Technical Report

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Horizontal deposition of canisters for spent nuclear fuel

Summary of the KBS-3H Project 2004–2007

Svensk Kärnbränslehantering AB

December 2008

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00

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Preface

SKB and Posiva both selected the KBS-3 method for the geologic disposal of spent nuclear fuel. The KBS-3 method relies on stable and favourable conditions of the bedrock, long-lived canisters containing the spent fuel and the buffer functions of clay surrounding the canister. The reference design is the KBS-3V, in which the canisters with spent nuclear fuel are emplaced vertically in individual deposition holes. For a number of years SKB and Posiva have also jointly studied a design in which the canisters are instead serially emplaced in long horizontal drifts (KBS-3H). The drivers behind the development of the KBS-3H concept are that both cost and environmental impact could be reduced without compromising long-term safety. There are many similarities between KBS-3H and KBS-3V as both designs are based on the KBS-3 method.

This report is an account of the KBS-3H development work conducted between 2004 and 2007, during which many desk studies from 2001–2003 were brought from theory to practice. The technology for the excavation of horizontal drifts was demonstrated at Äspö Hard Rock Laboratory (HRL). Equipment for the handling and deposition of a heavy supercontainer and for grouting rock using a Mega-Packer were also manufactured and tested at Äspö HRL. The overall knowledge base was broadened by studies of operational and long-term safety, environment and cost. The report is intended for readers who are familiar with R&D for the final disposal of spent nuclear fuel in Finland and Sweden.

Several people have been engaged in this work during the period 2004–2007, see the list of KBS-3H specific reports in Appendix A. They are all acknowledged for their excellent contributions. Erik Lindgren at SKB was the project manager for the overall KBS-3H project during 2004 to spring 2005 and thereafter Erik Thurner (SKB) took on the responsibility. Jorma Autio and Margit Snellman, both at Saanio & Riekkola Oy, have been in charge of design and long-term safety analyses, respectively. Bo Halvarsson at Vattenfall Power Consultants was responsible for technical development. Rickard Karlzén (SKB), and later Anders Eng (Acuo Engineering AB), were responsible for demonstration projects. Marina Molin (Adlibrakonsult) managed QA aspects and project administration. Göran Bäckblom (Conrox AB) was the lead author of this summary report, with contributions from Erik Thurner, Jorma Autio, Pekka Anttila (Fortum Heat and Power), Bo Halvarsson, Anders Eng , Barbara Pastina (Saanio & Riekkola Oy) and Margit Snellman, all of whom were also involved in planning the next project phases.

The steering group for the project, chaired by Stig Pettersson, SKB, was composed of the following members: Tommy Hedman and Fred Karlsson, SKB, Timo Äikäs, Jukka-Pekka Salo and Aimo Hautojärvi, Posiva. A draft version of the report was reviewed by selected members of the SKB Site Investigation Review Group (SIERG), and by several other experts both in Finland and in Sweden.

The development and demonstration of the deposition equipment and construction of a low-pH concrete plug were partly financed by the Sixth Euratom Framework Programme for nuclear research and training through the Engineering Studies and Demonstrations of Repository Designs (ESDRED) Project, Contract FI6W-CT-2004-07-20 -508851. SKB and Posiva have jointly decided to continue the development of the KBS-3H design for the period 2008–2010.

Stockholm, December 2008

Tommy Hedman
Director, Technology & Safety
Svensk Kärnbränslehantering AB

Timo Äikäs
Director Engineering
Posiva Oy

Erik Thurner
KBS-3H Project Manager
Svensk Kärnbränslehantering AB

Summary

Background

SKB in Sweden and Posiva in Finland have selected the KBS-3 method for the final disposal of spent nuclear fuel. The KBS-3 method is based on achieving long-term safety by isolating the spent fuel using multiple barriers. The spent nuclear fuel is encapsulated in a copper canister with a cast-iron insert. The canister is surrounded by a bentonite buffer and emplaced in crystalline rock at sufficient depth to ensure effective isolation from the surface and favourable thermal, hydraulic, mechanical and chemical conditions.

In the SKB reference design (KBS-3V), (Figure 1, left), the canisters are emplaced vertically in individual 1.75 m-diameter deposition holes, some 8 m deep, and separated from one another by a distance of 6–8 m. The canisters are emplaced from a deposition tunnel around 200–300 m long that will be subsequently backfilled and finally plugged at the junction between the deposition tunnel and the adjacent main tunnel. As part of the ongoing design optimisation work, in the early 90's SKB initiated studies of alternative designs for the KBS-3 method using horizontal emplacement of the canisters (Figure 1, right). The concept, referred to later as KBS-3H, involves several canisters emplaced serially in 1.85 m-diameter deposition drifts approximately 100–300 m in length.

The obvious advantages of the KBS-3H design are much less excavation and backfilling as the deposition tunnels of the KBS-3V are not needed. This contributes to cost savings and reductions in environmental impact, as the excavated and backfilled volumes are reduced by some 50% with the SKB design. With respect to long-term safety, both the KBS-3V and KBS-3H alternatives use the canister, the buffer and the rock as the primary safety barriers.

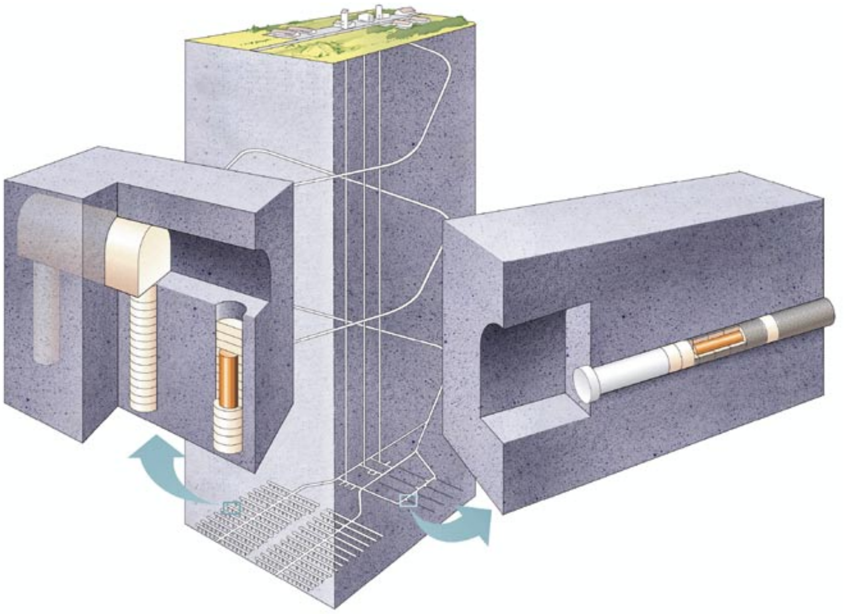

Figure 1. *Left: The KBS-3 method with vertical emplacement of the canisters (KBS-3V) – the reference design. Right: The KBS-3 method with horizontal emplacement of the canisters in up to 300 m-long deposition drifts (KBS-3H).*

After additional investigations and studies, in 2001 SKB and Posiva decided to carry out a Research, Development and Demonstration (RD&D) programme for horizontal emplacement. The work on evaluating the feasibility of the method during 2001–2003 showed that KBS-3H is a promising alternative to KBS-3V, and therefore SKB and Posiva jointly decided to develop and demonstrate technology and to further investigate safety, environment and cost issues. A new feature of the KBS-3H design was the use of a "supercontainer", i.e. that the canister and buffer, surrounded by a shell would be deposited as a package in the horizontal deposition drift.

The key issues that were highlighted for further study in the 2004–2007 phase of the programme were long-term safety, the overall KBS-3H design and specific buffer issues, the excavation of the deposition drift, assemblage and emplacement of the supercontainer as well as retrievability, cost and environmental impacts.

The KBS-3H Design

KBS-3H is a variant of the KBS method, which means that there are many similarities in requirements, assumptions and conditions for KBS-3V and KBS-3H. The spent fuel, the canister, the buffer and the bedrock are all the same. Many of the surface and underground facilities and technology are identical or similar in both designs. A brief description is given below of some of the main features of the KBS-3H.

A supercontainer shell of metal is fabricated and the buffer and canister assembled, see Figure 2. The weight of the supercontainer is approximately 46 tonnes, length 5,525 mm and diameter 1,765 mm assuming the most common spent fuel elements in Sweden and Finland. The supercontainer is transported and emplaced as one unit in a 100–300 m-long horizontal drift with a diameter of 1,850 mm. The tolerance for the radial gap between the supercontainer and the rock is set so that the package can be properly installed and that the density of the buffer is sufficient after swelling.

The distance between the supercontainers in the drift is set so as not to generate excessive temperatures that may impair the buffer performance (< 100°C) close to the canister surface after closure of the repository. Another function is to separate the supercontainers (canisters) hydraulically from each other. The spaces in between the supercontainers are filled with "distance blocks" to be manufactured of bentonite, see Figure 3. The lengths of the distance blocks are approximately 2.5 m for SKB and 5.5 m for Posiva due to different separations between the deposition drifts (SKB 40 m and Posiva 25 m) and different thermal properties of the bedrock at Forsmark/Laxemar in Sweden and Olkiluoto in Finland.

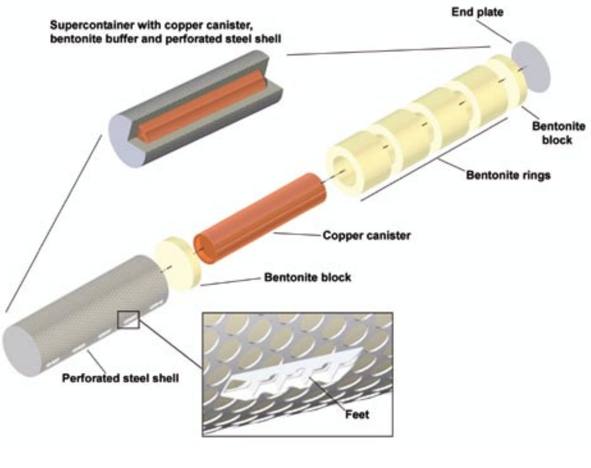

Figure 2. *The components of the supercontainer.*

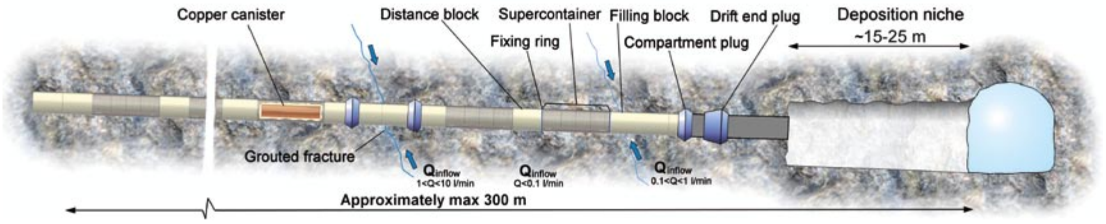

Figure 3. *KBS-3H components. Some of the components are applicable only for certain design alternatives of the KBS-3H design.*

The limiting of groundwater seepage into the deposition openings is essential for both KBS-3H and KBS-3V. “Compartment plugs” made of metal may be used to isolate the water-bearing fractures or fracture zones in the deposition drifts that are unsuitable for the deposition of canisters from those parts that are suitable, and to rapidly seal the compartments after emplacement of the supercontainers and distance blocks. The overall long-term safety criterion for the transmissivity of fractures intersecting the drifts at a supercontainer unit section (the combined length of the supercontainer and distance block) is that it should be less than $3 \cdot 10^{-9}$ m^2/s, corresponding to a groundwater inflow of less than 0.1 litres per minute, as it then ensures that the host rock provides an effective barrier to the transport of radionuclides released in the event of canister failure. It also protects the buffer against piping and erosion, which could occur if the maximum initial inflow rate of groundwater into a drift section containing a supercontainer and distance block is higher than 0.1 litres per minute. The inflow level set is preliminary and needs to be confirmed by tests. From the point of view of piping and erosion, higher transmissivities may be allowable, if inflows can be reduced or prevented for a sufficient period of time by grouting potentially problematic fractures. For higher inflow sections, up to 1 litre per minute, extra “filling blocks” are installed.

“Drift end plugs” will be placed at the beginning of the drifts at their junction with the deposition niche. All the plugs are, in principle, temporary structures with respect to long-term function. The compartment plugs positioned inside the deposition drift are only required to function during the early saturation phase, whereas the plug that seals the drift must maintain its function throughout the period prior to the sealing of the repository.

Owing to the use of supercontainers for KBS-3H, certain parts of the underground infrastructure will be different compared to the KBS-3V repository, especially in the case of the reloading station, where the supercontainer will be assembled.

KBS-3H Project 2004–2007

Based on the findings of previous studies, the programme for 2004–2007 was designed to meet the following main objectives: to demonstrate that the deposition alternative is technically feasible and that KBS-3H fulfils the same long-term safety requirements as KBS-3V.

For practical reasons, the project was divided into two phases. Phase 1 covers the period from 2004 to 2005 with technical development, excavation work and technical investigations and Phase 2 covers the period from 2006 to 2007 with tests of the deposition equipment, preliminary safety analyses and refined design and analyses of the design. The project was divided into four subprojects: long-term safety, design, technical development and demonstration.

Most of the main and subsidiary objectives have been accomplished but some items still remain for continued studies.

Objectives and achievements

Below, the objectives of Project 2004–2007 are highlighted in **bold,** and for each objective the achievements and present knowledge status are described.

Main objectives and achievements

The main objectives of KBS-3H Project 2004–2007 were to **demonstrate that the deposition alternative is technically feasible and that it fulfils the same long-term safety requirements as KBS-3V.**

These main objectives have only been partially met owing to the restrictions imposed before the start of the project and during its execution. More work is needed for the full demonstration of the engineering feasibility with due consideration to anticipated, site-specific conditions. In KBS-3H Project 2004–2007, it was demonstrated that it was possible to excavate horizontal drifts that would fulfil most of the stringent requirements on geometry dictated by the use of current standard technology. It was further demonstrated that it is possible to emplace a 46-tonne supercontainer in a deposition drift using water-cushion technology.

A critical[1] issue for the robustness of the KBS-3H during emplacement and saturation is that the groundwater seepage into the deposition drift is low (< 0.1 l/min over the entire length of the supercontainer section) as higher inflow may cause piping/erosion of the buffer during the saturation period. A Mega-Packer was developed and used successfully for grouting operations at the Äspö HRL.

The complete drift design, including all components of the KBS-3H concept, needs to be demonstrated by means of integrated full scale testing, and such tests should be preceded by full-scale tests of the individual components. Examples of important component tests that remain to be executed are the emplacement of a supercontainer with real buffer instead of a mock-up, the manufacture and emplacement of distance and filling blocks and the manufacture and installation of compartment plugs.

The main conclusions from the safety assessment conducted and based on a preliminary design of the KBS-3H design were that features or processes that are specific to KBS-3H have mostly minor impacts on the safety functions of the host rock, the buffer or the canister and their evolution over time. In spite of several limitations in the present safety assessment, it can be concluded that the KBS-3H design alternative offers potential for the full demonstration of safety for a repository at the Olkiluoto site and for demonstrating that it fulfils the same long-term safety requirements as KBS-3V.

Subsidiary objectives and achievements

To demonstrate that horizontal blind deposition drifts with a diameter of 1,850 mm and a length of up to 300 m can be excavated using a method that produces drifts that fulfil the functional requirements.

Two drifts 15 m and 95 m long were excavated at Äspö HRL using push-reaming (reversed raise-boring). The method is feasible and acceptable with respect to occupational safety and environmental impact, and reasonably efficient despite the fact that neither the equipment nor the working procedures are optimised. The maximum daily advance rate during reaming was in the order of 6 m per 12-hour day. The technology would also be applicable for 300 m long drifts provided that the technique is developed and tested to drill sufficiently straight pilot holes. More experience is needed to understand for what rock conditions additional pre-grouting would be necessary before the drift is reamed and for what rock conditions the drift might need temporary ground support during construction and before emplacement of the supercontainer. Several suggestions for additional technical development and improvements have been identified in addition to the developments during the project. The geometrical requirements should be reconsidered and methods to show geometrical compliance improved. Techniques for the directional drilling of pilot-holes should be adapted and tested.

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[1] An issue is defined as critical if there is uncertainty that requirements (functional/design/safety) can be met. In many instances such uncertainties can be reduced by improved design.

To design and manufacture equipment that can deposit a pre-assembled supercontainer consisting of a canister and its surrounding bentonite in the deposition drift.

Industrial standard technology for lifting a heavy load using a water-cushion was adapted to the KBS-3H design. Based on this technology, deposition and auxiliary equipment was designed, manufactured and tested at Äspö HRL. Using a mock-up supercontainer (with a canister and low-strength concrete instead of a bentonite buffer) with correct dimensions and weight it was concluded that water-cushion technology is technically feasible for the emplacement of supercontainers and distance blocks. It was also concluded that the water-cushion technique is sensitive to load variations, which means that to transport the supercontainers the load must be well balanced, i.e. the centre of gravity should be the same as the geometrical centre of the supercontainer. The test programme has covered a cumulative deposition distance of approximately 12 km during 2007. The transportation has been performed in both manual and automatic modes. For the Forsmark case (assuming a 260 m long drift split into two compartments), it is estimated that 28 supercontainers can be deposited in 9 days with 24 h operation and that is well above the requirement of "one canister per day".

By means of investigations and trials show that the buffer function requirements can be fulfilled.

The uncertainties concerning the buffer are considered to be the main factors that potentially affect the robustness of the KBS-3H design. Three broad modes can be envisaged by which a bentonite buffer could conceivably cease to fully perform its safety functions: loss or redistribution of buffer mass, mineral alteration of the buffer or freezing of the buffer. Many of the functional requirements are identical for KBS-3V and KBS-3H. Specific issues relating to KBS-3H covered in Project 2004–2007 are loss or re-distribution of buffer mass and mineral alteration of the buffer.

During the studies in 2004–2007 it was concluded that the KBS-3H buffer design should be made more robust for the site-specific conditions foreseen at Olkiluoto. The most significant functional uncertainties and problems were related to buffer behaviour where heterogeneous groundwater inflow and uneven saturation of the buffer could cause displacement or rupturing of the distance block, and piping and erosion of the buffer.

It was decided to improve the design using the following approaches:

- division of the deposition drifts into "good quality" compartments to be used for the deposition of canisters and plugging of unsuitable sections,
- use of "filling components" in positions with high groundwater inflow to increase the robustness of the buffer and plug design,
- installation of temporary pipes to drain the drift artificially and to wet the buffer and to evacuate the air, and thereby control the initial state of saturation and hydraulic heterogeneity,
- develop grouting methodology to decrease seepage of groundwater into the deposition drift.

The project then developed a design alternative called DAWE (Drainage, Artificial Watering and air Evacuation) in which air and water pipes are installed for artificial wetting and air drainage. The pipes are removed before the deposition drift is sealed. The DAWE alternative has been assessed as feasible, although there are several issues that require further consideration.

As regards mineral alteration of the buffer, it is noted that a key difference between the KBS-3V and KBS-3H designs is the use, in KBS-3H, of additional steel components (in particular the supercontainer shells) that will corrode and generate hydrogen gas. The preliminary assessment indicates that the iron/bentonite interactions will remain spatially restricted for very long periods of time because of diffusional limitations and the strong affinity of the clay for Fe^{2+} released from the corroding supercontainer steel shell. However, issues impacting repository performance remain, and consequently the possibility of substituting the steel by other metals, e.g. titanium and copper, are being considered for the next phase of the study.

Seal at least one deposition drift by constructing a plug made of low-pH shotcrete and designing alternative drift end plugs.

Within the framework of the European project ESDRED, a shotcrete plug was designed and constructed at Äspö HRL. The conclusions from the testing are that a shotcrete plug may function properly, but it is recommended that the low-pH concrete plug should be cast instead of using the shotcrete technology. Alternative plug designs using steel and concrete plugs in series have been investigated. The steel plug enables rapid temporary sealing and isolation from a few weeks to a few months during the early wetting of drifts, and the concrete plug provides longer term sealing after the concrete reaches full compressive strength.

Perform a KBS-3H safety assessment based on site data from Olkiluoto and knowledge concerning the barrier performance of the design.

The KBS-3H long-term safety assessment based on the preliminary KBS-3H design focussed on the differences between KBS-3V and KBS-3H, and whether these differences have the potential to lead to unacceptable radiological consequences. Another issue for consideration was whether KBS-3H is a feasible option at the Olkiluoto site from a long-term safety point of view.

The KBS-3H safety case compares radionuclide releases and calculated doses with Finnish regulatory guidelines as the site data are from Olkiluoto, and it is based on the preliminary Basic Design alternative of KBS-3H as described in the KBS-3H Design Description 2006 /Autio et al. 2007/. Since then, the design alternatives have improved and are likely to be more robust. Examples of issues addressed in the analyses were the following:

- piping and erosion during repository operations and drift saturation,
- steel components external to the canisters, their corrosion products and their impact on mass transport,
- the effects of gas from the corrosion of these components,
- interactions involving leachates from cementitious components,
- thermally-induced rock spalling, and
- expulsion of water and dissolved radionuclides from a defective canister interior by gas.

The issues related to piping and erosion, interactions with cementitious leachates, and the thermally induced rock spalling are of concern for both KBS-3H and KBS-3V, but were addressed because their likelihood, extent or impact may be significantly different for the two designs.

The results of the release and transport calculations indicate compliance with Finnish regulations assuming single canister failure by any of the modes identified, i.e. canister with an initial penetrating defect, canister failure due to copper corrosion and canister failure due to rock shear. The highest calculated dose maxima are for the cases involving canister failure by corrosion or by rock shear, in which there is no assumed period in which the failed canister provides a transport resistance and the geosphere transport resistance is assumed to be lower than in other cases.

A number of conclusions based on the studies were made, see Chapter 5, some of which are presented below.

- No features or processes that are specific to KBS-3H have been identified which could lead to a loss or substantial degradation of the safety functions of the engineered barrier system over a million year time frame. However, the extent to which it is possible to identify and avoid fractures with the potential to undergo shear movements that could damage the engineered barriers in the event of a major earthquake remains to be evaluated, and may be different for KBS-3H compared with KBS-3V.
- Radionuclide release from the repository near field in the event of canister failure may also be affected by perturbations to the buffer/rock interface, but in all cases releases are limited and comply with Finnish regulatory criteria. Only single canister failure cases have, however, been considered, and the possibility of multiple canister failures must be addressed in future studies.

- Several issues have been identified for further study, many of which are relevant to both KBS-3V and KBS-3H. These include, for example, site-specific issues such as the transport rate of methane and the kinetics of sulphate reduction in the rock. While some issues, such as those related to gas generation prior to canister failure, are relevant mainly to KBS-3H.

In spite of several limitations in the present safety assessment, it can be concluded that the KBS-3H design alternative offers potential for the full demonstration of safety for a repository at the Olkiluoto site and for demonstrating that it fulfils the same long-term safety requirements as KBS-3V. The conclusions are based on the analysis of a KBS-3H design, termed the Basic Design, and its application to the Olkiluoto site.

Several issues for future work relating to methodology, evolution of the engineered and natural barriers, radionuclide release and transport and design were identified. Issues concerning design comprise the avoidance of distance block displacement and deformation during early evolution, avoidance or limitation of thermally induced rock spalling, the use of possible alternative supercontainer shell materials, and layout adaptation strategies to avoid potentially problematic fractures.

Contribute with reports and other information which can be used in order to show that horizontal emplacement is more cost effective and has less environmental impact than vertical emplacement.

SKB makes yearly cost estimates for the total radioactive management system. The same methodology was used to assess the cost difference for a KBS-3V and KBS-3H system at Forsmark. An important aspect is that the cost analysis does not account for possible additional development works, other possible costs associated with change of reference design to KBS-3H and costs due to possible delays in the overall programme for SKB and Posiva. Based on the assumptions used, the disposal of 6,000 canisters using the KBS-3H design would realise savings of €305 million at Forsmark (€51,000 per canister). In the event that titanium is used instead of carbon steel for the supercontainer shell and compartment plugs, the cost saving would be €230 million (€38,000 per canister).

Posiva estimated the difference in cost between the KBS-3V and KBS-3H design alternatives for the Olkiluoto site. Based on Posiva's assumptions, cost estimate methods and an inventory of 2,840 canisters, it was estimated that KBS-3H would realise savings of €96 million (€34,000 per canister). If titanium is used instead of carbon steel for the supercontainer shell and compartment plugs, the cost saving would be €50 million (€18,000 per canister).

The striking difference between the SKB and Posiva cost estimates is a result of site-specific assumptions and layout differences. One of the most important assumptions in this context is the emplacement by SKB of 28 canisters per deposition drift compared to the 16 canisters per deposition drift adopted by Posiva. This is partly due to the longer distance blocks for the Posiva design, due to different separations between the deposition drifts (SKB 40 m and Posiva 25 m) and different thermal properties of the bedrock at Forsmark/Laxemar in Sweden and Olkiluoto in Finland.

The environmental impact of adopting KBS-3H instead of KBS-3V was also investigated. The comparison shows the KBS-3H design to be positive in all aspects that could be assessed at this stage, except for steel and iron consumption. The factors with a large or substantial positive difference for the KBS-3H design are less emissions into the atmosphere and the consumption of rock, bentonite and concrete.

Investigate whether the KBS-3H design affects SKB's site investigation programme.

The KBS-3H design is supposed to be more sensitive to water-bearing fractures and possible bedrock movements along vertical fractures than KBS-3V, and this will also influence the planning and execution of site investigations in detail. However, the project did not judge the Swedish site investigations to be significantly different for the KBS-3V and KBS-3H design, and concluded that the ongoing site investigation programme did not need to be changed in order to adapt it to specific KBS-3H issues.

To develop KBS-3H candidate designs and lay-out adaptation based on Olkiluoto bedrock data.

The KBS-3H design is based on a number of sub-systems and components such as the deposition drift, the supercontainer, distance and filling blocks, compartment and drift end plugs, etc. The designs of the components are still preliminary and may be subject to revision before manufacture and testing during subsequent project phases. Many tests for a range of bedrock conditions are required in order to verify that it is feasible to manufacture and install the components and to ascertain their proper functioning during saturation. One important uncertainty that needs to be addressed, for example, is the installation of compartment plugs that would require slots being cut in the rock and the welding of heavy steel components some 200 m deep into a deposition drift of less than 2 m in diameter.

Groundwater control

A complex system of components is necessary to meet the functional requirements during water pressure build-up and saturation. To limit the ingress of water, alternatives for grouting were investigated. Post-grouting (i.e. the injection of sealing materials into the fractures after the drift has been excavated) was tested at Äspö HRL using a "Mega-Packer". It is expected that Silica Sol for very small fracture apertures and low-pH cement for wider fractures will be the preferred grouting materials. The preliminary results from the tests carried out in November 2007 show that Silica Sol can be used for post-grouting with satisfactory results.

Candidate designs

A number of KBS-3H design alternatives have been investigated since 2004. The Basic Design alternative was re-evaluated in May 2007 and put on hold as modelling and laboratory tests showed that the distance blocks would be impaired for high rates of water pressure build-up. The rapid build-up causes deformation between the supercontainer and the distance block with the entire block surface being subjected to full water pressure and displacement of the distance block in spite of fixing rings. The alternative DAWE (Drainage, Artificial Watering and air Evacuation) design is based on artificially filling the void spaces with water around the supercontainers to accelerate the swelling of the distance blocks. Pipes are installed for water injection, drainage and air evacuation before emplacing the supercontainer and distance blocks in the drift. Because all open connected void spaces are filled with water at hydrostatic groundwater pressure, there will be no significant pressure gradients immediately after water filling that could be the driving forces for flow between supercontainer sections. Pipes are removed before sealing the deposition drift. Pipe removal was tested at Äspö HRL in the autumn of 2007 and the results confirm that the pipes can be removed as planned. One of the challenges of the DAWE design is that it is difficult to guarantee there will be no bentonite slurry flow along the drift floor to that part of the drift where the installation takes place, since there could be both water dripping on to the blocks as well as humidity-induced cracking of the blocks which could result in bentonite erosion. During 2007 also a third design alternative, Semi Tight Compartments was briefly investigated.

Layout adaptation to the Olkiluoto site

The layout adaptation was based on the Olkiluoto Site Description 2006 and accounted for the established layout requirements. The layout was developed for 2,840 canisters in 171 deposition drifts using the preliminary design. The average deposition drift length is 272 m and the total deposition drift length some 46,400 m. However, bearing in mind the fact that the locations of the supercontainers may be moved by several metres to exclude locations with considerable water seepage, it was conservatively assumed that a total of 25% of the host rock should be excluded for disposal purposes. In comparison, it is estimated that the exclusion rate is 17% for a KBS-3V repository based on the same Olkiluoto 2006 site model.

Programme of full-scale tests at Äspö HRL in this phase and in a possible next phase of the project.

Several full-scale tests were carried out, such as drift excavation, emplacement of mock-up supercontainers and distance blocks, the installation of a low-pH shotcrete plug and post-grouting using Mega-Packers. Additional component tests and full-scale tests have been envisioned and planned for, and some of these tests will be carried out in the next phase.

To study the retrievability of canisters for the KBS-3H design.

Alternatives for retrieving the supercontainer were investigated. Retrieval in this context is understood to mean the removal of the canister after the buffer has absorbed water and become deformed or after plugging and sealing of the drift. The removal of the various barriers will take place through a combination of different techniques and equipment. It was proposed that the concrete and steel components should preferably be removed by means of hydro-demolition methods and water cutting. The removal of bentonite can be performed using hydrodynamic/chemical methods, which have already been tested for retrieval of a KBS-3V canister. Alternatively, hydro demolition methods using high water pressures (> 100 MPa) could be used, if tests show that the method will not damage the canister.

Next steps

SKB and Posiva have decided to continue the development work on horizontal emplacement. The complementary studies of horizontal emplacement during 2008–2010 will be used to develop the KBS-3H design to such a state that a decision on full-scale testing and demonstration can be made.

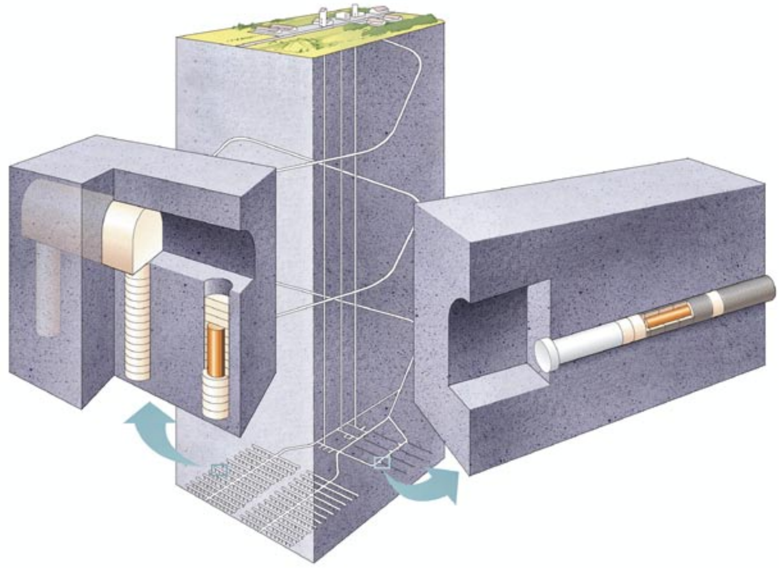
Sammanfattning

Bakgrund

SKB i Sverige och Posiva i Finland, har valt KBS-3 som metod för att slutförvara använt kärnbränsle. KBS-3-metoden bygger på att man med användande av flera barriärer uppnår långsiktig isolering av det använda kärnbränslet. Bränslet försluts i en kopparkapsel med en gjuten stålinsats. Kapseln omges av en bentonitbuffert och placeras i kristallint berg på tillräcklig djup för att uppnå effektiv isolering från markytan och gynnsamma hydrologiska, mekaniska och kemiska förhållanden.

I referensutformningen (KBS-3V) (vänstra delen av Figur 1), placeras kapslarna vertikalt i enskilda deponeringshål med diametern 1,75 m, cirka 8 m djupa med ett avstånd av cirka 6–8 meter från varandra. Kapslarna placeras ut från en deponeringstunnel 200–300 m lång, som sedan återfylls och pluggas vid anslutningen till en stamtunnel. Som en del i det pågående arbetet med att optimera utformningen, initierade SKB i början av 90-talet utredningar för horisontell deponering av kapslarna (högra delen av Figur 1). Utformningen benämndes senare KBS-3H, där flera kapslar placeras i serie i ett deponeringshål, som är ca 100–300 m långt.

Uppenbara fördelar med KBS-3H-utformningen är väsentligt mindre berguttag och återfyllningsarbete eftersom deponeringstunnlarna enligt KBS-3V inte behövs. Detta bidrar till kostnadsbesparingar och minskad miljöpåverkan, eftersom volym av berguttag och återfyllning reduceras med omkring 50 %, antaget SKB:s utformning. Med hänsyn till den långsiktiga säkerheten, utnyttjar både KBS-3V- och KBS-3H-kapseln, bufferten och berget som de huvudsakliga säkerhetsbarriärerna.



Figur 1. *Vänster: KBS-3-metoden med vertikal placering av kapslarna (KBS-3V) – referensutformning. Höger: KBS-3-metoden med horisontell deponering av kapslarna i upp till 300 m långa deponeringshål (KBS-3H).*

Efter ytterligare undersökningar och utredningar, beslöt SKB och Posiva att genomföra ett Forsknings-, Utvecklings- och Demonstrationsprogram (FUD) rörande horisontell deponering. Arbetet som genomfördes under åren 2001–2003, visade att KBS-3H var ett lovande alternativ till KBS-3V, och därför beslutade SKB och Posiva gemensamt att utveckla och demonstrera teknologin, och ytterligare studera säkerhet, miljö- och kostnadsaspekter. En ny, karakteristisk egenskap för KBS-3H-utformningen, var användningen av en ”supercontainer”, dvs att kapsel och buffert omslutet av ett skal, skulle deponeras som ett sammanhållet paket i de horisontella deponeringshålen.

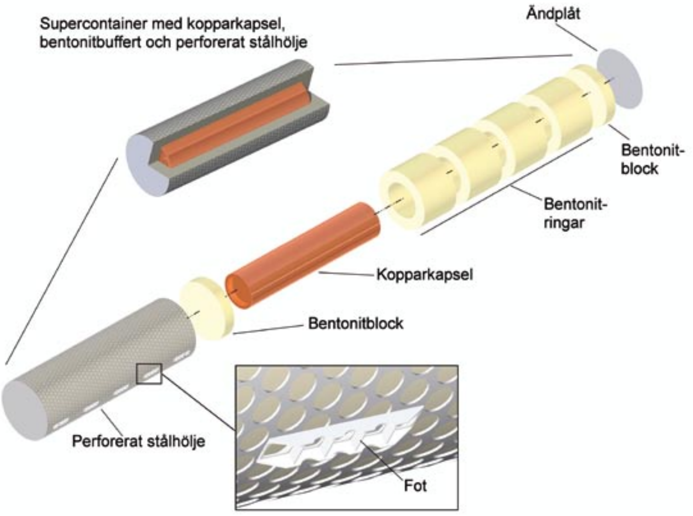
Nyckelfrågorna som belystes för ytterligare studier under åren 2004–2007, var den långsiktiga säkerheten, den generella KBS-3H-utformningen och ett antal specifika frågor relaterade till bufferten, berguttaget av deponeringsorten, montering och deponering av supercontainern, samt frågor rörande återtagbarhet, kostnader och miljöpåverkan.

Utformningen enligt KBS-3H

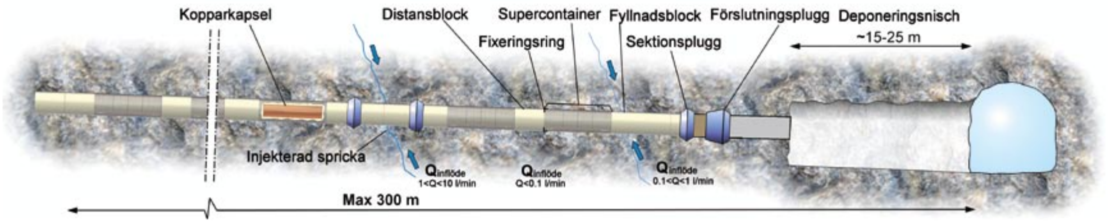
KBS-3H är en variant av KBS-metoden och därför finns det många likheter i krav, antaganden och förutsättningar för KBS-3V och KBS-3H. Bränslet är det samma, liksom kapsel, buffert och berg. Stora delar av ovanmarks- och underjordsanläggningen och tekniken är identiska eller liknande i de båda koncepten. I det följande beskrivs ett antal huvuddrag i KBS-3H-utformningen.

Ett skal av stål till supercontainern tillverkas och monteras tillsammans med kapseln och bufferten, se Figur 2. Supercontainern väger ca 46 ton, längden är 5 525 mm och diametern 1 765 mm om man antar de vanligaste bränsleelementen i svenska eller finska reaktorer. Supercontainern transporteras och deponeras som en enhet i ett 100–300 långt deponeringshål med diametern 1 850 mm. Det radiella avståndet mellan supercontainern och berget bestäms så att behållaren kan deponeras på ett riktigt sätt, samtidigt som buffertens densitet efter svällning är tillräcklig.

Avståndet mellan supercontainers i deponeringshålen sätts så att alltför höga temperaturer inte skapas, som kan skada buffertens funktion (< 100 °C) nära kapselns yta efter förslutning. En ytterligare funktion är att separera supercontainers (kapslarna) hydrauliskt från varandra. Utrymmena mellan supercontainers fylls med ”distansblock” som tillverkas av bentonit, se Figur 3. Distansblockens längd är cirka 2,5 m för SKB och 5,5 m för Posiva, beroende på skilda avstånd mellan deponeringshålen (SKB 40 m och Posiva 25 m) och skilda termiska egenskaper för berget vid Forsmark/Laxemar och vid Olkiluoto i Finland.



Figur 2. *Supercontainerns komponenter.*



Figur 3. *KBS-3H komponenter. Några av komponenterna är endast tillämpliga för vissa av utformningsalternativen för KBS-3H.*

Begränsning av inläckande grundvatten till deponeringshål och -tunnlar, är väsentligt för både KBS-3H och KBS-3V. Sektionspluggar [”compartment plugs”] av metall kan användas för att isolera de vattenförande sprickor eller sprickzoner i deponeringshålen som är olämpliga från de delar av hålen som är lämpliga och för att snabbt kunna försegla de delar av hålen där supercontainer och distansblock har deponerats. Med hänsyn till kraven på den långsiktiga säkerheten ska sprickornas transmissivitet som skär en sektion med supercontainer och distansblock vara lägre än $3 \cdot 10^{-9}$ m^2/s, vilket motsvarar ett vatteninläckage på ca 0.1 liter per minut, eftersom detta värde innebär att berget är en effektiv barriär mot transport av nuklider, om en kapsel skulle gå sönder. Det skyddar också bufferten mot kanalbildning [”piping”] och erosion; kanalbildning och erosion kan ske om det största, inledande inflöde av grundvatten till hålsektion med en supercontainer och distansblock överskrider 0,1 liter per minut. Denna inflödesnivå är preliminär och behöver verifieras genom provning. Med hänsyn till kanalbildning och erosion, kan högre transmissiviteter tolereras, om inflödet reduceras eller undviks under tillräckligt lång tid genom att de vattenförande sprickorna tätas genom injektering. För större vattenflöden, upp till 1 liter per minut, installeras fyllnadsblock.

Förslutningspluggar [”drift end plugs”] placeras vid deponeringshålens början, i anslutning till deponeringsnischen. Alla pluggar är i princip temporära utan funktion för den långsiktiga säkerheten; sektionspluggarna inne i deponeringshålen behöver bara fungera under den tidiga vattenmättnadsfasen, medan förslutningspluggen ska fungera fram till den slutliga förseglingen av förvaret.

