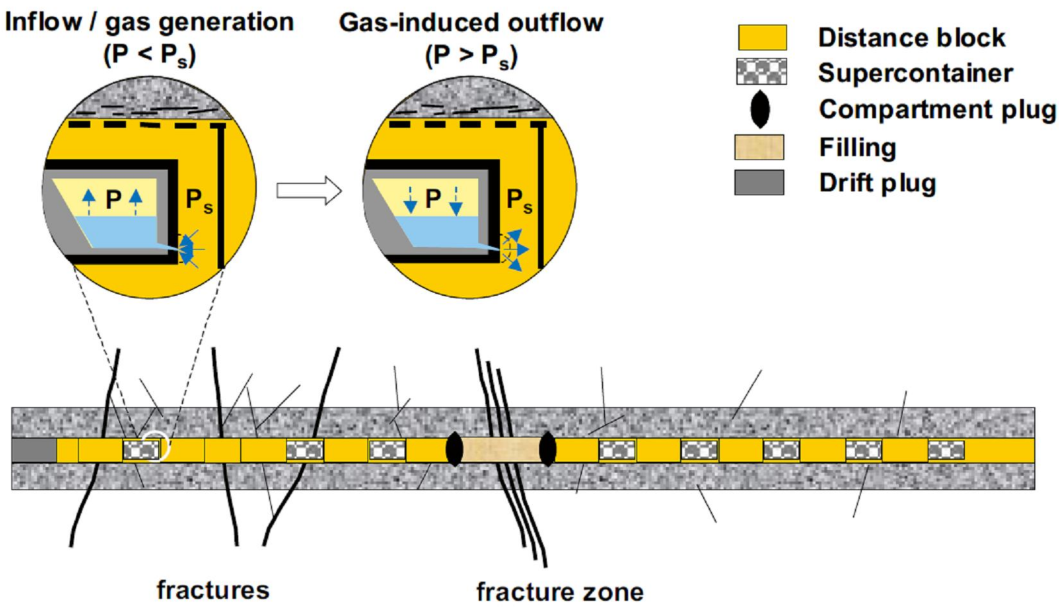

Figure 11.1 SKB's conceptual model for transport of water and gas into and out of a canister with an initial penetrating defect.

SKB/Posiva (Smith et al., 2008, page 14) argue, however, that this scenario is unlikely because "…*water entering the canister will be completely consumed by corrosion of the cast iron insert, and there will be no gas-induced displacement of contaminated water through the defect into the saturated bentonite*."

11.3 BRITE comments

Although the conceptual model described in section 6.5 of Smith et al. (2008) is broadly reasonable, any assessment needs to be properly parameterised, and BRITE considers that SKB/Posiva's bounding analysis is based on several unlikely assumptions and parameter values concerning the timing and way in which the canister and insert might fail, on their geometry after failure, and how these factors relate to radionuclide release. In particular, there can be no release of radionuclides by either aqueous diffusion or *gas-expulsion* until the cast-iron insert fails, which could be considerably longer than assumed in SKB/Posiva's analysis.

The most likely mechanism for failure of the insert is by mechanical buckling. For example, SKB/Posiva's mechanical/corrosion experts note that, "*Eventually, weakening of the insert by corrosion will lead to the canister collapsing under the external load*" (Smith et al., 2007a, page 125). It seems likely, therefore, that the collapse and buckling of the insert into the interior voids in the channels containing the spent fuel assemblies will limit the space available for gas build up and is unlikely to preserve the specialized geometry necessary for forming and maintaining a trapped gas phase within a failed waste package.

In conclusion, consideration of linking mechanical failure analyses of waste packages with performance assessment constraints would seem to indicate that the unique geometry necessary for this speculative scenario is unlikely to occur or persist under realistic repository conditions.

12. Implications of the horizontal arrangement with respect to potential for earthquake shear

12.1 Issue description

Earthquake induced rock shear movement across a deposition hole/drift may cause a canister to fail. According to TR-06-09 (SKB 2006), this is one of the three key potential failure modes. With respect to the shear loading, the EBS components in the KBS-3 concept have different tasks. The iron insert gives stability to the canister, and the ductile copper canister shell functions as a container keeping the radionuclides apart from the surrounding. The bentonite buffer acts as a cushion and reduces the shear deformation of the canister (Börgesson et al. 2003).

