R-08-44

KBS-3H Design Description 2007

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Keywords: KBS-3H, Horizontal emplacement, Repository, Nuclear waste.

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Abstract

The presented KBS-3H design work was carried out in KBS-3H project in 2004 – 2007, which was a joint project between Svensk Kärnbränslehantering AB (SKB) in Sweden and Posiva Oy in Finland. The overall objectives of the project phase were to demonstrate that the horizontal deposition alternative is technically feasible and to demonstrate that it fulfils the same long-term safety requirements as the reference design KBS-3V. The KBS-3H design is a variant of the KBS-3 method and an alternative to the KBS-3V design. In the KBS-3H design alternative, multiple canisters containing spent fuel are emplaced at about 420 m depth in bedrock in parallel, 100 – 300 m long, approximately horizontal deposition drifts whereas the KBS-3V design calls for vertical emplacement of the canisters in individual deposition holes. As a result of design work, the two previous KBS-3H repository candidate designs called Basic Design (BD) and design based on Drainage, Artificial Watering and air Evacuation (DAWE) were developed on two different functional principles. At later phase of the project the BD alternative was found not to be robust in drifts with several large inflows and therefore a third less mature alternative called Semi Tight Compartments design (STC) was introduced to function in these conditions.

Significant effort was made in the project to resolve studies and testing the functional uncertainties related to buffer behaviour which could e.g. cause piping, erosion, displacement and rupture of distance blocks. Major work was also carried for the design of supercontainer, development of large-scale post-grouting device, Mega-Packer, for grouting of rock, excavation of deposition drifts, layout design and evaluation of residual materials. This report also summarizes and highlights differences between different design alternatives and gives reasoning why DAWE design alternative is seen as the most interesting for future development together with novel less mature STC-alternative. All alternatives have still uncertainties and a proposal is therefore presented of the issues that should be considered in possible next phase of work. KBS-3H DESIGN DESCRIPTION 2007

Sammanfattning

Det presenterade KBS-3H utformningsarbetet genomfördes under 2004-2007 i KBS-3H projektet, ett samarbete mellan Svensk Kärnbränslehantering AB (SKB) och finska Posiva Oy. Projektfasens övergripande syfte var att demonstrera att horisontal deponering är ett tekniskt genomförbart alternativ, samt att demonstrera att utformningen uppfyller samma krav på långtidssäkerhet som referensutformningen KBS-3V. KBS-3H är en variant av KBS-3 metoden och ett alternativ till KBS-3V. I KBS-3H alternativet placeras ett flertal kapslar med använt kärnbränsle på ca 420 meters djup, i parallella 100-300 meter långa horisontala deponeringshål i berget, medan KBS-3V alternativet bygger på vertikal placering av kapslar i individuella deponeringshål.

De tidigare kandidatutformningarna för ett KBS-3H slutförvar utvecklades på två olika principer, kallade Basic Design och DAWE (Drainage, Artificial Watering and air Evacuation). Basic Designen konstaterades senare vara otillräckligt robust i deponeringshål med flera större inflöden och därför introducerades ett tredje utformningsalternativ kallat Semi Tight Compartments (STC) planerat att fungera under sådana förhållanden.

Projektet har genomfört en betydande insats för att undersöka de funktionella osäkerheterna kring buffertbeteende, vilka kan leda till erosion, kanalbildning, förskjutning eller bristning i distansblock. Stort arbete lades även på utformning av supercontainer, utvecklingen av redskap för efterinjektering i berg (Mega-Packer), borrning av deponeringshål, layout utformning och uppskattning av främmande material. Denna rapport summerar och belyser även skillnader mellan olika utformningsalternativ. DAWE resoneras i rapporten vara det mest intressanta alternativet för framtida utveckling tillsammans med det mindre utvecklade STC-alternativet. Samtliga alternativ har fortfarande osäkerheter att utreda, och ett förslag presenteras därför på områden som bör beaktas i möjlig kommande arbetsfas.