Genom att KBS-3H använder en supercontainer, kommer delar av undermarksanläggningens infrastruktur att vara annorlunda än ett KBS-3V-förvar, då särskilt för omlastningsstationen, där supercontainern sätts samman.

KBS-3H-projektet 2004–2007

Baserat på resultaten från de tidigare studierna, planerades programmet 2004–2007 för att uppnå följande huvudmål: att demonstrera att deponeringsalternativet är tekniskt genomförbart och att KBS-3H uppfyller samma krav på långsiktig säkerhet som KBS-3V.

Av praktiska orsaker delades projektet in i två faser, Fas 1 som täckte perioden 2004 till 2005 med teknisk utveckling, berguttag och tekniska studier och Fas 2 som täckte perioden 2006 till 2007 med tester av deponeringsutrustning, preliminär säkerhetsanalys och vidareutveckling av projekteringen och analys av alternativet. Projektet delades i fyra underprojekt: långsiktig säkerhet, projektering, teknisk utveckling och demonstration.

De flesta av huvudmålen och delmålen har uppnåtts, men några frågor kvarstår för vidare utredning.

Mål och uppnådda resultat

Målen för projektet 2004–2007 anges nedan i **fetstil** och för varje mål beskrivs uppnådda resultat och nuvarande kunskapsläge.

Huvudmål och uppnådda resultat

Huvudmålen för KBS-3H-projektet 2004–2007 var att **demonstrera att deponeringsalternativet är tekniskt genomförbart och att det uppfyller samma krav på långsiktig säkerhet som KBS-3V.**

Målen har delvis uppnåtts med hänsyn taget till de begränsningar som ställdes före projektet påbörjades och under projektets gång. Mer arbete behövs, för att fullt ut demonstrera den ingenjörmässiga genomförbarheten med hänsyn taget till förmodade, platsspecifika förhållanden. I KBS-3H-projektet 2004–2007 visades att det var möjligt att anlägga horisontella deponeringshål, som uppfyller de flesta av de strikta geometriska kraven med användande av nuvarande standardmetoder. Det var vidare visats att det är möjligt att deponera en 46 ton tung supercontainer i ett deponeringshål med användande av vattenkuddeteknik.

En viktig fråga för att KBS-3H ska vara robust under deponering och vattenmättnad är att grundvatteninflödet till deponeringshålen är lågt (< 0,1 l/min över längden av supercontainern och distansblocken), då högre inflöden kan medföra kanalbildning och erosion av bufferten under vattenmättnadsfasen. En Mega-Packer utrustning för efterinjektering utvecklades och framgångsrik tätning av berget demonstrerades vid Äspölaboratoriet.

Den detaljerade utformningen med alla komponenter i KBS-3H-alternativet återstår att fullfölja och sedan integrerat demonstrera i full skala, föregånget av fullskaletester av de enskilda komponenterna.

De huvudsakliga slutsatserna från den preliminära säkerhetsanalysen som genomförts och baserad på den preliminära utformningen, var att de karakteristiska egenskaperna och processerna som är specifika för KBS-3H mestadels har mindre påverkan på bergets, buffertens eller kapselns utveckling över tiden. Trots ett flertal begränsningar i den genomförda säkerhetsanalysen kan slutsatserna dras, att KBS-3H-alternativet erbjuder en möjlighet för full demonstration av säkerheten för ett förvar vid Olkiluoto och att det är möjligt att demonstrera att alternativet uppfyller samma långsiktiga säkerhetskrav som KBS-3V.

Delmål och uppnådda resultat

Att demonstrera att horisontella deponeringshål med en diameter av 1 850 mm och upp till en längd av 300 m kan anläggas med en metod som ger hål som uppfyller de funktionella kraven.

Två ortar 15 m och 95 m långa togs ut vid Äspölaboratoriet med användande av en tryckande raise-boring utrustning. Metoden är tekniskt genomförbar och acceptabel med hänsyn till arbetsmiljö och miljöpåverkan, och rimligt effektiv trots att varken utrustning eller arbetsrutiner är optimerade. Den största dagliga framdriften var i storleksordningen 6 m per 12 timmars skift. Tekniken är också tillämplig för 300 m långa hål, förutsatt att tekniken att borra långa, raka pilothål är utvecklad och demonstrerad. Mer erfarenhet är nödvändig för att förstå för vilka bergförhållanden som förinjektering av berget är nödvändig innan hålen ryms upp från pilothålet och för vilka bergförhållanden hålen kan behöva temporär bergförstärkning under anläggning av hålen och före deponering av supercontainers. Flera förslag för teknisk utveckling och förbättringar har identifierats utöver den utveckling som skedde inom projektet. De geometriska kraven bör ånyo studeras och metoderna att visa kravuppfyllnad förbättras. Teknik för styrd borrning av pilothål bör anpassas och provas.

Att projektera och tillverka en utrustning som kan deponera en förmonterad supercontainer med kapsel och omgivande bentonit i deponeringshålen.

Industriell standardteknik för att lyfta tunga laster med vattenkudde anpassades till KBS-3H-utformningen. Med utgångspunkt från denna teknik, projekterades, tillverkades och testades utrustning för deponering med kringutrustning vid Äspölaboratoriet. Med en an attrapp av supercontainern, (med en kapsel och betong med låg hållfasthet istället för bentonit) med korrekta dimensioner och vikt, drogs slutsatsen att tekniken med vattenkudde är tekniskt genomförbar för att deponera supercontainer och distansblock. Man drog vidare slutsatsen att vattenkuddetekniken är känslig för lastvariationer, vilket innebär att när supercontainern transporteras, ska lasten vara balanserad, det vill säga att supercontainerns tyngdkraftscentrum ska sammanfalla med supercontainerns origo. Testprogrammet har täckt en kumulativ deponeringssträcka av 12 km under

2007 och transport har skett både manuellt och automatiskt. Med antagande av förutsättningar för Forsmark (en 260 m långt hål indelad i två sektioner) uppskattas att 28 supercontainer kan deponeras på nio dagar för dygnet-runt drift, vilket är långt över kravet att kunna deponera ”en kapsel om dagen”.

Med utredningar och försök visa att buffertens funktionella krav kan uppnås.

Osäkerheter rörande bufferten är de viktigaste och de som möjligtvis kan påverka KBS-3H-alternativets robusthet. Det är på tre principiellt olika sätt som det är tänkbart att bentonitbufferten möjligtvis skulle tappa sin säkerhetsfunktion: förlust eller omflyttning av buffertmassa, mineralogiska förändringar eller att bufferten skulle utsättas för frysning. Flera av de funktionella kraven är identiska för KBS-3V och KBS-3H. Specifika frågor relaterade till KBS-3H som hanterades i projektet 2004–2007 är förlust eller omfördelning av buffertmassa och mineralogiska förändringar av bufferten.

Under studierna 2004–2007 drogs slutsatsen att utformningen av bufferten för KBS-3H skulle göras mer robust för de platsspecifika förhållanden som kan förutses vid Olkiluoto. De mest betydande funktionella osäkerheterna och problemen relaterades till buffertens beteende, där heterogent grundvatteninflöde och ojämn vattenmättnad av bufferten skulle kunna leda till förskjutningar eller brott i distansblocken, och kanalbildning och erosion av bufferten.

Det beslutades att förbättra utformningen genom följande tillvägagångssätt:

- indelning av deponeringshålen i sektioner med ”bra kvalitet” att användas för deponering av kapslar och pluggning av olämpliga sektioner,
- användning av ”fyllnadskomponenter” i lägen med högt grundvatteninflöde för att öka robustheten av buffert och pluggar,
- installation av temporära rör att dränera hålen och för att väta buffert och för att evakuera luften och därigenom styra initialtillståndet av vattenmättnad och hydraulisk heterogenitet,
- utveckla injekteringsteknik för att minska inflödet av grundvatten in till deponeringshålen.

Projektet utvecklade sedan ett utformningsalternativ benämnt DAWE (Drainage, Artificial Watering and air Evacuation), där luft- och vattenrör installeras för konstgjord bevätning och luftevakuering. Rören avlägsnas innan deponeringshålen försluts. DAWE alternativet har bedömts vara genomförbart, även om det finns flera frågor som behöver ytterligare arbete.

Rörande mineralogiska förändringar av bufferten, noteras en avgörande skillnad mellan KBS-3V och KBS-3H, eftersom KBS-3H har flera komponenter i stål (då särskilt skalen till superbehållarna) som kommer att korrodera och skapa vätgas. Den preliminära bedömningen är att växelverkan mellan järn/bentonit kommer att vara rumsligt begränsad för långa tidsrymder, beroende på diffusionsbegränsningar och stark affinitet för leran att ta upp den Fe^{2+} som löses ut från det korroderande stålskalet till supercontainern. Det finns trots allt frågor rörande påverkan på förvarets funktion, och därför kommer man i kommande projektsteg att undersöka möjligheten till att byta ut stålet mot andra metaller, som titan eller koppar.

Täta åtminstone en deponeringsort genom att tillverka en förslutningsplugg med låg-pH-sprutbetong samt även projektera alternativa förslutningspluggar.

Inom ramen för det europeiska projektet ESDRED, projekterades och tillverkades en sprutbetongplugg vid Äspölaboratoriet. Slutsatserna från försöket var att en sprutbetongplugg skulle kunna fungera, men det rekommenderas att man gjuter en plugg med låg-pH-betong istället för att använda sprutbetong. Andra utformningar med stål- och betongpluggar i serie har undersökts. Stålpluggen erbjuder snabb förslutning och isolering från några veckor till några månader då hålen fylls och betongpluggen uppfyller sin funktion och att betongen når full tryckhållfasthet.

Genomföra en säkerhetsanalys för KBS-3H, baserat på data från Olkiluoto och kunskap om barriärernas funktion i alternativet.

Den preliminära långsiktiga säkerhetsanalysen baserades på den preliminära projekteringen och var inriktad mot skillnaden mellan KBS-3H och KBS-3V och om dessa skillnader har en potential för att leda till oacceptabla radiologiska konsekvenser. Ytterligare en fråga var om KBS-3H är ett lovande alternativ avseende den långsiktiga säkerheten för Olkiluoto.

KBS-3H-analysen jämför radionuklidutsläpp och beräknade doser med de finska föreskrifterna, eftersom platsdata är från Olkiluoto. Analysen är baserad på den preliminära projekteringen av alternativet Basic Design som beskriven i projekteringsrapporten 2006 /Autio et al. 2007/. Sedan dess har utformningsalternativen förbättrats och är säkerligen mera robusta. Exempel på frågor som hanterades i analysen var följande:

- kanalbildning och erosion under förvarsdrift och vattenmättnad av deponeringshålen,
- stålkomponenter utanför kapslarna, dess korrosionsprodukter och påverkan på transport av massa,
- effekter av gas från dessa komponenters korrosion,
- växelverkan förenat med lakvatten från cementprodukter,
- termiskt inducerad spjälkning av berget, och
- utpressning av vatten och lösta radionuklider med hjälp av gas från det inre av en skadad kapsel.

Frågorna som relateras till kanalbildning och erosion, växelverkan med cementhaltigt lakvatten och den termiskt inducerade spjälkningen i berget är av intresse både för KBS-3H och för KBS-3V, men behandlades ändå, eftersom deras sannolikhet, utsträckning eller påverkan kan vara påtagligt olika för de två alternativen.

Resultaten från utsläpps och transportberäkningar indikerar att de finska föreskrifterna uppfylls under antagande av att en kapsel är skadad, antingen genom en initiell penetrerande skada i kapseln, att kapseln är skadad via korrosion eller att kapseln är skadad via skjuvningsrörelser i berget. De högsta beräknade doserna är för de beräkningsfall där kapseln är skadad via korrosion eller skjuvning i berget, där det inte antas någon tid för att kapseln erbjuder ett transportmotstånd och där man antar att transportmotståndet i berget är lägre än för andra beräkningsfall.

Ett antal slutsatser baserade på utredningarna gjordes, se kapitel 5: Här nämns några få:

- Inga karakteristiska egenskaper eller processer som är specifika för KBS-3H har identifierats, som skulle kunna leda till förlust eller avsevärd försämring av ingenjörsbarriärernas säkerhetsfunktion i ett miljonårsperspektiv. Emellertid, i vilken mån sprickor med potential att skjuvas vid jordskalv och som kan skada ingenjörsbarriärerna, kan upptäckas och undvikas, återstår att utvärdera och kan vara olika för KBS-3H jämfört med KBS-3V.
- Radionuklidutsläpp från förvarets närområde i det fallet en kapsel är skadad, kan också påverkas av störningar i gränssnittet mellan buffert och berg, men i alla beräkningsfall, är utsläppen begränsade och uppfyller de finska föreskrifternas krav. Hittills har bara en skadad kapsel studerats, och möjligheten till flera skadade kapslar måste undersökas i kommande utredningar.
- Ett flertal frågor har identifierats för ytterligare studier, och många av dessa är relevanta både för KBS-3H och för KBS-3V. De är till exempel platsspecifika frågor som tranportflödet av metangas och kinetiken för sulfatreduktion i berget. Medan några frågor, som gasbildning före kapselskada, huvudsakligen är relevant för KBS-3H.

Trots ett flertal begränsningar i den genomförda säkerhetsanalysen kan slutsatserna dras, att KBS-3H-alternativet erbjuder en möjlighet för full demonstration av säkerheten för ett förvar vid Olkiluoto och att det är möjligt att demonstrera att alternativet uppfyller samma långsiktiga säkerhetskrav som KBS-3V. Slutsatserna bygger på analys av en KBS-3H-utformning benämnd Basic Design och dess anpassning till platsen Olkiluoto.

Flera frågor för framtida utredningar som relaterar till metodik, utvärdering av de ingenjörsmässiga och naturliga barriärerna, radionuklidutsläpp och transport samt utformning har identifierats. Utformningsfrågor är undvikande av förskjutningar och deformationer av distansblock under den tidiga utvecklingen, undvikande eller begränsning av termiskt inducerad spjälkning av berget, möjligheten att använda alternativa material för supercontainerns skal och strategier för att platsanpassa förvaret för att undvika sprickor som potentiellt kan vara problematiska.

Bidra med rapporter och annan information som kan användas för att visa att horisontell deponering är mer kostnadseffektiv och har mindre miljöpåverkan än vertikal deponering.

SKB genomför årliga kostnadsuppskattningar för hela hanteringen av radioaktivt avfall. Samma metodik som för KBS-3V användes för KBS-3H under antagandet att 6 000 kapslar deponeras vid Forsmark. En viktig begränsning i kostnadsanalysen är att ingen hänsyn är tagen till möjligt utökade utvecklingskostnader, andra möjliga kostnader för byte av referensutformning till KBS-3H eller möjliga kostnader för möjliga förseningar i det övergripande programmen för SKB eller Posiva. Baserat på använda antaganden, skulle KBS-3H-utformningen spara €305 miljoner (€51 000 per kapsel). Om titan används istället för kolstål i skalet till supercontainern och i sektionspluggen blir besparingen €230 miljoner (€38 000 per kapsel).

Posiva uppskattade kostnadsskillnader mellan KBS-3V och KBS-3H för Olkiluoto. Baserat på Posiva:s antaganden, metod för kostnadsberäkningar och med 2 840 kapslar, skulle KBS-3H spara €96 miljoner (€34 000 per kapsel). Om titan används istället för kolstål i skalet till supercontainern och i sektionspluggen blir besparingen €50 miljoner (€18 000 per kapsel).

Den markerade skillnaden mellan kostnadsberäkningarna genomförda av SKB och Posiva beror på platsspecifika antaganden och skillnader i förvarsutformning, då särskilt SKB:s antagande om 28 kapslar per deponeringshål och med bara 16 kapslar per deponeringshål för Posiva, vilket delvis beror på längre distansblock för Posiva:s utformning, beroende på skilda avstånd mellan deponeringshålen (SKB 40 m och Posiva 25 m) och skilda termiska egenskaper för berget vid Forsmark/Laxemar och vid Olkiluoto i Finland.

Miljöpåverkan för KBS-3H som alternativ till KBS-3V undersöktes också. Jämförelsen visar att KBS-3H är positiv för alla aspekter som kunde uppskattas i nuläget, med undantag för järn- och stålförbrukning. Faktorer med stor eller positiv skillnad för KBS-3H-utformningen är mindre utsläpp till luft och bättre hushållning med berg, bentonit och betong.

Undersöka om KBS-3H-alternativet påverkar SKB:s platsundersökningsprogram.

KBS-3H-utformningen antas vara mer känslig för vattenförande sprickor och möjliga bergrörelser längs vertikala sprickor än KBS-3V och detta påverkar också planeringen och genomförandet av platsundersökningarna i dess detaljer; projektet bedömde dock att undersökningarna inte var markant olika för en KBS-3V- och KBS3-H-utformning och drog slutsatsen att det pågående platsundersökningsprogrammet inte behövde förändras för att anpassas till specifika frågeställningar för KBS-3H.

Att utveckla KBS-3H-utformningen och göra platsanpassning baserat på bergdata från Olkiluoto.

KBS-3H-utformningen bygger på ett antal undersystem och komponenter, som deponeringshål, supercontainern, distans- och fyllnadsblock, sektionerings- och förslutningsplugg med mera. Utformningen av komponenterna är fortfarande preliminär och kan bli förändrade före tillverkning och provning i kommande projektfaser. Ett flertal prov för varierande bergförhållanden är nödvändiga för att förvissa sig om att det är genomförbart att tillverka och installera komponenterna och försäkra sig om korrekt funktion under vattenmättnadsfasen. En viktig osäkerhet att behandla är till exempel monteringen av sektionspluggar, som kräver fasningar i berget och svetsning av tunga stålkomponenter kanske 200 m in i ett deponeringshål som är mindre än 2 m i diameter.

Hantering av grundvatten

Ett komplicerat system av komponenter är nödvändiga för att klara de funktionella kraven under uppbyggnad av vattentryck och vattenmättnad. För att begränsa inflödet av vatten har alternativ för tätning med injektering undersökts. Efterinjektering (det vill säga injektering av tätningsmaterial i sprickorna efter uttag av hålen) prövades vid Äspölaboratoriet med en ”Mega-Packer”.

Det förutses att Silica Sol företrädesvis används för att täta fina sprickor och låg-pH-cement för grövre sprickor. Preliminära resultat från försöken som genomfördes i november 2007 visade att Silica Sol kan användas för efterinjektering med tillfredsställande resultat.

Referensutformningar

Ett antal KBS-3H-utformningar har undersökts sedan 2004. Alternativet Basic Design omvärderades i maj 2007 och lades åt sidan sedan modellering och laboratorietester visade att distansblocken inte skulle klara snabb vattenuppbyggnad. Den snabba vattenuppbyggnaden ger deformation mellan supercontainern och distansblock och hela blockets ändyta får fullt vattentryck och distansblocket förskjuts trots fixeringsringar. Alternativet DAWE (Drainage, Artificial Watering and air Evacuation) baseras på att man konstgjort fyller tomrummen runt supercontainern med vatten för att snabba upp svällningen av distansblocken. Rör installeras för vatteninjektering, dränering av vatten och luft innan supercontainer och distansblock placeras i deponeringshålen. Eftersom alla öppna och sammanbundna tomrum fylls med vatten med hydrostatiskt tryck, blir det inga betydande tryckgradienter omedelbart efter vattenfyllnad som kan vara drivkrafter för flöden mellan sektioner av supercontainer. Rören tas bort innan deponeringshålen förseglas. Borttagning av rör prövades vid Äspölaboratoriet hösten 2007, och resultaten visar att rören kan tas bort som planerat. En utmaning med DAWE-utformningen är att det är svårt att visa att det inte uppstår suspenderad bentonit som strömmar längs sulan av deponeringshålet och över till de delar av hålet där installationer pågår, eftersom vatten som droppar på blocken och sprickbildning av blocken på grund av fuktighet, kan ske och orsaka bentoniterosion. Under 2007 undersöktes övergripande också ett tredje utformningsalternativ, ”Semi Tight Compartments”.

Platsanpassning till Olkiluoto

Layoutanpassningen baserades på Olkiluotos platsbeskrivningsrapport 2006 och de fastställda kraven på layouten. Anläggningen ritades för 2 840 kapslar i 171 deponeringshål med den preliminära barriärutformningen som grund. Medellängden av hålen är 272 m och den totala längden av deponeringshålen är cirka 46 400 m. Med hänsyn till att lägena för supercontainrar kan flyttas flera meter för att undvika lägen med större vattenläckage, antogs det försiktigtvis att 25 % av förvarsberget behövde uteslutas från deponering. I jämförelse, är det uppskattat att 17 % av berget utesluts för ett KBS-3V-förvar vid Olkiluoto baserat på samma platsbeskrivning 2006.

Program för fullskaleprov vid Äspölaboratoriet i denna fas och möjligtvis i nästa fas av projektet.

Ett flertal fullskaleprov genomfördes, som borrning av deponeringshål, deponering av en attrapp av en supercontainer och distansblock, byggnation av en förslutningsplugg med låg-pH-sprutbetong och efterinjektering med en Mega-Packer. Ytterligare komponent och fullskaleprov har förutskickats och planerats för, och dessa prov genomförs i nästa fas.

Att studera återtagbarhet av kapslar för KBS-3H.

Alternativ för återtag av kapsel studerades. Med återtag menas här borttagande av kapsel efter det att bufferten har absorberat vatten och deformerats, eller efter det att deponeringshålet pluggats och förseglats. Borttagande av de olika barriärerna kommer att ske genom en kombination av olika tekniker och utrustningar. Det föreslogs att betong- och stålkomponenter med fördel avlägsnas med vattenrivning och -skärning. Bentonit kan avlägsnas med vattendynamiska/kemiska metoder, som redan testats för återtag av en KBS-3V-kapsel. Alternativt skulle vattenrivning med höga vattentryck (> 100 MPa) kunna användas, förutsatt att prov visar att metoden inte skapar kapseln.

Nästa steg

SKB och Posiva har beslutat att fortsätta arbetet med horisontell deponering. Kompletterande studier av horisontell deponering 2008–2010 kommer att användas för att utveckla utformningen av KBS-3H så långt att ett beslut om fullskaleprov och demonstration kan tas.

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1 Introduction

SKB (www.skb.se) in Sweden and Posiva (www.posiva.fi) in Finland both selected the multi-barrier KBS-3 method as the reference design for the deep geologic disposal of spent nuclear fuel, see Figure 1-1. The principle of the KBS-3 method is that the spent nuclear fuel is held in place by a cast-iron insert and encapsulated in a copper canister. The canister is placed in a repository constructed in a crystalline host bedrock about 400–500 metres below the surface. The canister is surrounded by highly compacted bentonite clay and the tunnel system is backfilled with bentonite clay. The basic engineering of a KBS-3 repository is developed in parallel with the site investigations with the overall objective that the repository is safe, effective and fully compliant with international guidelines and standards, national regulations and the general design requirements for the facility.

The vertical emplacement design (KBS-3V, see Figure 1-1) has been SKB's reference design for the last 30 years. Posiva embraced the KBS-3V design more than 20 years ago, and since then it has been developing the KBS-3V reference design in parallel with the Swedish programme /Posiva 2006/. Posiva and SKB also cooperate on parts of the KBS-3V development programme.

Alternative designs within the KBS-3 method have also been evaluated /Sandstedt et al. 2001/. One alternative was the serial emplacement of canisters in long horizontal drifts instead of vertical emplacement of single canisters in the deposition hole. The design with horizontal emplacement was later referred to as KBS-3H and has been studied since the late 90's as a joint SKB/Posiva undertaking. The sketch in Figure 1-2 shows the general layout of a KBS-3H repository with the horizontal deposition drifts. The plan to investigate horizontal emplacement as a variant to the reference design has been supported by the authorities in Sweden (SKI and SSI) and Finland (STUK).

The investigation of the KBS-3H design is part of the national programmes for the geological disposal of spent fuel in Sweden and Finland. SKB in Sweden has reached the final phase of site investigation at the two candidate sites at Forsmark and Laxemar. A general description of the overall programme to implement the repository in Sweden is to be found in the latest Research, Development and Demonstration Programme /SKB 2007/.

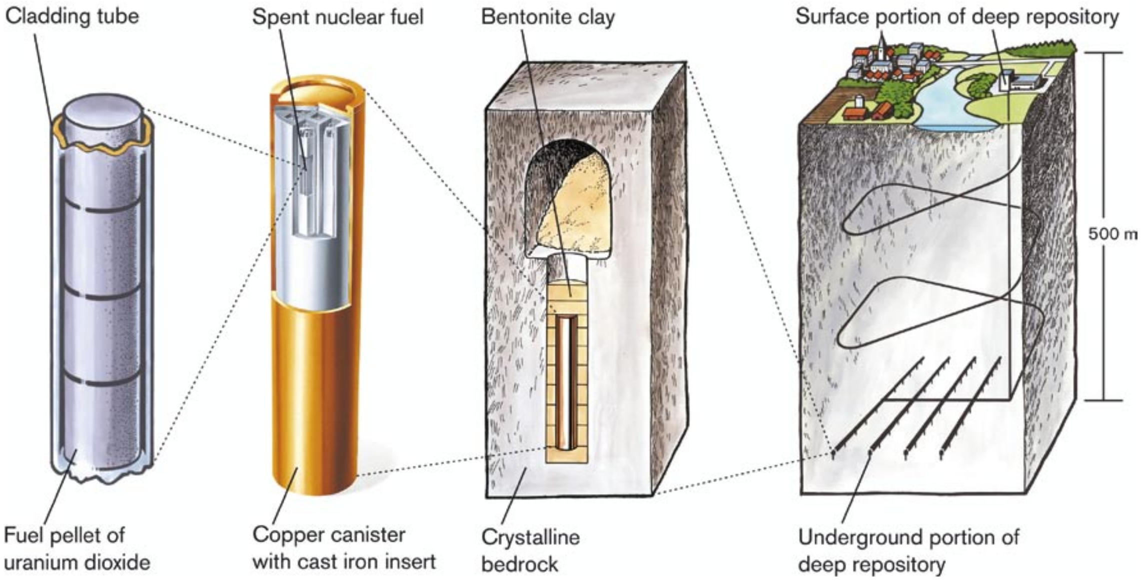


Figure 1-1. The barriers of the KBS-3 method. The figure shows the KBS-3V reference design.

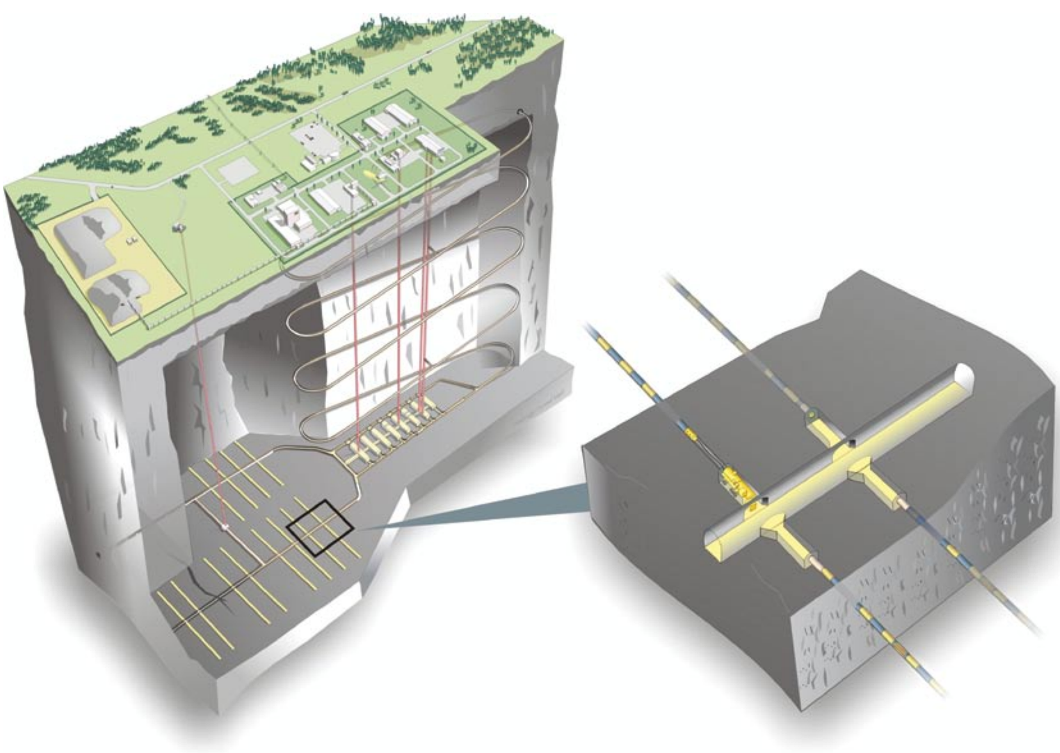


Figure 1-2. General layout for a KBS-3H repository for spent fuel. The sketch to the right shows the transport tunnel, deposition niche and deposition drifts with supercontainers.

Posiva applied for the Decision in Principal (DiP) for spent fuel disposal at Olkiluoto based on the KBS-3 method in spring 1999. The Government issued the DiP in December 2000 and Parliament endorsed it in May 2001. In June 2004, Posiva started building the Olkiluoto Underground Rock Characterisation Facility, ONKALO, for site-specific underground investigations. ONKALO may also be used as part of the future repository. On the basis of these confirming site investigations and other research, technical design and development work, Posiva will plan the repository in detail, prepare construction engineering solutions and assess safety. According to the decision of the Ministry of Trade and Industry on 23 October 2003, Posiva is to submit an application for the construction licence for a KBS-3 disposal facility by the end of 2012. In 2009, Posiva will submit the first outline version of the Preliminary Safety Analysis Report (PSAR) in support of construction license application. The PSAR will then be gradually updated to become the actual licensing application. A Final Safety Assessment Report (FSAR) will be submitted at the time of the operational license application in 2018. The target is to begin disposal operations in 2020.

The purpose of this report is to document the results of the KBS-3H Project 2004–2007 as well as to serve as a basis for the future plans.

Essential issues for the work over the period 2004–2007 have been to develop the barrier system design, the technology for the excavation of horizontal drift with a high degree of accuracy, the equipment for emplacing the heavy canister assemblies in the drift and assessment of the long-term safety of the method based on a preliminary engineering design and the properties of the host rock in Olkiluoto in Finland. The preliminary safety assessment is reported in /Smith et al. 2007c/ based on the preliminary design as reported in the Design Description 2006 report /Autio et al. 2007/, Olkiluoto site data and the Finnish regulatory context. The Design Description Report 2007/Autio et al. 2008/ summarises the work executed on the design of the barrier system, construction of horizontal drifts, manufacture and demonstration of the supercontainer, deposition equipment and systems for groundwater control. In addition, environmental impact and cost are compared with the KBS-3V reference design. Many specific KBS-3H reports based on the work from 2004–2007 have been published, see Appendix A. A KBS-3H glossary of technical terms is presented in Appendix B. The terminology differs occasionally between SKB and Posiva, but efforts have been made to harmonise the language in the main KBS-3H reports.

2 Development of the KBS-3H alternative for geological disposal

This chapter provides a background to the historical development of the KBS-3 method for horizontal emplacement, a description of the previous KBS-3H projects, a short account of the work during 2004–2007 and a short discussion on similarities and differences between KBS-3V and KBS-3H.

2.1 Alternative methods and KBS-3 designs

The development of systems for the encapsulation and final disposal of long-lived waste from nuclear power plants was initiated in Sweden in the mid-seventies. The work resulted during the period 1977 to 1983 in a series of reports that were gradually focused on encapsulation of the spent nuclear fuel in copper canisters and the deposition of these canisters surrounded by highly compacted bentonite clay at a depth of approximately 500 m in the Swedish bedrock. The resulting method, KBS-3, was examined in detail by Swedish and foreign experts on behalf of the Swedish authorities. In 1984, the Swedish Government found that the system "in its entirety can be approved with regard to safety and radiation protection". Since then the KBS-3 method has constituted the reference method in the Swedish programme, and later also in the Finnish Programme. In parallel, SKB and Posiva have developed and evaluated several other alternatives to ensure that KBS-3 is the most suitable method. These studies were summarised in the PASS project over the period 1990 to 1992, /SKB 1993/. The alternatives studied and rejected for further study were the WP-Cave method, Very Deep Boreholes (2–4 km below the ground surface) and the deposition of relatively large canisters in 3–5 km long horizontal drifts, Very Long Holes (VLH). The KBS-3 method was found to be favourable and various designs were studied, see Figure 2-1. However, the vertical emplacement of individual canisters (KBS-3V) remained the reference design. In this context, it should be noted that the many countries are planning for horizontal emplacement, see for example /Enresa 1998/.

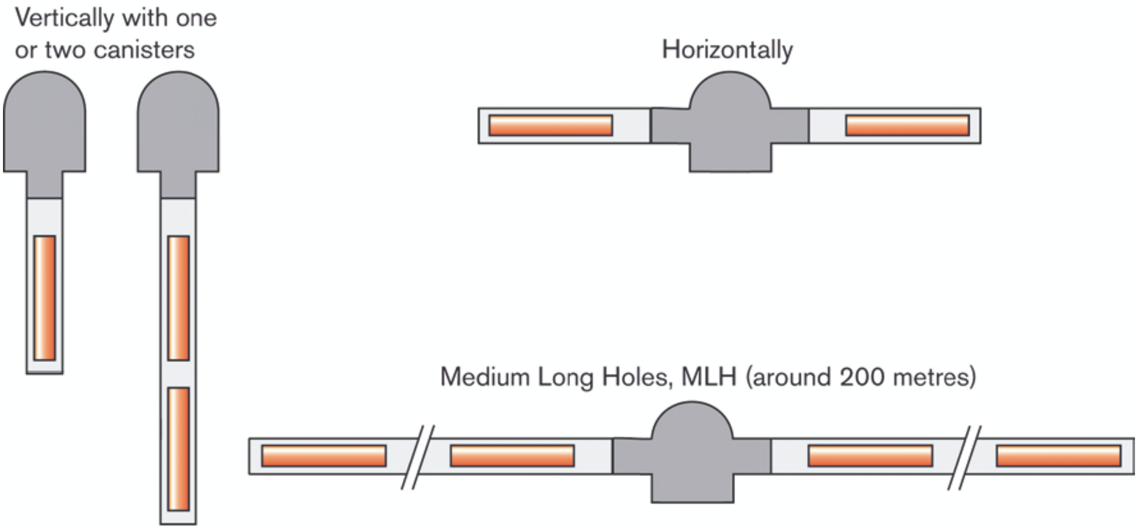


Figure 2-1. Variants of disposal according to the KBS-3 method, /SKB 1993/.

The remaining KBS-3 design alternatives were later again analysed in the JADE project (Comparison of disposal methods) from 1996 to 1998 /Sandstedt et al. 2001/. The comparison of the design alternatives (see Figure 2-1) was carried out separately for the factors "technology", "long-term performance and safety" and "costs" respectively. The results of each of these comparisons were then ranked, with the outcome that KBS-3V, involving the deposition of a single canister in one deposition hole, was ranked first followed by the design alternative Medium Long Holes (MLH). The design alternative with one canister per horizontal drift showed limited potential and was not recommended for further studies.

The drawbacks for MLH were deemed to be the uncertainty of the excavation and emplacement technique, the impact of poor rock and groundwater seepage into a long deposition drift for several canisters before closure of the drift. The advantage was considered to be smaller volumes of rock excavation. The overall conclusion was that KBS-3V should continue to be the reference design and that the MLH design – later known as KBS-3H – should be studied further with the aim of clarifying the technical feasibility of emplacement and the means of handling water inflow into the deposition drift before closure. Another important conclusion drawn by the JADE project was that the canister and the buffer should be emplaced as an integrated waste package and not as separate components. Various emplacement techniques were studied and the conclusion reached was that a waste package – "supercontainer" – should be developed.

Figure 2-2 shows in the left-hand part of the figure the alternative methods and designs evaluated in the PASS and JADE projects. The remaining alternatives after evaluation are shown in red text. The right-hand part of Figure 2-2 shows the evolution of the KBS-3 project for horizontal emplacement since 2001, details of which are provided in the following sections.

2.2 KBS- 3H development during the period 2001–2003

Based on the recommendations of the JADE project, in 2001 SKB presented a Research Development & Demonstration (RD&D) programme for a KBS-3 repository with horizontal emplacement /SKB 2001/. Some of the key elements of this programme are highlighted below, see the right-hand part of Figure 2-2.

It was noted in the programme that although the underground facilities for a KBS-3V and KBS-3H repository are in many instances identical or similar, the excavated rock volume is 50% less for the KBS-3H design based on SKB's premises. It was proposed that an underground layout adaptation should be made as the basis for a preliminary safety assessment.

Since KBS-3V and KBS-3H both use the same system of engineered barriers and are designed for a similar geological environment, it was thought that the safety assessment methodology applied for KBS-3V would also be applicable for KBS-3H. Several KBS-3H issues were identified as needing further attention in a preliminary safety assessment, such as modelling of the following:

- evolution of the supercontainer including the waste, the canister, the buffer and a supercontainer shell,
- the degradation of the bentonite due to chemical interaction with the corrosion products of the supercontainer shell,
- thermo-hydro-mechanical evolution during the saturation, and
- the effects of plugs and distance blocks (bentonite blocks that separate canisters) in the local groundwater flow.

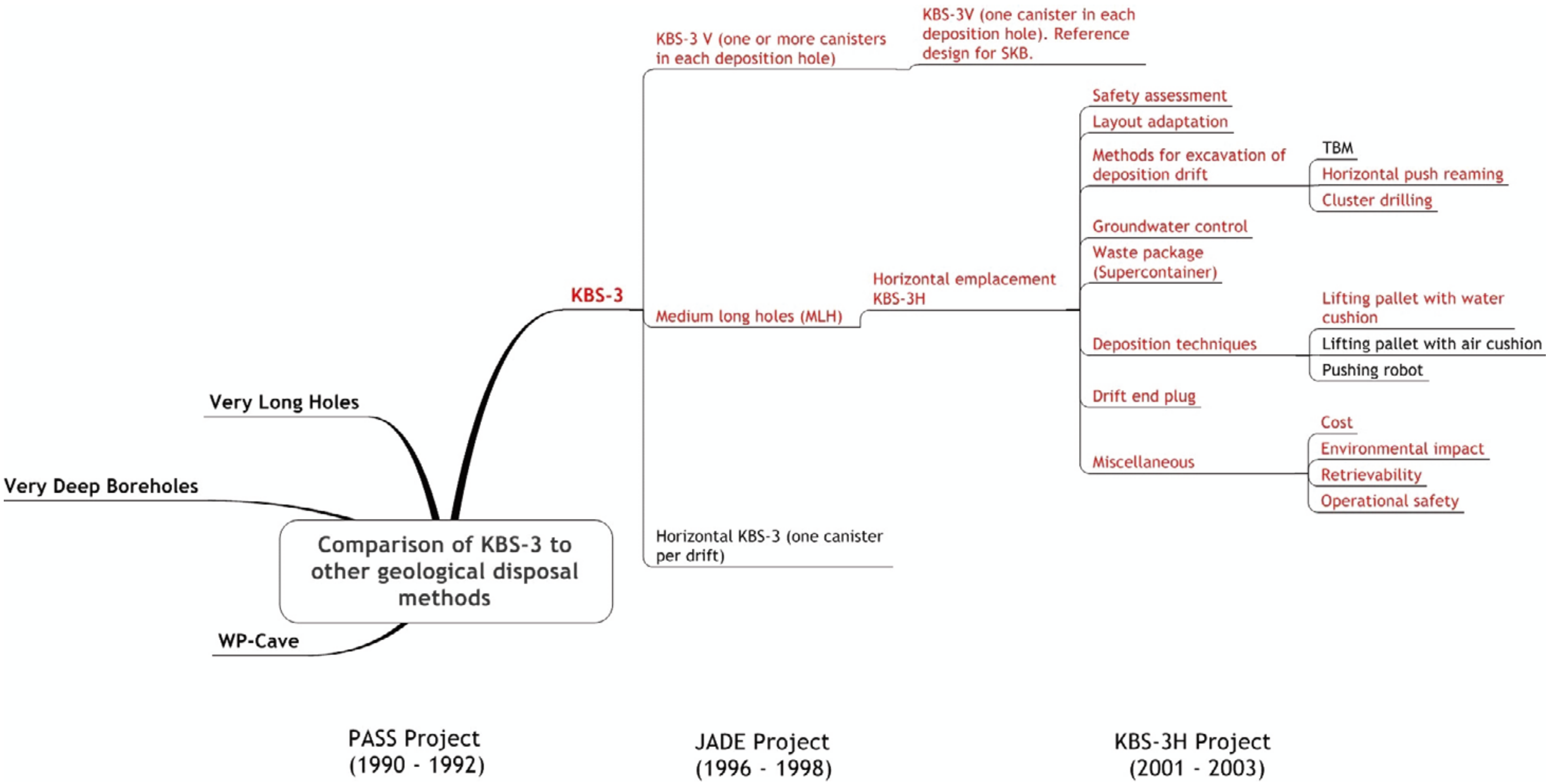


Figure 2-2. *The design selection process for geological disposal from 1994–2003 studied in the PASS, JADE and KBS-3H projects. The text in red indicates design alternatives and scope of works that remain after the successive evaluations. The text in black is alternatives that were discarded.*

The issues associated with the buffer behaviour were deemed to be of high priority for detailed studies, such as the thickness of the buffer, the swelling and homogenisation of the buffer between the supercontainer and the rock wall of the deposition drift, the effect of water seepage into the deposition drift before closure, local saturation of the buffer, the risk of piping/erosion and the mineralogical effects due to contact with the supercontainer shell in steel.