Canisters may fail during a single large earthquake or due to the cumulative effect of multiple smaller earthquakes. Failure of a canister is expected if the shear deformation of the deposition hole exceeds a certain threshold value. Until recently, both SKB and Posiva's criterion for shearing was 10 cm. SKB/Posiva have now reduced their criterion to 5 cm. The background for this change is, at this moment, not clear.

The aim with the present evaluation is to compare the two repository concepts KBS-3V and KBS-3H and emphasize areas where differences are found with respect to long-term safety. Regarding the earthquake shear scenario, the canister and the bentonite buffer initially can be regarded as principally equivalent for the two repository concepts. The only difference is the buffer thicknesses, which are 350 and 341 mm for KBS-3V and KBS-3H Basic Design, respectively. For the KBS-3H, the canister and the buffer are contained in a supercontainer. If the supercontainer is made of steel, it is expected to corrode within a few thousand years from deposition (SKB, 2008). The iron from corrosion is suggested to interact with the bentonite forming "iron-bentonite" and thereby changing the bentonite properties of the outer layer (some few centimetres) of the buffer. Other parameters of importance in the comparison of the two repository concepts are: the stress state in the bedrock (both background stresses and glacial induced stresses (Lund, 2006)); size, orientation and frequency of fractures in the bedrock, and distance and earthquake magnitude (La Pointe et al., 2000).

12.2 SKB/Posiva's perspective

In order to avoid shear deformation of a deposition hole/drift, the layout of the repository will be placed in a region well away from faults or fracture zones in the bedrock. Munier & Hökmark (2004) define the term respect distance, i.e. the perpendicular distance from a deformation zone that defines the volume within which deposition of canisters is prohibited, due to anticipated, future seismic effects on canister integrity. In addition for KBS-3V, deposition holes with large fractures are rejected for deposition. For KBS-3H, where the deposition drift can be up to 300 meters, canisters will not be deposited in regions of the drift with fractures.

For canisters that, despite the precautions taken, will be subjected to rock shear, the KBS-3 concept is developed to withstand a certain amount of shear deformation as described above.

The methodology in Hedin (2005) was applied for the Olkiluoto site and the risk for a canister shear failure caused by a large earthquake was determined for both the KBS-3V and KBS-3H. For KBS-3V, 20 out of 3000 canisters were predicted to fail (Pastina and Hellä, 2006; section 8.3.2.). For a KBS-3H repository, the corresponding number of canisters that would fail was 16 out of 3000 canisters (Smith et al., 2007). The difference in number of canister failures for the two repository types was essentially due to the relatively dense population of sub-horizontal fractures at Olkiluoto, in combination with the greater vertical extent of the KBS-3V repository.

12.3 BRITE comments

The earthquake shear scenario has been thoroughly analysed over the years. The canister and the bentonite buffer have been investigated by parametric studies where the impact of different properties of the bentonite, different amount of shear deformation, different locations and inclinations of shear and different constitutive models of copper have been studied (Börgesson et al., 2003; Börgesson and Hernelind, 2006; Hernelind, 2006). Valuable results have been produced describing the response of the KBS-3 concept to shearing and these have been used in its development.

In calculating the fracture displacement as an effect of earthquake, La Pointe et al. (2000) have found by simulation that distance and earthquake magnitude are the most important factors, followed by fracture size. Fracture orientation is much less important.

If only the fracture orientation is varied, this means that the risk of canister failure by earthquake-induced bedrock shear is the same for KBS-3V and KBS-3H if the fractures are randomly distributed in the bedrock. A further consequence of this is that a certain orientation of the fractures in the repository bedrock may favour one of the two repository concepts.

In TR-08-03 (SKB, 2008) it is stated that with respect to potential damage to the engineered barrier system by rock shear, KBS-3V is more sensitive to sub-horizontal than sub-vertical fractures. For KBS-3H, the opposite prevails. Information about the actual fracture situation at Forsmark (the repository site chosen by SKB) is not given in the report, but will need to be considered in detail.