Denna rapport finns även tryckt i Posivas rapportserie POSIVA 2008-01

Nyckelord: KBS-3H, Horisontal deponering, Slutförvar, Använt kärnbränsle

Foreword

This KBS-3H design work carried out during 2005–2007 was managed by Jorma Autio from Saanio & Riekkola Oy. The work was coordinated by him and from spring 2007 onwards together with Pekka Anttila (Fortum Nuclear Services Ltd). The work was carried out by KBS-3H Design Group in close cooperation with KBS-3H Safety Case subproject.

The KBS-3H Design Group consisted of the following members with the specified field of responsibility and reporting being shown:

- Jorma Autio (KBS-3H design manager, Saanio & Riekkola Oy) project management, coordination, reporting.
- Pekka Anttila (Fortum Nuclear Services Ltd) project coordinator, reporting, activity leader in Groundwater control, steering of pilot boring and pipe removal.
- Lennart Börgesson (Clay Technology AB) activity leader in buffer design.
- Torbjörn Sandén (Clay Technology AB) buffer design.
- Paul-Erik Rönnqvist (Fortum Nuclear Services Ltd) mechanical engineering, steel design, pipe removal.
- Jarno Berghäll (Finnmap Oy) compartment plug design.
- Raimo Kotola (Finnmap Oy) compartment plug design.
- Erik Johansson (Saanio & Riekkola Oy) layout design, acitivity leader.
- Magnus Eriksson (Vattenfall AB) groundwater control.
- Bo Halvarsson (Vattenfall AB) project manager of Technical Development subproject; supercontainer, deposition equipment, Mega-Packer design, operation, environmental assessment, retrievability and delayed reverse operation.
- Anders Eng (Acuo Engineering AB) project manager of Demonstration subproject.
- Margit Snellman (Saanio & Riekkola Oy) project manager of KBS-3H Safety Case subproject.
- Nina Sacklén (Saanio & Riekkola Oy) project administration, quality control, secretarial services, reporting.
- Erik Thurner (SKB) KBS-3H project manager.
- Marina Molin (Adlibrakonsult AB) project secretary.

In addition the following persons have been involved in the work and reporting: Ilpo Parkkinen (Finnmap Oy) compartment plug design; Annika Hagros (Saanio & Riekkola Oy) evaluation of engineered and other residual materials; Antti Öhberg (Saanio & Riekkola Oy) steering of pilot boring; Timothy Schatz (Saanio & Riekkola Oy) and Barbara Pastina (Saanio & Riekkola Oy) technical editing and Mario Salutskij (Illustrerad Teknik AB) illustrations. The long-term safety requirements (Appendix B) and the list of input parameters (Appendix C) have been provided by the Safety Case group.

The following persons from the Safety Case group, in addition to the Safety Case project manager Margit Snellman, were following the work and contributed significantly to it: Barbara Pastina (Saanio & Riekkola Oy), Lawrence Johnson (Nagra), Paul Smith (SAM LtD), Peter Gribi (S+R Consult) and Bill Lanyon (Fracture Systems).

The report was reviewed in draft form by the following individuals: Per-Eric Ahlström (Sweden), Roland Pusch (Geodevelopment International AB, Sweden), John Hudson (Rock Engineering Consultants, UK) and Ivars Neretnieks (KTH, Sweden).

Executive Summary

The KBS-3H design is a variant of the KBS-3 method and an alternative to the KBS-3V design. The KBS-3H design is based on horizontal emplacement of several spent fuel canisters in a drift whereas the KBS-3V design calls for vertical emplacement of the canisters in individual deposition holes, see Figure 1.