With respect to the bedrock conditions, it was, for instance, deemed important to investigate the degree of potential bedrock utilisation, i.e. how many canisters could be deposited within a certain volume of the site.

It was preliminarily decided that the deposition drifts should be 1.75 m in diameter, 200–500 m long and that they should be straight and parallel, and slightly inclined. Various excavation techniques were investigated, such as the use of a tunnel boring machine, a raise boring machine adapted for horizontal boring or water percussion drilling machines employed in clusters. It was proposed that a 50 m test drift should be excavated at the Äspö Hard Rock Laboratory (HRL) using either horizontal push-reaming or cluster drilling. It was necessary that groundwater seepage into the deposition drift should be low in order not to erode the buffer during emplacement and saturation, and the RD&D Programme defined a need to verify methods of groundwater control.

Another key issue that was identified in the programme was the technique to be used for deposition, in which three aspects were considered. The first aspect was the reloading of the canister from the transport cask that is used to shield the canister during transport from the encapsulation plant to the central underground area; the second was the shielded transport from the central area into the deposition drift and the third was how to move the heavy supercontainer inside the deposition drift. At that time it was thought that the supercontainer should be pushed. It was proposed that the design of the supercontainer and the deposition equipment should be worked on so they could be manufactured and demonstrated at the Äspö HRL.

A deposition drift that has been filled with supercontainers and distance blocks between the supercontainers needs to be sealed with a drift end plug. It was proposed that the various drift end plug alternatives should be investigated and that one should subsequently be selected for design, manufacture and demonstration at the Äspö HRL.

The final key issue identified in the programme was retrievability, i.e. removal of the canister after the buffer has absorbed water and become deformed or after plugging and sealing of the drift. It was proposed that the RD&D Programme should establish the technical assumptions and identify efficient solutions for retrievability that would not damage the canister.

The step-wise RD&D Programme proposed was accepted by the boards of SKB and Posiva in 2001 and has subsequently been executed in the following stages: the Feasibility Study Stage during 2002, the Basic Design Stage during 2003 and the Demonstration Stage over the period 2004–2007.

The results of the Feasibility Study Stage were summarised in the SKB R&D Programme 2004 /SKB 2004/. The main conclusion was that the design is technically feasible and that it would meet the requirements for long-terms safety. Critical points with respect to long-term safety were identified during the course of the work. The feasibility study, which was conducted in 2002, dealt mainly with technical matters such as rock excavation techniques, the handling of deposition equipment and the design of the supercontainer.

The work on devising a basic design was carried out during 2003. The purpose of this phase of the project was to identify critical points with regard to long-term safety in the programme. The work involved three areas: technical development, preparations for a demonstration, and initial studies of the long-term safety of the design. It was planned that the horizontal deposition drifts should be up to 300 metres long and have a diameter of 1.85 metres, which is 10 centimetres more than the deposition holes in KBS-3V. The deposition drifts were to be straight and meet stringent dimensional tolerances so that deposition could proceed smoothly. Work on the development of deposition techniques and machinery continued. According to the plans, the remote-controlled deposition machine was to utilize water cushions, as studies showed that this method would be more efficient than air cushions. Such technology is already used world-wide for lifting and handling heavy loads of up to several hundred tonnes. Studies of the bentonite function showed that some 60 per cent of the surface area of the supercontainer shell should be perforated thereby allowing the bentonite to swell and seal the deposition drift. The function of the distance blocks in sealing and preventing erosion of the bentonite buffer was studied in laboratory tests on different scales. The tests showed that there is a risk of piping/erosion if there is a large hydraulic gradient in the drift.

The safety evaluation of the proposed design was reviewed by external experts from waste management organisations in Spain, Switzerland and Japan, and they concluded that the design is technically feasible and that it could meet the requirements for long-term safety.

The results of the Basic Design Stage, which were reported in /Thorshager and Lindgren 2004/, were as follows:

- there are good possibilities to design and manufacture the equipment necessary for the construction and operation of a repository based on the KBS-3H design. Conclusions on the overall performance of the design and further optimizations can only be reached after completion of the demonstration tests at the Äspö HRL,
- a study regarding the behaviour of the buffer during and just after operation shows that there are many factors which affect the function of the buffer and that it is difficult to design a simple yet robust system,
- the information on the early evolution of the buffer and the processes following the saturation of the bentonite buffer is limited and further information may change the views of the design.

The issues identified served as the basis for planning the Demonstration Phase 2004–2007.

2.3 KBS-3H Project 2004–2007

As described in preceding sections, several issues were identified that needed to be resolved to demonstrate the feasibility of the KBS-3H design. Examples of such issues were the technique for excavating the horizontal drift with a high degree of accuracy, equipment for emplacing the heavy supercontainers in the drift as well as the preparation of a safety case based on a fundamental understanding of the behaviour of the engineered barrier and the host rock.

KBS-3H Project 2004–2007 was planned on the basis of the understanding developed up to 2003. Figure 2-3 is an overview of KBS-3H Project 2004–2007 with design options that were studied over the period 2004–2007. The text in red indicates the main alternatives for future studies.

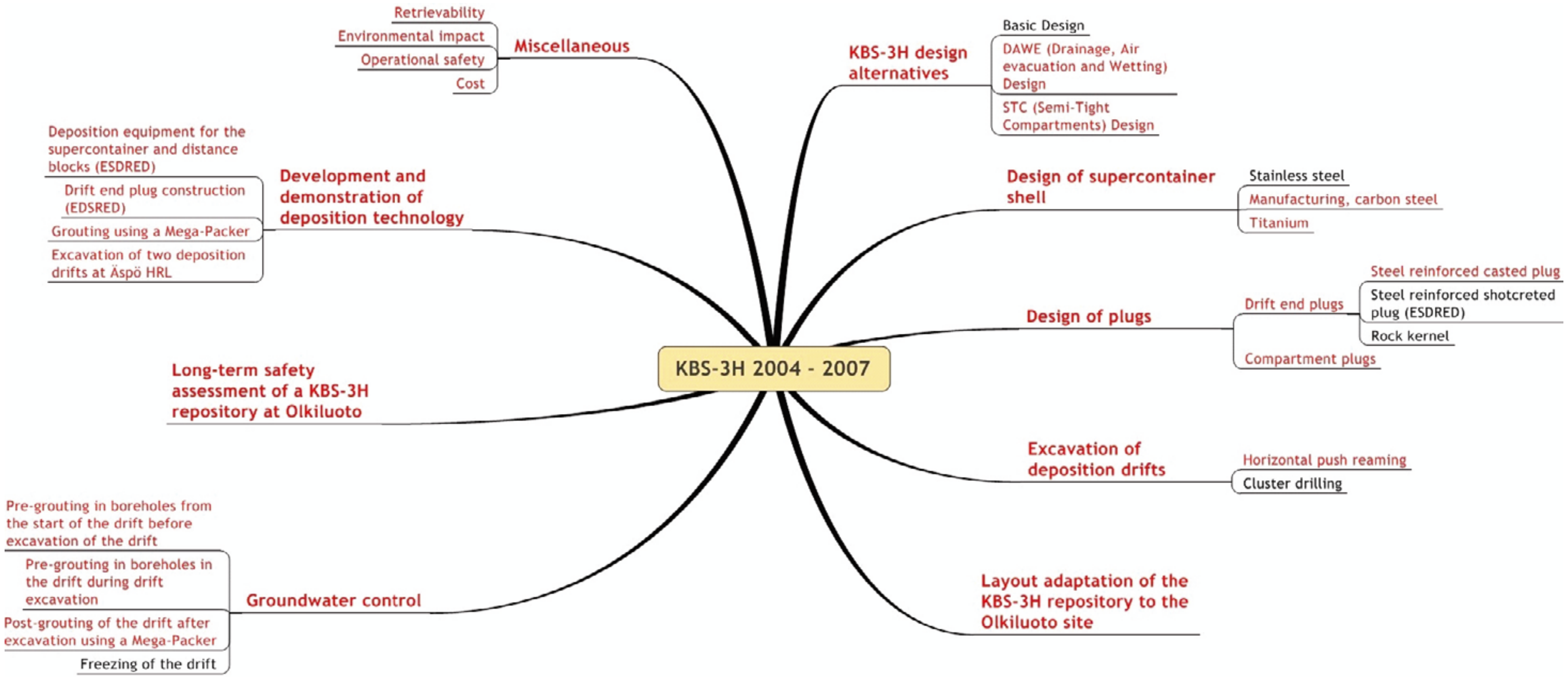


Figure 2-3. *Overview of the KBS-3H project 2004–2007 and design options that have been studied 2004–2007. The texts in red font indicate main design alternatives and issues for future studies. The text in black is alternatives that were discarded.*

2.3.1 Objectives and restrictions

The overall objectives of KBS-3H Project 2004–2007 were to use practical trials to demonstrate that the deposition alternative is technically feasible and that it fulfils the same long-term safety requirements as the reference design KBS-3V. Several subsidiary, detailed objectives were also formulated:

- to demonstrate that horizontal blind deposition drifts with a diameter of 1,850 mm and a length of up to 300 m can be excavated using a method that produces drifts which fulfil the functional requirements,
- to design and manufacture equipment that can deposit a pre-assembled supercontainer consisting of a canister and its surrounding bentonite in the drift,
- to show by means of investigations and trials that the buffer function requirements can be fulfilled, and
- to seal at least one deposition drift by constructing a plug made of low-pH shotcrete,
- to perform a KBS-3H safety assessment based on site data from Olkiluoto and knowledge of the barrier performance of the design,
- to contribute with reports and other information which can be used in order to show that horizontal emplacement is more cost effective and has less environmental impact than vertical emplacement,
- to investigate whether the KBS-3H design affects SKB's site investigation programme,
- to develop KBS-3H candidate designs and layout adaptation based on Olkiluoto bedrock data,
- to plan for a prototype repository at Äspö HRL, and
- to study the retrievability of canisters for the KBS-3H design.

It was decided that the demonstration should focus on the elements that were unique to KBS-3H. The aspects that SKB has already demonstrated in the framework of KBS-3V or a discussion of techniques that exist in normal industrial applications, such as handling in a reloading station, would not be included. Furthermore, it was decided that the deposition equipment would not need to be designed to fulfil radiation shielding requirements. Existing transport equipment and other temporary equipment would be used for the demonstration wherever possible in order to reduce costs. For example, low-strength concrete blocks were used as mock-ups during demonstration instead of bentonite. The rationales for this simplification were manifold. It was considered sensible to first see whether the emplacement technique would be at all feasible before investing in new moulds to manufacture the bentonite blocks. It was decided that the development of grouting material, e.g. low-pH cement, was not part of the project, but that these materials should be developed in other projects. Full-scale tests of a prototype KBS-3H repository at Äspö HRL (at a level of –420–450 m) did not fall within the present scope of the project and would require a separate decision. Finally, detailed operational safety aspects were also excluded as it would be more efficient to develop these once the KBS-3H design had reached a higher level of maturity.

2.3.2 Progress of Project 2004–2007

Since it was decided that the preliminary safety case should be based on Olkiluoto data, Posiva in cooperation with their suppliers was more involved in the layout adaptation of a KBS-3H repository to Olkiluoto site data, for design development and the safety assessment. SKB with its designated resources was more involved in the aspects related to the Äspö HRL, such as the excavation of the deposition drifts, design, manufacture and demonstration of the deposition equipment and the development of systems for groundwater control and plugging of the deposition drift.

A key issue during 2004–2007 was the development of the barrier design. The work was conducted in close cooperation with the safety assessors to decide the requirements and potential design alternatives. Important requirements are, for example, the requirements for the deposition drift with respect to geometrical variations and permissible groundwater inflow into the deposition drifts. The work on layout adaptation, barrier design development and systems for groundwater control was reported in annual Design Description Reports, see Appendix A. A key element of the KBS-3H is the use of a supercontainer. Efficient horizontal emplacement requires the canister and the buffer to be assembled into one unit – the supercontainer – which is then transported into the deposition drift. The supercontainer consists of a perforated steel shell cylinder in which the buffer material and one copper canister are assembled, see Figure 2-4. During the course of the project, the design of the shell, including choice of materials, was studied.

To resolve the potential buffer problems during the emplacement and saturation phase that could be caused by piping/erosion and possible distance block displacement or rupture, it was proposed that the deposition drift be divided into compartments using manufactured steel compartment plugs, see Figure 2-5a.

The project was a continuation of previous work on the Basic Design alternative (Figure 2-5b), where the idea is to hydraulically isolate supercontainer sections from each other. During the installation of a supercontainer there will be no water flow from adjacent supercontainer sections. This is mainly achieved by the distance blocks, which are designed to prevent all water flow between supercontainer sections during the installation as well as during the following saturation phase.

However, after further studies, the robustness of the Basic Design was questioned (see Chapter 4). Therefore, it was proposed that the robustness could be improved by controlling the saturation phase using drainage, artificial watering and air evacuation, see Figure 2-5c. In the DAWE design alternative, the empty void space in the gaps between the drift wall and buffer inside a sealed compartment will be artificially filled with water to accelerate the swelling of the distance blocks and the void spaces around the supercontainers. As connected void spaces are filled with water at hydrostatic groundwater pressure, no significant pressure gradients will exist that may cause mechanical displacement of the supercontainers and distance blocks. The pipes needed for air evacuation and artificial watering will be removed before drift closure.

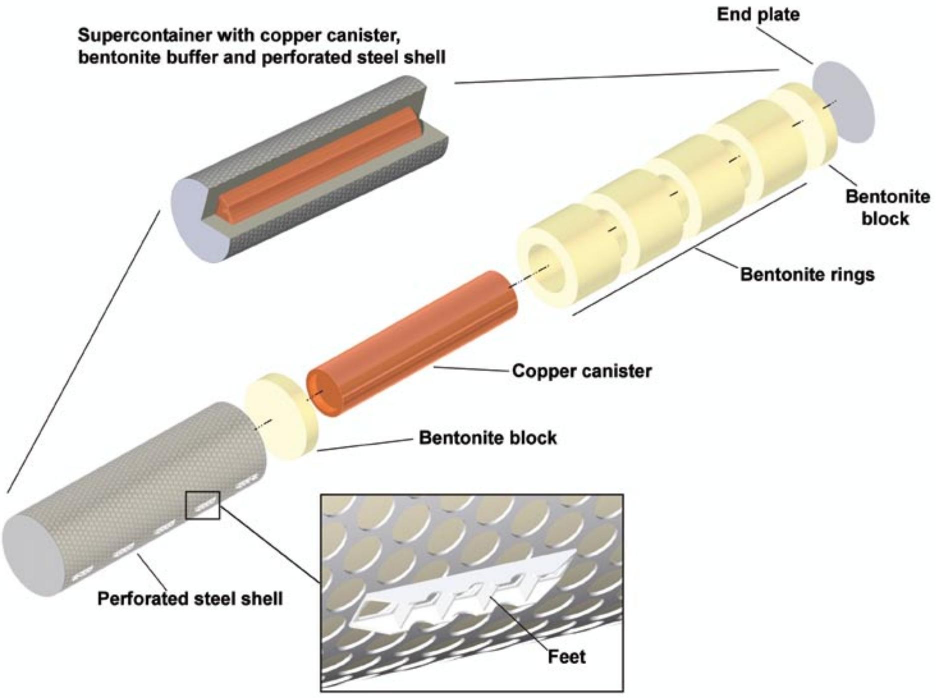
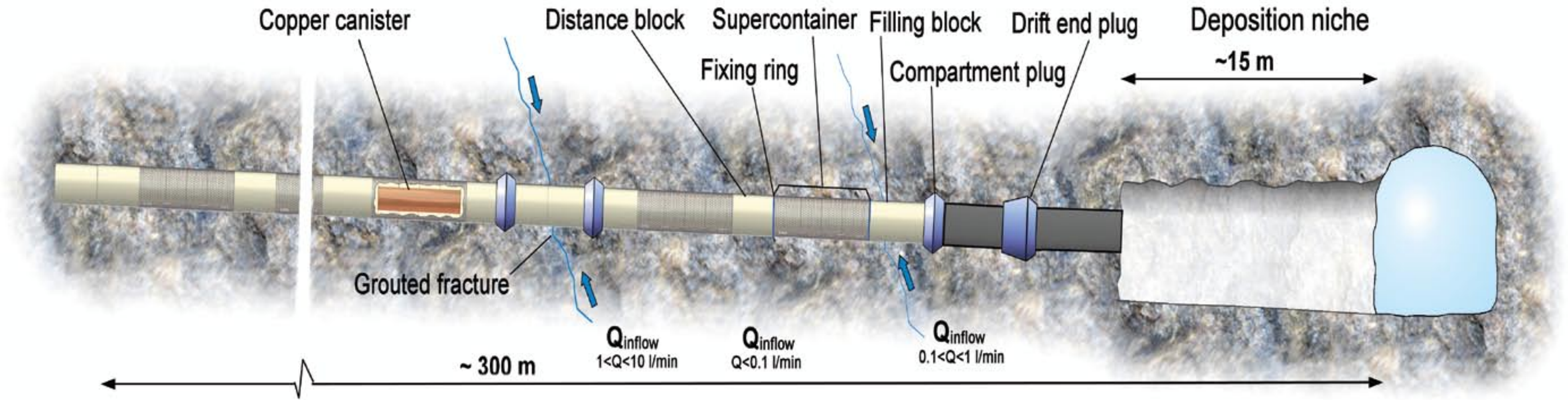
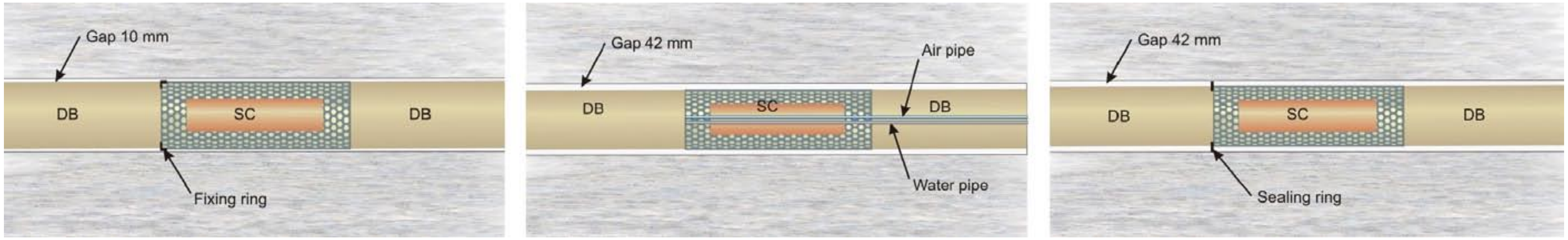


Figure 2-4. *The KBS-3H supercontainer.*



a. Overview of the KBS-3H design and its main components.



b. BD design

c. DAWE design

d. STC design.

Figure 2-5. *a. Sketch of the KBS-3H design with its components and associated requirements for maximum groundwater inflow before drift closure. Three design alternatives have been studied, but with identical supercontainers to deal with the early saturation phase b. Basic design (BD) c. (Drainage, Artificial Watering and air Evacuation (DAWE) and d. Semi Tight Compartments (STC).*

The STC design idea (Figure 2-5 d) was proposed in mid-2007 and may be studied further in the future. In the preliminary STC design alternative, each supercontainer section will 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 of metres, the blocks can be made with the same gap between rock and block as the supercontainer.

The planning of the safety assessment started in 2005 based on the understanding and data at that time and assuming the Basic Design alternative as the KBS-3H reference design, see Figure 2-6. As described earlier, the design studies continued in parallel with the work on the safety assessment. At the time of selection of the reference design for the long-term safety studies, no major differences between the Basic Design and DAWE design could be identified that were relevant to long-term safety. Both designs were judged to be potentially feasible, and the Basic Design was selected for the safety assessment. It was also judged that the differences between the design alternatives principally affected the early evolution phase, prior to any possible release of any radionuclides. The final saturated state of the repository is essentially the same whichever option is implemented. The safety assessment summary report /Smith et al. 2007c/ covers those aspects that have a different significance to, or potential impact on KBS-3H compared with KBS-3V, but not several issues that are identical or similar to the assessment of the KBS-3V repository, see Chapter 5. The input to the safety assessment is outlined in Figure 2-6. The site data used was originally based on the Olkiluoto Site Description 2005 /Posiva, 2005/ but was then updated to incorporate data from the Olkiluoto Site Description 2006 /Andersson et al. 2007/ whenever possible. The Basic Design alternative was described in the Design Description Report 2006, /Autio el al. 2007/.

One essential aspect of Project 2004–2007 was the demonstration of technology, and most of these activities were carried out at the Äspö HRL. Two horizontal drifts, 95 m and 15 m long, were excavated to demonstrate the technology. These two drifts were later used for testing techniques for deposition of the supercontainer, for drift end plugging and for reducing groundwater inflow into the deposition drifts. Many components still remain to be demonstrated, for example the manufacture and deposition of distance and filling blocks, the construction and installation of compartment plugs and the overall system behaviour during saturation.

SKB's QA-system was used in Project 2004–2007. Other organisations in the project have used their own QA-systems together with a quality plan which ensures that they comply with the SKB's QA-system. Some minor differences observed during the audits have been identified between the QA-systems and these differences have been resolved. Non-conformities (deviations) of major importance to the project were reported to the Project Manager and the Project Manager then decided if the deviation should be reported to the project Steering Group. Deviations of importance that were reported to the Steering Group were, for example, changes in objectives, exceeding of the total project budget, loss of important resources and delays in time that could affect the entire project schedule. The Steering Group then decided what action should be taken.

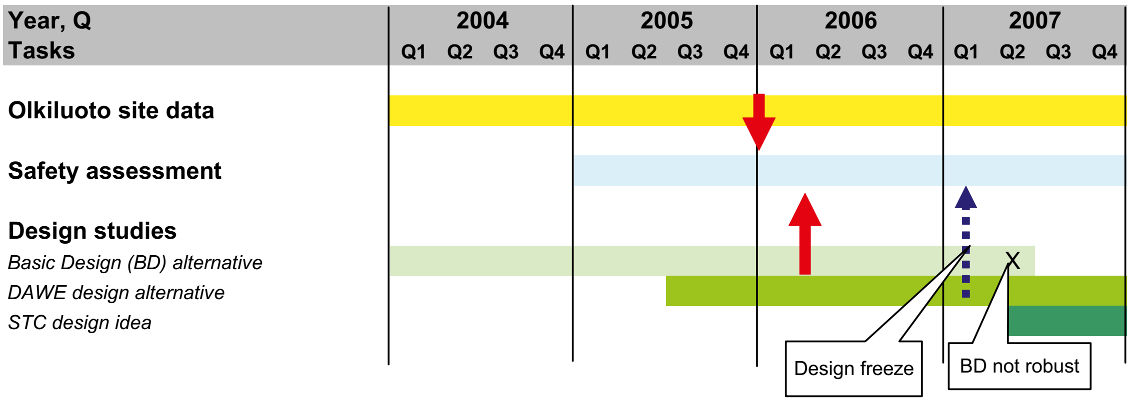


Figure 2-6. Input to the safety assessment. The design variants were progressively developed 2004–2007 with a design freeze in 2007 as the input to the safety assessment.

Project audits were held at least once a year. The time and focus of the audits were planned by the Quality Assurance Co-ordinator together with the Project Manager. Separate audits were held on the sub-projects Demonstration, Design and Safety Case. In accordance with the QA-system, a project evaluation report has been prepared.

2.4 Main differences between KBS-3V and KBS-3H

As described in the introductory chapter, the KBS-3 reference design for both SKB and Posiva is based on vertical emplacement. It is important to stress that there are more similarities than differences between the KBS-3V and KBS-3H alternatives; they are both multi-barrier systems relying on the mechanically and chemically stable bedrock, a long-lived fabricated canister, a buffer surrounding the canister to limit the inflow of corroding agents and water flow around the canister, and to retard the migration of nuclides if the canister is at the same time damaged. Regulation and overall requirements are identical, or almost identical, for KBS-3V and KBS-3H, but construction and deposition would be different for the horizontal emplacement variant.

In RD&D Programme 2007, SKB /SKB 2007/ presented the KBS-3V repository as a set of "production lines", see Figure 2-7. An analogue graph has been prepared for the KBS-3H design, see Figure 2-8. Many elements, such as the canister, are identical for both KBS-3H and KBS-3V. However, instead of using a "rock line" in the same way as for KBS-3V, it is considered to be more appropriate to define a "drift line": KBS-3H-specific issues are depicted with a red border and KBS-3V-specific with a dashed black border. For example, "Backfill" [for deposition tunnels] is only for KBS-3V.

Although there are a multitude of similarities between the alternatives, the selection of horizontal or vertical emplacement will have many engineering, operational and safety implications, some of which are elaborated below.

From an engineering point of view, one major difference is the absence of large deposition tunnels and therefore the elimination of a need to backfill these tunnels. There are also major differences with respect to the emplacement work. The supercontainer, including the canister, weighs approximately 46 tonnes. This weight has to be moved into a deposition drift up to 300 m in length compared with KBS-3V, in which the canister, weighing some 25 tonnes, is lowered into the vertical deposition hole. The KBS-3H alternative is sensitive to the inflow of groundwater during emplacement and the early saturation phase, whereas the selection of deposition hole locations in KBS-3V design is more flexible, as locations with larger inflows can be avoided. A key consideration in the design is to minimise the possibility of hydraulic pressure differences developing rapidly, as this could result in movement of the distance blocks and supercontainers, or in transient water flows ("piping") along the interface between the super-container and the deposition drift. Piping could in turn lead to erosion and loss of bentonite density in some super-container sections, which would impair the function of the buffer by, for example, reducing the swelling pressure that ensures good physical contact between the buffer and rock. In KBS-3H loss of buffer around one canister in the deposition drift due to piping/erosion may affect the buffer around neighbouring canisters, since the buffer density along the drift will tend to homogenise over time. With respect to retrievability, both KBS-3H and KBS-3V design alternatives are retrievable (see Section 6.5).

There are certain considerations with respect to the KBS-3H alternative from a long-term safety point of view (see also Table 5-1). Key issues related to the presence of the supercontainer shell and to other structural materials are the formation of corrosion products and hydrogen generation by anaerobic corrosion of the steel and iron/bentonite interactions in the present design. Chemical alteration could have an adverse effect on swelling, and hydraulic and rheological properties of the buffer in the outer region. In particular, enhanced hydraulic conductivity of the outer region of the bentonite could ensue, which could increase the transport of detrimental solutes to the canister or increase the rate of radionuclide transport from the canister in the event of a release.

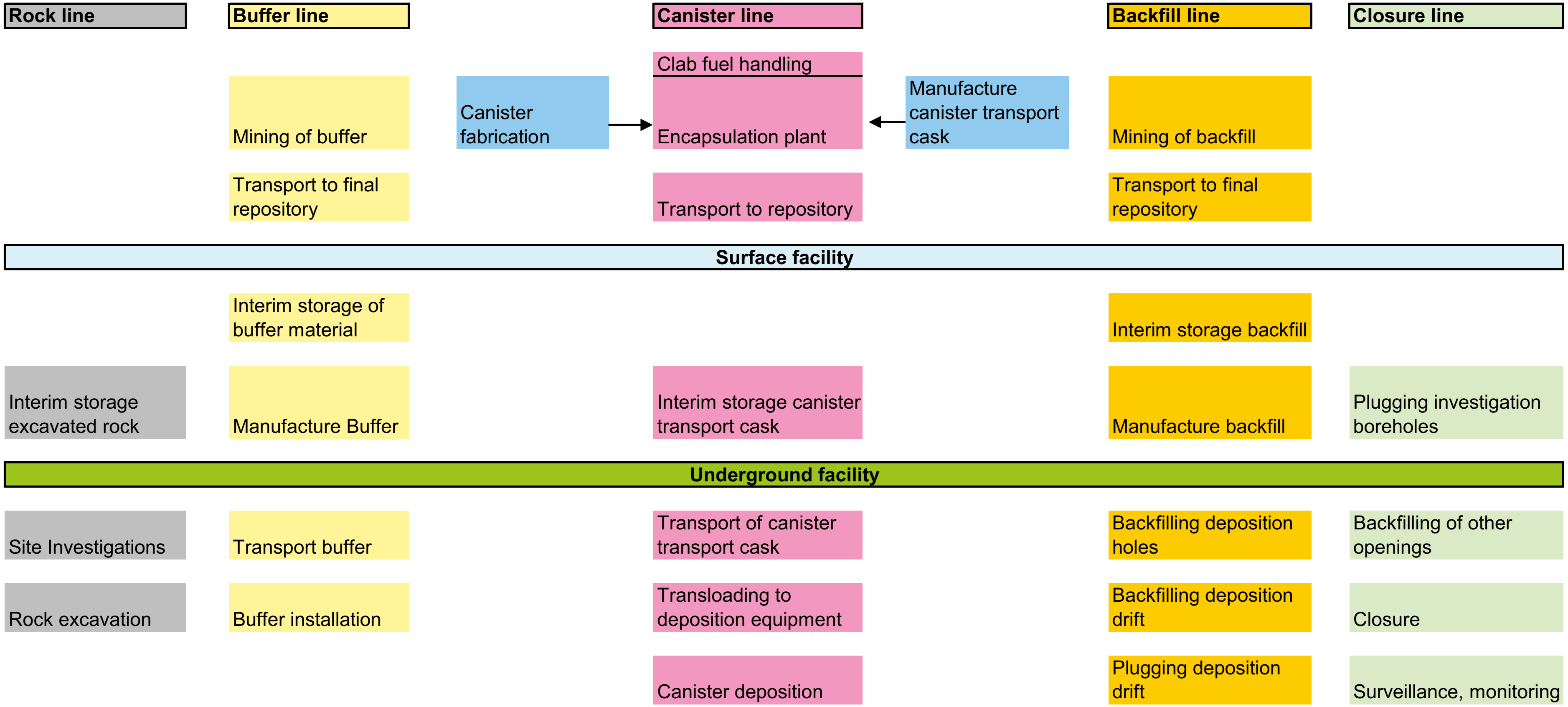


Figure 2-7. *Production lines for KBS-3V /SKB 2007/.*

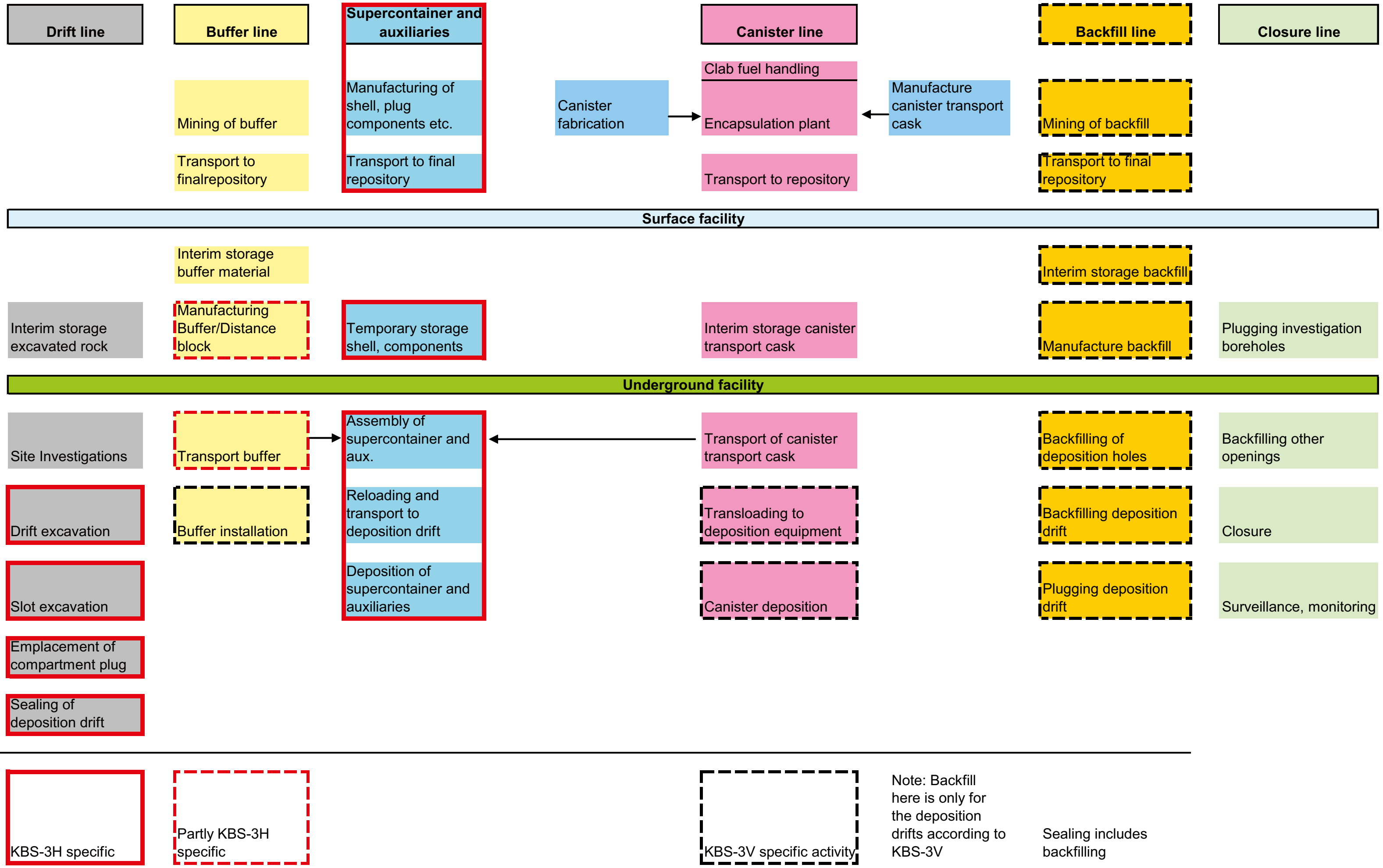


Figure 2-8. *Production lines for KBS-3H. Activities only related to KBS-3V are shown with a black and dashed border. The production activities that are KBS-3H -specific are only shown with a red border and the partly KBS-3H-specific activities with a dashed border.*

As long as the copper canisters remain intact (i.e. no contacts between the steel insert and porewater from the buffer) there is no direct equivalent to iron/bentonite interactions and hydrogen generation in KBS-3V. The durations of the gas production periods resulting from supercontainer and compartment plug corrosion are, however, generally limited to a short period (several thousand years). To avoid potential problems with the iron/bentonite interaction and gas generation due to corrosion, titanium was investigated as a substitute metal. Additional issues that may lead to perturbation of the buffer/rock interface are related to thermally induced spalling of the rock, especially in tighter sections with limited access to water, and chemical interactions of the buffer with high-pH leachates from cementitious components used to deal with water inflow into the drift, see also Table 5-1.

The situation for technology development has been estimated in the same way as for the KBS-3V "production lines" /SKB 2007/, (Figure 2-9, Figure 2-10). Uncertainties concerning KBS-3H are for the time being related to the preparation of sufficiently straight pilot holes for the deposition holes, groundwater control and the assembly of components, such as the compartment plug, in the deposition drift.

The KBS-3H project also investigated whether the site investigation programme from the surface should be different for a KBS-3V design and the KBS-3H design. In general, the requirements for site properties and site characterisation are fairly similar in the KBS-3H and KBS-3V alternatives. Some of the data can be collected during the surface investigation phase, whereas investigations on a detailed scale during the underground investigation phase are also needed. The KBS-3H design is supposed to be more sensitive to water-bearing fractures than KBS-3V and possible bedrock movements along vertical fractures, and this will also influence the planning and execution of site investigations in detail. However, the project did not judge the investigations to be significantly different in the case of the KBS-3V and KBS-3H designs, see /Smith et al. 2007c/.

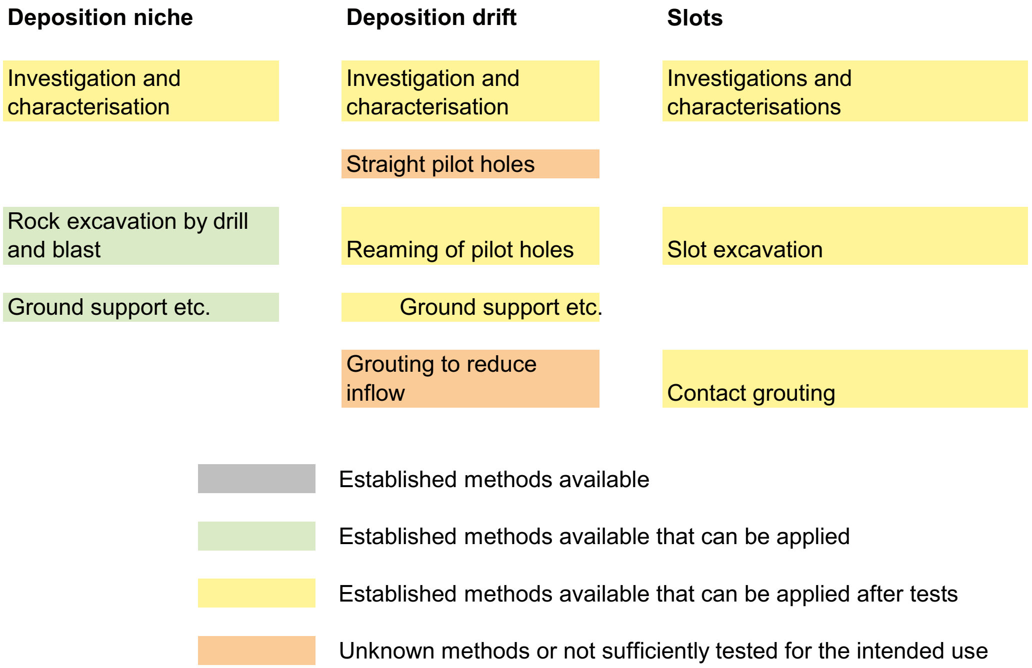


Figure 2-9. *Production lines for excavation work for KBS-3H and an estimate of the situation for technology development.*

***Figure 2-10.** Production lines for supercontainer and auxiliary installations for KBS-3H and an estimate of the situation for technology development.*

The differences in design between KBS-3V and KBS-3V highlight certain benefits of KBS-3H compared to KBS-3V:

- KBS-3H is more of an industrial prefabricated method, which is to be preferred to obtain quality with small deviations (variations) as human influence is restricted. The drift is "manufactured" by an industrial process (mechanical excavation) that is more consistent than the KBS-3V "manual" drill and blast for, for example, the deposition tunnel, although the deposition holes for KBS-3V are also made by means of mechanical excavation. The supercontainer is made by a pre-fabricated process, which is likely to be more consistent than the "manual" emplacement of backfill and buffer for the KBS-3V alternative.
- Reduced environmental impact due to less excavation and backfilling work. For a KBS-3H repository at Forsmark, excavation and backfilling in total is decreased from 1,365,000 theoretical m^3 to 700,000 m^3 (–650,000 m^3) assuming 4,500 canisters and for a repository at Olkiluoto in Finland a decrease from 1,360,000 theoretical m^3 to 894,000 m^3 (–466,000 m^3 assuming 2,840 canisters). The reduced volume decreases the need for raw materials and transportation, which is beneficial from the point of view of sustainable development.
- The cost saving due to smaller volumes of excavated rock and backfill.