As already discussed, the advantages and drawbacks with the two repository concepts, in the context of the earthquake shear scenario, are site dependent. As Forsmark now has been chosen as SKB's repository site, a detailed evaluation of KBS-3V and KBS-3H should be performed. In this assessment and comparison of the two KBS-3 concepts, the potential effect of stress state in the bedrock, the potential impact of the corroded supercontainer on the bentonite properties, and the frequency and orientation of fractures will need to be addressed.

13. Integration of Topics

It is reasonable to consider if, and to what degree, might the various individual processes discussed in the previous sections of this report ever occur and act together. For example, there are obvious links among Topics 6, 7, 8 and 10 related to impacts arising from the corrosion of steel/iron components of the KBS-3H concept.

SKB/Posiva (Smith et al., 2008) have focused on conducting analyses of what might be described as "one-off" barrier neutralization type calculations in which a single process or impact on barrier performance is evaluated at some estimated bounding value. The calculated radionuclide release rates from a single canister for each "bounding case" is then compared to the radionuclide release rates calculated for the expected evolution of a single waste package. In this way, impacts for a given process or impact have been assessed with respect to consequences and overall compliance with Finnish (although not Swedish) regulatory standards. The use of such bounding analyses can be a viable way of resolving an issue. For example, such analyses may be used to show that even if the credible maximum impact were to occur based on current knowledge, no unacceptable consequence would result with respect to compliance with long-term safety standards.

There are, however, no analyses in Smith et al. (2008) for cases in which two or more processes or impacts might arise (e.g., degradation of buffer properties arising from both interaction with iron and interaction with cementitious fluids). In addition, the exclusive use of highly conservative bounding analyses can present a misleading picture of the true significance of process issues and the relative contribution of barriers to long-term safety. Unless such bounding analyses are supplemented by more realistic assessments, this approach could lead to sub-optimal decision-making with respect to the EBS, for example. Exclusive reliance on bounding analyses also has potential adverse consequences on the most efficient and effective allocation of limited programmatic resources. This, in turn, could lead to the repository may becoming 'over-engineered' rather than optimized with respect to long-term safety.

As SKB/Posiva progress in their next phase of demonstration and evaluation of the feasibility and long-term safety of the KBS-3H concept, it might be necessary for SKB/Posiva to expand their identification and analyses of key issues if they intend to argue for data sufficiency and issue resolution using performance assessment calculations. There are numerous recommendations to make in this regard, including:

- SKB/Posiva should explicitly identify its approach to addressing and resolving issues, whether by bounding analysis, integrated performance and safety assessment calculations, additional R&D to reduce uncertainties, design modification, substitution of materials, etc. In some cases SKB/Posiva may pursue more than one approach to issue resolution, but none of the published

KBS-3H summary reports reviewed contain clear enough statements as to SKB/Posiva's plans for the issue resolution approach, the resources to be devoted the various issues, and an approximate schedule by when SSM might expect to learn of progress toward resolution of specific issues.

- Consideration of linked impacts (e.g., combined formation of iron-rich smectite with degraded properties, formation of volumetrically large iron corrosion products and formation of a free hydrogen gas phase within the buffer).
- Consideration of separate, but possibly coincident impacts (e.g., combined impacts on buffer performance from formation of iron-rich smectite and influx of cementitious fluids).
- Up-to-date verification and benchmarking of the sub-models and input data used in performance and safety assessment calculations.
- Direct comparison of the KBS-3V and KBS-3H design concepts using the same models, input data and design parameters.
- Better modelling representation of gradual and localized changes in the properties of EBS components, as well as gradual evolution of repository conditions. This would provide a much more credible basis by which to evaluate and defend results from "bounding analyses".
- Consideration that while some issues may be eliminated by changes in design parameters or materials, these same changes may introduce new issues that will require consideration.
- Analysis of the release behavior of different radionuclides having different properties (e.g., high/low solubility, high/low sorption on buffer, long/short half lives, high/low inventory, etc.) in order to fully illustrate the effects of different processes on overall radionuclide release rates from the EBS.

14. Summary

SKB and Posiva are careful to stress that these initial reports on the KBS-3H conceptual design present only preliminary information and analyses. It is acknowledged that considerable uncertainties remain that limit the ability to assess the feasibility and long-term safety of the KBS-3H design concept. In particular, no single reference design and emplacement/operational concept has been adopted, so that issues and concerns that might be valid for one alternative KBS-3H design may or may not be valid for another alternative design. These limitations mean that a complete or final evaluation cannot be reported at this time for the KBS-3H concept, and that there is not a sufficient basis to fully or fairly compare the KBS-3H concept to the current reference KBS-3V concept.