The development of the presented KBS-3H design work was carried out in KBS-3H project in 2004–2007. The work was based on previous PASS and JADE projects. In the early phase of KBS-3H project in 2005 it was noted that there were significant functional uncertainties related to buffer behaviour which could cause piping, erosion, displacement and rupture of distance blocks. Distance blocks are bentonite blocks between the supercontainers and the roles of the distance blocks are to provide hydraulic separation and thermal spacing. Therefore it was decided to develop the KBS-3H and especially distance block design more robust based on Olkiluoto site data by:

- *Dividing the deposition drifts into* "good quality" *compartments* to be used for deposition of canisters and by plugging the unsuitable sections.
- *Reducing the operational time* and related problems by dividing the drifts into compartments.
- *Using filling components* in positions with problematic inflows to increasing the robustness of the buffer and plug design.
- *Using drainage, artificial watering and air evacuation* for controlling, if necessary, the initial state of saturation and hydraulic heterogeneity by using watering.
- Development of *Mega-Packer* and other effective *groundwater control techniques* for use different phases to improve the drift utilisation degree and the inflow conditions during operation.

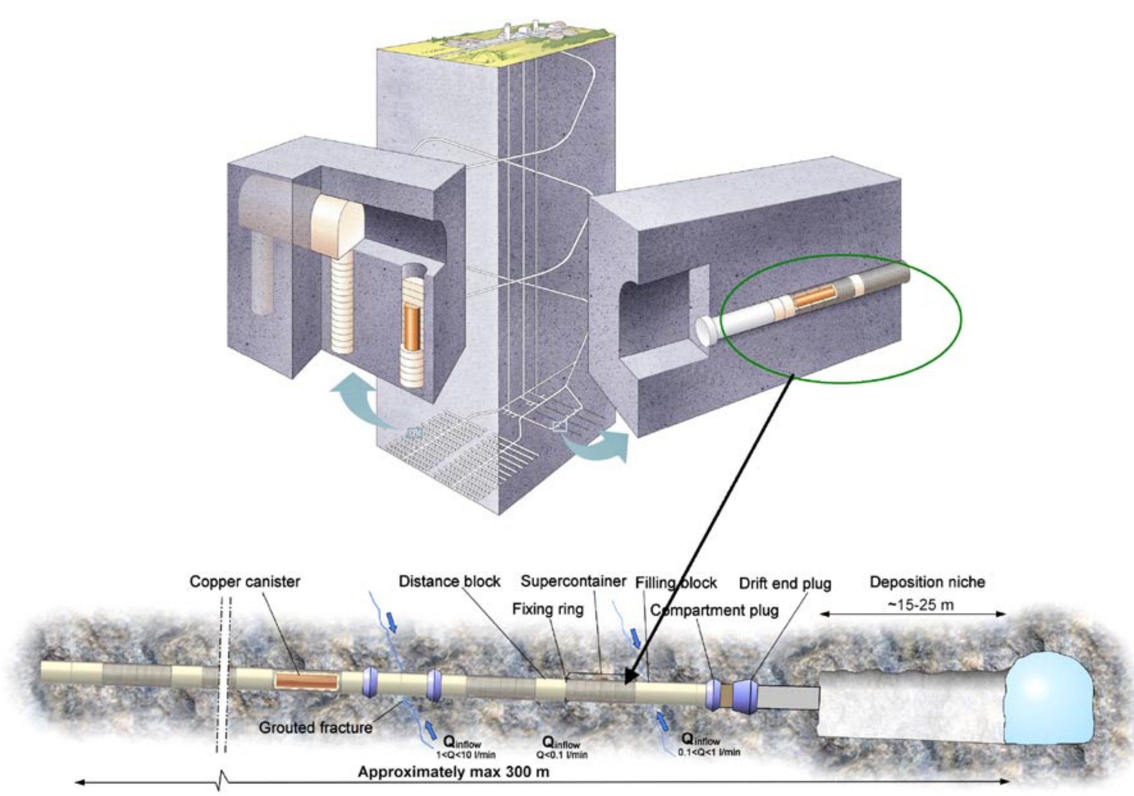


Figure 1. *Principles of the KBS-3V (upper left) and KBS-3H (upper right) repository designs and a more detailed illustration of the KBS-3H design (lower).*