3 General KBS-3 and KBS-3H-specific requirements

SKB and Posiva have developed KBS-3 requirements in parallel and they show many similarities, but due to differences in regulatory frameworks and historical development, they are not identical. Most of the requirements are applicable to both the KBS-3V and the KBS-3H designs, but at a component level they naturally differ, as KBS-3V has many components that do not exist with the KBS-3H alternative, and vice versa.

SKB has previously compiled general requirements for the KBS-3 system /SKB 2002/ with KBS-3V in mind, although most of the requirements are applicable to both KBS-3V and KBS-3H. The "V-model" is one way of organising requirements and showing how the technical components, subsystem and system fulfil these requirements, see Figure 3-1. Requirements are in this context presented in a hierarchy from general stakeholder requirements from society and the nuclear power plant owners down to detailed design requirements for components. As KBS-3V and KBS-3H are design variants of the same method, it is likely that stakeholder requirements are identical. It is also likely that requirements will be very similar on a system level. In general both KBS-3V and KBS-3H will require additional development work and tests before the final "acceptance tests".

The canister, the buffer and the rock will have the same safety functions and requirements both for KBS-3H and KBS-3V. At component level, the KBS-3H alternative has many components that are not included in the KBS-3V reference design, such as the supercontainer shell and compartment plugs. These components have not been assigned safety functions but are designed to be compatible with, and support, the safety functions of the canister, the buffer and the host rock. With this in mind, it is obvious that there are design requirements at component level that are different for KBS-3H and KBS3V.

The principle for how to show that the requirements are fulfilled is the same for KBS-3V and KBS-3H. With respect to nuclear safety, the general process is defined by the authorities in Finland and Sweden.

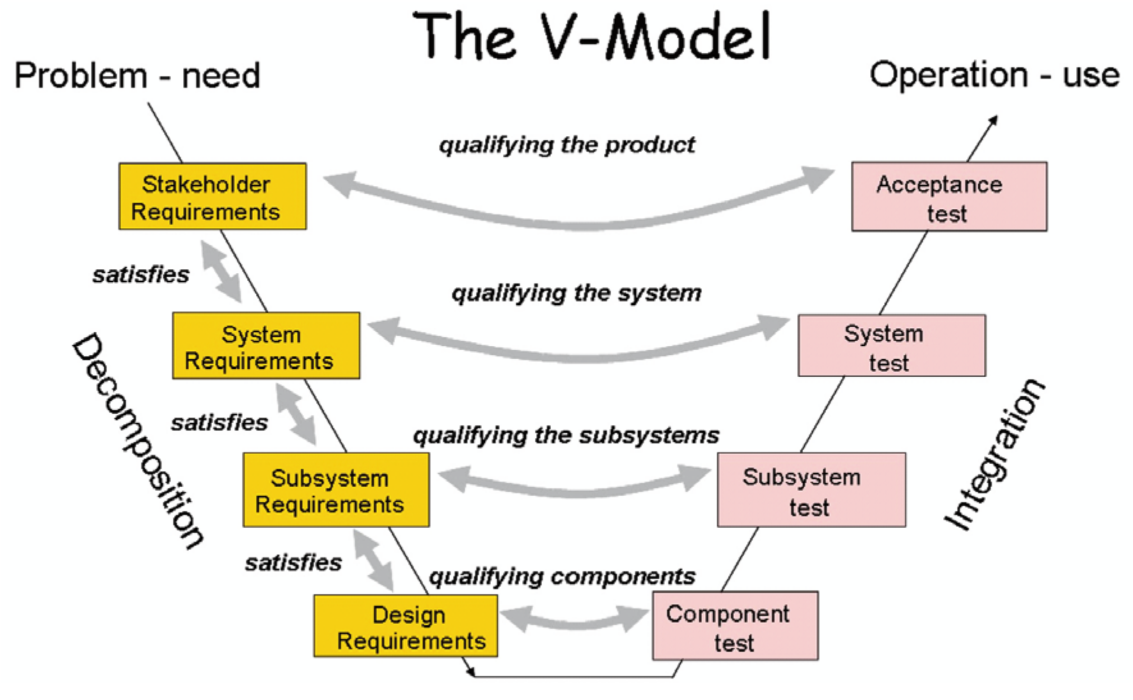


Figure 3-1. *The V-Model for managing requirements and solutions.*

3.1 Long-term safety requirements common for KBS-3V and KBS-3H

A complete description of the long-term safety requirements for a KBS-3H system is given in the Evolution Report /Smith et al. 2007a/ and in Appendix A of the Design Description 2006 /Autio et al. 2007/. The description includes the safety functions and safety function indicators for each component that will have a long-term function. The safety function is defined in SR-Can report /SKB 2006a/ as a *"qualitative role through which a repository component contributes to safety."* One or more safety function indicators is assigned to each safety function.

A safety function indicator is *"a measurable or calculable property of the system that is critical to a safety function being fulfilled*" /SKB 2006a/. If the safety function indicators meet specific criteria, then the safety functions can be assumed to be provided. If, however, plausible situations can be identified in which the criteria relating to one or more safety function indicators are not fulfilled, then the consequences of loss or degraded performance of the corresponding safety function should be evaluated in the safety assessment.

In the following section, the long-term safety functions and associated indicators and criteria are presented for the host rock, the canister and the buffer.

3.1.1 Host rock

The safety functions of the host rock are common to the KBS-3H and KBS-3V designs. They are to:

- isolate the spent fuel from the biosphere,
- provide favourable and predictable mechanical, geochemical and hydrogeological conditions for the engineered barriers, protecting them from potentially detrimental processes taking place above and near the ground surface, and
- limit and retard the inflow to and release of harmful substances from the repository.

Loss or degradation of its protective role could occur if chemical conditions in the groundwater become unfavourable to buffer and canister longevity, or if a fracture intersecting the deposition drifts near a canister location were to slip sufficiently to cause rupturing of the canister. The host rock safety function indicators and associated criteria as presented in SR-Can are adapted for KBS-3H /from Smith et al. 2007ac/ and summarised in Table 3-1. These criteria are closely related to the layout adaptation and should be considered in the selection of the placement of the deposition drifts.

Table 3-1. Safety function indicators and criteria for the host rock for KBS-3H (adapted for KBS-3H from Figure 7-2 of /SKB 2006a/).

Safety function indicator	Criterion	Rationale
Redox conditions	No dissolved oxygen	The presence of measurable O_2 would imply oxidising conditions
Minimum ionic strength	Total divalent cation concentration $> 10^{-3}$ M	Avoid buffer erosion
Minimum pH or maximum chloride concentration	$\mathrm{pH}^{GW} > 4$ or $[\mathrm{Cl}^-]^{GW} < 3$ M	Avoid chloride corrosion of canister
Limited alkalinity	$\mathrm{pH}^{GW} < 11$	Avoid dissolution of buffer smectite
Limited salinity (expressed in terms of total dissolved solids, TDS)	[NaCl] < 100 g/l (or other compositions of equivalent ionic strength)	Avoid detrimental effects, in particular on swelling pressure of buffer and distance block
Limited concentration of detrimental agents for buffer, distance block and canister	Applies to HS^-, K^+ and Fe(II) / Fe(III). The lower the better (no quantitative criterion)	Avoid canister corrosion by sulphide, avoid illitisation (K^+) and chloritisation (Fe) of buffer and distance block
Limited rock shear at canister/distance block locations in deposition drift	< 10 cm	Avoid canister failure due to rock shear in deposition drift

3.1.2 Canister

The main safety function of the canister, which is common to the KBS-3H and KBS-3V designs, is to ensure a prolonged period of complete containment of radionuclides. As long as its copper shell is not breached, a canister will provide complete containment of radionuclides, and the spent fuel will interact with the environment only by means of heat generation and low-level gamma and neutron radiation penetrating through the canister walls. This safety function depends first and foremost on the mechanical strength of the canister insert and the corrosion resistance of the copper surrounding it. In the current reference design, the canisters have a design lifetime of at least 100,000 years. This means that the canisters are designed to maintain their integrity taking into account the processes and events that are considered likely to take place in the repository over a design basis period of 100,000 years. It does not exclude the possibility that canister integrity will be retained significantly beyond the design basis period, nor that less likely, extreme conditions will give rise to earlier canister failures, and these possibilities must be considered in connection with safety assessment. The terminology is similar to that used in the reactor safety area: a design basis is defined to reflect the most likely conditions for the reactor but safety assessment also addresses less likely situations. If the copper shell is breached, then a canister is considered to have failed, even though it may continue to offer some resistance to the ingress of water and the release of radionuclides for a significant period thereafter.

The canister safety function indicators and associated criteria for the canister are identical for KBS-3V and KBS-3H, as presented in SR-Can and summarised in Table 3-2 /from Smith et al. 2007ac).

3.1.3 Buffer

The buffer in the KBS-3H design comprises the bentonite in the supercontainer surrounding the canister and the bentonite in the distance block.

Safety functions of the buffer include (a), protection of the canisters, and (b), limitation and retardation of radionuclide releases in the event of canister failure. These safety functions are also common to the KBS-3V and KBS-3H designs. A final safety function of the KBS-3H buffer (or, more specifically, the distance blocks) is, (c), in addition, to separate the supercontainers hydraulically one from another, thus preventing the possibility of preferential pathways for flow and advective transport along the drift. Bentonite clay also has a self-healing capability, which means that any potential advective pathways for flow and transport that may arise, for example as a result of piping and erosion, sudden rock movements or the release of gas formed in a damaged canister, should be rapidly closed.

Three broad modes can be envisaged by which a bentonite buffer could conceivably cease to perform these functions fully: loss or redistribution of buffer mass, mineral alteration of the buffer, and freezing of the buffer.

Table 3-2. Safety function indicators and criteria for the canister (after Figure 7-2 of /SKB 2006a/).

Safety function indicator	Criterion	Rationale
Minimum copper thickness	> 0 mm	Zero copper thickness anywhere on the copper surface would allow relatively rapid water ingress to the canister interior and radionuclide release
Isostatic pressure on canister	< pressure for isostatic collapse (varies between canisters, but probability of collapse at 44 MPa is vanishingly small)	An isostatic pressure on the canister greater than 44 MPa would imply a more significant possibility of failure due to isostatic collapse
Shear stress on canister	< rupture limit	A shear stress on the canister greater than the rupture limit would imply failure due to rupture

The loss or redistribution of buffer mass due, for example, to piping and erosion by flowing water could in principle lead to /Smith et al. 2007a/:

- a loss of swelling pressure at the drift wall, which could, if sufficiently large, lead to a loss of tightness of the contact between the buffer and the rock, and, in turn, enhance the transfer of mass (dissolved corrosive agents – especially sulphide – and radionuclides) between the rock and the buffer and thus compromise or reduce the ability of the buffer to perform any of its three safety functions. A loss of swelling pressure at the drift wall could also lead to enhanced thermal spalling due to reduction in confining pressure associated with time-dependent degradation of rock strength,
- a more general loss of swelling pressure which could, if sufficiently large, lead to microbial activity within the buffer, potentially increasing the rate of canister corrosion by reducing dissolved sulphate to sulphide, and, for still larger losses in swelling pressure, the possibility of canister sinking,
- an increase in the hydraulic conductivity of the buffer which, if sufficiently high, could lead to the advective transport of dissolved corrosive agents and radionuclides in the buffer and hence compromise the ability of the buffer to perform any of its three safety functions (note that isolated regions of higher hydraulic conductivity around the canisters would have a less significant effect),
- a reduction in buffer density which, if sufficiently large, could lead to the possibility of colloid-facilitated radionuclide transport in the buffer and reduce the ability of the buffer to limit and retard radionuclide releases (note again that isolated regions affected in this way would have a less significant affect), and
- an increase in buffer density at some locations along the drift which, if sufficiently large, could lead to mechanical damage of the rock, and compromise the ability of the buffer to protect the canisters from rock shear movements of less that 10 cm.

Mineral alteration of the buffer due, for example, to high temperatures around the canisters or to chemical interactions between the buffer and the steel or cementitious components could in principle lead to:

- a change to a less plastic material which, if it affects a significant proportion of the buffer between the canisters and the drift wall, could compromise the ability of the buffer to protect the canister from rock movements, including shear displacements at canister locations,
- a loss of swelling pressure, with potential consequences as described above in the context of loss or redistribution of buffer mass, and
- a loss of self-healing capacity, which could lead to fracturing of the buffer and an increase in hydraulic conductivity, again with potential consequences as described above in the context of loss or redistribution of buffer mass.

Freezing of the buffer as a result, for example, of the deep penetration of permafrost following a major climate change would, if it were to occur, lead to detrimental changes in buffer properties that could compromise its capacity to protect the canister and to limit and retard radionuclide releases from a failed canister. As noted in Section 12.4.1 of the SR-Can report /SKB 2006a/, it is uncertain what transport properties the buffer would have after thawing.

Consideration of the various possibilities leads to the safety function indicators and associated criteria that are summarised in Table 3-3 /from Smith et al. 2007ac/. Most of them are taken directly from SR-Can and adapted to KBS-3H. It should be noted that the criterion given in Table 3-3, that there is a negligible impact on the rheological and hydraulic properties of the buffer due to mineral alteration, subsumes that the criterion buffer temperature remains below 100°C to avoid significant chemical alteration of the buffer. The potential chemical processes which may occur at elevated temperature are, for example, silica dissolution close to the canister followed by transport outwards by diffusion to colder parts and precipitation, as well as buffer cementation due to the dissolution, transport and precipitation of silica or aluminosilicate minerals.

Table 3-3. Safety function indicators and criteria for the buffer for KBS-3H (adapted for KBS-3H from Figure 7-2 of /SKB 2006a/).

Safety function indicator	Criterion	Rationale
Bulk hydraulic conductivity	$< 10^{-12}$ m s^{-1}	Avoid advective transport in buffer
Swelling pressure at drift wall	> 1 MPa	Ensure tightness, self sealing
Swelling pressure in bulk of buffer	> 2 MPa	Prevent significant microbial activity
	> 0.2 MPa[1)]	Prevent canister sinking
Saturated density	> 1,650 kg m^{-3}	Prevent colloid-facilitated radionuclide transport
	< 2,050 kg m^{-3}	Ensure protection of canister against rock shear
Mineralogical composition	No changes resulting in significant perturbations to the rheological and hydraulic properties of the buffer (e.g. from iron or cement interactions or related to temperature)	See main text
Minimum buffer temperature	> –5°C	Avoid freezing

[1)] Although developed for KBS-3V, this criterion is also expected to be applicable to KBS-3H, and is likely to be more conservative for this design since, in KBS-3H, the weight of the canister is distributed over a larger horizontal area compared with KBS-3V.

However, neither experimental nor natural analogue studies have shown that this will actually occur. The effect of buffer cementation due to silica precipitation is, however, an issue for further work. It should be noted that no specific safety function indicators have been developed specifically for the distance blocks.

3.2 Design requirements to support the long-term safety functions

The KBS-3H project also defined "design requirements" which are intended to support the safety functions, and indicate how they are met in the current design. Design requirements are *"attributes that the repository is ensured to have by design at the time of emplacement of the first canister, or during the early evolution of the repository in the period leading up to saturation"* although some design requirements also affect the long-term evolution of the system.

Many design requirements are similar or identical to KBS-3V, for example that no component should contain amounts of chemical constituents that lead to significant negative effects on the performance of the others. In the following, some specific design requirements are presented.

Design requirements for layout and dimensions

The general layout of the repository assumes that the maximum buffer temperature is 100°C, which is satisfied by ensuring an adequate spacing of the canisters along and between the drifts.

Design requirements for the deposition drift

The number, length and orientation of the drifts themselves will be constrained by a range of factors, including safety-related requirements regarding:

- the hydraulic properties of fractures intersecting the deposition drifts at canister and buffer emplacement locations,
- the maximum allowable temperature within the deposition drifts, and
- the extent and hydraulic conductivities of the excavation-damaged zones (EDZ's) around the drifts, including the risk of rock spalling.

Efforts will be made to avoid fractures at canister emplacement locations that could undergo shear movements that might damage the canisters in the event of a large post-glacial earthquake. The extent to which it will be possible to identify and avoid fractures capable of undergoing potentially damaging displacements is currently under investigation for both the KBS-3V and KBS-3H designs.

The overall long-term safety criterion regarding the transmissivity of fractures intersecting the drifts at supercontainer and distance block emplacement locations is that it should be less than $3\cdot10^{-9}\ \mathrm{m^2/s}$. This criterion is derived from considerations as to the role of the geosphere as a transport barrier, as it ensures that the host rock provides an effective barrier to the transport of radionuclides released in the event of canister failure. It also protects the buffer against piping and erosion.

This transmissivity assumption is equivalent to a single fracture giving an inflow (without grouting) of 0.1 litres per minute in the approximately ~ 10 m long supercontainer sections[2] assuming a 4 MPa pressure difference between the drift and the undisturbed rock during saturation and a distance of 50 m between the drift wall and the nearest major fracture zone.

In KBS-3H, the requirements for the geometry of the deposition drift are very stringent and are justified for reasons of both long-term safety as well as emplaceability. Since the unsaturated buffer volume is fixed, the buffer density and swelling pressure are determined by the initial void, which is to a large extent the air slot between the supercontainer and the drift wall. In other words, there is a substantial benefit in excavating the drift with very stringent tolerances on the drift diameter.

Figure 3-2 illustrates the geometrical requirements for the deposition drift. The justifications for the requirements are compiled in Table 3-4.

Distance blocks

The adequate thermal spacing between the canisters in the drift is provided by the distance blocks. Furthermore, in order to fulfil their function of separating the supercontainers one from each other hydraulically, the distance blocks – in addition to being impermeable once saturated – are required to provide tight interfaces with the host rock within a reasonable period of time.

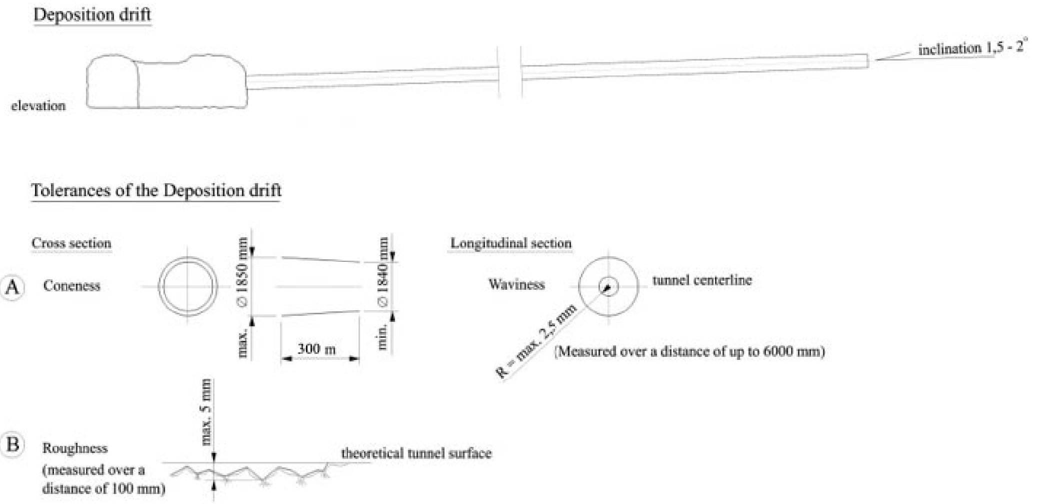


Figure 3-2. SKB requirements governing geometrical tolerances for the deposition drift.

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[2] 10 m is the approximate combined length of a supercontainer and distance block for the Posiva design.

Table 3-4. Justification for preliminary geometrical tolerances for the KBS-3H deposition drifts based on the SKB design. Revised from /Bäckblom and Lindgren 2005/.

Issue	Requirement	Justification
Length	< 300 m	The repository layout shall be similar to KBS-3V The length is considered to be feasible from a construction and operational point of view. However, optimisation of this length will be necessary after the KBS-3H technology has been demonstrated.
Diameter	1,845 ± 5 mm	The drift diameter is based upon operational as well as thermal heat flow and buffer density considerations.
Inclination	2° ± 1°	A positive inclination is a prerequisite for water drainage.
Deviation of pilot hole	< 2 m from the nominal position at a distance of 300 m	A minimum distance between the drifts of 36 m has been adopted in thermal dimensioning of the repository layout.
Diameter variation	≤ 10 mm	The void outside the supercontainer must be kept within these tolerances to ensure acceptable buffer density and swelling pressure after saturation.
Steps	≤ 5 mm	Full-scale laboratory tests have verified that the emplacement equipment can move properly in the drift for steps of up to 5 mm.
Roughness	≤ 5 mm	Full-scale laboratory tests have verified that the emplacement equipment functions properly for a roughness up to 5 mm.
Straightness (waviness or deviation from the centre line	± 2.5 mm over a length of 6,000 mm	The centre line deviation must be kept within small tolerances to prevent the supercontainer from contacting the rock surface during transport in the drift.

These generic design requirements are satisfied by a bentonite buffer with a design saturated density of 2,000 kg/m^3. Furthermore, a saturated buffer density in the range of 1,890 to 2,050 kg /m^3 is consistent with the long-term safety functions of the buffer, allowing for some variability of buffer density in space and time. The lower limit of 1,890 kg/m^3 is derived from the demand for the buffer to prevent significant microbial activity for the foreseen variability in groundwater salinity with time.

Filling blocks

Filling blocks will be emplaced along the drift where inflows exceed 0.1 litres per minute but do not exceed approximately 1 litre per minute. The maximum allowable inflow of 1 litre per minute is thus higher in the case of filling blocks compared with the 0.1 litres per minute allowed for distance blocks. This is due to the different functions of these two components. The distance blocks should prevent significant water flow as a result of piping between adjacent supercontainer drift sections during saturation of the drift, which could otherwise lead to buffer erosion. The limit of 0.1 litres per minute is related to this requirement. The filling blocks, on the other hand, are not used to separate adjacent supercontainers and so the prevention of piping is not a primary consideration in deciding where they can be emplaced. There is, however, a requirement to avoid erosion of these blocks by water flowing around the drift through intersecting transmissive fractures. The relevant inflow criterion is expected to be higher, although the present choice of 1 litre per minute is preliminary and somewhat arbitrary value that may be updated in light of future studies and possible design changes.

Compartment and drift end plugs

Compartment plugs will be used to seal off drift sections intersected by clusters of transmissive fractures giving inflows above 1 litre per minute, thus dividing the drift into compartments. The compartment and drift end plugs have no safety functions in that they are not required to contribute directly to the isolation of the waste and containment of radionuclides, but they have the function of keeping the adjacent buffer in place, and not allowing any significant loss or redistribution of buffer mass over time and isolating the canisters from zones of high transmissivity. In addition, the presence of the plugs should not lead to the build-up of potentially damaging pressures due to repository-generated gas along the drift (this does not imply that the drift end plugs need to be gas permeable, provided gas can escape from the drift by other routes, e.g. via transmissive fractures in the rock).

The fixing and sealing rings, the supercontainer shell and other structural materials

The fixing and sealing rings, supercontainer shells and other structural materials, such as cementitious grout or other sealing materials have only short-term functions. Fixing rings have the function of preventing displacement of a distance block while the adjacent components are installed and during saturation. Cementitious grout or other water inflow-controlling materials will be needed during repository construction generally to avoid the drawdown of surficial waters and the upconing of saline waters. They will also be needed to ensure operational safety and, more specifically, for the deposition drifts to reduce inflows for a sufficient time to prevent piping and erosion of the buffer. It should be noted, however, that grouting also affects the rock mass properties. Conventional cementitious materials, such as ordinary Portland cement, are not envisaged in the deposition drift because the pH of the leachates is too high ($pH > 12$) and could have a negative effect on the bentonite composing the buffer and the distance blocks. Shotcreting is not envisaged in the deposition drifts but it is allowed elsewhere in the repository.

Construction materials

Construction materials have no design requirements related to long-term safety other than those of compatibility with other system components. Compatibility with the host rock, in particular, implies limited concentrations of detrimental agents for buffer, distance block and canister. Long-term safety implications of these materials and their additives are being thoroughly tested and documented for the KBS-3V design. No differences (except for quantities used) are expected in the case of the KBS-3H design. The composition, quantities and removal capability of construction material for a KBS-3H repository have been estimated by /Hagros 2007a/. These should be checked against long-term safety requirements, and the amounts used in the repository should be carefully documented.

Backfilling and sealing of repository cavities

Backfilling and sealing of other repository cavities outside the deposition drifts are common to KBS-3V. These support the safety functions of the host rock, being carried out with the main purpose of preventing the formation of water conductive flow paths, and making inadvertent human intrusion into the repository more difficult.

3.3 Requirements from the operational point of view

Operation should fulfil the requirements on nuclear safety as well as other regulatory requirements and guidelines for occupational health and safety. Many of these requirements are identical for KBS-3V and KBS-3H and this is why the scope of the KBS-3H project 2004–2007 did not focus on operational aspects as much as on aspects of long-term safety.

4 KBS-3H design adapted to the Olkiluoto site

The design work over the period 2004–2007 was focussed on the development of a KBS-3H design adapted to the conditions at the Olkiluoto site in Finland, the design necessary to manufacture and demonstrate parts of the system at the Äspö HRL and preparation of the necessary information for the safety assessment based on the Olkiluoto site data and a preliminary design.

The starting point for the project was the work in the PASS, JADE projects and the achievements in the previous phases of the KBS-3H project as described in Section 2.2, which presents the main results related to the barrier design.

4.1 Evolution of the KBS-3H design

The general design and design variants of KBS-3H are discussed in Section 2.3 and shown in Figure 2-5. The rationale for the design variants is explained in the following.

Two different design alternatives Drainage, Artificial Watering and air Evacuation (DAWE) and Basic Design (BD) were selected as basis for development work and were presented in Design Description 2005 /Autio 2007/. These candidate designs included several options for design components. The number of alternative options were then reduced and some design components such as compartment plug were developed on a more detailed level and reported in the Design Description 2006 /Autio et al. 2007/. The design was developed further by e.g:

- preparing a new design alternative called STC (Semi Tight Compartment), intended to solve some of the problems in the Basic Design alternative,
- development of distance block design, design and testing of Mega-Packer post-grouting technique, evaluation of steering of pilot boring, development and testing of pipe removal and several other issues.

The result of the design work was eventually reported in the Design Description 2007 Report /Autio et al. 2008/.

During the 2004–2007 studies, it was concluded that the KBS-3H design alternative should be made more robust for the conditions foreseen at Olkiluoto. The most significant functional uncertainties and problems were related to early evolution of buffer behaviour where heterogeneous groundwater inflow and uneven saturation of the buffer could cause displacement, deformation and piping and rupturing of the buffer.

It was decided to improve the design by applying the following approaches:

- division of the deposition drifts into “good quality” compartments to be used for deposition of canisters and plugging of unsuitable sections,
- use of “filling components” in positions with high groundwater inflow to increase the robustness of the buffer and plug design,
- installation of temporary pipes to artificially wet the buffer and to evacuate the air and thereby control the initial state of saturation and hydraulic heterogeneity,
- development of grouting methodology to decrease seepage of groundwater into the deposition drift.

The present key components, major requirements, important issues and the maturity of the design alternatives Basic Design (BD), Drainage, Artificial Watering and air Evacuation (DAWE) and Semi Tight Compartment (STC) are presented in Table 4-1. “Schematic design” is design on a conceptual level (lowest level of detail). “Preliminary design” is the subsequent stage that is used to approximately describe and estimate the structural composition, material qualities and quantities.

Table 4-1 Overview of important components, issues and maturity of design.

Key components	Note of important design requirements	Uncertainties and important issues	Maturity of design
Components common to all design alternatives (BD, DAWE, STC)			
Deposition drift	The rock should fulfil the general requirements for the rock functioning as a barrier. The requirements regarding the drift are mainly related to geometry, surface straightness and inflows of groundwater.	Estimated maximum inflow into a 300 m long deposition drift is approximately 10 l/min. Drift acceptance criteria are to be developed.	Detailed design Tested at Äspö
Deposition niche	Similar for all alternatives.	Dimensions and shape are to be optimized.	Schematic design
Compartment	Sections with an inflow larger than 1 l/min but lower than 10 l/min per supercontainer section (approximately 10 m) are isolated by compartment plugs.	The inflow limit is preliminary and needs to be defined after field tests. The lengths of the compartments need to be optimised depending on the success of groundwater control and procedures for pipe removal (DAWE design). A maximum of one drift can be used as one compartment depending on the feasibility of pipe removal.	Preliminary design
Compartment plugs	Similar for all alternatives.	The inflow limit is preliminary and needs to be defined. after field tests. The function of the plugs need to be verified by testing. The lengths of plugged inflow sections may vary and are site specific.	Detailed design
Drift end plug	Similar for all alternatives.	Alternative designs available. The total length of drift end plug and filling components is to be defined more thoroughly in the next phase when the detailed design is prepared.	Preliminary design Tested at Äspö HRL
Spray and drip shields	Similar for all alternatives.	Number of drip shields is site specific. These will be left in the drift after closure.	Detailed design Tested at Äspö HRL
Supercontainer (shell and bentonite buffer (rings and blocks) inside)	Inflow to supercontainer section ≤ 0.1 l/min.	Steel or titanium for the supercontainer shell. Integrity of the buffer during transport and installation. The initial water content and dry density of the bentonite buffer is dependent on the choice of design alternative.	Detailed design Mock-up supercontainer tested at Äspö HRL
Filling blocks	Placed in positions with inflow > 0.1 l/min and < 1 l/min per supercontainer section to resist erosion and support the function of distance blocks.	Similar uncertainties as for the distance blocks in DAWE and STC design alternatives. The inflow limits are preliminary and need re-evaluation. Limiting distances to inflows need adjustment. Lengths and dimensions need to be defined in more detail to improve efficiency.	Schematic design

Key components	Note of important design requirements	Uncertainties and important issues	Maturity of design
Filling material	Resist erosion and support the distance blocks and the filling blocks.	Dimensions are preliminary and may be too conservative in the design	Schematic design
Components specific to the Basic Design alternative			
Distance block (tight gap of about 5 mm)	Positioned in supercontainer sections with an inflow of ≤ 0.1 /min. The blocks swell, fill the voids and withstand full groundwater pressure (4–5 MPa).	Laboratory tests showed that the design is not robust and may not fulfil the requirements. Several critical issues related to buffer behaviour, such as piping, erosion and the build-up of groundwater pressure on block surfaces leading to displacements, led to the conclusion that the design was not robust.	Detailed design
Fixing rings	Positioned adjacent to distance blocks in positions with an inflow of > 0.01 l/min to prevent displacement of the distance blocks under full groundwater pressure (4–5 MPa).	The inflow limit is a rough estimate and needs to be evaluated more thoroughly. Modelling and laboratory tests of hydraulic forces on the fixing rings showed that the design is not robust and may not fulfil requirements.	Preliminary design
Components specific to the DAWE design alternative			
Distance block (loose gap of 42 mm)	Positioned in supercontainer sections with an inflow of ≤ 0.1 l/min. The distance blocks absorb water, swell and seal.	The behavior after wetting and the development of swelling to prevent possible piping is uncertain and is to be verified. Uncertainties related to possible erosion during the emplacement ofsupercontainers need verification as well.	Preliminary design
Wetting and air evacuation pipes	Removal without impairing the barrier.	The wetting times (= 14 hours per 150 m long compartment)) are rough estimates. The number of watering pipes needs to be optimised.	Preliminary design Pipe removal tested on a laboratory scale
Components specific to the Semi Tight Compartment design alternative			
Distance block (loose gap of about 42 mm)	Placed in supercontainer sections with inflow ≤ 0.1 l/min. Distance blocks swell but allow for piping and some erosion as they are not designed to seal until the whole compartment is filled with inflowing water.	Behaviour during and after wetting. The extent of possible piping, erosion and development of swelling is uncertain and needs verification.	Preliminary design
Sealing rings	Each supercontainer is provided with a sealing ring that temporarily prevents water from flowing from one adjacent section containing a distance block and a supercontainer to another section before the first section is filled with the inflowing water.	The function of sealing rings is to be developed.	Schematic design

"Detailed design" describes the design in sufficient detail to permit implementation. The components are described in detail in the following Section 4.2. The general design and modus of operation are depicted in Figure 4-1. The reader is referred to Figure 2-5 for the schematics of the design alternatives.

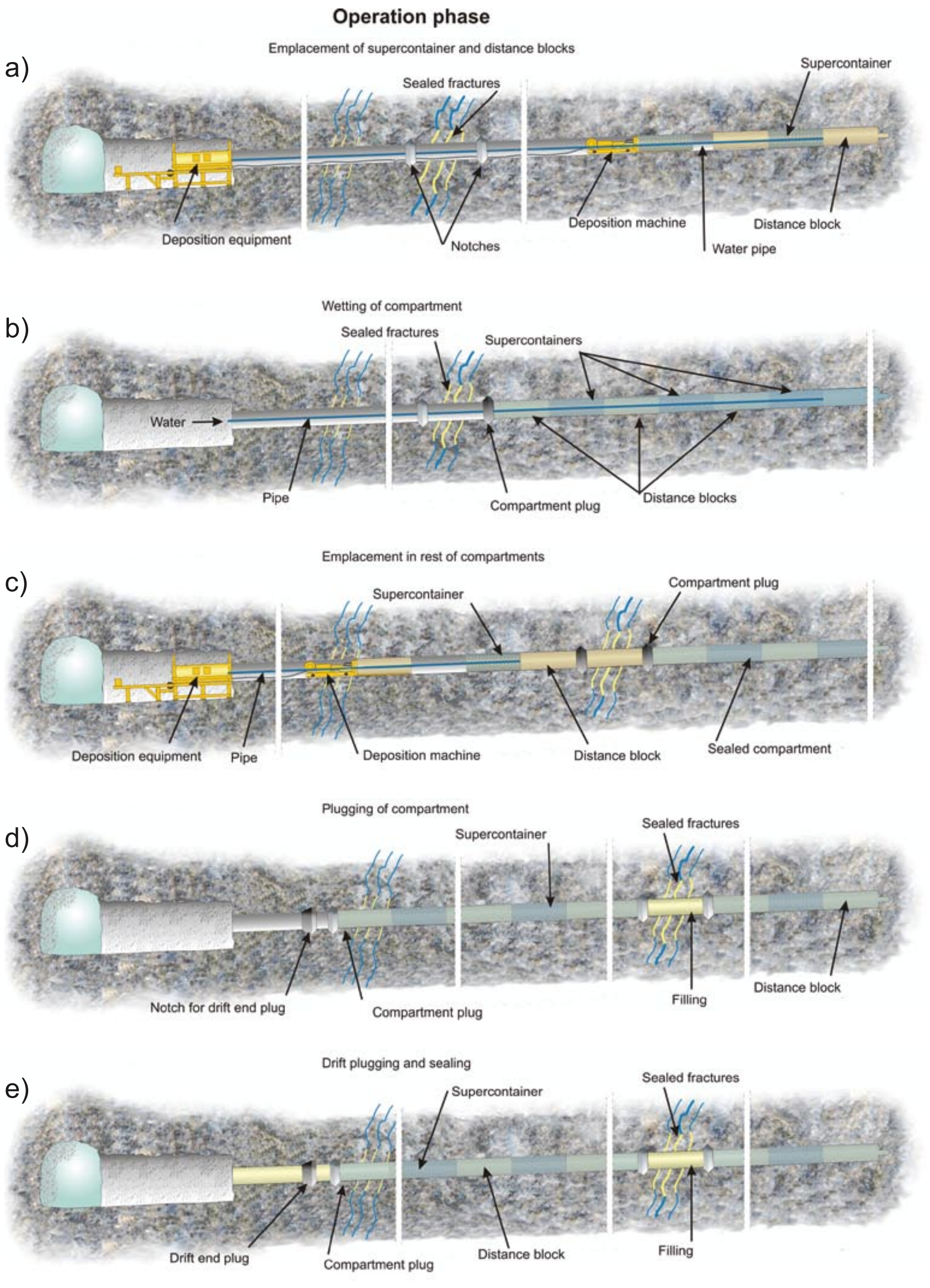

Figure 4-1. *Operation phases of disposal: a) Installation of supercontainers and distance blocks in the first compartment, b) Plugging of the first compartment, filling it with water and removal of pipes (only DAWE alternative), c) Plugging the highly leaking fracture section and continuation of supercontainer and distance block emplacement, d) Plugging the second compartment, filling it with water and removing pipes from the second compartment followed by construction of drift end plug. After operation, all the open spaces in drifts are filled with water and the drift is plugged using the drift end plug, see e).*

Supercontainers are not to be positioned in deposition drifts where a significant inflow of groundwater occurs. The inflow will be drained along the floor of the inclined drift. For the DAWE design alternative there is a gap of 42 mm between the distance blocks and the drift walls, which is larger than in the Basic Design (roughly 5 mm) and should prevent any contact with the water flowing along the floor of the drift. The drainage of inflowing water along the drift floor is planned to continue until the drift or the drift compartment is plugged. The compartments can be as long as the maximum lengths of the deposition drift (300 m) but can also be shorter, depending on the inflow of groundwater. For the DAWE design alternative, the length of the compartment will also depend on the feasibility of removing the pipes.

After the compartment has been sealed, artificial watering takes place at the same time as air is evacuated to avoid gas pressurisation. Steel pipes along the surface of the drift are used for watering and air evacuation, see Figure 4-1. The air evacuation pipe is led to the upper end of the drift to ensure that no air pockets are left. The sides of the drift are the preferred position for watering pipes to avoid possible damage during operation. Nozzles, which are directed downwards in the watering pipes, are distributed along the drift in each supercontainer section to ensure uniform inflow and to minimise any axial water flow in the drift that could create bentonite erosion. Water is not directly injected in those sections where the distance blocks are positioned to avoid possible erosion of the blocks. The watering time is estimated to be 14 hours at most for one 150 m long drift compartment. Only about a third of the total void space (including bentonite pores) would be filled with water in this way and the remaining voids would be less saturated. Therefore, the system would remain in a partially saturated state even after artificial watering. All supercontainers within a compartment section will be filled simultaneously to avoid axial water flows that could give rise to bentonite erosion and redistribution along the drift.

Testing and modelling of the distance blocks in the Basic Design alternative indicated that the distance block sections may not withstand the full hydrostatic 5 MPa water pressure, as illustrated in Figure 4-2. The Basic Design alternative was judged to be technically complicated, not robust and characterized by significant uncertainties in functional behaviour in those cases with large inflow and short compartment filling times. The DAWE design alternative is deemed not to possess these weaknesses and is therefore a more interesting alternative for future development.