SKB/Posiva are still actively working on the design of the EBS for the KBS-3H concept, but have completed some useful testing (e.g., of supercontainer emplacement). However, further trials will be required to demonstrate feasibility, and further experimentation and testing will be required to determine the properties of the engineered components and assess their ability to fulfil their design and safety requirements.

Processes potentially affecting the EBS for a generic KBS-3H concept are clearly identified by SKB/Posiva, and bounding analyses of the impact of such processes on long-term radionuclide release rate have been conducted. In certain cases, it may be argued that SKB/Posiva have shown that the consequences of individual processes do not significantly compromise the ability of the repository system to comply with long-term safety standards. However, only a limited range of assessment cases has been considered using simplified models (SKB, 2008).

While acknowledging the limitations in available information, multiple design alternatives, and only preliminary progress in large-scale, field testing, an initial comparative evaluation between the KBS-3H and the current reference KBS-3V design concepts has been made in the body of this report. The major conclusions of these initial evaluations are summarized in Table 14-1. The evaluations are based on the information published by SKB/Posiva on the KBS-3H concept, and are focused on differences between the KBS-3H and KBS-3V conceptual designs potentially leading to differences in operations and long-term performance. The intent in identifying potentially open and unresolved issues as summarized in Table 14-1 is to provide a clear basis by which SSM can continue to constructively engage and communicate with SKB on overall engineered barrier system topics, and on aspects of the KBS-3H concept specifically.

Appropriately, SKB and Posiva have decided to continue with development and testing of the KBS-3H design until at least 2012, in order provide a more compelling basis for deciding among possible design options. As more information is collected, further evaluations can be made to confirm, resolve or revise the topics identified in Table 14-1.

Table 14-1. Summary of Preliminary Comparison between KBS-3H and KBS-3V Concepts.

Topic Descriptions		Differences between KBS-3H and KBS-3V Potentially Leading to Differences in Operations and Long-term Performance
1	Assessment of the feasibility of repository and EBS construction and implementation (e.g., including the accuracy of deposition drift construction, supercontainer assembly and emplacement, and drift/access tunnel sealing). Demonstration of reproducible, quality-assured waste and EBS emplacement technologies	• *Supercontainer:* Unlike KBS-3V, the KBS-3H concept requires the construction of an outer 'supercontainer' composed of a mild-steel mesh by which to enable the emplacement of the buffer and waste package into long horizontal deposition drifts. There has been limited demonstration of fabrication and quality assurance of this required supercontainer at an industrial scale, although demonstration of such a capability seems likely to be achievable. Note that in addition to emplacement concerns, the introduction of the mild-steel supercontainer for the KBS-3H concept (compared to KBS-3V) also raises new performance issues, as identified in Topics 6 and 7. • *Excavating long deposition drifts:* KBS-3H (compared to KBS-3V) requires drilling of long, slightly inclined deposition drifts on the order of 300-m in length, without significant curvature or deviation over the deposition-drift length. There has been only limited, albeit successful, demonstration of this needed construction procedure. • *Impact of damaged rock*: Because of the great length of the KBS-3H deposition drift compared to KBS-3V, there are increased concerns about encountering areas of weak rock (rubble) or regions of concentric spalling at the rock-drift interface (see Topic 2). Counter-measures to either avoid or repair deficiencies in rock quality for KBS-3H are not yet identified.