Two KBS-3H repository candidate designs called Basic Design (BD) and design based on Drainage, Artificial Watering and air Evacuation (DAWE) were developed in KBS-3H project based on two different functional principles, see Figure 2. At later phase of the project the BD alternative was found not to be robust in drifts with several large inflows of the order of 0.1 l/min for a supercontainer section of about 10 m in length or less and therefore a third less mature alternative called Semi Tight Compartments design (STC) was introduced to function in these conditions. The different design alternatives have several similar design components, the most important ones being the deposition drift, compartment, supercontainer, compartment plug, drift end plug and distance blocks. The similar components, differences in design and maturity of these are summarised in Table 1. The maturity reflects the status of work on that specific component and focusing of limited design resources on issues which were assessed as being critical for the technical feasibility of the design alternatives. The maturity of these designs is presented in three different levels: a) Schematic design describes the conceptual design principles (lowest level of details) made in schematic design phase, b) Preliminary design describes the design made in design development phase after schematic design. This is used to estimate roughly e.g. material types, quantities and structural composition, c) Detailed design describes the design in sufficient details to be implemented (highest level of details).

The three different KBS-3H designs were based on using Olkiluoto as the reference site with Posiva's design basis. There are differences between SKB and Posiva e.g. in design of main tunnels, deposition drift spacing resulting from different layout optimisation principles, canister dimensions and number of canisters. Therefore some of the results, such as layout efficiency, volumes etc are not directly applicable. The basic features of different design alternatives are presented below.

BD design alternative is based on assumption that the distance blocks will seal the supercontainer sections in wet sections stepwise in sequence independently of each other, see Figures 1 to 3. The main idea with the BD design is to hydraulically isolate every supercontainer section from each other immediately after installation. During the installation of a deposition drift there will be no water flow from one supercontainer section to another. This is mainly achieved by the rapidly sealing distance blocks, which are designed in order to prevent all water flow between the supercontainer sections during the installation and also during the following saturation phase. Important design features specific to BD design alternative are the small, about 5 mm, gap between the distance blocks and the rock surface, requirement for a small gap between the supercontainer and the distance block and need for fixing rings to keep the distance blocks from moving when exposed to hydraulic pressure.

In the case of *DAWE design*, like in BD, fractures that could give rise to significant water flows to adjacent unsaturated drifts or transport tunnels will be avoided as supercontainer emplacement locations. The drainage of inflowing water along the floor of the drift during operations in the DAWE alternative is achieved by inclining the drift towards its entrance. There is a gap of ca 40 mm (37.5–42.5 mm) between the distance blocks and the drift walls, which is larger than in the BD (roughly 5 mm) and should prevent any contact with the water flowing along the bottom of the drift. Furthermore, a higher initial-water-content bentonite is used to prevent humidity-induced fracturing of the distance blocks. Drainage of inflowing water along the drift floor is expected to continue until the drift or the drift compartment is plugged. Following sealing of the compartment, artificial watering takes place simultaneously with evacuation of air to avoid gas pressurisation. Steel pipes along the surface of the drift are used for watering and air evacuation. The sides of the drift are the preferred position for watering pipes to avoid possible damage during operations. Nozzles, which are directed downwards in the watering pipes are distributed along the drift in each supercontainer section to ensure uniform inflow and minimise any axial water flow in the drift that could give rise to bentonite erosion. Water is not directly injected in the sections where the distance blocks are positioned, again to avoid possible erosion.

In the new *STC design* alternative each section will be sealed with the distance blocks and sealing rings that temporarily prevents water from flowing from one section to another before the section is filled with inflowing water, see Figure 2. When the section is filled with water the distance blocks cannot withstand the high water pressure, so there will be piping and flow of water into the next section. Since there are no demands on the distance blocks and sealing rings but to seal for hydrostatic water pressure of a couple of meters the blocks can be made with the same gap between the rock and the block as the supercontainer (same as in DAWE).