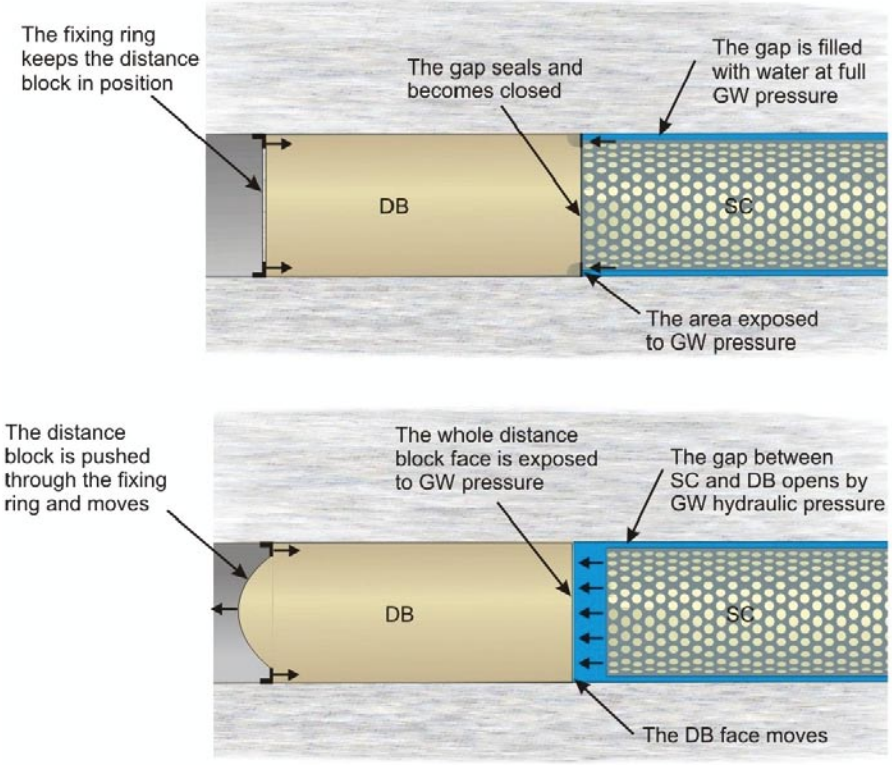

Figure 4-2. *Probable behaviour of the distance block due to the full hydrostatic pressure of 5 MPa in the Basic Design alternative. Top: First assumption, Bottom: Probable evolution based on testing and modelling. DB = distance block, GW = groundwater, SC = supercontainer.*

A third design variant, Semi Tight Compartments (STC), was also developed toward the end of the 2004–2007 Project. In the STC design alternative, each supercontainer section is sealed with distance blocks and sealing rings that temporarily prevent water from flowing from one adjacent section to another before the first section is filled with inflowing water. When the section is filled with water, the distance blocks would not be able to withstand the high water pressure, so piping would occur and water would flow into the adjacent section. Since there are no requirements governing the distance blocks and sealing rings other than to seal against the hydrostatic water pressure of a few metres, the blocks can be manufactured with the same (larger) gap between the rock and the block as the gap used for the supercontainer in the DAWE design alternative.

4.2 Key components of the KBS-3H design and experience gained

4.2.1 Design and assemblage of the supercontainer

Evaluations made during the JADE project (see Section 2.2) led to the conclusion that efficient horizontal emplacement requires the canister and the buffer to be assembled into one unit, called a supercontainer, see Figure 2-4, which is then moved into the deposition drift. The supercontainer consists of a perforated steel cylinder in which the buffer material and one copper canister are assembled before emplacement.

The dimensions of the different components vary depending on the canister type, with different designs for fuel elements from the Boiling Water Reactor (BWR) the Pressurized Water Reactor (PWR) and European Pressurized Water Reactor (EPR). For this study, Posiva´s reference fuel and canister is a BWR canister, the weight of the supercontainer steel shell is approximately 1,100 kg, the length is 5.525 m and the diameter is 1.765 m. The 8 mm thick shell is perforated with 100 mm diameter holes covering 62% of the cylindrical surface. In order to guarantee good contact between the supercontainer and the adjacent distance blocks, the surfaces of the end plates are not perforated. The total weight of the supercontainer with buffer and canister is approximately 46 tonnes, although this depends on the type of fuel elements used.

The buffer is comprised of a set of bentonite ring blocks (type MX-80 bentonite) surrounding the canister and two end blocks. The ring blocks have 10% initial water content by weight and dry density of 1,885 kg/m^3. The end blocks also have 10% initial water content by weight, but with a lower dry density (1,753 kg/m^3). The buffer will swell through the perforations of the supercontainer shell during saturation. The design value of the buffer density and porosity of the buffer after saturation and filling of the void around the supercontainer are 2,000 kg/m^3 and 0.44, respectively. The supercontainer is designed to function in unfavourable load conditions which might be influenced by the irregularities of the drift shape and size.

As the corrosion of iron could have a negative influence on the functional long-term properties of bentonite (see Section 5.3), substitute materials have been investigated for the supercontainer shell, such as copper alloys, nickel-based alloys, titanium alloys and high performance stainless steels. Steel and titanium will be studied further in the next phase of the KBS-3H project.

Two full-scale supercontainers were assembled at the Äspö HRL to gain experience for future development work, see Figure 4-3 (left). The supercontainer is assembled around the canister in a vertical position and tilted after assemblage to a horizontal position for transportation, see Figure 4-3 (right). The tolerances are precise as the radial space between the different components is only some 3–4 mm. One item of experience gained was that, due to the limited space, the welding of the lower end plate of the steel shell and subsequent inspection were difficult to perform. Further optimization and development will be needed. It is also proposed that the buffer should be placed inside the steel shell before emplacing the canister. A procedure like this would also be desirable with respect to requirements for radiation shielding.

Figure 4-3. Left: Assembled supercontainer in the vertical position at Äspö. Right: The supercontainer is placed into a transport tube for transportation down to the underground test site at Äspö HRL.

4.2.2 Distance and filling blocks, and general bentonite issues

A distance block of bentonite is placed between each supercontainer in the drift. The purpose of the distance block is to seal off each supercontainer position from the others and to prevent the transport of water and bentonite along the drift. The distance blocks also provide adequate spacing between the canisters in order to keep the temperature below the maximum permissible temperature of the canister and the buffer. The safety function of the distance block is the same as for the buffer in the supercontainer, see Section 3.1.3.

Filling components are used in positions that are not suitable for supercontainer emplacement or where there is a need to compensate for the potential reduction of buffer density. The reduction of buffer density may be caused by the filling of open volume. Such volumes may result from the dissolution of buffers within a compartment or drift end plugs or from open volume adjacent to the compartment plugs or fixing rings left in the drift during operation. The filling components have not been designed in detail.

The filling components will inevitably undergo physical and chemical changes in time due to mineral transformations, shrinkage, swelling etc. However, it is required that these processes should not cause volume changes that could lead to significant changes in the buffer density of the distance blocks.

Filling components are used in a drift adjacent to the compartment plugs, i.e. between steel compartment plugs, in the drift entrance side of compartment plug and in the drift end side of compartment plug. Filling blocks will also be used in positions with water leakage. The present assumption is that if the water inflow into a supercontainer section (including supercontainer and distance block, totalling about 10 m in length) is higher than 0.1 l/min before sealing and less than or equal to 1 l/min after sealing, the section cannot be used for deposition of a canister but should be filled with a filling block with properties similar to the distance block.

The main issues to resolve in the design work for the period 2004–2007 were the following uncertainties related to the behaviour of the bentonite in the supercontainer, distance blocks and the filling blocks:

- **Humidity-induced swelling**. Humidity-induced swelling and possible cracking would have an effect on the early behaviour of distance blocks before saturation. The magnitude of this effect would have been much more significant for the DAWE design alternative.
- **Erosion of buffer and filling blocks**. Physical erosion of the bentonite in the supercontainer, in distance and filling blocks due to free-flowing water in the drift between the blocks and the rock, or from fracture flow that could result in bentonite transport and variation of buffer density within the deposition drift.
- **Piping through distance blocks**. In the Basic Design alternative the distance blocks are supposed to prevent water flow between the adjacent supercontainer sections, but the validity of this assumption needs to be tested to ensure that piping or displacements will not occur, since such effects could adversely affect the system performance.
- **Hydraulic pressure on the end surfaces of the distance block**. The magnitude and distribution of the pressure-induced load on the distance blocks are important since they will affect the movement of these blocks and determine the design of the fixing rings in the Basic Design alternative. The principal uncertainty is whether the pressure is exerted on a narrow rim on the inner end face, which is not covered by the supercontainer end surface, or whether it is exerted on the entire surface. If so, the displacing force would be much higher.
- **Artificial watering of distance blocks**. The saturation process of distance blocks has a significant impact on the sealing ability and piping resistance. The saturation process is different in the DAWE and the Basic Design alternatives. In the case of the DAWE design alternative, the effect of artificial watering on saturation and possible later drying and shrinkage is an important process and needs to be studied. This re-distribution of water could be caused by either the thermal output of the nearby container or suction-induced water redistribution from the outer perimeter to the drier interior regions of the distance block.

The issues described above were studied in the laboratory and by modelling. The tests were typically conducted on a scale of 1:10 supplemented by certain tests on a scale of 1:2. The 1:2 test scale was used to study the behaviour of swelling pressure and erosion rate.

The main results from testing /Börgesson et al. 2008/ were:

- humidity-induced swelling and cracking during transport and emplacement can be controlled by adjusting the initial water content of the buffer and would be avoided by initial water content above 20%,
- the erosion rate is between 1 and 10 g bentonite per litre of eroding water. Longer exposure time or higher salinity concentration increases the erosion rate,
- for bentonite blocks enclosed in a constant volume with a water-filled gap with no access to additional water, the gap will swell and close when the gap is small compared to the block volume. The results indicate that in the KBS-3H geometry the swelling pressure will remain at a few hundred kPa after water has migrated to the central parts of the blocks,
- the piping of water past a distance block can only be avoided if the gap between the distance block and the supercontainer (Basic Design alternative) is small, which would be technically very challenging,
- the build-up of a hydraulic groundwater pressure on the major area of a distance block end surface would be difficult to avoid during the emplacement of supercontainers in one deposition drift compartment and subsequent plugging (Basic Design Alternative).

The results of the tests were used to further develop the design of the distance blocks. The distance blocks in the DAWE design alternative are assumed to have the same initial diameter as the supercontainer, giving a gap to the drift walls of 42 mm. The length of distance block using the Posiva reference design and a canister for BWR fuel elements is 5.475 m. The length of the distance blocks for SKB repository design and Forsmark bedrock conditions is 2.5 m. The reason for the difference SKB/Posiva is the distance between the deposition drifts being 25 m for the Posiva case and 40 m for the SKB case. The initial water content of bentonite in the distance block is 21% and the initial dry density 1,712 kg/m^3 ± 85 kg/m^3 to obtain the final fully saturated density of 2,000 kg/m^3 ± 50 kg/m^3.

A specific issue concerning the DAWE design alternative is the removal of watering pipes, which were tested at Äspö HRL by using a three metre-long pipe, see Figure 4-5. A 42 mm gap between the blocks and the test tube (equivalent to the distance block design) was filled with water. Due to the swelling pressure from the bentonite caused by the saturation and the friction between the bentonite and the steel tube, shear forces were created when the pipes were pulled out. During the first five days, the friction developed fairly slowly up to 0.5 kN and then up to 2.2 kN in one month.

Figure 4-4. *Example of cracking of buffer by humidity; block with low initial water content after 8 hours (left) and with high water content after 3 months (right) /Börgesson et al. 2008/.*

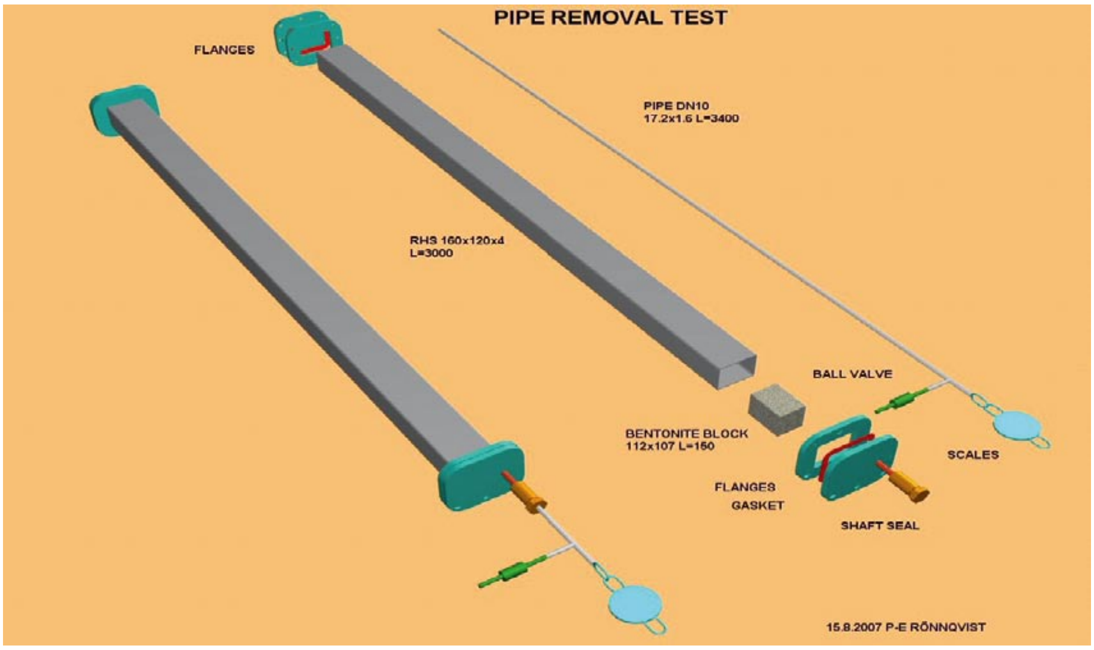

Figure 4-5. *Equipment for the pipe removal test.*

Using the test results for the real case with a compartment length of 150 metres, the maximum force of 40 kN which the steel pipes can tolerate without breaking is exceeded in less than 10 days. Hence, the results clearly indicate that the pipes should be removed as soon as the compartment is filled with water /Autio et al. 2008/.

4.2.3 Compartment plug

Compartment plugs made of metal (steel or potentially titanium if steel is not acceptable from a long-term safety point of view) will be used to seal off drift sections with inflows of approximately 1–4 litres per minute after grouting, see Figure 4-6.

A steel collar structure in the rock is installed in the deposition drift before the deposition operation starts. The collar is attached to the rock surface and sealed by using low-pH concrete. The centre part of the plug is installed rapidly during deposition. The plug consists of a V-shaped slot excavated in the periphery of the drift, a steel fastening ring, a collar mounted against the ring and a cap installed on the collar.

The excavation of slots for the compartment plug has been developed and tested at Äspö HRL, see Figure 4-7. The method used was sawing. Fourteen parallel cuts were made with varying depths creating a V-shape with a flat bottom. The slabs were later broken by wedging. A special rail was built to allow the cuts to be sawn along the circumference of the drift, see Figure 4-8. The excavation method for slots will be further developed.

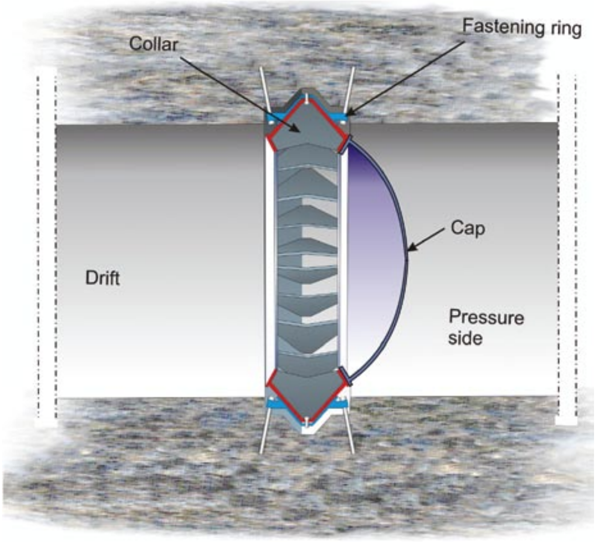

Figure 4-6. The compartment plug and main structural parts.

Figure 4-7. Template for verifying the shape of the slot for the compartment plug.

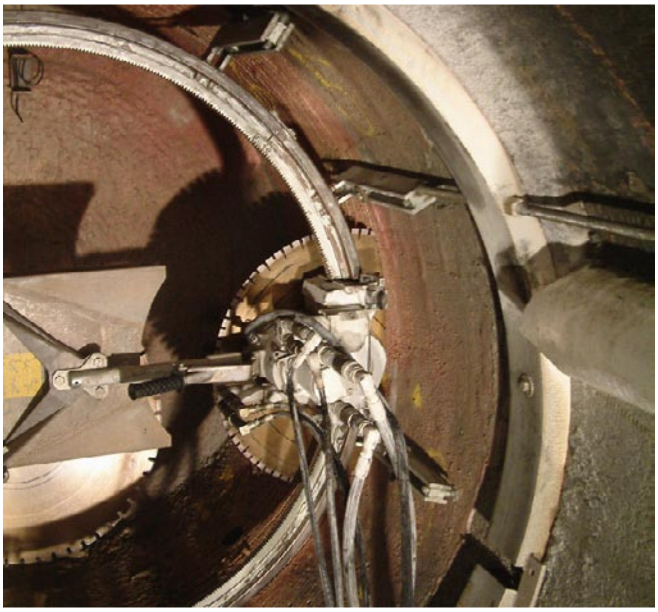

Figure 4-8. Sawing of slots for the compartment plug by a specially developed rig.

The plugs are designed to withstand the full hydrostatic pressure exerted on the convex side of the cap. The spaces within and around the compartment plugs will be filled, see Section 4.2.2, to prevent voids that could lead to a loss of the distance block buffer density. In the current design, cylindrical transition blocks will be placed between the compartment plugs and the adjacent distance blocks. The remaining voids next to the convex surfaces of the plugs will be filled with MX-80 type bentonite pellets or sand. The volume in the compartment plug will probably be filled with sand, but the design is not yet final.

The drift section with high water inflow will be sealed off by two compartment plugs. The backfill material between the plugs has not been defined yet, but in certain parts it should be permeable enough, e.g. crushed rock, to allow water flow across the drift. In addition, the backfill should be graded so that the erosion of bentonite around the plugs is prevented.

The assembly of a compartment plug will be tested on a full-scale bsis at Äspö to demonstrate that the plug can be constructed as planned and to verify that requirements for water tightness and hydrostatic pressure (5 MPa) can be met. The excavation of the slots (Figure 4-7) was the initial phase of the tests for the compartment plug, which will be continued in the next project phase.

4.2.4 Drift end plug

The drift end plugs are used to seal the deposition drift. The plugs are designed to be compatible with and to support the safety functions of the canister, the buffer and the host rock, see Section 3.2. The drift end plug is required to function during the period from operation to plugging, backfilling and sealing of the repository.

Different plug designs were studied, for example using a cylindrical rock kernel to reduce the amount of concrete, but finally a plug made of a combination of steel and concrete was selected, Figure 4-9. The steel enables rapid temporary sealing and isolation from a few weeks to a few months during the early wetting of drifts and the concrete provides sealing after a few weeks of concrete curing.

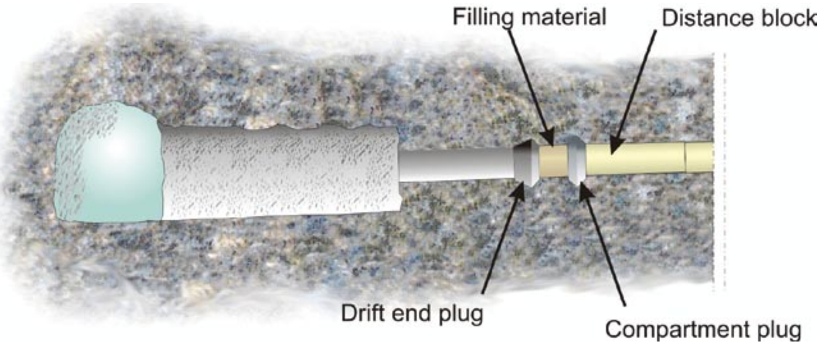

Figure 4-9. The drift end plug arrangement based on a rapidly installed compartment plug (steel) and a drift end plug (steel-reinforced concrete) with filling material between them to compensate for a possible future density reduction. The rest of the drift will be sealed no later than when the niche and the main tunnel are backfilled.

Low-pH cement (porewater leachate pH < 11) will be used in the repository to limit the chemical disturbances due to the high pH leachates from cement pore water when using standard cement. The concrete plug can be constructed by casting the plug or by shotcreting (i.e. spraying concrete at high speed). The ESDRED project (www.esdred.info) tested the construction of a low-pH shotcrete friction plug at the Äspö HRL /García-Siñeriz et al. 2007/. The results of the tests and experience from other similar tests led to the conclusion that it is preferable to cast the concrete plug and not use the shotcrete method.

4.3 General repository layout

The general KBS-3H repository layout based on SKB's design is outlined in Figure 4-10. The spent fuel canister is transported via an access ramp tunnel to a reloading station where the supercontainer is assembled. The supercontainer is then transported to the deposition niche, where the deposition equipment, start tube and transport tube are located as described later in Chapter 6.

The access to the deposition areas and general design of the deposition areas are different for the SKB and Posiva KBS-3 repositories, due partly to different regulations in Sweden and Finland and partly to the fact that optimisation led to different results. These differences are not specific to the KBS-3H design and it is beyond the scope of this report to further explain the rationales for the differences. However, some of the main differences are outlined below:

Access to the SKB deposition area is through one transport tunnel, whereas the Posiva design assumes two transport tunnels with separate functions. Another important difference is how to ensure that the temperatures on the canister surface are not so high that they impair the buffer functions. The optimization work at SKB resulted in the deposition drifts being separated by 40 m whereas in the case of the Posiva design the drifts are separated by 25 m. In all, approximately 45,000 m of deposition drifts are needed with a total volume of some 120,000 m^3 for the Swedish programme assuming 4,500 canisters and approximately 46,000 m of deposition drifts for the Finnish programme assuming 2,840 canisters. The 40 m separation distance means that in the SKB design, the canisters can be placed closer together in a drift than in the Posiva design. Up to 30 canisters will be deposited in each 300 m long deposition drift in the case of Swedish spent fuel and the layout principle adopted at Forsmark. For Olkiluoto, with Finnish spent fuel and layout principle, the estimated number of canisters per drift is 16–18.

The results of the KBS-3H design, bearing in mind the site-specific thermal properties of the rock, are that the nominal length of the distance block is 5.475 m for the Posiva reference conditions and 2.5 m in the case of the anticipated SKB reference conditions.

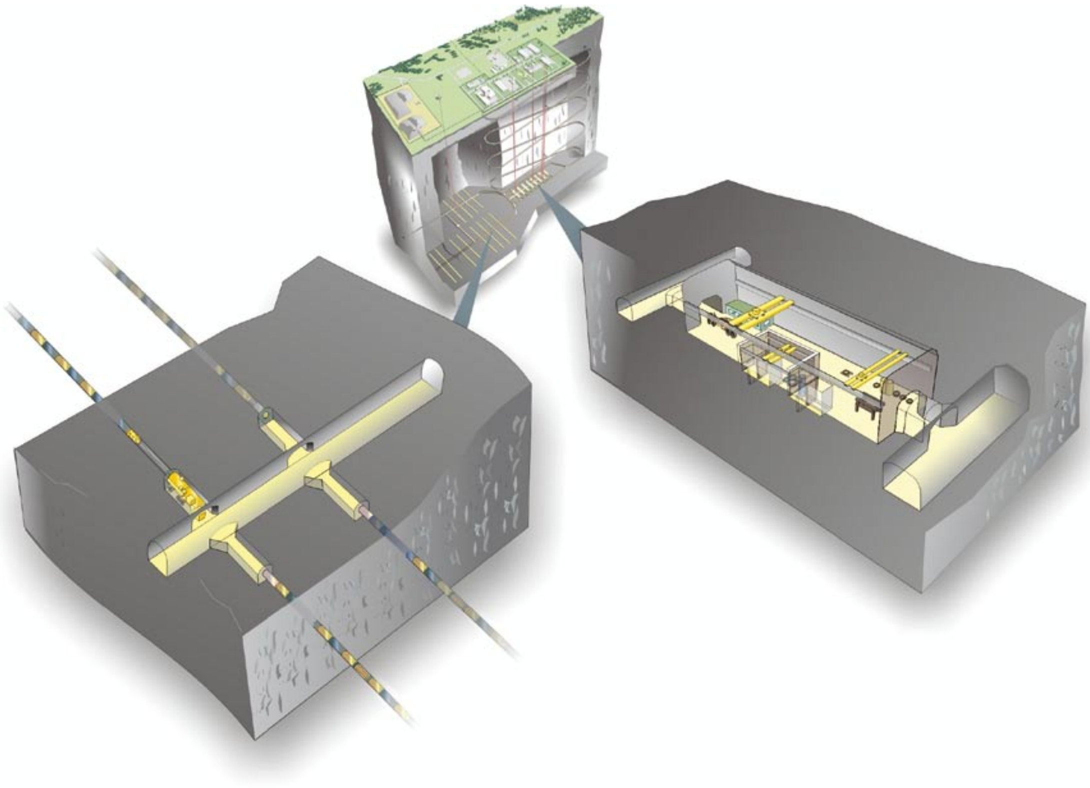

Figure 4-10. *General KBS-3H layout (top) with the reloading station (right) and deposition area with the transport tunnel, the deposition niche and deposition drifts (left).*

A general feature of the layout is the different types of spent fuel elements that will be used, depending on the reactor type. In the case of the Posiva design, for example, three types of fuel elements will have to be considered from the Olkiluoto 1 and 2 (Boiling Water Reactor), from Loviisa 1 and 2 (Pressurised Water Reactor) and from Olkiluoto 3 (Pressurised Water Reactor) and each fuel type will define the lengths of the supercontainers and the distance blocks. For example, the length of the supercontainer is estimated to be 5.53 m for Olkiluoto 1 and 2, 4.33 m for Loviisa 1 and 2 and 5.98 m for the Olkiluoto 3 reactor. For the Swedish case, all reactors have the same length of spent fuel elements and the length of the supercontainer will be 5.53 m.

One difference between KBS-3V and KBS-3H is the function of the reloading station. In KBS-3H, the following functions will be performed, see also /Autio et al. 2008/:

- movement of the copper canister from the transport cask used for transportation in the access ramp,
- assembly of the supercontainer,
- transfer of the copper canister from the transport cask and its placement in the supercontainer inside the shielded handling cell, and
- assembly of the supercontainer inside the transport tube within the shielded handling cell. The transport tube with the supercontainer will later be transferred from the reloading station to the deposition area.

4.4 Olkiluoto site-specific layout

The site-specific layout of the KBS-3H design is necessary to show the extent of the repository, to evaluate cost and environmental impact, but most of all to carry out the safety assessment.

The site-specific layout of the KBS-3H, see Figure 4-11, is based on the same site data from Olkiluoto as that used for the layout adaptation of the KBS-3V design to the Olkiluoto site. It was estimated /Johansson et al. 2007/ that 25% of the site would not be suitable for disposal within the actual bedrock resource at Olkiluoto. In comparison, it is estimated that the exclusion rate is 17% for a KBS-3V repository based on the same Olkiluoto 2006 site model. The lower degree of utilization for the KBS-3H design is due to the compartment sections, sections with filling blocks etc, but the design is preliminary and therefore the results should be treated as indicative.

The exclusion rate of 25% will, as a consequence, require an increase in the total length of deposition drifts by 33% so that it would be possible to deposit the 2,840 supercontainers in suitable locations. The total volume of the Olkiluoto KBS-3H repository is estimated to be 894,000 m^3 compared to 1,360,000 m^3 for the KBS-3V design, i.e. 34% less volume for the KBS-3H design based on the current design and assumptions for the Olkiluoto layout.

An important part of the engineering task is to estimate the amounts of construction and stray materials in the repository as the material remaining in the closed repository could have an influence on the chemical and biological processes that might influence the safety functions. The estimated quantities of engineered and other residual materials were based on the site-specific adaptation to the Olkiluoto site and the Basic Design alternative as described in Section 4.2. The difference in quantities, between the Basic Design alternative and the DAWE design alternative is mainly related to 10% less steel in the latter design, due to the absence of fixing rings.

The quantities of remaining materials after closure in a KBS-3H repository at Olkiluoto /Hagros 2007a/ were compared with those for the KBS-3V design /Hagros 2007b/. Most of the quantities of materials are very similar (± 5%) or typically less (–20%, e.g. due to the lower volumes of backfill and construction material, such as shotcrete) in the case of the KBS-3H design compared to the KBS-3V design. The remaining quantity of cement, however, is estimated to be reduced from 5,800 tonnes to 1,500 tonnes (–74%) and zinc from 140 tonnes to 4.3 tonnes (–97%).

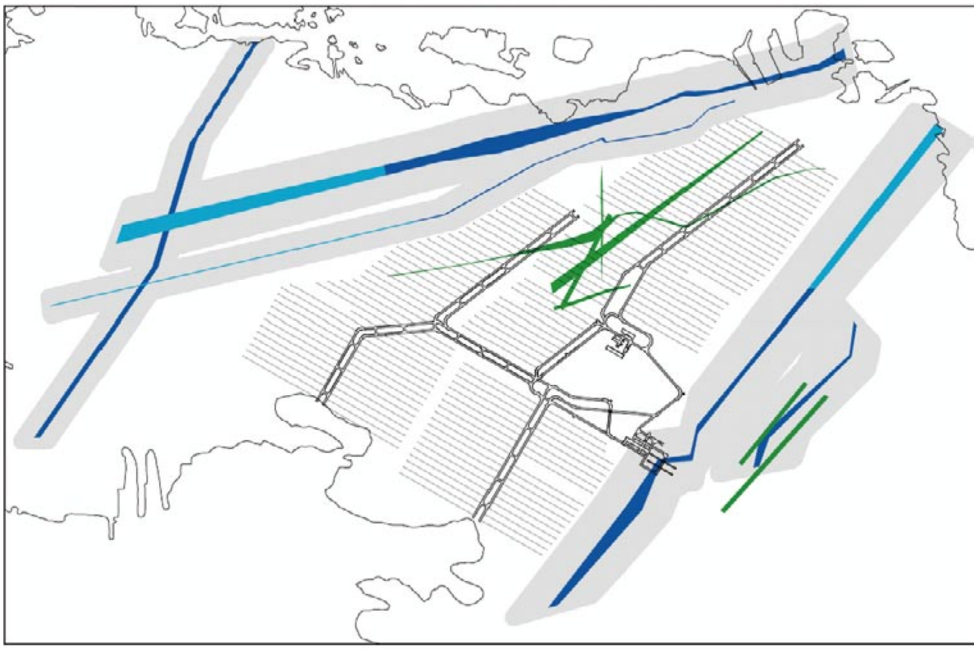

Figure 4-11. The KBS-3H layout with a canister drift orientation of 120°, level –420 m at Olkiluoto. Light blue areas indicate respect distances to the layout-determining fracture zones (shown in dark blue). Features shown in green are allowed to intersect the deposition drifts /Johansson et al. 2007/.

Zinc is used in rock support bolts and miscellaneous construction materials. The main difference comes from the use of massive concrete plugs at the end of the disposal tunnel in KBS-3V (130 tonnes of zinc). On the other hand, for some materials the quantities increase, the most noticeable example of which is the increase in steel due to the steel in the supercontainer shells and in the compartment plug. Based on the Basic Design alternative, and assuming that the drift end plug is made of a low-pH concrete plug, the estimated remaining steel quantity is 4,600 tonnes compared to 1,500 tonnes for the KBS-3V design (+210%).

Overall, the total quantity of all materials used in a KBS-3H repository assuming Olkiluoto conditions is some 20% less than in the KBS-3V alternative. The smaller quantities in 3H are due mainly to the fact that the deposition drifts are much smaller than the KBS-3V deposition tunnels and that they are not constructed and equipped in the same way as the KBS-3V deposition tunnels. In particular, the lack of KBS-3V-type concrete plugs at the end of the deposition tunnel causes a major reduction in the total quantity of cement used in a KBS-3H repository /Hagros 2007a/.

4.5 Deposition drift

The layout for the KBS-3H design is similar to that of the KBS-3V, but the deposition tunnels and deposition holes are replaced by up to 300 m long deposition drifts that are excavated from niches in the main tunnel. One of the key issues in the KBS-3H project was to test the ability to excavate horizontal deposition drifts according to requirements. The objectives for this work as stated in 2004 were as follows:

- to show the feasibility of meeting the geometrical and other requirements,
- to construct two "deposition drifts" needed for the later project stages. One drift was needed to demonstrate that heavy load – a supercontainer – can be transported into the drift. The second drift was needed to demonstrate components of the KBS-3H system, e.g. the low-pH shotcrete drift end plug, and
- to evaluate the applicability of selected excavation methods for realistic repository conditions and, based on the project experience, to define needs for technical developments/improvements. A detailed account of the results and an evaluation of the excavation project are reported in /Bäckblom and Lindgren 2005/.

To meet the objectives, two deposition drifts were excavated at the Äspö Hard Rock Laboratory over the period October 2004 to February 2005, see Figure 4-12. One horizontal drift was 15 m in length and the other 95 m in length. The drifts are situated 220 m below the surface.

4.5.1 Choice of drilling technology

SKB evaluated several methods of excavating horizontal drifts, both in desk studies as well as through practical field tests. Based on the findings, it was decided to test excavation by horizontal push-reaming, in which a pilot hole is bored, then reamed to full diameter using fairly conventional raise-boring equipment. Other options, such as cluster technology and Tunnel Boring Machines, were ruled out /Bäckblom et al. 2004/. Key components of the system are the raise-boring machine, the cutter head, the drill string and the stabilisers, Figure 4-13. Mucking-out is performed by flushing the deposition drifts with water.

As described in Section 3.2, the geometrical requirements for straightness are very strict. For this reason, SKB decided to use active steering for the pilot hole in the 95 m long drift. Due to the availability of active steering technology on the market, it was decided that the pilot hole for the 95 m drift should be drilled in stages. The plan was first to drill the 152 mm hole by using active steering since the hole diameter was commensurate with the equipment for the active steering of the pilot hole. The second stage was to ream the 152 mm hole to produce the 279 mm pilot hole needed for the guidance pin in front of the reamer head. In view of the forces generated by the reamer head, it was decided that the guidance tool diameter needed to be much larger than 152 mm.

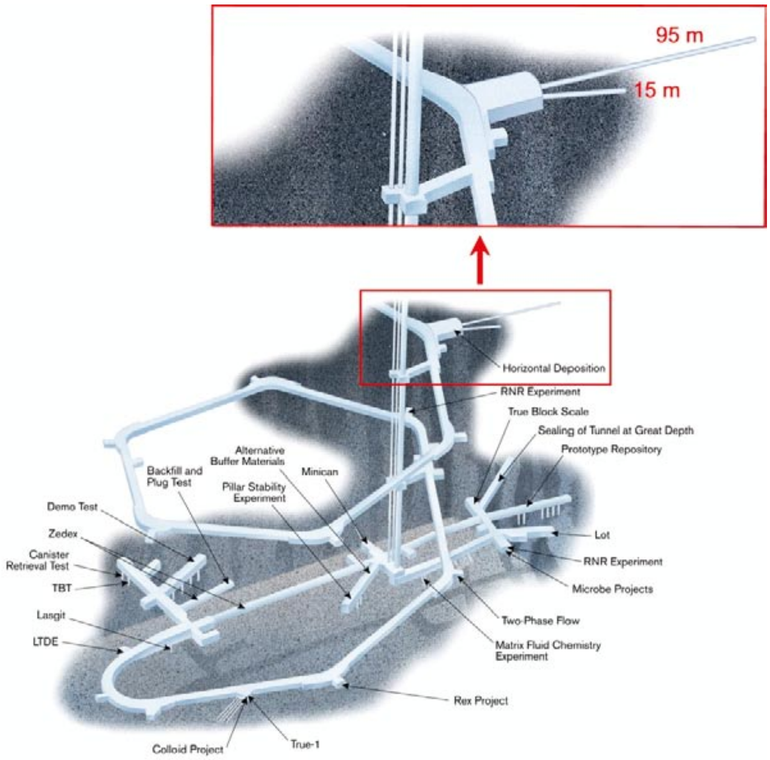

Figure 4-12. *The location of the drifts for the KBS-3H project. The figure also shows locations of other Äspö HRL experiments.*

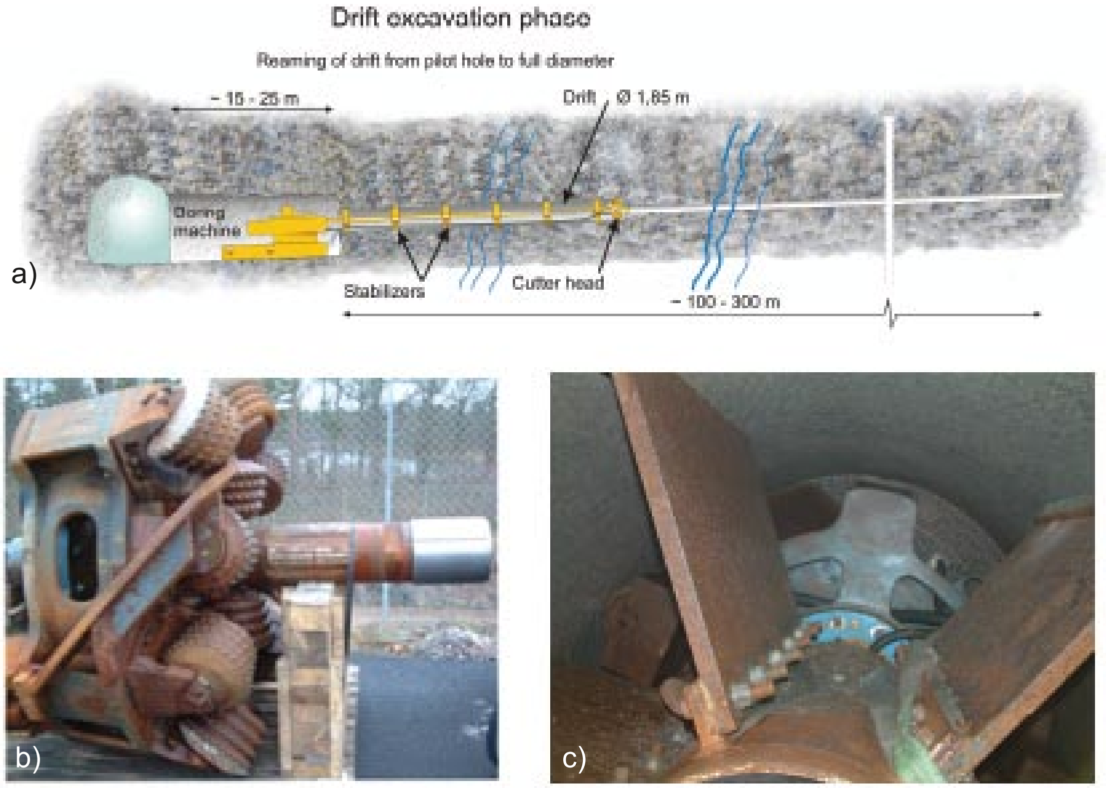

Figure 4-13. *a) Principle for boring the KBS-3V deposition drifts by using rotary crushing. b) Photo of the cutter head with the guidance pin. c) Photo inside the drift showing the wing-stabilizers in front and the cutter head in the background.*

Before, during and after the excavation, several types of data were collected, or planned to be collected. Examples were hole geometry, operating characteristics of the rig and muck system (capacity, availability, utilization, Mean Time Between Failure, torque, thrust, rotation, penetration, etc) as well as the consumption of consumables and energy, noise emission and the particle size distribution of muck. The reader is referred to the report by /Bäckblom and Lindgren 2005/ for an account of the detailed machine set-up and descriptions of equipment for excavation and measurements.