		• *Sealing of major water-conducting fracture zones:* The horizontal excavations in both KBS-3H and KBS-3V concepts may encounter major, water-bearing fracture zones, hence, control of inflow of water (see Topic 3) during emplacement operations and potential piping of bentonite-based materials after emplacement but prior to closure and return to ambient hydrodynamic conditions is of concern with respect to both emplacement feasibility and post-closure performance. The KBS-3V concept requires rapid backfilling of access drifts, a process that had yet to be fully resolved and demonstrated, based on visits to SKB research facilities in late 2008. For the KBS-3H concept, a series of engineering counter-measures to control water inflow have been identified and are under development and testing. These methods (see Topic 5) include cementitious seals (see Topic 9), emplacement of ‘distance blocks’, ‘filling blocks’, and sealing of fractures with high inflows (> 1 litre/ minute) with grout/cement or silica gel using a novel ‘super-packer’. Based on the information available for this review, both the KBS-3V and KBS-3H concepts still have remaining concerns regarding fully demonstrated methods for controlling water inflow to avoid potential impacts on operations and post-closure performance. The silica-based colloidal solutions pumped into a ‘super packer’ device have been tested for sealing fractures encountered in KBS-3H deposition drifts. The limited results to date show successful sealing, although the longer-term durability of such sealing is not yet demonstrated. • *Emplacement methods:* Several different emplacement methods have been identified for KBS-3H. This compares to the demonstrated, although still evolving and being optimized, method for KBS-3V waste package emplacement. None of the proposed KBS-3H emplacement methods have been tested using a bentonite-based buffer, or for emplacement of multiple waste packages, nor has there been demonstration of if and how emplacement of heat-producing packages might impact the viability and reproducibility of any of the KBS-3H em-

		placement methods.
2	Rock spalling and effects	• *Impacts on operations and post-closure performance:* Rock spalling might hinder successful placing of the supercontainers, as well as the distance blocks (see Topic 1), for the KBS-3H concept. Rock spalling is probably of greater concern for KBS-3H than for the KBS-3V concept because of the restricted access resulting from the long length and smaller diameter of deposition drifts in the KBS-3H concept. Incomplete filling of voids caused by spalling might lead to loss in density of the bentonite, thus possibly adversely impacting long-term repository performance. If a deposition drift must be abandoned because of encountered spalling that cannot be mitigated, this would have much more severe impacts on operations and possibly on long-term performance than spalling occurring for the single container holes used for KBS-3V. Specific plans would be needed for dealing with the possible need to abandon a KBS-3H deposition drift (e.g., specifying how it is to be backfilled and sealed).
3	Water inflow to the deposition drifts from fractures in the host rock and the ability to seal such fractures	• *Repository feasibility and layout:* Water inflows have the potential to significantly affect safety, and their successful control and management will be key to any safety case for disposal by the KBS-3H method (see Topic 1). Water inflows will affect where canisters can be disposed of, and will influence the choice of EBS design and the size and layout of the repository. Compared to the KBS-3V method, KBS-3H may be more prone to some ‘uncomfortable’ cases that have the potential to make the use of a deposition drift for disposal difficult. Such cases include the effects of fairly regularly spaced flowing fractures that intersect a horizontal deposition drift, and the effects of potential sub-horizontal fractures at the deposition drift level. These would need to be considered further on a site-specific basis.

4	Piping and erosion of the bentonite buffer	• *Degradation of bentonite-based barriers:* Severe piping and erosion of the buffer could cause the buffer not to fulfil its safety functions (see Topic 1). For example, the bulk hydraulic conductivity of the buffer could increase. This could allow increased sulphide transport to the canister, which could cause more rapid canister corrosion, potentially leading to canister failure. The KBS-3H design may be more vulnerable than KBS-3V because piping and erosion could connect between canisters and cause multiple canister failures. However, the issue is still one of active research, and assessments of the effects of piping and erosion are not yet comprehensive or complete. There are significant uncertainties, for example, in the degree to which the buffer would re-homogenise following localized erosion.
5	Sealing of deposition drifts (seals, buffer and distance blocks)	• *Complexity and volume for infilling:* There are several more components involved in the KBS-3H concept compared to the KBS-3V, such as supercontainer, distance blocks, filling blocks, drip shield, compartments plugs, etc. (see Topic 1). Each of these components require further development, and the procedure for placing the deposition drift is sensitive to disturbance in the production line, probably to a much greater extent than for the KBS-3V. All these components are important for the long-term safety. One major advantage with the KBS-3H concept, however, is that the total volume of the deposition drift and tunnels to be filled with bentonite is much smaller than for the KBS-3V alternative.
6	Corrosion of steel components external to the canister	• *Supercontainer steel as a reactant:* This issue is relevant exclusively to the KBS-3H concept, and cannot be avoided. Two major mechanisms are identified which have a potential impact on long-term performance: • The effect of steel corrosion products on mass transport. • The effects of gas from the anaerobic corrosion of steel components.