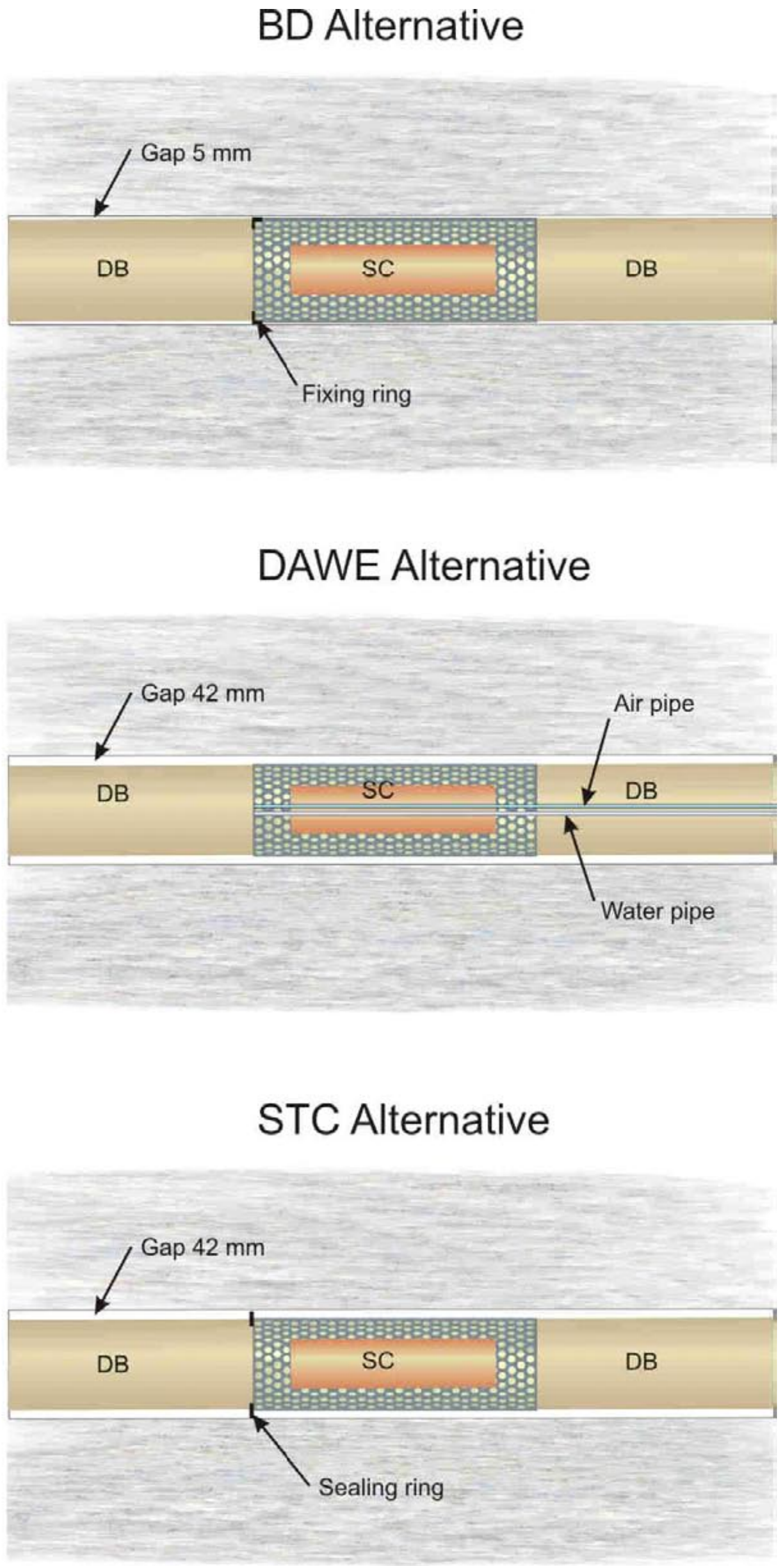


Figure 2. *A section containing a supercontainer (SC) with adjoining distance blocks (DB) in different KBS-3H design alternatives: Basic Design (BD) (on top), Drainage, Artificial Watering and air Evacuation (DAWE) design (in the middle) and Semi Tight Compartment (STC) design (on bottom). Note that the pipes in DAWE alternative are removed during operation.*