4.5.2 General operating experience and principal results

The rock conditions were appropriate for the excavation work and in no way caused any excavation problems. The drift was in typically homogeneous rock conditions, with generally hard rock, some zones of extremely hard rock, and occurrences of layers of narrow weak zones. The conditions in general are ideal for controlled drilling with generally small natural deviations caused by stratification or inhomogeneous rock. The maximum inflow of water measured was low and within a range of 0.4 litres/min for the 15 m drift and 12 litres/min for the 95 m drift.

Horizontal push-reaming generates substantial volumes of muck at a high rate (up to some 3 m^3/h) and the rock cuttings need to be removed from the almost horizontal drift using flushing water. Effective mucking was considered at an early stage to be vital for efficient excavation, and several options were successively tested and rejected during the excavation of the test drifts. The removal of the debris using a re-circulated water flow (3,000 litres/min) was sufficient to clean the drift at a 2° inclination.

The water was flushed into the drift at the reamer head and re-circulated at the drift end by using a container system. Since the groundwater head was substantial, there was no risk of the flushing water entering the groundwater system from the drift. If SKB had used cluster drilling technology for the drift, 5,000 litres/min would also have been necessary, but this water would not have been re-circulated /Bäckblom et al. 2004/.

The equipment for active steering of the 152 mm pilot hole did not work properly with respect either to deviations or durability. When the tool for active steering broke down and was not to be replaced for a couple of months, SKB and their contractor launched a contingency plan to drill the pilot hole without any active steering in a horizontal direction but aiming to provide vertical guidance by using water level measurements, a plan that succeeded, see Figure 4-14.

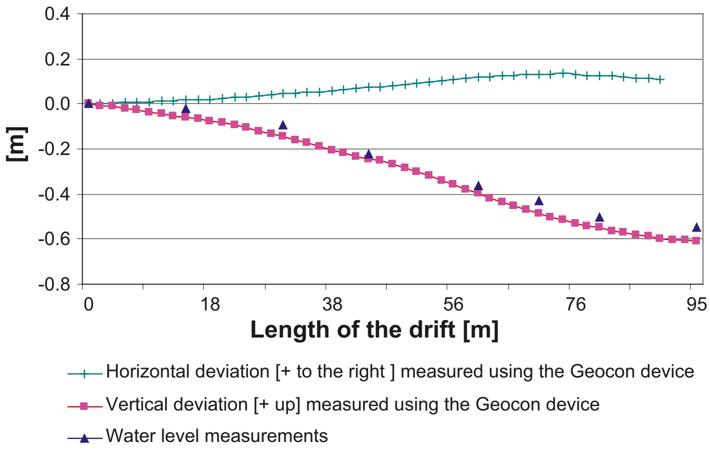

Figure 4-14. *Horizontal and vertical deviations for the 95 m pilot hole (279 mm). Drift 1,619 A. Deviations are calculated for a theoretical line based on the actual set-up of the drill rig where the inclination is 3.6% upwards (= 2.1°). Details on the Geocon device, see /Bäckblom and Lindgren 2005/.*

The vertical deviation from the theoretical line based on the direction of the machine set-up was approximately –0.6 m and the horizontal deviation some 0.1 m (maximum 0.134 m at 78 m).

According to the requirements, the inclination of the borehole was meant to be in the range of 2°±1°, and this requirement was met for the 95 m drift. The theoretical line for the 95 m drift based on the machine set-up was 2.09° and the final results showed an inclination of between 1.86° and 2.43°.

A dummy was used to demonstrate that a 6 m-long and 1,765 mm-diameter device would fit into the drift. The insertion of the dummy into the drift proved that the drift could accommodate the dummy. As the dummy was fitted with gauges, the roughness along the drift as well as the gap between the dummy and the rock wall were measured. The roughness was interpreted to be < 5 mm for most of the drift, but occasionally the measurements indicated that roughness was at a higher level, as much as 8 mm.

The measurements from the dummy were also used to indicate the diameter variations by measuring the gap between the dummy at the rear and at the front, and the drift wall. According to the requirements specifying that the diameter should be between 1,840 and 1,850 mm, and the dimension of the supercontainer 1,765 mm, the permissible gap should be approximately 75–85 mm. Some 11% of the measurements were outside the range of 75–85 mm. In the case of the rear gauges, all outliers were > 85 mm, for the front gauges one measurement was > 85 mm and 29 measurements were < 75 mm. For this reason, it was concluded that that the dummy was not yet the perfect tool for measuring a diameter of 1,765 mm.

For the 95 m-long drift, the daily advance rate improved considerably when the mucking started to work better after some 40 m of boring, see Figure 4-15. The typical daily advance (10 h shifts) had increased to 6 m by the end of the project. At this rate effective penetration was around 0.5–0.6 m/h with downtime practically zero. Figure 4-16 shows the drift after excavation.

The main conclusion from the demonstration at Äspö HRL was that horizontal push-reaming can produce 95 m drifts in good rock (no ground support required) that will probably meet the requirements for operational and long-term safety. The technology would also be applicable for 300 m-long drifts, provided that a technique is developed and tested to drill sufficiently straight pilot holes. More experience is needed to understand for what rock conditions additional pre-grouting would be necessary before the drift is reamed and for what rock conditions the drift might need temporary support during construction and before emplacement of the supercontainer.

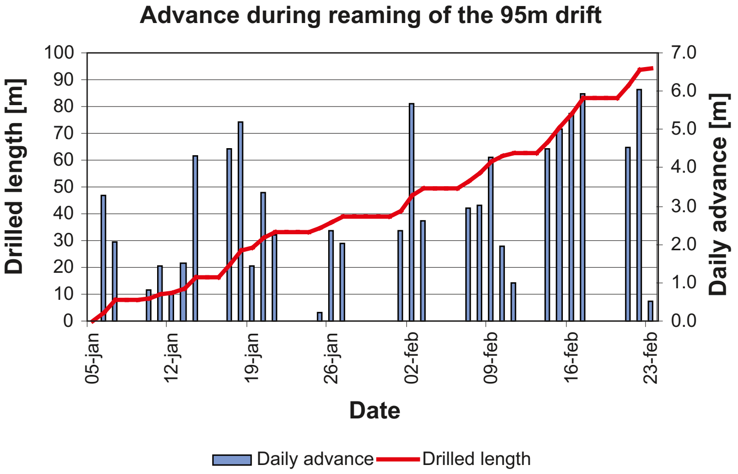

***Figure 4-15.** Daily advance during drilling of the 95 m drift.*

Figure 4-16. *Photo taken inside the drift at Äspö HRL showing the good rock conditions and the surface roughness in the drift wall.*

Several suggestions for additional technical development and improvements were identified in addition to the developments during the project. The KBS-3H project during 2007 studied methods of drilling straight pilot holes. One obvious method would be to core-drill a pre-pilot hole using a directional core drilling method with a bit size of 76 mm. The pilot hole would then be reamed in steps (one or most likely several) into the final pilot-hole diameter of 279 mm or larger by using a rotary tricone bit with a guiding nozzle. The final pilot-hole diameter would depend on the design of the reamer head, but in general a larger pilot-hole diameter for guiding the reamer head would make the system stiffer, hence leading to straighter holes.

4.6 Groundwater control

The KBS-3H design is sensitive to groundwater flow into the deposition drift during the operational phase and various means have been developed to limit the groundwater flow along the deposition drift or to develop a design that copes with groundwater flow. The idea of dividing the drift into compartments, for example, has merits but also some drawbacks, one example of which is that the compartments significantly reduce the degree of drift utilization, which lead to higher costs. In spite of the design development, efficient methods need to be deployed to limit the seepage into the deposition drifts.

The project prepared studies concerning groundwater control based on the principles of either pre-grouting or post-grouting. Alternative sealing methods such as draining or freezing were ruled out due to the many uncertainties surrounding them, for example drill holes outside the drift perimeter and disturbance of the near-field rock due to freezing /Autio et al. 2008/.

The groundwater control programme adopted for the KBS-3H design is composed of different parts:

- Methods of investigations and evaluations to determine whether a position in a drift is suitable for the emplacement of a supercontainer or not, i.e. to define sections with an inflow less than 0.1 l/min before grouting.
- Methods and investigations to determine whether to grout or not and to decide the type of grouting that is most effective for limiting the inflow to the drift, e.g. grouting before or after excavation.

Investigations to confirm the locations of the deposition drifts are made by the drilling of one or more holes and characterizing the geological and hydrogeological conditions in the rock around the holes, for example fracture frequency, aperture, filling and transmissivity of the fractures. If the location is accepted, the need for and method of grouting are assessed. The basic principle for grouting is to grout the leakage as early as possible in the overall operation. However, it is expected that some leakages will not appear until after the drift has been excavated. Three different situations for grouting the drift are briefly described below and illustrated in Figure 4-17:

- In a situation where one or a few fractures with a hydraulic aperture larger than approximately 50 µm (an inflow of over 1–2 l/min) is recorded in the investigation/pilot holes, it is useful to carry out grouting even before excavation is started, see Figure 4-17a. The grouting is conducted in the investigation/pilot holes using a double-packer system. The expected reduction of inflow (sealing effect) is estimated to be > 60%. Smaller leakages, < 1 l/min, are not groutable from a single hole.
- In a situation where the hole contains several fractures with a small aperture, grouting before excavation is meaningful. Investigation holes are drilled inside the periphery of the deposition drift in order to obtain more detailed information on the possible leakages, Figure 4-17b. These investigation holes are then used for grouting. If the investigation shows that more grouting holes are required, additional holes are drilled inside the drift perimeter and later used for grouting. The expected sealing effect is > 99%.
- In a situation, after drift excavation, where leakages still remain, a Mega-Packer is used for the post-grouting of leakage areas, Figure 4-17c. Post-grouting is primarily used for leakages that arise after excavation, which hamper the function of the drift.

Grouting tests using Mega-Packer equipment (Figure 4-18, left) were initiated in autumn 2007. The tests were executed at the KBS-3H test drift at the –220 m level at Äspö, see Figure 4-12.

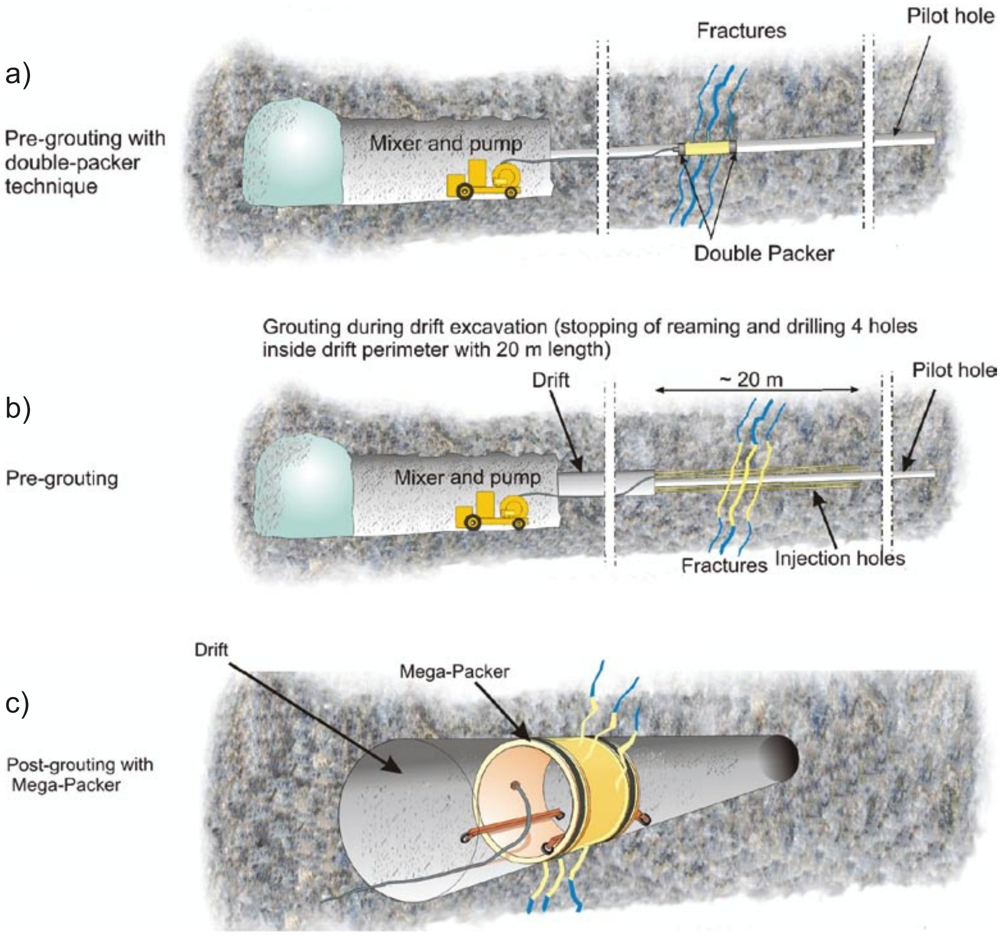

Figure 4-17. *Illustration of grouting methods: a) Pre-grouting of the investigation/pilot hole, b) Pre-grouting during drift excavation, c) Post-grouting with the Mega-Packer.*

Figure 4-18. *Left: Installation of the Mega-Packer in the Äspö HRL KBS-3H drift. Right: After grouting the Silica Sol is shown as a white rim at the drift periphery. The rim is later cleaned away.*

Preliminary results using Silica Sol as grout are promising and indicate that inflows can be significantly reduced, (Figure 4-18, right). Silica Sol is preferred for the narrow fractures where cement-based grout will clog. The sealing effect was estimated by measuring inflow before and after grouting. In the first test a sealing effect of approximately 97% was obtained when the inflow was reduced from 0.45 l/min to some 0.015 l/min after grouting. In the second test, the sealing effect was estimated to be 99.7%. The inflow of 2.2 l/min was reduced to 0.007 l/min. Additional tests are planned for the next project phase.

4.7 Remaining issues and future work

After the work over the period 2004–2007, a number of critical[3] issues and uncertainties remain.

- **Supercontainer shell.** (All design alternatives.) Selection of a suitable metal. Perforation degree of shell cylinder and end plates to optimise buffer performance.
- **Division of drifts into compartments.** (All design alternatives.) The uncertainty is both conceptual and site-specific. If the number of leaking fractures which should be isolated by a compartment plug is large and the fractures are distributed evenly along the drift, it may not be feasible to divide the drift into compartments. The principle of division into compartments seems to be feasible at Olkiluoto based on the present site investigations despite the uncertainties regarding data, which could be managed by adequate groundwater control.
- **Compartment plugs.** (All design alternatives.) It is likely that the demonstration of a compartment plug at the Äspö HRL will result in further development of the design, manufacture and installation methods of the plug. If the design principle is not found to function properly, there are alternative design principles available to develop a new prototype with a different shape or manufacturing technique. The final design of the plug is also dependent on the choice of metal, steel or titanium.
- **Pipe removal.** (Only the DAWE design alternative.) There are uncertainties in the feasibility of pipe removal under realistic conditions, some of which relate to the evolution of the buffer due to saturation.
- **Buffer swelling pressure related to spalling.** (Mainly relevant to the DAWE and STC design alternatives.) There are strong indications that spalling of the rock during the thermal period may take place in dry deposition drift sections. The uncertainties in the early evolution phase relate both to the development of the sufficient swelling pressure of bentonite in time to prevent thermal spalling as well as to the probability of occurrence as well as to the acceptability of the consequences of spalling.

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[3] An issue is defined as critical if there is uncertainty that requirements (functional/design/safety) can be met. In many instances such uncertainties can be reduced by improved design.

- **Buffer evolution related to internal piping.** There is uncertainty as to whether or not piping will take place during the early saturation phase and to what extent internal piping of the buffer would be acceptable.
- **Steering of pilot holes.** The excavation of the deposition drifts according to quality requirements requires a straight pilot hole. There is evidence that techniques are available for drilling straight pilot holes but verification is necessary.
- **Semi Tight Compartments.** The extent of possible piping and erosion during and after wetting of the buffer is uncertain and needs verification. Also the function of the sealing rings needs to be evaluated.

Several design issues have been identified for future development, both to resolve the critical issues and to develop the design. A few examples follow:

- **Detailed design of key design components.** Several components are at the design level of "schematic" or "preliminary" design, e.g. distance block, filling components, sealing rings in STC and drift end plug. Although not critical in principle, all the design components should be designed to a detailed level in the future work.
- **Optimisation of design with respect to the degree of drift utilization.** The design presented is likely be conservative. The starting point was to present a design that would function even in extreme conditions and allowing for uncertainties. In cases where the design basis is uncertain, conservative assumptions have been used. Examples are the plugged sections in the compartments, compartment lengths and length of filling components in general.
  The work will probably lead to increased utilization of the rock in the drifts.
- **Optimisation of watering in the DAWE design alternative.** Natural wetting has been one option in the DAWE design alternative. The operation would be significantly simplified if natural wetting were to be used and should be studied further.
- **Use of longer compartments.** It is possible that the improvements in groundwater control techniques would enable longer compartments or even the use of one drift as a compartment: This option should be studied further due to the positive impact on efficiency and cost.
- **Verification and demonstration of design functions under realistic conditions.** The most important components such as the buffer in the supercontainer, distance blocks, pipe removal, etc should be tested on a large scale in the laboratory before large-scale field tests are initiated. Since the functions of many components are coupled to the functions of other components, integrated testing should be carried out with relevant combinations.
- **Use of control measures to ensure that the emplacements of supercontainers and other components have been carried out in accordance with specifications.** The design work has been focused on developing alternative designs which fulfil the functional requirements. The appropriate control programmes have not been drafted, although the need for developing such programmes has been acknowledged and further emphasized by the fairly complex emplacement procedure.

5 Assessment of long-term safety

5.1 General

The KBS-3H project included long-term safety studies, i.e. studies addressing the consequences of a spent fuel repository for humans and the environment from the time the first canisters are emplaced in the KBS-3H repository. The quantitative safety assessment calculations extend to several thousands of years (up to 10,000 years) after the closure of the repository according to Finnish regulations. In the long term, after several thousands of years, the assessment is based on constraints on the release rates of long-lived radionuclides from the geosphere to the biosphere. In the very long term, after several hundred thousand years, no rigorous quantitative safety assessment is required, and the judgement of safety as based on more qualitative considerations or complementary evaluations /Neall et al. 2007/.

The KBS-3H long-term safety studies, based on the Finnish regulatory requirements, utilised data from the Olkiluoto site selected for further studies as the intended site for a spent fuel repository in Finland. Three fuel types were considered: VVER-440 PWR (Pressurized Water Reactor) fuel from the Loviisa 1 and 2 reactors, BWR (Boiling Water Reactor) fuel from the Olkiluoto 1 and 2 reactors and EPR (European Pressurized Water Reactor) fuel from Olkiluoto 3. The reference fuel type for the majority of safety assessment calculations is the BWR fuel from Olkiluoto 1-2. The current basis for safety assessment is that approximately 5,500 tU fuel will need to be disposed of, encapsulated in 2,840 canisters.

The reference design for the safety assessment[4] was the Basic Design alternative as described in the Design Description 2006 /Autio et al. 2007/. At the time when the reference design for the long-term safety studies was selected, no major differences between the Basic Design alternative and the DAWE design alternative were identified as being relevant to the long-term safety. Both designs were judged to be potentially feasible, and the Basic Design alternative was selected for the safety assessment.

Specific high-level questions addressed by the KBS-3H safety studies were:

- Are there safety issues specific to KBS-3H with the potential to lead to unacceptable radiological consequences?
- Is KBS-3H promising at a site with the broad characteristics of Olkiluoto from the long-term safety point of view?

The KBS-3H and KBS-3V safety concept is based on the long-term isolation of spent fuel and containment of radionuclides. In KBS-3H, as in KBS-3V, the copper canister, the bentonite clay buffer surrounding the canister and the host rock are the main system components that together ensure long-term safety. In order to assess the performance and safety of a repository, it is necessary to determine the conditions under which the identified safety functions of these components will operate as intended, and the conditions under which they may fail, or operate with reduced effectiveness.

Following the methodology adopted in the Swedish SR-Can safety assessment report /SKB 2006a/, the KBS-3H safety assessment made use of safety functions, safety function indicators and associated criteria, see Section 3.1. One or more safety function indicators were assigned to each of the safety functions of the system components. If the safety function indicators fulfilled specific criteria, then the safety functions were assumed to be provided. If, however, plausible situations were identified where the criteria for one or more safety function indicators were not fulfilled, then the consequences of loss or degraded performance of the corresponding safety function were evaluated as part of the safety assessment. The majority of the criteria used in the KBS-3H safety assessment was identical to or adapted from the SR-Can safety assessment report.

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[4] In the following it as assumed that ”safety assessment” means “long-term safety assessment”.

The methodology used to identify scenarios for the KBS-3H safety assessment is analogue to the methodology used for SR-Can and can be described in terms of the following steps:

1. Consider the safety functions of each of the main components of the disposal system.
2. For each safety function, identify one or more safety function indicators.
3. For each safety function indicator, derive safety function indicator criteria.
4. Develop an understanding of the system and its evolution – with a focus on the safety functions.
5. Identify the failure modes (loss of safety functions) that could occur in the course of system evolution.
6. Consider if and when the occurrence of such failure modes is plausible.
7. Consider the implications of loss of one safety function on the others.
8. Identify plausible descriptions of the evolution of safety functions over time.

Additional steps were undertaken in the Swedish SR-Can's safety assessment structure and methodology due to the additional criteria related risk in the Swedish regulatory system. These steps are described in Chapter 2 of SR-Can Main Report /SKB 2006a/. Differences between the Finnish and the Swedish regulatory systems are discussed in the Complementary Evaluations of Safety Report /Neall et al. 2007/. The products of this methodology – plausible descriptions of the evolution of safety functions over time – are described as "scenarios" in the KBS-3H safety assessment.

5.2 Reporting of KBS-3H safety studies

The several reports that document and support the preliminary safety studies of a KBS-3H repository at Olkiluoto are outlined in Figure 5-1 and are based on Posiva's safety case plan /Vieno and Ikonen 2005/.

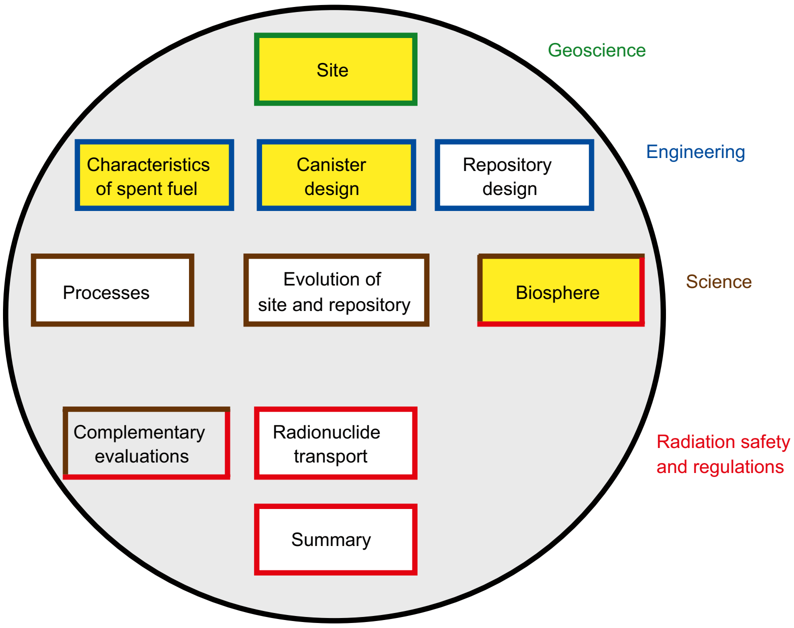

__Figure 5-1.__ The reporting structure for KBS-3H long-term safety studies. The colours of the boxes indicate the areas covered by the reports (as listed on the right-hand side of the figure). Yellow filling indicates reports common to the KBS-3H and KBS-3V safety studies. All the other boxes represent reports produced within the KBS-3H safety studies or design studies.

The Summary report /Smith et al. 2007c/ is supported by a number of reports as shown in Figure 5-1. The safety assessment includes a description of the initial conditions within and around a KBS-3H deposition drift, based largely on the preliminary design specifications of the repository in the Design Description Report 2006 /Autio et al. 2007/, on the Olkiluoto Site Description Report 2006 /Andersson et al. 2007/ and on a repository layout information contained in the Design Description Report 2006 /Autio et al. 2007/.

The assessment also includes a description of radiation-related, thermal, hydraulic, mechanical, chemical (including microbiological) and radionuclide transport-related processes in the KBS-3H that may occur within and around the repository over time. The Process Report /Gribi et al. 2007/, as its name indicates, describes the individual processes and discusses the relevance of selected processes (e.g. gas generation) through scoping calculations. The evolution of the repository in successive time frames, including a description of the main uncertainties affecting this evolution, is to be found in the Evolution Report /Smith et al. 2007a/. The Evolution Report describes the most relevant processes highlighted in the Process Report, but in broadly chronological order, highlighting the interactions between the processes and their coupling whenever possible, starting from repository construction and continuing up to one million years from the beginning of repository operations. The evolution in the farthest future, beyond a million years, is also described, though only briefly and in qualitative terms. The Process and Evolution Reports provide the basis for selection of the assessment cases calculated in the Radionuclide Transport Report /Smith et al. 2007b/. Radiological safety and compliance with regulatory guidelines are mainly dealt with in Biosphere Analysis Reports /Broed et al. 2007/, the Radionuclide Transport Report and the Complementary Evaluations Report /Neall et al. 2007/.

Because of a project decision not to prepare a separate data report as for the SR-Can /SKB 2006b/, all main data used in the reports of the preliminary KBS-3H long-term safety studies are reported in Appendix A of the Process Report /Gribi et al. 2007/. Input data were selected on the basis of the preliminary design information presented in the KBS-3H Design Description 2006 /Autio et al. 2007/, laboratory data, field data, modelling, calculations and, in some cases, expert judgment.

5.3 Scientific basis of KBS-3H safety studies

The scientific basis of the safety assessment includes some 30 years of scientific R&D and technical development in the Swedish and Finnish KBS-3V programmes. Much of this scientific basis is directly applicable to the KBS-3H design. This has allowed KBS-3H safety studies and the safety assessment to focus on those issues that are unique to KBS-3H identified in a systematic “difference analysis” of KBS-3H and KBS-3V.

In both alternatives, the system evolves from its initial state through an early, transient phase towards a quasi-steady state, in which key safety-relevant physical and chemical characteristics (e.g. temperature, buffer density and swelling pressure) are subject to much slower changes than in the transient phase. Long-term safety assessment starts from the time of emplacement of the first canisters in the repository. This is also the starting point for the early evolution of the system. The end-point of early evolution is not well defined; many of the transient processes that occur during this period do not suddenly cease, but rather gradually diminish over time. Nevertheless, two key transient processes – heat dissipation from the spent fuel and saturation of the repository near field – may take up to several thousand years (or even longer in the case of saturation of the tightest sections) and this may be taken as the rough duration of the “early evolution” period.

Processes or issues that have a different significance to, or potential impact on, KBS-3H compared with KBS-3V have been identified by means of a difference analysis of safety-relevant features or processes in the two alternatives (see Table 5-1).The difference analysis has shown that most of the differences between KBS-3H and KBS-3V relate to internal processes involving KBS-3H-specific components, such as the supercontainer and other structural components, and variations in hydraulic conditions in KBS-3H deposition drifts and their immediate environment (supercontainer-buffer-rock interface, near-field rock, drift end plugs).

Table 5-1. Major differences identified in the difference analysis of safety-relevant features and processes in KBS-3V and KBS-3H.

System components/ (groups of) processes	KBS-3V	KBS-3H
Copper canister, cast iron insert, fuel/cavity in canister		
The canister, insert and fuel are the same in both alternatives.		
Buffer		
Piping/erosion by water and gas, chemical erosion	Within deposition hole at buffer/rock interface in the case of high initial inflow rates (however, the holes can be selected individually and those with larger inflows will be rejected). Also, in the longer term, chemical erosion is possible in the event of an influx of glacial meltwater. Loss of buffer around one canister due to piping/erosion or chemical erosion by glacial meltwater will not affect the buffer around neighbouring canisters.	Piping/erosion may affect buffer density at bentonite/rock interface in canister sections with high initial inflow rates and in canister sections adjacent to these; mitigating the effects of piping/erosion is considered to be a major challenge in the design of KBS-3H and has led to the consideration of two candidate designs and various design alternatives. Deposition drift sections with inflows larger than a specified limit are not used for deposition – but sealed tightly. This will affect the utilisation degree of deposition drifts. Design is still under development /Autio et al. 2007/. Chemical erosion is possible in the event of an influx of glacial meltwater. Loss of buffer around one canister due to piping/erosion or chemical erosion by glacial meltwater may affect the buffer around neighbouring canisters, since the buffer density along the drift will tend to homogenise over time.
Displacement of buffer/distance block (leading to a reduction in bentonite density)	Swelling of buffer from deposition hole into drift above the hole may lead to lowering of bentonite density. Rock stress distribution leads to risk of rock slabs at mouth of deposition hole.	Axial displacement of distance block by hydraulic pressure build-up may lead to the lowering of bentonite density and must be counteracted by a rapid emplacement rate and by the use of steel plugs and steel rings bolted to rock, as described in the current reference design /Autio et al. 2007, Börgesson et al. 2005/. Axial displacement due to heterogeneous swelling is limited by friction and by drift end plug.
Iron/bentonite interaction	Relevant only for failed canisters.	In addition to the processes relevant to KBS-3V, significant geochemical interactions between supercontainer and buffer will take place (iron/smectite interaction, iron-silicate formation, cation exchange, etc). These processes may affect the buffer density, swelling pressure, hydraulic conductivity and other properties. The effects are locally limited at early stages, but may develop with time and affect larger parts of the buffer /Johnson et al. 2005, Carlson et al. 2006, Wersin et al. 2007/.
Gas transport and possibly gas-induced porewater displacement	Relevant only for failed canisters.	In addition to the processes relevant to KBS-3V, significant gas effects are expected /Johnson et al. 2005/ due to anaerobic corrosion of supercontainer and other steel components (retarded resaturation, air trapping, gas dissolution/diffusion/advection, gas pressure build-up, gas leakage, gas pathways along drifts, etc). During this early phase, no radionuclide transport is expected.
Effects of engineering and stray materials	Effects of concrete bottom plate, stray materials, bentonite pellets.	Effects of steel rings, rock bolts, steel feet, water/gas evacuation pipes, grouting, spray and drip shields, cement.
Supercontainer and other structural components within the deposition drifts		
Materials, geometry, properties	N/A	
Steel corrosion and formation of corrosion products	N/A	For the expected steel corrosion rate, complete conversion to oxidised species occurs within a few thousand years.
Gas generation by anaerobic corrosion of steel	N/A	Gas generation rates are significant although the overall amount of gas produced is moderate; for the effects of gas, see buffer.
Effects of volume expansion (magnetite formation)	N/A	Volume expansion of corrosion products may increase buffer density and swelling pressure.

System components/ (groups of) processes	KBS-3V	KBS-3H
Ion release to bentonite porewater	N/A	Leads to iron/bentonite interaction.
Effect of supercontainer on water flow paths along the periphery of the drift	N/A	The physical properties of the corroded supercontainer have not been evaluated. Although the porosity and hydraulic conductivity of the corrosion products may be low, the possibility that fracturing could lead to the formation of pathways for water flow and advective transport cannot currently be excluded. Selected radionuclide transport calculation cases cover the case of a disturbed buffer/rock interface due to the presence of iron corrosion products in contact with bentonite.
Displacement of supercontainer/buffer by swelling of distance blocks	N/A	See buffer.
Breaching of supercontainer shells by bentonite swelling	N/A	The supercontainer shell may be breached by the different forces due to bentonite swelling acting inside and outside the supercontainer shell (secondary effect, because the supercontainer has no safety function).
Deposition drift, central tunnel, access tunnel, shafts, boreholes		
A major difference is in the geometry and backfilling of the KBS-3H deposition drifts compared with the KBS-3V deposition tunnels. In KBS-3H, supercontainers are emplaced along relatively narrow deposition drifts, separated by compacted bentonite distance blocks. In KBS-3V, deposition holes are bored from relatively large diameter deposition tunnels, backfilled with swelling clay or clay/crushed rock mixture.		
For other underground openings (access tunnel, shafts, boreholes) no major differences have been identified.		
Geosphere		
Gas transport, gas-induced porewater displacement	Relevant only for failed canisters.	Limited storage volume and transport capacity within deposition drift, combined with increased gas generation (rates and total amount). Gas dissolution/diffusion/advection in groundwater, gas pressure build-up, gas-induced porewater displacement, capillary leakage. For tight canister sections: gas transport along drift (EDZ) to the next transmissive fracture, possibly involving reactivation of fractures in near-field rock, when minimal principal stress is exceeded.
Transmissive fractures and flow conditions	The selection of deposition holes locations is more flexible than in KBS-3H because rock sections with larger inflows can be rejected.	Local variations in groundwater flow conditions along the drift may lead to variable saturation time for the buffer along the drift.
Mechanical stability of the drift/tunnel	High stresses at the mouth of deposition holes and at the top of backfill tunnel.	Lower rock stresses than in KBS-3V because the deposition drifts can be better adapted to the stress field.
Orientation of fractures	KBS-3V is more sensitive to sub-horizontal than to sub-vertical with respect to potential damage to the engineered barrier system by rock shear.	KBS-3H is more sensitive to sub-vertical fractures than to sub-horizontal fractures with respect to potential damage to the engineered barrier system by rock shear.
Biosphere, human activities		
No major differences identified.		

Many of these differences affect the early, transient phase of repository evolution to a state that has the desired properties after saturation. During this phase, significant mass and energy fluxes will occur as a result of the various gradients created by repository construction and emplacement of spent fuel, although some differences will also occur at later times. For example, the radionuclide transport paths from a failed canister are affected by the differences in the geometry and backfilling of the KBS-3H deposition drifts compared with the KBS-3V deposition tunnels.

Table 5-1 shows the main differences between safety-relevant features and processes in KBS-3H and KBS-3V.

5.4 Key safety issues and evolution scenarios

The difference analysis of safety-relevant features and processes in the KBS-3V and KBS-3H design (Table 5-1), together with the description of system evolution presented in the KBS-3H Evolution Report, indicate a number of important issues with the potential to significantly disturb the safety functions of the repository components and which have a different significance to, or potential impact on, KBS-3H compared with KBS-3V. They concern the early, transient evolution of the repository, although they may have implications for canister integrity and radionuclide release and transport in the longer term. The subjects of KBS-3H-specific analyses are:

1. piping and erosion during repository operations and drift saturation,
2. steel components external to the canisters, their corrosion products and their impact on mass transport,
3. the effects of gas from the corrosion of these components,
4. interactions involving leachates from cementitious components,
5. thermally-induced rock spalling, and
6. expulsion of water and dissolved radionuclides from a defective canister interior by gas.

The issues related to piping and erosion, interactions with cementitious leachates, and the thermally induced rock spalling, are of concern for both KBS-3H and KBS-3V, but were addressed because their likelihood, extent or impact may be significantly different for the two alternatives.

Issue 1 is a critical issue for repository design as well as safety. Design measures must be devised to limit the possibility of significant piping and erosion during early evolution of the buffer. At the current preliminary design stage, however, the possibility of some degree of piping and erosion during buffer saturation cannot be completely eliminated, with potential consequences for canister corrosion (via its impact on the transport of sulphide from the groundwater through the buffer to the canister surface) and radionuclide transport in the event of canister failure. In the absence of other more significant perturbations to mass transport in the buffer or at the buffer/rock interface, scoping calculations indicate that limited piping and erosion will not lead to canister failure by copper corrosion in a million year time frame (see below). This is due to the limited sulphide concentration in the groundwater (although the variability and evolution of groundwater sulphide concentration with time is an issue for future study) and to the slow transport of sulphide through the buffer, which is expected to remain diffusion dominated even following the local erosion of up to a few hundred kilograms of bentonite, due to the swelling and homogenisation of this material over time. The consequences in terms of radionuclide releases to the geosphere and biosphere in the event of canister failure have been evaluated by means of radionuclide release and transport calculations as part of the safety assessment.

The most significant potential impact of issues 2, 3 and 4 is on mass transfer at the buffer/rock interface. The other issues and associated processes may also have some limited effects on the interface. Perturbation of mass transfer across the interface may again affect canister corrosion via its effect on the transfer of groundwater sulphide to the canister surface, and affect radionuclide release to the geosphere and biosphere in the event of canister failure. Scoping calculations indicate that the presence of a perturbed buffer/rock interface has the potential to lead to canister failure by copper corrosion within a million-year time frame in the case of canisters located near to more transmissive fractures, particularly if the sulphide concentration at the buffer/rock interface is significantly increased, e.g. by microbial activity. However, no canister failures are expected within the first 100,000 years. The failure of a single canister due to corrosion after 100,000 years is considered in radionuclide release and transport assessment cases addressing this particular canister failure mode. The presence of a hydraulically conductive zone at the buffer/rock interface due to 2, 4 or 5 could also perturb radionuclide release from the buffer to the geosphere in the event of canister failure, irrespective of the failure mode, and this possibility is also considered in radionuclide release and transport calculations.

Issue 3, hydrogen gas generated by the corrosion of steel in the supercontainers and other steel components external to the canisters may affect the saturation of the repository. In the tightest drift sections, repository-generated gas may hinder or prevent altogether the saturation of the buffer until gas generation by steel corrosion ceases and gas pressure falls, which may take up to tens of thousands of years. 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. Hydrogen generation may also affect the corrosion of the canisters, via its effect on the microbial reduction of sulphate to sulphide. Scoping calculations that include this effect 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. However, the impact of the hydrogen on bentonite porewater chemistry has yet to be evaluated. Finally, as gas rises through the fracture network within the host rock, it may carry water with it. Any perturbation to groundwater flow in the geosphere due to this process is, however, likely to have largely ceased by the time most radionuclides are released from failed canisters due to the limited duration of gas generation by corrosion (a few thousand years), except possibly in the tightest drift sections where the dissipation of generated gas is very slow, but in any case groundwater flow is virtually zero.

Issue 6, expulsion of water and dissolved radionuclides by gas from an initially penetrated canister (illustrated in Figure 5-2), is a possibility if the defect is located on the lower side of the horizontally-orientated canister. In this case, it is possible that gas generated principally by corrosion of the canister insert will become trapped above water lying in the lowest part of the canister, and gas pressure will build up until it is sufficient to expel the water and dissolved radionuclides into the buffer.