7	Effects of steel corrosion on bentonite and radionuclide transport.	• *Degradation of buffer functions:* Because of the use of a steel supercontainer, this issue is really relevant only to the KBS-3H concept. The current KBS-3H design could potentially degrade the physical properties of bentonite and thus offer pathways for canister corrodants and enhanced radionuclide transport upon canister failure.The use of a more inert container material (e.g. Ti) might avoid the problem,
8	Impact of gas from the corrosion of steel components external to the canister, gas flow and implications	• *Physical disruption of buffer:* In the KBS-3H design, hydrogen gas will be produced by anaerobic corrosion of the steel supercontainer and other steel repository components (also see Topic 10). The gas pressures that will be reached in the drifts will depend on the rates of gas generation and the gas transport capacity of fractures in the host rock. Significant gas overpressures are possible, particularly in the tightest sections of rock. Gas pressures may delay water inflow and prevent the buffer reaching full saturation. Pressures will vary along the drifts and could cause transient flows (e.g., along the buffer-rock interface and through the EDZ), which could cause piping and buffer erosion, loss of swelling pressure and lead to spalling. Hydrogen gas may also promote microbial sulphate reduction, and this may enhance canister corrosion rates. The presence of a discrete gas phase may affect water flows in the geosphere, and this could also affect radionuclide transport. There are, thus, many couplings between gas generation and other processes in the near field and far field, which may affect the safety of the KBS-3H design, which will not occur in the KBS-3V design. To-date the impacts of gas on the long-term safety of the KBS-3H design have not been thoroughly evaluated by SKB or Posiva, and so potential impacts remain unclear.
9	Impact of leachates from cementitious components	• *Degradation of smectite component in bentonite-based barriers.* Cementitious materials are used as plugs and grouts in both concepts. SKB plans to use low

		pH cement to minimise impacts of cement pore fluids upon potential mass loss and changes in physical properties of buffer clay. From a mass balance perspective however, SKB plans to use much more cement in KBS-3V (~9600 tonnes, see Puigdomenech and Sellin, 2005) compared with KBS-3H (1200-1800 tonnes, see Hagros, 2007), so that it could be considered that the KBS-3H concept would produce much smaller potential impacts from these materials.
10	Processes within horizontal failed canisters (e.g., expulsion of water and dissolved radionuclides from a defective canister interior by gas).	• *Unlikely persistence of necessary geometry.* SKB has appropriately attempted to identify any new scenarios that might be specific to the KBS-3H concept compared to the KBS-3V concept (see also Topic 6 and 7). This particular 'scenario' speculates on the formation of a penetration through the canister and cast iron insert at exactly the lowest point along the axis of a waste package in the KBS-3H horizontal orientation. This location might uniquely allow hydrogen gas from the corrosion of the cast iron insert (also see Topic 8) to build up within the trapped void spaces of a failed KBS-3H waste package. However, such a location cannot occur for a KBS-3V waste package. SKB's own corrosion and mechanical failure experts note that corrosion of the cast iron insert lowers its strength and eventually results in failure by buckling; such buckling is highly unlikely to preserve the idealized geometry assumed for this particular scenario. It is noted that SKB analyses for expulsion of water and dissolved radionuclides from a defective canister interior by gas did show a (factor of 2) increase in radionuclide release compared to the base case analysis.
11	Implications of the horizontal arrangement with respect to potential for earthquake shear	• *Site-specific analyses:* The advantages and drawbacks with the KBS-3H and KBS-3V repository concepts, in the context of the earthquake shear scenario, are site dependent. As Forsmark now has been chosen as SKB's repository site, a detailed evaluation of KBS-3V and KBS-3H for site-specific conditions with respect to future earthquake shear should be performed. In this assessment and comparison of the two KBS-3 concepts, the potential effect of stress state in the

		bedrock, the potential impact of the corroded supercontainer on the bentonite properties, and the frequency and orientation of fractures will need to be addressed. For shearing expected to be localized along pre-existing fractures, the durability and impacts of performance on distance blocks, filling blocks and grouted/silica-gel sealed fractures (see Topic 1) should be specifically addressed. Development of new shears cutting across waste packages should also be investigated.
12	Long-term performance differences, based on integration of evaluation of Topics 1 to 11	• *Combination of impacts.* SKB/Posiva conducted numerous 'one-off' performance assessment calculations for how a given process or impact might affect the subsequent release behaviour of a KBS-3H type waste package. This is a useful beginning point for evaluating and comparing the KBS-3H concept to the KBS-3V concept, as well as to regulatory compliance standards. Proper comparison of the performance offered by the two design concepts (KBS-3V and KBS-3H) would require use of more consistent performance assessment methodologies and data. There are two prominent areas where future performance assessments need to be extended; (1) assessment of waste packages in which two or more impacts (unless mutually exclusive) might occur, and (2) assessment of a larger number of waste packages in which impacts arising from one waste package (e.g., piping, gas formation, expansion of corrosion products, degradation of buffer by steel or cementitious fluids) might impact the performance of adjoining waste packages.

15. References

Börgesson, L., Johansson, L.E. and Hernelind, J., 2003. Earthquake induced rock shear through a deposition hole, Technical report TR-04-02, Swedish Nuclear Fuel and Waste Management Co (SKB), Stockholm, Sweden.

Börgesson, L. and Hernelind, J., 2006. Earthquake inclined rock shear through a deposition hole. Influence of shear plane inclination and location as well as buffer properties on the damage caused to the canister, Technical report TR-06-43, Swedish Nuclear Fuel and Waste Management Co (SKB), Stockholm, Sweden.

Carlson, L., Karnland, O., Olsson, S., Rance, A. and Smart, N. R., 2008. Experimental studies on the interactions between anaerobically corroding iron and bentonite, SKB Report R-08-28, Swedish Nuclear Fuel and Waste Management Company, Stockholm, Sweden.

Charlet, L. and Tournassat, C., 2006. Fe(II)-Na(I)-Ca(II) cation exchange on montmorillonite in chloride medium: evidence for preferential clay adsorption of chloride - metal ion pairs in seawater. *Aquatic Geochemistry*, 11**:** 115-137.

Crossland, I., 2005. Long term corrosion of iron and copper. *The 10th International Conference on Environmental Remediation and Radioactive Waste Management*, September 4-8, 2005, Glasgow, Scotland. Paper 1272.

Géhin, A., Greneche, J.-M., Tournassat, C., Brendlé, J., Rancourt, D. G. and Charlet, L., 2007. Reversible surface-sorption-induced electron-transfer oxidation of Fe(II) at reactive sites on a synthetic clay mineral. *Geochimica et Cosmochimica Acta,* 71**:** 863-876.

Gribi, P., Johnson, L. H., Suter, D., Smith, P. A., Pastina, B. and Snellman, M., 2008. Safety assessment for a KBS-3H spent nuclear fuel repository at Olkiluoto: Process report, SKB Report R-08-36, Swedish Nuclear Fuel and Waste Management Company, Stockholm, Sweden.

Hagros, A., 2007. Estimated quantities of residual materials in a KBS-3H repository at Olkiluoto, SKB Report R-08-33, Swedish Nuclear Fuel and Waste Management Company, Stockholm, Sweden.

Hedin, A., 2005. An analytic method for estimating the probability of canister/fracture intersections in a KBS-3 repository, SKB Report R-05-29, Swedish Nuclear Fuel and Waste Management Co. (SKB), Stockholm, Sweden.

Hernelind, J., 2006. Earthquake induced rock shear through a deposition hole when creep is considered – first model. Effect on the canister and the buffer, SKB Report R-06-87, Swedish Nuclear Fuel and Waste Management Co. (SKB), Stockholm, Sweden.

Johnson, L. H., Marschall, P., Wersin, P. and Gribi, P., 2008. HMCBG processes related to the steel components in the KBS-3H disposal concept, SKB Report R-08-25, Swedish Nuclear Fuel and Waste Management Company, Stockholm, Sweden.

Lantenois, S., Lanson, B., Muller, F., Bauer, A., Jullien, M. and Plançon, A., 2005. Experimental study of smectite interaction with metal Fe at low temperature: 1. Smectite destabilization. *Clays and Clay Minerals*, 53**:** 597-612.