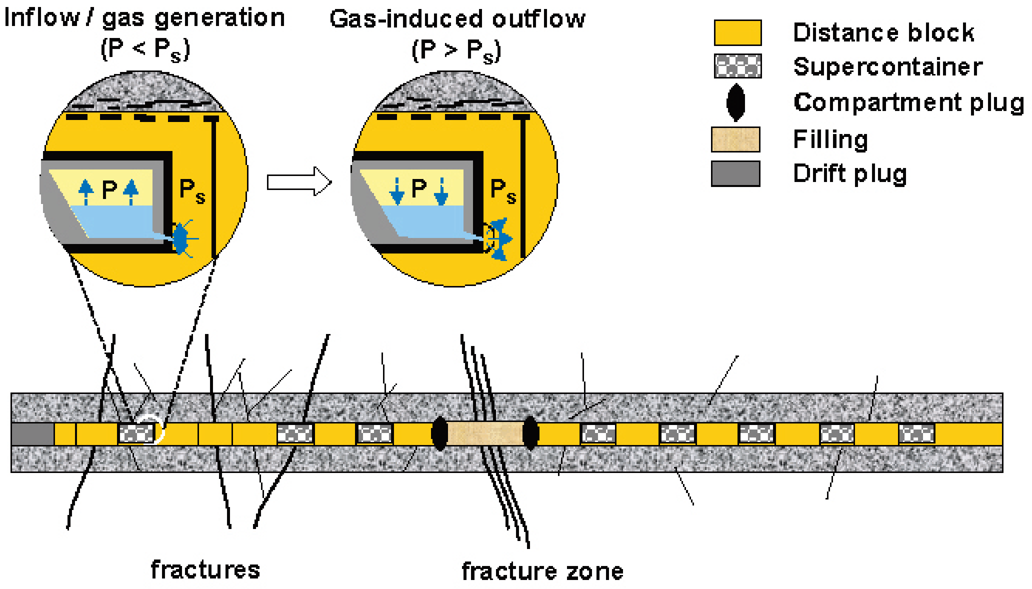

Figure 5-2. Conceptual model for transport of water and gas into and out of a canister with an initial penetrating defect (after /Gribi et al. 2007/). The amount of free gas (light yellow) within the canister is changed by a number of different processes (gas generation, advection and diffusion of dissolved gases, dissolution/degassing).

Scoping calculations indicate that the more likely situation is that 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. The possibility of expulsion of contaminated water by gas cannot, however, be completely excluded, and its impact on radionuclide release and transport is addressed in a radionuclide release and transport assessment case.

In addition to these key safety issues that are judged to have a different significance to, or potential impact on KBS-3H compared with KBS-3V, there are a number of other key issues that are judged to have similar significance or a potential impact. Such issues, which relate to longer-term evolution, include buffer freezing, oxygen penetration at repository depth, canister failure due to rock shear, loss of buffer from exposure to glacial meltwater ("chemical erosion") and the implications of a prolonged period of temperate climate ("greenhouse gas effect"). These will not be discussed here, except for canister failure due to rock shear because this is the only issue for which the number of canisters that could be affected depends on their orientation.

By considering the potential impact of the key safety issues – those with different significance to, or potential impact on, KBS-3H compared with KBS-3V as well as others that are common to KBS-3H and KBS-3V – on the safety functions of the repository, and taking into account the processes affecting the evolution of the repository and site, various possible evolution scenarios have been identified.

The Base Scenario assumes (as required by Finnish regulations) that the performance targets defined for each barrier are met. This is interpreted as meaning that each barrier fulfils the safety functions assigned to it in the safety concept for a period extending to a million years or more. There are, however, scenarios whereby one or more canister failures lead to radionuclide release and transport, and the exposure of humans and other biota to released radionuclides, in a one million year time frame. These are initiated, in the first place, by:

- the presence of an initial, penetrating defect in one or more of the canisters,
- perturbations to the buffer and buffer/rock interface, giving rise to an increased rate of transport of sulphide from the geosphere to the canister surface and an increased canister corrosion rate,
- the penetration of dilute glacial meltwater to repository depth, giving rise to chemical erosion of the buffer, an increased rate of transport of sulphide from the geosphere to the canister surface and an increased canister corrosion rate, and
- rock shear movements of sufficient magnitude to give rise to shear failure of the canisters.

5.5 Radionuclide release and transport analyses

The consequences of scenarios leading to canister failure, taking into account uncertainties in processes, evolution and release and transport processes, are assessed by defining a range of assessment cases – i.e. specific model realisations of different possibilities or illustrations of how a system might evolve and perform in the event of canister failure – and analysing these cases in terms of hazard to humans and other biota. Given that a key question addressed by the KBS-3H safety studies is whether or not there are safety issues identified in the KBS-3V/KBS-3H difference analysis with the potential to lead to unacceptable[5] radiological consequences, a number of specific assessment cases are defined addressing uncertainties related to features and processes that are significantly different in KBS-3H and KBS-3V. Additional cases are also analysed to illustrate the impact of other uncertainties in key features of the safety concept. Radionuclide release and transport processes and analyses are described in detail in the Radionuclide Transport Report /Smith et al. 2007b/.

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[5] According to the Finnish regulatory requirements in YVL 8.4.

Radionuclide release and transport calculations have been carried out for each identified canister failure mode:

(i) an initial penetrating defect,

(ii) canister failure due to corrosion, and

(iii) canister failure due to rock shear.

For each canister failure mode, a Base Case has been defined against which to compare the results of variant assessment cases that illustrate the impact of specific uncertainties on the radiological consequences of canister failure. Parameters in the Base Cases are, in most instances, selected to be either realistic or moderately conservative in the sense that they are expected to lead to an overestimate of radiological consequences.

Perturbations to radionuclide release and transport caused, for example, by the steel and cementitious components of the KBS-3H repository external to the canisters are assumed to be negligible in the Base Cases. The variant cases are chosen to cover the various scenarios that have been identified as leading to loss or major degradation of repository safety functions, and to canister failure. In addition to these "scenario uncertainties", there are additional uncertainties that have a more limited impact on the repository safety functions. Based on the KBS-3V/KBS-3H difference analysis approach, a limited number of assessment cases are defined addressing uncertainties related to features and processes that are specific to KBS-3H design, or are significantly different in KBS-3H and KBS-3V. Additional cases are also analysed to illustrate the impact of other uncertainties in key features of the safety concept. The variant cases for the most part take a more pessimistic view of uncertainties than the Base Cases. Various measures, including the use of process tables as check lists, have been used to ensure that no important processes and associated uncertainties have been overlooked in the identification of scenarios and assessment cases.

In evaluating the assessment cases, extensive use has been made of SR-Can parameter values and model assumptions, except where these are affected by differences in the materials to be disposed of in Finnish and Swedish repositories, and differences between conditions at Olkiluoto and those at the Swedish sites considered in SR-Can. Where differences arise, the selection of parameter values and model assumptions has been made largely according to "expert judgement", based on considerations such as use in previous assessments, additional data gathering and laboratory studies. In the case of geosphere transport modelling, the modelling approach and parameter values used are based largely on the safety assessment TILA-99 /Vieno and Nordman 1999/, although more recent data from the Olkiluoto Site Description 2006 /Andersson et al. 2007/ are used to provide additional support for the parameter values selected (for example, in terms of their conservatism).

The primary assessment endpoints in the present safety assessment are:

- annual effective dose[6] to most exposed individual considering multiple exposure pathways in the biosphere, which is used for comparison with the Finnish regulatory dose criterion for the "environmentally predictable future", and
- activity fluxes to the biosphere (geo-bio fluxes) which are used for comparison with Finnish regulatory geo-bio flux constraints.

In addition, a safety indicator based on an indicative stylised well scenario – WELL-2007 dose – has been calculated for all assessment cases. The ingestion of contaminated water by humans is the only exposure pathway considered in this stylised well scenario[7]. WELL-2007 dose refers to committed effective[8] doses due to ingestion of water over one year, where the effects of ingestion are integrated over the adult life of an individual human /ICRP 1991/.

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[6] In the present safety assessment, the annual effective dose to the most exposed individual considering multiple exposure pathways is termed the annual landscape dose.

[7] A second stylised well scenario that includes additional exposure pathways, AgriWELL-2007, has also been used in calculations described in the Biosphere Analysis Report /Broed et al. 2007/.

[8] Effective dose is used in radiological protection to relate exposure, internal or external, to ionising radiation to stochastic effects, such as the induction of cancer and hereditary effects.

Dose conversion factors for WELL-2007 are given in the Radionuclide Transport Report. Calculation of WELL-2007 dose further facilitates comparison with regulatory guidelines for the "environmentally predictable future", as well as the results from other safety assessments and safety cases, without the need to justify a wide range of biosphere modelling assumptions. The releases from the geosphere into the biosphere (WELL-2007 dose) cannot be directly compared with the Finnish regulatory dose guideline of 10^{-4} Sv per year because they do not take into account the radionuclide transport processes in the biosphere.

Forty-one calculation cases have been calculated for the KBS-3H Radionuclide Transport Report /Smith et al. 2007b/. These are summarised in Table 5-2. The overview of results is presented in Figure 5-3.

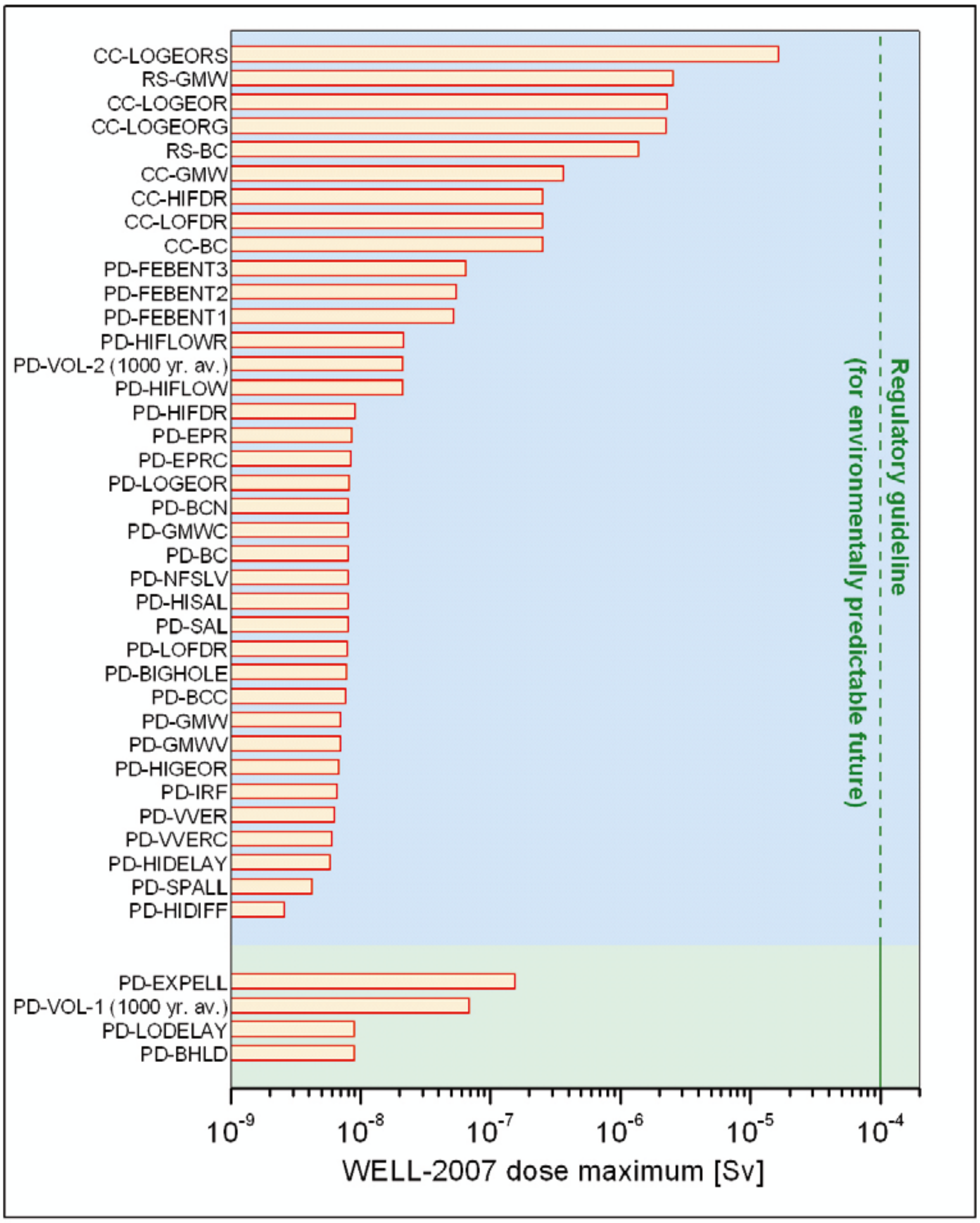

Figure 5-3. *Calculated dose maxima in all assessment cases. Green background shading indicates the maxima that occur within the first 10,000 years of post- closure, which is interpreted in the present study as the "environmentally predictable future". Note that the WELL-2007 dose maximum is used as a safety indicator and not to determine regulatory compliance. Regulatory compliance in the first 10,000 years of post- closure is determined through fluxes and doses in the biosphere, which are not shown in this figure. The regulatory guideline is shown here for a qualitative order-of-magnitude comparison of the releases from the geosphere into the biosphere.*

Table 5-2 Overview of assessment cases.

Case	Description
Cases assuming a single canister with an initial penetrating defect (PD-)	
PD-BC	Base Case for initial penetrating defect in BWR-type canister for spent fuel from Olkiluoto 1-2
PD-VVER	Initial penetrating defect in VVER-440 PWR-type canister for spent fuel from Loviisa
PD-EPR	Initial penetrating defect in EPR-type canister for spent fuel from Olkiluoto-3
PD-HIFDR	Increased fuel dissolution rate
PD-LOFDR	Reduced fuel dissolution rate
PD-IRF[a]	Evaluates transport only of radionuclides present in instant release fraction (see footnote a below this table)
PD-BIGHOLE	Increased defect size
PD-HIDELAY	Increased delay until loss of defect transport resistance
PD-LODELAY	Decreased delay until loss of defect transport resistance
PD-BHLD	Increased defect size plus decreased delay until loss of defect transport resistance
PD-HIDIFF	Increased diffusion rate in buffer
PD-FEBENT1	Perturbed buffer-rock interface – high conductivity, narrow perturbed zone
PD-FEBENT2 PD-FEBENT3	Perturbed buffer-rock interface – more extensive perturbed zone (2 different thicknesses)
PD-SPALL	Perturbed buffer-rock interface – high conductivity, narrow perturbed zone, lower flow through intersecting fractures than that assumed in cases PD-FEBENT1 , 2 and 3
PD-EXPELL	Dissolved radionuclides expelled by gas from canister interior and across buffer to geosphere
PD-VOL-1 PD-VOL-2	C-14 transported in volatile form by gas generated by corrosion (2 rates of gas generation)
PD-BCN	Initial penetrating defect in BWR-type canister; Nb present in near field and geosphere in anionic form
PD-BCC	Initial penetrating defect in BWR-type canister; C-14 present in geosphere in anionic form (carbonate)
PD-VVERC	Initial penetrating defect in VVER-440 PWR-type canister; C-14 present in geosphere in anionic form (carbonate)
PD-EPRC	Initial penetrating defect in EPR-type canister; C-14 present in geosphere in anionic form (carbonate)
PD-NFSLV	Near-field solubilities varied according to uncertainties in redox conditions
PD-SAL	Brackish/saline water present at repository depth (all time)
PD-HISAL	Saline water present at repository depth (all time)
PD-GMW PD-GMWV	Change from reference (dilute/brackish) water to glacial meltwater at 70,000 years (release also starts at 70,000 years – two alternative meltwater compositions)
PD-GMWC	Change from reference (dilute/brackish) water to glacial meltwater at 70,000 years (release starts at 1,000 years, as in the reference case)
PD-HIFLOW	Increased flow at buffer-rock interface
PD-LOGEOR	Reduced geosphere transport resistance
PD-HIGEOR	Increased geosphere transport resistance
PD-HIFLOWR	Increased flow at buffer-rock interface and reduced geosphere transport resistance
Cases assuming a single canister failing due to copper corrosion (CC-)	
CC-BC	Base Case for failure due to copper corrosion; buffer treated as mixing tank
CC-HIFDR	Increased fuel dissolution rate
CC-LOFDR	Reduced fuel dissolution rate
CC-GMW	Glacial meltwater present at repository depth (impact on near-field solubilities and geosphere retention parameters)
CC-LOGEOR	Reduced geosphere transport resistance
CC-LOGEORG	Reduced geosphere transport resistance, glacial meltwater[b]
CC-LOGEORS	Reduced geosphere transport resistance, saline groundwater[b]
Cases assuming a single canister failing due to rock shear (RS-)	
RS-BC	Base case for failure due to rock shear
RS-GMW	Glacial meltwater present at repository depth (impact on near-field solubilities and geosphere retention parameters)

Case	Description
Additional cases (hypothetical pulse release to geosphere) (MD-)	
MD-1 MD-2 MD-3	Variations in matrix diffusion depth (3 cases)

a Certain radionuclides are enriched at grain boundaries in the fuel, at pellet cracks and in the fuel/sheath gap as a result of thermally driven segregation during irradiation of the fuel in the reactor. These are assumed to enter solution rapidly once water contacts the fuel pellet surfaces, and are termed the Instant Release Fraction (IRF).

b Glacial meltwater is a very dilute ice-melting water. Saline groundwater represents water with a Total Dissolved Solids (TDS) of about 20 g/l. For detailed composition of the waters used in the assessment, see Appendix D of Radionuclide Transport report /Smith et al. 2007b/.

An example of an assessment case is shown in Figure 5-4 exemplifying the process of the expulsion of water and dissolved radionuclides by gas (see Figure 5-2). This case, referred to as PD-EXPELL, addresses the possibility of an initial penetrating defect. This defect is unfavourably located on the underside of the canister, and the possibility of a gas-induced release of contaminated water from the canister interior to the buffer, where it is assumed that a gas-driven water pulse, beginning at 2,800 years after deposition and lasting for a further 1,300 years, propels water from the canister interior through the buffer to the fracture. This example was chosen because it is the most pessimistic case from a range of model calculations of the fate of water/vapour/gas and radionuclides described in Section 2.5 of the KBS-3H Process Report /Gribi et al. 2007/.

Figure 5-4 shows the calculated time-dependent WELL-2007 dose for this case. Figure 5-5 shows time-dependent releases from the geosphere to the biosphere divided by the geo-bio flux constraints specified by the Finnish regulator and the sum of these releases over all calculated radionuclides. The summed release maximum is significantly increased with respect to the Base Case (PD-BC), but remains about one order of magnitude below the regulatory guideline (applicable at times beyond about 10,000 years) of one.

The likelihood of this case and the possibility that gas expulsion could occur from multiple canisters at similar times have not been evaluated. However, as in all cases addressing an initial penetrating defect, the water inflows may be much reduced due to sealing of the hole by bentonite and corrosion products, making this variant case less likely.

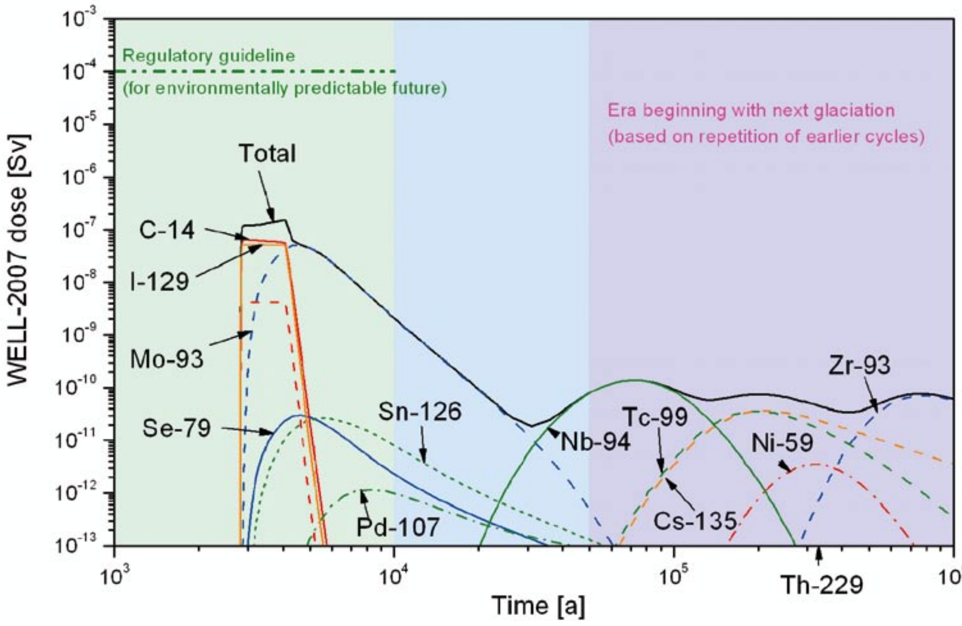

Figure 5-4. *WELL-2007 dose as a function of time in case PD-EXPELL.*

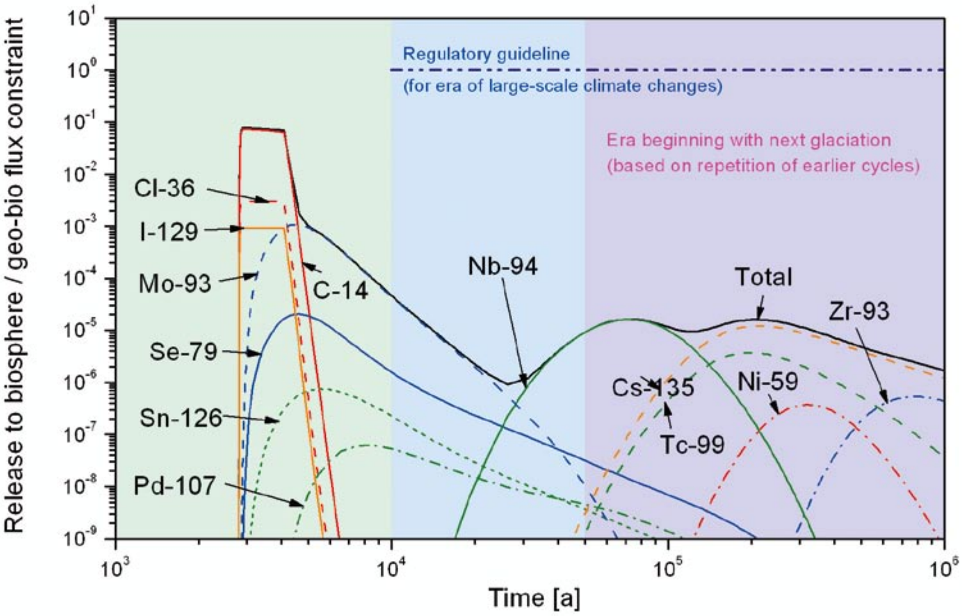

Figure 5-5. Ratios of nuclide-specific activity releases to their respective geo-bio flux constraints in case PD-EXPELL.

Results shown in Figure 5-3 indicate a release to the biosphere within 10,000 years only in the assessment cases assuming an initial penetrating defect (and excluding cases PD-HIDELAY and PD-VOL-2). It is in these cases that dose assessments are explicitly required by regulations, and annual landscape doses have therefore been estimated for the environmentally predictable future (the period up to 10,000 years in the future). Results from seven representative assessment cases are shown in Figure 5-6. There is a sharp increase in the landscape dose starting at about 9,000 years in cases PD-BC, PD-FEBENT3, PD-HISAL, PD-LOGEOR which is an artefact of the finite time step in geosphere transport modelling. This is associated with the assumption of the loss of transport resistance of the defect, which occurs at 10,000 years, and the following release of radionuclides from the canister. The maximum dose is reached after about 10,000 years and it is thereafter decreasing to a lower level.

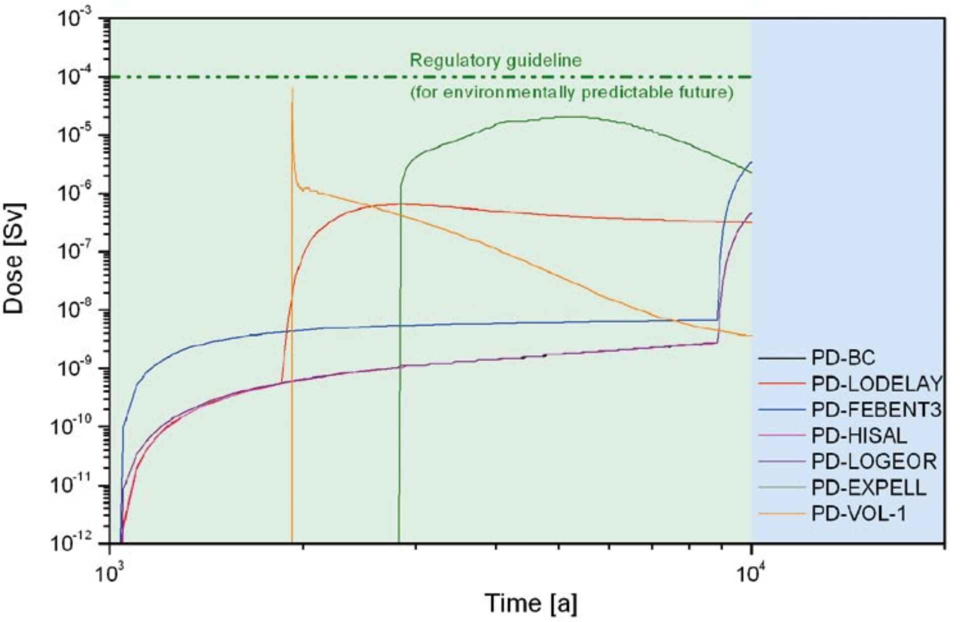

Figure 5-6. Annual landscape dose to the most exposed individual due to potential releases from the repository in six most representative assessment cases for a canister with an initial penetrating defect (results for PD-BC, PD-HISAL and PD-LOGEOR approximately coincide).

Other cases assuming an initial penetrating defect have been treated by scaling approaches or qualitative arguments, as described in the Biosphere Analysis Report /Broed et al. 2007/. Other canister failure modes occur after the "environmentally predictable future" and so no evaluation of annual landscape dose is required.

The highest calculated annual landscape dose for the most exposed individual is about $6 \cdot 10^{-5}$ Sv, and arises in the assessment case PD-VOL-1. This is a little less than a factor of two below the regulatory constraint of 10^{-4} Sv. For all other assessment cases, the maxima range from $5 \cdot 10^{-7}$ to $2 \cdot 10^{-5}$ Sv, and are thus around an order of magnitude or more below the regulatory constraint. It should be noted that only a single failed canister is considered in each case.

The probability of multiple canisters failures at similar times has been evaluated only in the case of canister failure due to rock shear – the expectation value of the number of canisters in a KBS-3H repository that could potentially be damaged by rock shear in the event of a large earthquake has been estimated to be 16 out of the total number of 3,000 canisters. The geo-bio flux constraint will still be met in cases RS-BC and RS-GMW if 16 canisters fail in the event of a single large earthquake. However, the number of canisters that might fail over a million-year time frame (and contribute to the Ra-226 dose at a million years) has not so far been evaluated. More generally, a key issue for future safety assessments will be to better quantify the probability of the failure of several canisters at similar times.

The consequences of the ultimate failure of the repository multi-barrier system in the farthest future (beyond a million years), including the possible exhumation of the repository, are discussed in the Complementary Evaluations of Safety Report /Neall et al. 2007/. In addition to assessment endpoints based on radiation doses, further evaluations of the repository releases are also described on the basis of radiotoxicity flux. These evaluations confirm the insignificance of the calculated repository releases when compared with natural radiotoxicity fluxes associated with groundwater discharge in the Olkiluoto area, or erosion of the not particularly uranium-rich rocks in the area. The Complementary Evaluation of Safety Report also compares the methodology and results of the KBS-3H safety assessment with the earlier TILA-99 and SR-Can safety assessments, as well as other international safety assessments, to ensure the completeness, consistency and reasonableness of the present assessment.

5.6 Conclusions

Overall, the conclusions of the long-term safety assessment carried out for a preliminary design of a KBS-3H repository at the Olkiluoto site are as follows.

1. In the absence of any initial penetrating defect in the canisters, no canister failures should occur during the first several thousand years after canister deposition provided the repository system evolves as expected. Thereafter, the processes that are potentially the most detrimental to repository safety are related to glacial conditions. This was also a main conclusion arising from SR-Can in the case of a KBS-3V repository for spent fuel at two Swedish sites, but the importance of some geosphere properties may differ, e.g. the KBS-3H design is more sensitive to sub-vertical fractures with respect to potential damage to the engineered barrier system by rock shear.
2. Safety issues related to a future change to glacial conditions at the Olkiluoto site are generally the same as those identified in SR-Can for the KBS-3V design at Swedish sites, the most significant being canister failure due to rock shear in the event of a large, post-glacial earthquake and loss of buffer from exposure to glacial meltwater, which may lead to the early failure of some canisters by corrosion. There are, however, some differences compared with SR-Can and KBS-3V, e.g. the probability of, and possibility of avoiding by design, fractures that can undergo rock shear movements that damage canisters in the event of a large post-glacial earthquake. Furthermore, in the case of KBS-3H, loss of buffer around one canister due to exposure to glacial meltwater may affect simultaneously the corrosion rate of neighbouring canisters, since the buffer density along the drift will tend to homogenise over time.

This also means that the impact on buffer density and on the corrosion rate of the first canister will diminish with time. In the case of KBS-3V, on the other hand, buffer loss around one canister will not affect the state of the buffer around the canisters in other deposition holes.

3. A difference analysis has shown that the key differences in the evolution and performance of the KBS-3H and KBS-3V designs relate mainly to the engineered barrier system and to the impact of local variations in the rate of groundwater inflow on buffer saturation along the drifts. The safety functions of the geosphere are generally not expected to differ significantly between the two designs.
4. No features or processes that are specific to KBS-3H have been identified that could lead to a loss or substantial degradation of the safety functions of the engineered barriers over a million-year time frame. However, the degree to which fractures with the potential to undergo shear movements that damage the engineered barriers in the event of a large earthquake can be identified and avoided remains to be evaluated, and may be different for KBS-3H compared with KBS-3V.
5. Particularly in tight drift sections, the gas generated by the steel components of the KBS-3H repository external to the canister in the current reference design (principally the supercontainer shell) may accumulate at the buffer/rock interface, possibly resulting in a prolonged period during which the significant inflow of water from the surrounding rock will be limited and the buffer will remain only partially saturated.
6. The timing of eventual canister failure by corrosion may be affected by perturbations to the buffer/rock interface caused, for example, by the presence of the steel supercontainer shell and its corrosion products. The issues related to the impact of iron and its corrosion products on the buffer bentonite are potentially detrimental to the safety functions of the buffer and subject to significant uncertainties. Hydrogen generation during the first thousands of year may also affect the corrosion of the canisters via its effect on the microbial reduction of sulphate to sulphide, but the sulphides formed may be precipitated as iron sulphides by reacting with the iron corrosion products, thus reducing the flux of sulphide to the canister surface. The conclusions from the analyses performed are that these perturbations are not expected to lead to canister failure by corrosion within a million-year time frame.
7. Radionuclide release from the repository near field in the event of canister failure may also be affected by perturbations to the buffer/rock interface, but in all cases releases are limited and comply with Finnish regulatory criteria. Only single canister failure cases have, however, been considered and the possibility of multiple canister failures must be addressed in future studies.
8. Several issues have been identified for further study, many of which are relevant to both KBS-3V and KBS-3H. These include, for example, site-specific issues such as the transport rate of methane[9] and the kinetics of sulphate reduction in the rock. While some issues, such as those related to gas generation prior to canister failure, are relevant mainly to KBS-3H, it should also be noted that there are some issues that are specific to KBS-3V.

These conclusions are based on the analysis of a KBS-3H reference design, termed the Basic Design and its application to the Olkiluoto site. It should, however, be emphasised that this choice of reference design is preliminary, and that design alternatives are being developed. Furthermore, differences between the fuel, canisters and repository sites under consideration in Sweden and Finland will have to be considered in transferring the detailed findings of the present safety assessment to a Swedish context. On the other hand, the focus of the safety assessment is on the evolution and performance of the engineered barrier system, and, with the exception of overall inventory, this system is broadly similar in the Swedish and Finnish contexts, although local variations, for example in the hydraulic conditions, will have an impact on the evolution of the system. Still, many of the broad findings on the engineered barrier system are expected to be readily transferable.

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[9] Methane in the Olkiluoto groundwater is thought to have two primary sources. Thermal abiogenic hydrocarbons (a crustal inorganic carbon source without biogenic processes) dominate at greater depth where the highest methane contents are observed and are near saturation. At repository level, biogenic methane seems to dominate; total contents are smaller and far from saturation but the methane mass is clearly higher than mass of sulphate in sea water.

The present safety assessment has some important limitations, such as the limited number of assessment cases analysed and simplified models, especially for the geosphere, including the fact that the feasibility of implementing the current reference design has been assumed, even though several design issues remain to be addressed. Nevertheless, it can be concluded, based on the present safety assessment, that the KBS-3H design alternative offers potential for the full demonstration of safety for a repository at Olkiluoto site and for the demonstration that it fulfils the same long-term safety requirements as KBS-3V. Studies are being undertaken to address remaining critical scientific and design issues. These include the further development of the DAWE design alternative to avoid the possibility of distance block displacement or deformation, which could lead to significant piping and erosion, as well as studies of iron/bentonite interaction and the possible use of alternative materials, such as titanium for the supercontainer shell and some other engineered structures in the drift.

5.7 Ongoing work and issues for further consideration

This section lists issues for further consideration that have been identified during the KBS-3H safety studies 2004–2007. Many of the issues below are relevant to both KBS-3V and KBS-3H. Some of them are already the object of ongoing work and some are included in the next phase of the KBS-3H programme (2008–2010). The issues listed below are not prioritised and are to be considered in the context of the development of the general KBS-3 method, taking into account programmatic objectives and constraints, such as schedule and resources both in Posiva and SKB. A comprehensive list of limitations and uncertainties identified is given in Chapter 11 of the safety assessment summary report /Smith et al. 2007c/. These issues are summarised below.

Methodological issues and improvements to be considered in future studies

The present safety assessment has some important limitations. Firstly, the present safety assessment was conducted while design development and associated laboratory testing were still underway. It was necessary to select a reference design for the assessment (the Basic Design), even though there were uncertainties regarding the feasibility of implementing this preliminary design in practice. Data for analysing assessment cases are based on the preliminary information available for the design and buffer components at the time of writing the safety assessment reports.

Although a broad range of assessment cases has been considered in the present safety assessment, the range of cases analysed is significantly smaller than that considered, for example, in either the TILA-99 /Vieno and Nordman 1999/ or the SR-Can safety assessments /SKB 2006a/ and not all conceivable uncertainties and combinations of uncertainties are covered. For example, uncertainties in the transport barrier provided by the geosphere, biosphere uncertainties and uncertainties related to future human actions are either not addressed or are analysed in less detail than others.

Therefore, application to the Swedish candidate sites, a more comprehensive set of calculation cases and the compilation of a data report are examples of improvements to be considered for the next KBS-3H safety assessment.

Issues related to the evolution of the engineered and natural barriers

The effect of significant amounts of iron in a KBS-3H repository on the safety functions of the buffer (i.e. the bentonite inside the supercontainer and the distance blocks) is subject to significant uncertainties. Iron can affect the stability and, to some extent, the swelling pressure of the buffer and its hydraulic and radionuclide retention properties. Results of the preliminary reactive transport modelling indicate that the extent of the buffer zone potentially undergoing mineral transformation is likely to remain spatially limited (a few centimetres) for a very long time. Nevertheless, in view of its potential impact on mass transfer at the buffer/rock interface, it remains an issue for further study.

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 also issues requiring more thorough investigation.

Another issue for further consideration is the effect of the various strain mechanisms that are involved in the early (and long-term) evolution of the supercontainer shells on the outer part of the buffer. Depending on how the shell deforms during saturation, it may generate heterogeneities in the buffer.

In the reference design used for the safety studies (Basic Design), significant thermally-induced spalling could occur in tighter drift sections where buffer swelling pressure on the drift wall takes a few years or more to develop. In addition to thermally-induced rock spalling, various other features and processes have been identified in the safety assessment that may lead to detrimental changes in the mass transfer properties of the buffer/rock interface (e.g. iron/bentonite interaction, cement/bentonite interaction). Determining bounding estimates for the hydraulic properties of the perturbed buffer/rock interface is an issue for future studies.

Other issues identified warranting further consideration are the evolution of conditions external to the repository (e.g. evolution of sulphide and methane concentrations in groundwater, and microbial activity in the rock, penetration of dilute glacial meltwater at repository depth and consequences for the buffer), the gas pressurization and migration of radionuclides in relation to the properties of the EDZ, as well as the effect of hydrogen gas due to the corrosion of steel components external to the canister on the buffer porewater chemistry.

Properties and processes. Issues related to radionuclide release and transport

Several issues having significant uncertainties and an impact on the results have been highlighted during the radionuclide release and transport calculations. The issues are not specific to KBS-3H and concern the radionuclide inventory and partitioning, the probability of canister failure, the internal evolution of a failed canister, the solubility limitation and speciation also in high pH conditions, radionuclide sorption, buffer transport properties, the treatment of the perturbed buffer/rock interface, geosphere transport properties and processes, and biosphere transport properties and processes.

The analysis of a limited range of assessment cases with highly simplified models, especially of the geosphere, is not considered sufficient to test whether the KBS-3H design at the Olkiluoto site satisfies all relevant regulatory guidelines in Finland. In SR-Can, for example, the treatment of geosphere variability had an important impact on the conclusions, affecting, for example, the likelihood of canister failure by corrosion and this would also be expected to be the case for a KBS-3H repository at Olkiluoto. A further significant limitation of the present safety assessment is the assumption of steady groundwater flow and composition.

Design issues

The feasibility of implementing a KBS-3H design has been assumed, even though several design issues remain to be addressed. Whatever the final chosen design may be, feasibility of implementation must be justified as part of any future safety case. The long-term safety implications of variability or errors in the manufacture or installation of system components have also not been systematically addressed in the present safety assessment, although the impact of an initial penetrating defect in a canister has been considered in radionuclide release and transport calculations.

The KBS-3H design issues that have been identified in the safety studies are the following: avoidance of distance block displacement and deformation during early evolution, avoidance or limitation of thermally induced rock spalling, the use of possible alternative supercontainer shell materials, and layout adaptation strategies, such as the application of the Expanded Full Perimeter Criterion to the KBS-3H layout to avoid potentially problematic fractures and limit the risk of canister failure due to rock shear.

6 Emplacement, operational safety and retrievability

As already described in Section 2.2, a key issue was development and verification of technology for emplacing the 46 tonnes supercontainer in a narrow horizontal drift. Previous studies indicated that the most promising technology would be to utilize water cushion technology: The technique is proven and is used worldwide for lifting and handling heavy loads up to several hundred tonnes (for example hovercraft). However, it has been developed for flat surfaces and not for curved walls as in the case of deposition drifts. This section outlines the development and verification work to prove the usefulness and feasibility of the technique for KBS-3H. The development of the deposition equipment and the subsequent demonstration is part of the ESDRED ("Engineering Studies and Demonstration of Repository Designs") project supported and partly financed by the European Commission.

Based on present assumptions and understanding, selected aspects of operational safety were investigated. Another key issue related to the KBS-3H design is retrievability. In the case of the KBS-3V design, the canisters can be retrieved individually, but since in the KBS-3H design the canisters are emplaced horizontally in series, the feasibility of retrieval warranted specific studies.

6.1 Basic assumptions and objectives for the design and testing of the emplacement technique

In 2005, SKB commissioned the French company Constructions Industrielles de la Méditerranée (CNIM) to develop and manufacture equipment for the deposition of supercontainers and distance blocks. The equipment was tested at Äspö HRL during 2007 to verify, in full scale, that the water cushion technique is technically feasible for the emplacement of supercontainers and distance blocks.

The equipment consists of the following main components /Halvarsson 2008/:

- deposition machine used to move the supercontainer and distance blocks in the drift,
- start tube for the deposition machine. The start tube is used to connect the deposition equipment with the transport tube,
- transport tube for the supercontainer with gamma gates (i.e. gamma radiation protection shielding). The transport tube is used for transferring the supercontainer from the reloading station to the deposition niche and for connection to the entrance of the deposition drift, and
- transport supports for the start tube and the transport tube. The transport supports for the present test equipment are designed to allow for transportation with SKB's existing transport vehicles.

Figure 6-1 shows the test set-up at the KBS-3H drift at the Äspö HRL.