La Pointe, P.L., Cladouhos, T.T., Outters, N. and Follin, S., 2000. Evaluation of the conservativeness of the methodology for estimating earthquake-induced movements of fractures intersecting canisters, SKB report TR-00-08, Swedish Nuclear Fuel and Waste Management Co. (SKB), Stockholm, Sweden.

Lund, B., 2006. Stress variation during a glacial cycle at 500 m depth in Forsmark and Oskarshamn: Earth model effects, SKB Report R-06-95, Swedish Nuclear Fuel and Waste Management Co. (SKB), Stockholm, Sweden.

Marcos, N., 2003. Bentonite-iron interactions in natural occurrences and in laboratory – the effects of the interaction on the properties of bentonite: a literature survey, Posiva Working Report 2003-55, Posiva Oy, Olkiluoto, Finland.

Milodowski, A. E., Cave, M. R., Kemp, S. J., Taylor, H., Vickers, B., Green, K., Williams, C. L. and Shaw, R. A., 2009. Mineralogical investigations of the interaction between iron corrosion products and bentonite from the NF-PRO Experiments (Phase 1), SKB Technical Report TR-09-02, Swedish Nuclear Fuel and Waste Management Company, Stockholm, Sweden.

Munier, R. and Hökmark, H., 2004. Respect distances – Rationale and means of computation, SKB Report R-04-17, Swedish Nuclear Fuel and Waste Management Co. (SKB), Stockholm, Sweden.

Pastina, B. and Hellä, P. (eds.)., 2006. Expected evolution of a spent nuclear fuel repository at Olkiluoto, Report POSIVA 2006-05, Posiva Oy, Olkiluoto, Finland.

Savage, D. and Benbow, S., 2007. Low pH cements. SKI Report 2007:32, Swedish Nuclear Power Inspectorate, Stockholm, Sweden.

Savage, D., Watson, C., Benbow, S. and Wilson, J., in press. Modelling iron-bentonite interactions. *Applied Clay Science*.

SKB, 2006. Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation, Main report of the SR-Can project. report TR-06-09, Swedish Nuclear Fuel and Waste Management Co (SKB), Stockholm, Sweden.

SKB, 2008. Horizontal deposition of canisters for spent nuclear fuel. Summary of the KBS-3H Project 2004-2007, TR-08-03, Swedish Nuclear Fuel and Waste Management Company, Stockholm, Sweden.

Smith, P.A., Johnson, L.H., Snellman, M., Pastina, B. and Gribi, P., 2007a. Safety assessment for a KBS-3H spent nuclear fuel repository at Olkiluoto: Evolution report, SKB R-08-37. Swedish Nuclear Fuel and Waste Management Co (SKB), Stockholm, Sweden.

Smith, P. A., Nordman, H., Pastina, B., Snellman, M., Hjerpe, T. and Johnson, L. H., 2007b. Safety assessment for a KBS-3H spent nuclear fuel repository at Olkiluoto: Radionuclide transport report, SKB Report R-08-38, Swedish Nuclear Fuel and Waste Management Company, Stockholm, Sweden.

Smith, P. A., Neall, F., Snellman, M., Pastina, B., Nordman, H., Johnson, L. H. and Hjerpe, T., 2008. Safety assessment for a KBS-3H spent nuclear fuel repository at Olkiluoto: Summary report, SKB Report R-08-39, Swedish Nuclear Fuel and Waste Management Company, Stockholm, Sweden.

Wersin, P., Birgersson, M., Olsson, S., Karnland, O. and Snellman, M., 2008. Impact of corrosion-derived iron on the bentonite buffer within the KBS-3H disposal concept: the Olkiluoto site as case study, SKB Report R-08-34, Swedish Nuclear Fuel and Waste Management Company, Stockholm, Sweden.

Wersin, P. and Snellman, M., 2008. Impact of iron on the performance of clay barriers in waste disposal systems: Report on the status of research and development, SKB Report R-08-45, Swedish Nuclear Fuel and Waste Management Company, Stockholm, Sweden.

Strålsäkerhetsmyndigheten
Swedish Radiation Safety Authority

SE-171 16 Stockholm
Solna strandväg 96

Tel: +46 8 799 40 00
Fax: +46 8 799 40 10

E-mail: registrator@ssm.se
Web: stralsakerhetsmyndigheten.se