For demonstration purposes at this stage, a number of simplifications were made:

- the transport tube and the gamma gates are presently designed with no consideration to radiation shielding,
- the start tube is only a "half" tube, i.e. the tube is open to 70%, to allow for observation of the deposition machine during the demonstration. In the real situation with deposition of spent fuel, the start tube will be closed to obtain radiation shielding,
- the deposition drift is not provided with a gamma gate, and

- supercontainers and distance blocks are mock-ups with concrete instead of bentonite as buffer material. The mock-ups, however, have the real payloads and correct physical dimensions. The reason for using concrete instead of a real buffer at this stage was firstly to test the technique on a large scale and secondly to avoid the need to manufacture the buffer. Buffer manufacture would have required substantial investments in new manufacturing capability, and was judged to be premature bearing in mind the early design phase. The concrete buffer used for the integrity testing of the supercontainer and the distance blocks was a special, unreinforced concrete mixture with mechanical properties close to the mechanical properties of bentonite.

The design of the deposition equipment is based on the transport principle whereby the supercontainer is moved stepwise. The process is repeated continuously until the supercontainer is in the correct position in the deposition drift. The same principle is used for transporting distance blocks according to the DAWE and the STC design alternatives. The transport principle is described in Figure 6-2 and has been chosen in order to reduce the forces required to move the supercontainer, which will minimize the risk of damage to the surrounding steel shell and the bentonite buffer.

The supercontainer, which is provided with feet, is moved with the help of a lifting cushion pallet and a slide plate placed in the space between the feet underneath the supercontainer. The lift cushions are standard air cushions for heavy load handling that have been adapted to run on a cylindrical surface with water as medium pressure. Water (instead of air) was finally chosen as the pressure medium after mock-up tests which showed water to be more energy-efficient than air.

The main objectives for the demonstration tests were to:

- verify in full-scale that the KBS-3H design with water cushion technology is technically feasible for emplacement of supercontainers and (mock-up) distance blocks in a horizontal disposal drift with narrow gaps between the supercontainer and the deposition drift,
- test the reliability and availability of the developed machine and auxiliary equipment, and
- demonstrate the integrity of the supercontainer and distance blocks during the deposition process.

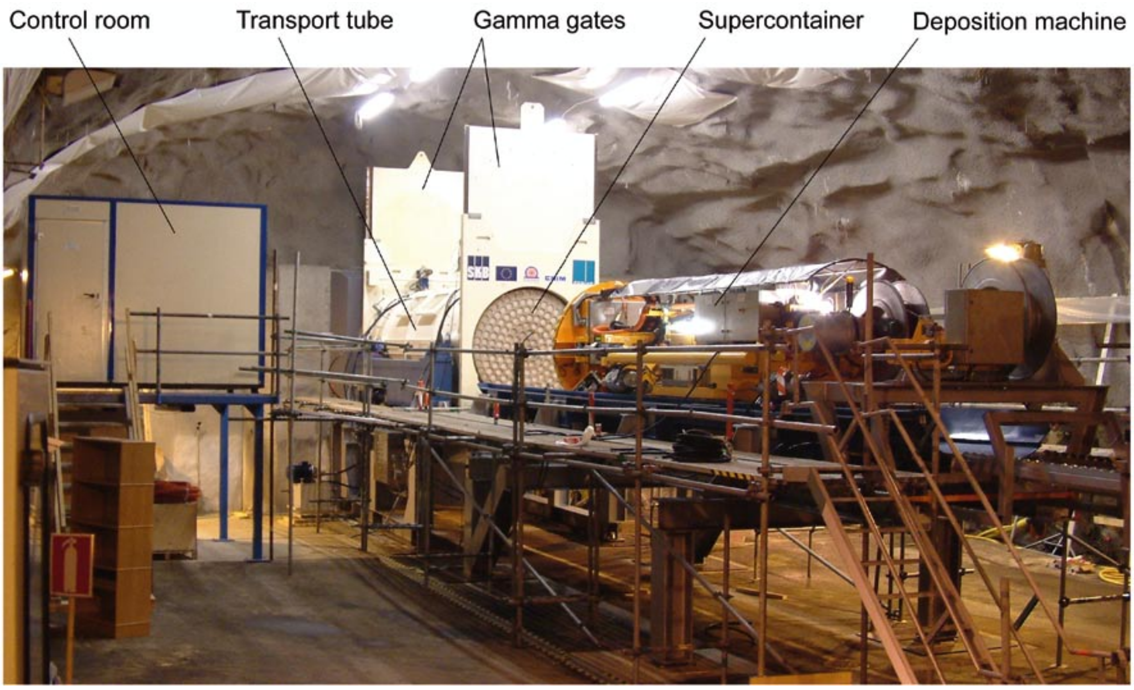
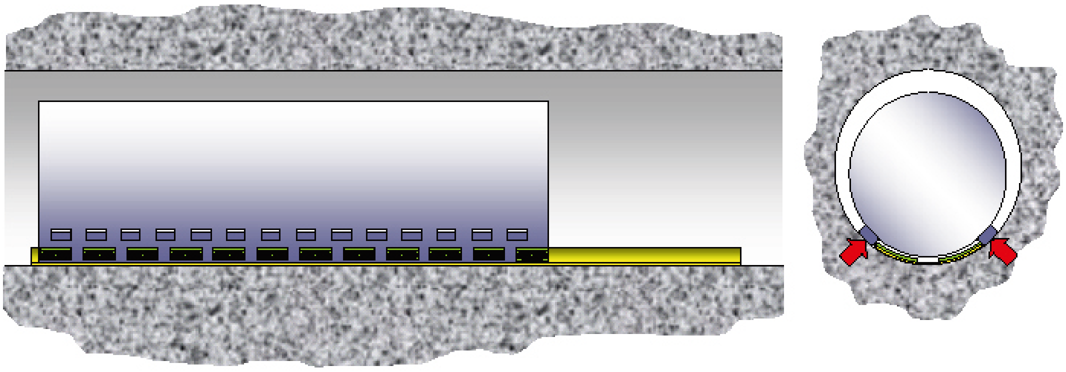
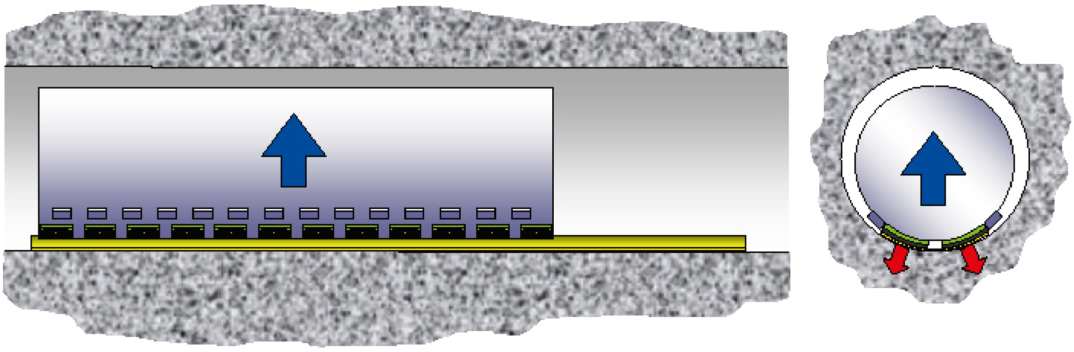


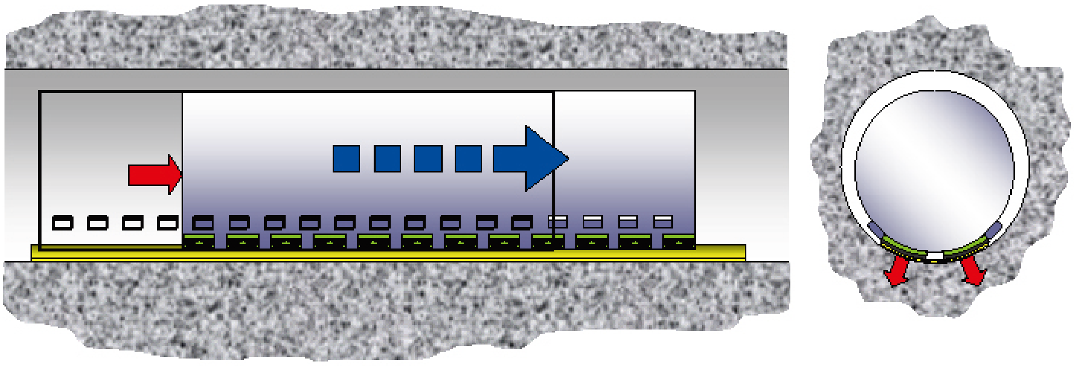
Figure 6-1. *Set-up of equipment at the test site at Äspö HRL, level –220 m.*



Step1. The supercontainer is resting on its support feet (indicated with red arrows). The lifting pallet/slide plate located between the feet is inactivated.



Step 2. When the lifting cushions on the pallet are activated (indicated with red arrows) the supercontainer is lifted. The supercontainer floats on a thin film of water.



Step 3. Floating on the water film, the supercontainer is moved forward one stroke (1.5 metres) on the slide plate. After fulfilled stroke the lifting cushions are inactivated and the supercontainer is lowered for support on the feet; the slide plate is moved forward to prepare for the next cycle.

Figure 6-2. *Schematic representation of the transport principle.*

6.2 Description of the deposition machine

The main components of the deposition machine are shown in Figure 6-3. The machine is wheel-driven with electrical gear motors for all wheels. The deposition machine is designed to emplace one supercontainer and one distance block per day. To meet this requirement, the average design speed of a supercontainer was set at 20 mm/s and for the transport of distance blocks at 30 mm/s. The design transport speed for the machine was set at 100 mm/s.

The slide plate on to which the lift pallet is slid is attached to the main frame. The front of the slide plate, see Figure 6-4, is equipped with two cameras with lighting facing forward and backwards. The slide plate is also equipped with sensors (forward and backward) for the detection of obstacles in front of the machine and for positioning of the supercontainer and/or distance blocks.

The lift pallet is attached to the radiation shield, which is connected to the machine frame by three synchronized actuators that permit stepwise movement. The stroke of the actuators is 1,500 mm. The lift pallet is guided on to the slide plate in order to prevent rotation of the supercontainer during transportation, see Figure 6-5. The position and orientation of the machine and the supercontainer are continuously monitored and adjusted by means of an inclinometer on the radiation shield and the movable ballast on the machine. In order to centre the slide plate and pallet between the supercontainer feet, the radiation shield is equipped with "forks", see Figure 6-6. The lift pallet, which is equipped with 24 water cushions in two longitudinal rows left/right, is shown in Figure 6-7.

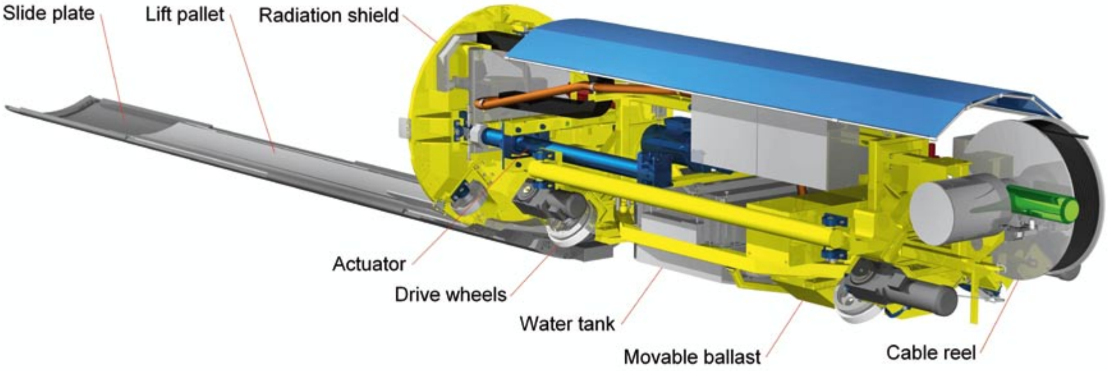


Figure 6-3. *Illustration of the deposition machine.*

Figure 6-4. *Front of slide plate with camera and lighting.*

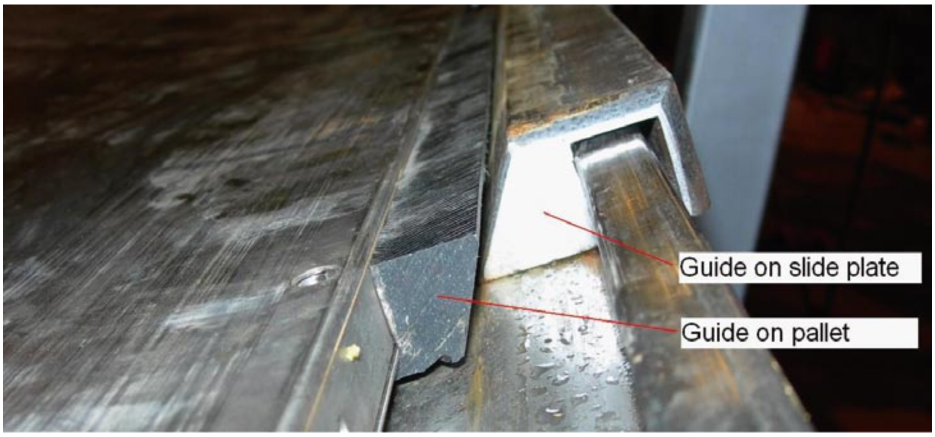


Figure 6-5. *Guides between the pallet and the slide plate.*

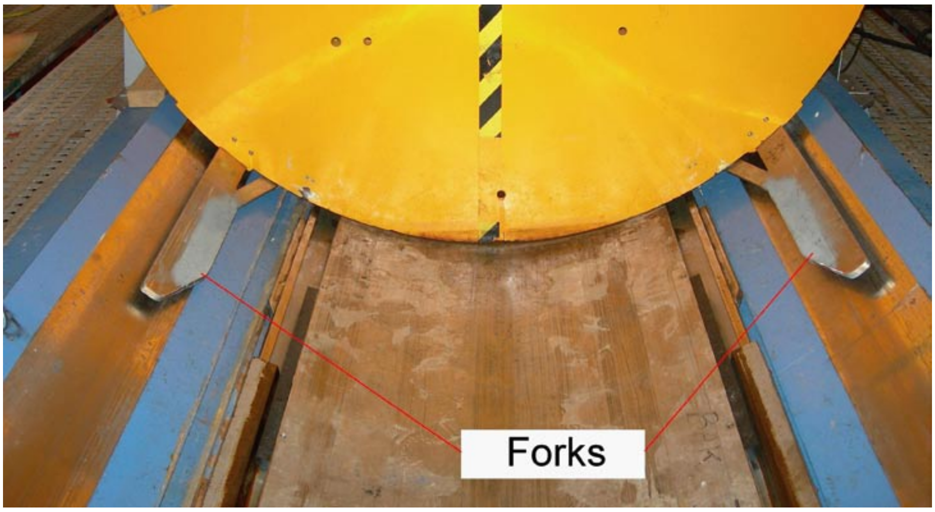


Figure 6-6. *Forks mounted on the radiation shield for centring of the container.*

Figure 6-7. *View of underside of the lift pallet during the installation of water cushions.*

The pallet is normally lifted 20–25 mm, which results in a lift of the supercontainer of approximately 10 mm when measured between the feet on the bottom part and the rock surface. The pallet is provided with lift sensors for indication of the lifting height.

The water cushions are fed with water from a pump, which takes its water from a tank located in the middle of the machine. The water pumped out from the cushions is pumped back to the tank via a recovery pump located in a sump at the rear of the slide plate. All electric power and communication is via a cable with integrated optical fibres wound on a motor-driven cable reel located at the rear of the machine. The machine is equipped with an automatic fire-fighting system.

If considered necessary, the whole deposition machine can at any time be pulled out and back to the niche using a steel wire that is connected to the rear of the machine.

6.3 Demonstration tests performed with the deposition equipment

The KBS-3H deposition equipment, Figure 6-8, has been tested at Äspö HRL since March 2007. The total transportation distance covered since the site acceptance tests were carried out in March 2007 until the end of September is approximately 12 km.

As stated earlier, the objective was to make one deposition and subsequent recovery per day. Statistics from the tests shows that the average deposition distance during the test period was 141 m, but distances of up to 340 m were reached during the test period. The tests resulted in a number of recommendations for future improvements of the equipment.

The tests performed showed that the emplacement equipment operates effectively for the transport and deposition of the supercontainer. The performance requirements, i.e. an average deposition speed of 20 mm/s and a transportation speed for the machine of 100 mm/s, were verified. It was also concluded that the water cushion technique used is sensitive to load variations, which meant that the supercontainers had to be well balanced for transportation. In order for the canister to be properly balanced, all fuel positions in the spent fuel canisters have to be filled with fuel elements or fuel dummies. The technique is also sensitive to the alignment of the transport tube for the supercontainer with the deposition drift and the start tube for the deposition machine.

__Figure 6-8.__ The deposition machine has entered the deposition drift (left). The supercontainer is placed approximately 20 m into the deposition drift (right).

After the feet of the distance blocks had been fixed firmly in place, the transportation tests with the mock-up distance blocks could be performed without any major problems. It was concluded that the pallet used for transportation of the supercontainers would not be optimal and that it would be preferable to use a pallet designed specifically for the distance blocks.

The supercontainer integrity was tested and no evidence was found that its integrity could be jeopardised. The testing was carried out using a supercontainer made of a carbon steel shell and with un-reinforced concrete of similar mechanical properties as the bentonite buffer and similar weight as the buffer. The copper canister used was fully filled with fuel dummies of the Boiling Water Reactor type. The supercontainer was transported in and out through the 95 m long deposition drift twice, covering a total transport distance of approximately 360 m. After this, the supercontainer was transferred to a workshop for examination of potential deformations and/or cracks using the following methods:

- visual examination of the supercontainer steel shell to observe potential deformations,
- penetrating liquid examination of welds around the feet to observe potential cracks, and
- visual examination of the concrete buffer with respect to potential cracks and fallouts.

No visual deformations or cracks were found in the supercontainer steel shell and no visual cracks and/or fallouts were found in the concrete buffer.

6.4 Operational safety

A very limited pre-study of the operational safety for a KBS-3H repository was carried out, focussing on events that may cause radiological consequences in the reloading station or in the repository area. Due to the early stage of design, it was not deemed beneficial to carry out detailed studies on operational safety. Steps that were considered similar or identical for the KBS-3V design were not studied. The operational safety will be further addressed in future work when the design has been detailed. The most important issues found at this stage are outlined in the following sections.

Reloading station

- The probability that the grab hook for the canister could open in the event that the position of the traverse crane is incorrect.
- The likelihood of fire is probably higher than for the KBS-3V due to longer exposure time, more fire ignition sources and fire load. The risk could be mitigated by proper fire protection systems.
- The design of the opening and closing of the handling cell doors.

Deposition work

The emplacement of a supercontainer and distance blocks in a narrow drift is a technological challenge. A few risk events have been identified:

- The fire load and number of ignition sources is higher than for KBS-3V and due to the narrow drift, high temperatures will be reached quickly.
- Problems could occur when leading in the deposition machine that could be difficult to solve. It might require personnel to enter the deposition drift to retract the deposition machine, which may involve personnel being exposed to radiation doses in spite of the radiation protection mounted on the deposition machine.
- Verification of the correct, final position of the supercontainer or distance blocks in the deposition drift is not straightforward in the Basic Design as the tolerances on distance block dimensions are tight. The accuracy of the positioning is, however, not very important in the case of the DAWE design alternative.

- Loosening of parts (rubber, screws etc) that might be left in the drift. This might affect operational safety as well as the long-term safety.
- Incorrect measurement of water flow into the deposition drifts. In the present requirements, water inflows into the drifts are used to determine the division of the drift into compartments, the selection of positions for supercontainers, etc. The consequences of errors could affect several supercontainer sections.

6.5 Reverse operation and retrievability

A part of the present KBS-3H project 2004–2007 was to study the feasibility of reverse operation and retrievability. *Reverse operation* is defined as an operation to remove the supercontainer and other components from the deposition drift before the buffer has absorbed water and its initial size and shape change. *Retrieval* is defined as removal of the canister after the buffer has absorbed water and starts to swell or after plugging and sealing of the drift. In this context, a set of scenarios and methodologies for removal of barriers and components was explored.

It is assumed that, at any time during the operation period of the repository after the disposal of canisters or installation of other equipment in the drift, it should be possible to retrieve/remove emplaced items from the drift bearing in mind the following considerations:

- the waste disposal process itself must be reversible in the event of a serious error or accident occurring during emplacement,
- supercontainer recovery could be necessary as a result of faults occurring during or after emplacement,
- supercontainer recovery could be necessary if the repository does not function correctly, and
- future generations might have an interest in retrieving emplaced material.

SKB and Posiva are developing their respective requirements on reverse operation and retrievability to comply with the national requirements and guidelines as well as with other stakeholder requirements.

6.5.1 Scenarios

Two main scenarios have been identified for spent fuel canister recovery: 1) the bentonite buffer has absorbed water or 2) the buffer has not absorbed water before recovery. Before the bentonite buffer has absorbed water, supercontainer recovery can be carried out using the same equipment as that used to emplace it, i.e., *reverse operation.* Reverse operation of the deposition equipment was successfully demonstrated during the Äspö HRL test period. Reverse operation will remain a viable option for quite a long period of time (to be evaluated) using the DAWE design alternative, since the supercontainer and the distance blocks are designed to keep the drift drained during the emplacement phase for canisters. Once the entire drift or individual drift compartments have been sealed, it can be assumed that it will no longer be possible to recover canisters by reverse operation.

Once the bentonite buffer has absorbed water, reverse operation will not function and other means will be required for the recovery of spent fuel canisters, i.e., retrieval. In the following section potential techniques for retrieval are presented.

6.5.2 Techniques for retrieval

The basic principle planned for the retrieval is to free the spent fuel canister from the supercontainer. Due to the swelling pressure of the buffer, considerable forces may be needed to retract the canister, which could result in unacceptable damage to the canister. It was therefore concluded that the bentonite surrounding the canister should be removed before the canister is retracted.

Several different techniques and steps will be required, firstly to remove the components of the system, then to retrieve the canisters. The steps needed for retrieval are the following:

- remove concrete, bentonite, filling materials and steel components (the compartment plugs),
- cut the end plate of the supercontainer,
- remove the bentonite inside the supercontainer,
- retrieve the canister,
- remove the supercontainer steel shell, and finally
- clean the deposition drift.

It was concluded that the concrete and steel components should preferably be removed by hydro-demolition methods and water cutting. The bentonite would be removed by using hydrodynamic/chemical methods, which have already been tested at Äspö HRL for retrieval of a KBS-3V canister. As an alternative, hydro-demolition methods could be used, pending tests to verify that the method will not damage the copper canister.

Figure 6-9 illustrates the "catching tube" with water nozzles to remove the buffer surrounding the canister. The bentonite can be removed by hydrodynamic/chemical or hydro-demolition methods. When the bentonite is being removed/dissolved, the canister must be supported. This can be done by means of a "catching" tube, which is pushed forward when the bentonite is removed/dissolved. The water nozzles for the bentonite removal can be attached to the front of the tube. When all the bentonite has been removed, the canister will rest inside the tube.

Based on the preliminary desk studies and previous field tests at Äspö HRL to retrieve a canister for the KBS-3V design, it is concluded that the supercontainer and other components can be removed after installation. The techniques involved must be further developed and verified.

6.6 Remaining issues and uncertainties

The most critical issue and uncertainty for the emplacement work is how the bentonite buffer will withstand the handling and transportation. Further tests are also required to show that water will not come into contact with the buffer during emplacement.

The most significant uncertainties in connection with retrieval are the length of time during which reverse operation is feasible as well as the efficiency of the proposed techniques for retrieval.

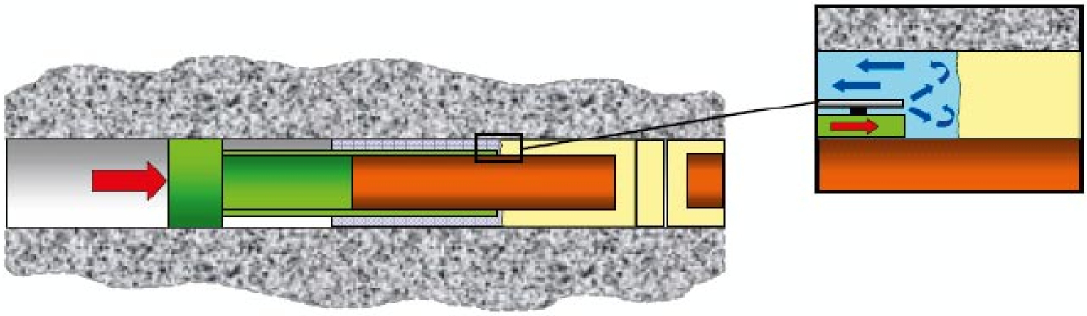


Figure 6-9. *Illustration showing the "catching" tube with water nozzles to remove the buffer surrounding the canister.*

7 Evaluation of cost and environmental impact

As stated earlier in Chapter 2, the rock excavation and backfilling work for the KBS-3H design is much reduced when compared to the KBS-3V design. The decrease in work will also lead to a decrease in cost and environmental impact. The differences in cost and environmental impact were studied in the KBS-3H project 2004–2007 and the results are here outlined based on current design and understanding.

7.1 Evaluation of cost

The purpose of the cost evaluation was to estimate the cost difference between the KBS-3V design and the KBS-3H preliminary design. The evaluation was limited to costs related to the technical part of the system and to costs that are variable with respect to the number of canisters. Fixed costs were assumed to be considered equal or differences to be insignificant in the long run. The cost analysis considered neither costs pertaining to the current development work nor risks connected with changes from one design to the other, for example the costs due to possible delays.

Cost evaluations were made both for Swedish, assuming Forsmark, and Finnish conditions, assuming site-adaptation to the Olkiluoto site. The main assumptions used for the cost compilation are presented in Table 7-1.

For the Swedish case, the cost estimate was made using the same methodology as that used for the yearly report on costs for management of the radioactive waste products from nuclear power production as stipulated by the law. The cost is calculated by a stochastic method where the difference is given as a stochastic variable, linking a range of possible outcomes with their likelihood of occurrence ("the Lichtenberg Method"). The report /SKB 2003/ provides a description in English of the "successive principle".

Based on the assumptions in Table 7-1, the KBS-3H design would realise savings of approximately €305 million at Forsmark (€51,000 per canister). The stochastic model shows that the probability is 90% that KBS-3H will be less costly than KBS-3V.

Posiva independently calculated the cost difference between the KBS-3H and the KBS-3V designs for the Olkiluoto site. Based on Posiva's assumptions and cost estimate method, it was calculated that KBS-3H would realise savings of approximately €96 million (€34,000 per canister).

Table 7-1. Assumptions for the cost compilation

Item	Forsmark	Olkiluoto
Number of canisters	6,000	2,840
Average length of deposition drifts	260 m	272 m
Distance between deposition drifts	40 m	25 m
Distance between canisters	7.2 m	10 m
Drift utilisation degree	85%	70%
Length of drift end plug	25 m	25 m
Numbers of canisters in one deposition drift	28	16
Number of deposition drifts	214	171
Number of compartment plugs in each drift	2	3

The differences in costs between the KBS-3V and the KBS-3H designs are mainly related to less volume of excavated rock and the amount of backfill for the deposition drifts compared with the deposition tunnels and deposition holes in the KBS-3V design. The total volume of the Olkiluoto KBS-3H repository is estimated to be 894,000 m^3 compared to 1,360,000 m^3 for the KBS-3V design.

The relatively substantial difference in cost reduction between Forsmark and Olkiluoto is mainly due to site-specific assumptions regarding the degree of drift utilisation,, the longer distance blocks in the Posiva design and the number of compartment sections, resulting in 28 canisters in one deposition drift for the Forsmark site and 16 canisters in one deposition drift for the Olkiluoto site.

The costs presented above assume carbon steel for the supercontainers and compartment plugs. Because of the long-term safety consequences of using iron in the vicinity of the bentonite buffer and owing to the hydrogen developed during iron corrosion in the early evolution (see Section 5.3), titanium is an alternative for the supercontainer and the compartment plugs. The use of titanium gives an additional cost of €11,000 per supercontainer and €22,000 per compartment plug. Using titanium, the KBS-3H design would realise savings of approximately €230 million (€38,000 per canister). Similarly, the KBS-3H design, based on Posiva's assumptions and cost estimate, would realise savings of approximately €50 million (€18,000 per canister).

7.2 Evaluation of environmental impact

The environmental impact of the KBS-3H design has been assessed and compared to the KBS-3V design for a number of aspects such as land utilisation, noise, emissions into the atmosphere and surface water, the effect on groundwater and finally on resource consumption, e.g. rock, bentonite, concrete, steel and iron, explosives, grout materials, energy, equipment and waste.

The major differences with respect to environmental impacts relate to the handling of rock spoil and bentonite/clay. A reduction in the excavation of rock and backfill generates a decrease in the consumption of resources and less transportation, which gives less air pollution, etc. The comparison of the KBS-3H and KBS-3V designs shows the KBS-3H design to be positive in all aspects that could be assessed at this stage, with the exception of steel and iron consumption. Those factors with a large or substantial positive difference for the KBS-3H design are emissions into the atmosphere and the consumption of rock, bentonite and concrete resources. Several factors could not be assessed at this stage, such as effects on the groundwater, energy consumption and the consumption of equipment.

8 Conclusions

The main objectives of KBS-3H Project 2004–2007 were to demonstrate that the deposition alternative is technically feasible and that it meets the same long-term safety requirements as KBS-3V. These objectives have been met with respect to the restrictions imposed before the start of and during execution of the project.

In KBS-3H Project 2004–2007 it was demonstrated that it is possible to excavate horizontal drifts that will fulfil most of the stringent requirements for the KBS-3H geometry by using present standard technology. To increase overall productivity and to ensure that 100–300 m-long horizontal drifts are sufficiently straight, further development of technology is necessary. It was further demonstrated that it is possible to emplace a 46-tonne supercontainer in a deposition drift using water-cushion technology.

A critical issue for the robustness of the KBS-3H during emplacement and saturation is that the groundwater seepage into the deposition drift is low (< 0.1 l/min over the length of the supercontainer section) since a higher inflow could cause piping/erosion of the buffer during the saturation period. A Mega-Packer post-grouting device was developed for groundwater control purposes and successful grouting was demonstrated at the Äspö HRL using this device.

A drift end plug of low-pH shotcrete was developed and tested at Äspö HRL as part of the ESDRED Project. The conclusion reached in this testing was that casting the concrete is more efficient than the use of shotcrete.

The KBS-3H design is still under development. In order to meet design requirements that support the long-term safety functions, novel components have been developed, such as the compartment plug. Based on studies of the Basic Design as described in the Design Description 2007 /Autio et al. 2008/ it was concluded that the robustness of the design during saturation would not be satisfactory, and therefore design alternatives were further developed. Further studies are required before a robust design can be developed and selected. The complete design including all components of the KBS-3H design remains to be carried out and demonstrated during full-scale tests, and such tests should be preceded by full-scale tests of the individual components. Examples of important component tests that remain to be executed are the emplacement of a supercontainer with a real buffer, the manufacture and emplacement of distance and filling blocks and the manufacture and installation of compartment plugs.

With regard to long-term safety, the KBS-3H safety assessment focussed on the differences between KBS-3V and KBS-3H, and whether these differences have the potential to lead to unacceptable radiological consequences. The main conclusions from the safety assessment, and based on a KBS-3H preliminary design, were that features or processes that are specific to KBS-3H mostly have a minor impact on the safety functions of the host rock, the buffer and the canister, and their evolution over time. In spite of several limitations in the present safety assessment, it can be concluded that the KBS-3H design alternative offers potential for the full demonstration of safety for a repository at the Olkiluoto site and for the demonstration that it fulfils the same long-term safety requirements as KBS-3V.

SKB and Posiva have decided to continue the development work on horizontal emplacement. Several significant issues have been identified that need to be addressed to reduce uncertainties. The focus of the complementary studies of horizontal emplacement during 2008–2010 will be used to develop the KBS-3H design to such a state that a decision on full-scale testing and demonstration can be made. From the list of significant issues to address, the following items were prioritized for the next phase:

- the behaviour of the buffer and other components (container, plugs) after emplacement,
- the long-term performance of the buffer including interaction with other materials, and
- on the feasibility of construction, manufacturing and installation of the system.

The project will focus its work on solving issues unique to the KBS-3H design. Common issues with the reference design KBS-3V will be recognised and coordinated to avoid overlap. The tests required in this phase will only be conducted in the laboratory except full-scale field tests of the compartment plug, the Mega-Packer and the deposition equipment.

The project 2008–2010 will be split in sub-projects: Examples on main activities are shown below:

- **Drift Design:** Design alternatives will be optimized and a main KBS-3H reference design selected. Critical issues related to the buffer should be solved.
- **Production and Operation:** Production Line Reports, preliminary Facility Description Report and preliminary system descriptions will be prepared. The report in operational safety will be updated. Boring technique for the pilot hole (deposition drift) and grouting techniques will be selected. The deposition equipment will be tested to verify that water will not come in contact with bentonite during the emplacement work.
- **Safety Case:** Metal for the supercontainer shell will be selected. Long-term safety requirements will be updated along with the development of design.
- **Demonstration and Preparation of Full-Scale Tests:** Tests will be made in full scale for the compartment plug, pipe removal (DAWE) and the Mega-Packer. Plans will be prepared for manufacture of buffer block moulds, full-scale tests of system components as well as for full-scale tests of the complete system under realistic conditions.

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Appendix B

KBS-3H specific nomenclature

Term	Description
Air evacuation	Removing of air from a drift compartment through pipes during artificial watering.
Artificial watering	Adding water through pipes to a supercontainer section to facilitate buffer saturation.
Backfilling	Filling the deposition niche, transport tunnels and other parts of the repository.
Basic Design	KBS-3H design alternative.
BD	Basic Design.
Buffer	Bentonite originally inside the supercontainers and the bentonite distance blocks.
Candidate design	Design alternative to be used for selecting a suitable design.
Catching tube	Equipment for catching the copper canister during retrieval.
Compartment	Drift section used for emplacement of supercontainers. Typically, the 300 m-long drift is divided into 2 compartments by a compartment plug.
Compartment plug	Steel plug used to seal off drift sections where inflows are higher than 1 litre per minute after grouting, thus dividing the drift into compartments.
Cutting tool	Device for removal/cutting of supercontainer end plate during retrieval.
DAWE	Drainage, Artificial Watering and air Evacuation design alternative. KBS-3H design alternative.
DD-2005, DD-2006, DD-2007	KBS-3H Design Description 2005, 2006 and 2007 reports, respectively.
Deposition drift	100–300 m long hole with a diameter of 1.85 m for horizontal emplacement of supercontainers.
Deposition equipment	Includes all equipment needed for the emplacement of supercontainer and installation of distance blocks.
Deposition machine	The machine used in the deposition drift for emplacement of supercontainers and distance blocks.
Deposition niche	A tunnel section in front of the deposition drift hosting the deposition equipment.
Design component	A component in design which fulfils a specific functional requirement, e.g. compartment plug, distance blocks.
Distance blocks	Bentonite blocks between the supercontainers. The roles of the distance blocks are to provide hydraulic separation and thermal spacing.
Drift end plug	A steel-reinforced low-pH concrete bulkhead positioned in a notch situated at the end of deposition drift close to the intersection with the deposition niche.
Drip (and spray) shield	Thin steel (or copper) sheets over inflow points preventing erosion of bentonite due to the spraying, dripping and squirting of water from the drift walls onto the distance blocks and supercontainers.
EDZ	Excavation Damaged Zone; section of the rock damaged by the boring of deposition drifts.
End plate	Unperforated steel end plate for the supercontainer shell.
Engineered and residual materials	Materials introduced during construction and operation of the repository that will remain underground after closure.
Erosion	Loss or redistribution of bentonite mass in the deposition drift due to physical or chemical processes, such as piping or chemical erosion by dilute water.
Fastening ring	Steel ring used to fasten the steel compartment plug to the rock.
Filling block	Filling blocks are placed at positions where supercontainer units cannot be positioned because inflow is higher than positioning criteria.
Filling material	Material between and in the vicinity of the compartment plugs to fill empty space which cannot be filled by using filling blocks.

Term	Description
Fixing ring (BD design only)	Steel rings installed, where necessary, to avoid displacement of the distance blocks prior to the installation of compartment and drift end plugs.
Gamma gate	Sliding radiation protection gates located on the transport tube or at the entrance of the deposition drift.
Gripping tool	Device for removal of canister from the drift during retrieval.
Handling cell	Shielded space for handling of spent fuel canister.
Handling equipment	Equipment for handling of spent fuel canister within the reloading station.
Horizontal push-reaming	Excavation method to ream the pilot hole to full drift size, known also as horizontal blindboring, reverse raiseboring or horizontal box-hole boring.
KBS	(Kärnbränslesäkerhet). The method for implementing the spent fuel disposal concept based on multiple barriers (as required in Sweden and in Finland). KBS-1, KBS-2 and KBS-3 are variations of this method.
KBS-3H	(Kärnbränslesäkerhet 3-Horisontell). Design alternative of the KBS-3 method in which several spent fuel canisters are emplaced horizontally in each deposition drift.
KBS-3V	(Kärnbränslesäkerhet 3-Vertikal). The reference design alternative of the KBS-3 method in which the spent fuel canisters are emplaced in individual vertical deposition holes.
LHHP cement	Low-Heat High-Performance cement, used for spent fuel repository applications, characterized by a low heat of hydration, and a lower release of free hydroxide ions and lower pH than for ordinary cement.
Mega-Packer	Large-scale post-grouting device for grouting of rock.
ONKALO	Underground rock characterisation facility in Olkiluoto, Finland.
Parking feet	Feet on the supercontainer.
Pilot hole	Rotary drilled hole for guiding horizontal push-reaming excavation.
Piping	Formation of hydraulically conductive channels in the bentonite due too high water flow and hydraulic pressure difference along the drift.
Post-grouting	Grouting method used in deposition drift after excavation.
Pre-grouting	Grouting made through investigation or pilot holes before reaming the drift to full size.
Pre-pilot hole	Core-drilled investigation hole made before drilling the pilot hole. This may be used for guiding the boring of pilot holes.
Reloading station	Station at repository level where the spent fuel canister is transferred from the transport cask to the supercontainer.
Retrievability	Possibility of removal of canisters after the buffer has absorbed water and started to swell within the deposition drift.
Retrieval	Removal of the canister after the buffer has absorbed water and started to swell within the deposition drift.
Reverse operation	Operation to remove the supercontainer from the deposition drift before the buffer has absorbed water and started to swell within the deposition drift.
Safety studies	Long-term safety studies performed for the 2004–2007 KBS-3H project consisting of five main reports: Process, Evolution, Radionuclide transport, Complementary Evaluations of Safety and Summary.
Sealing ring	Design component in the STC design (still at a conceptual stage) presented in DD-2007.
Silica Sol	Type of colloidal silica used for groundwater control purposes.
Spalling	Breaking of the rock surface of deposition drift induced by high rock stresses into splinters, chips or fragments.
Start tube	Support structure for the deposition machine.
STC	Semi Tight Compartments design alternative.
Supercontainer	Assembly consisting of a canister surrounded by bentonite clay and a perforated shell.
Supercontainer section	Section of the drift (about 10 m long for the reference type BWR fuel from Olkiluoto 1–2) in which a supercontainer and a distance block are located.

Term	**Description**
Supercontainer shell	Perforated shell (8 mm thick) that holds together the canister and the bentonite surrounding it.
Transition block	A component in the filling system adjacent to compartment plug.
Transport tube	Tube for the handling of the supercontainer.
Transport vehicle	Vehicle for transportation of deposition equipment.
Water cushion system	System for the transportation of supercontainers and distance blocks.

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