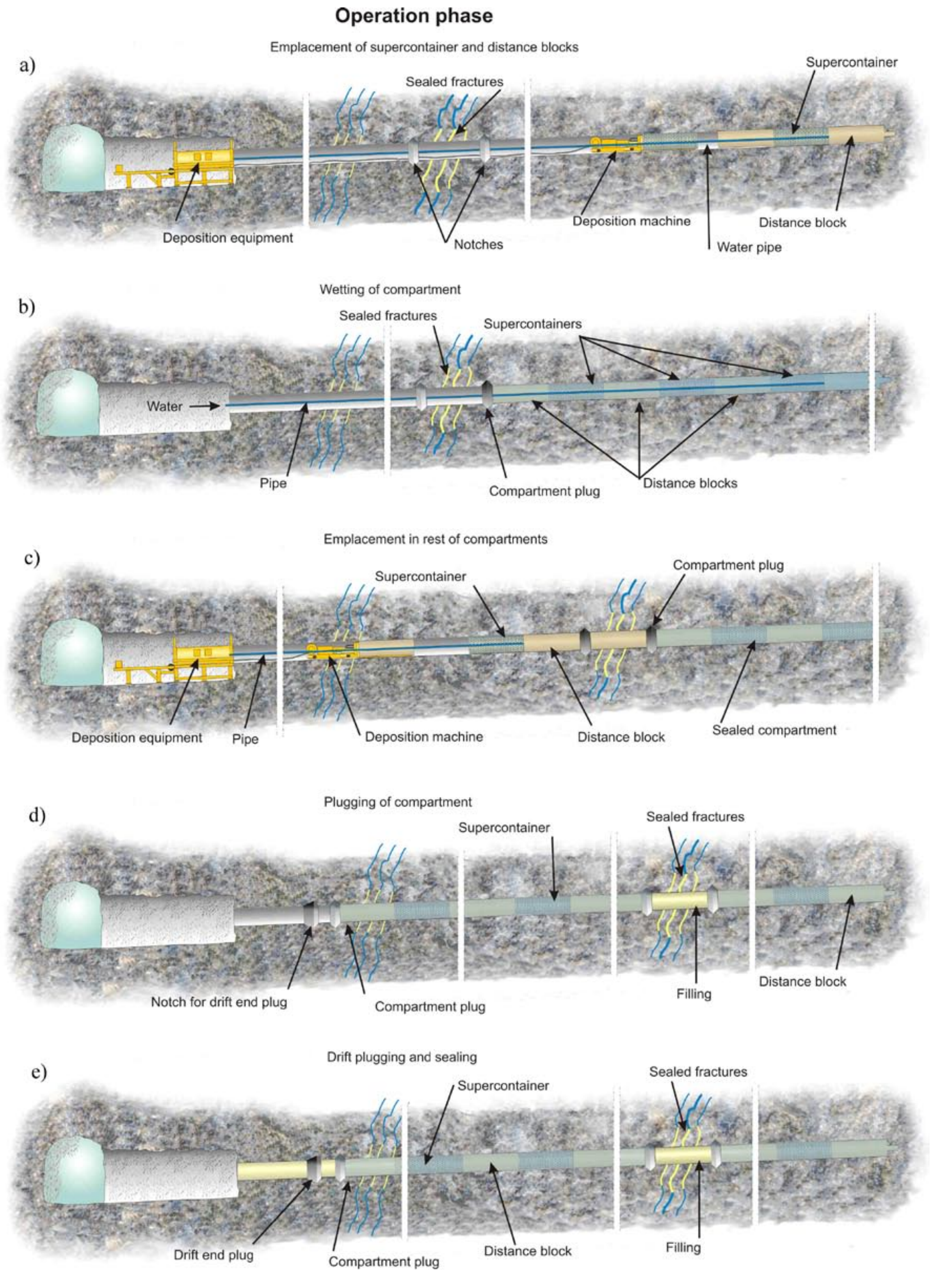


Figure 3. *Operation phases of disposal: a) Installation of supercontainers and distance blocks in the first compartment, b) Plugging of the first compartment, filling it with water and removal of pipes (only DAWE alternative) c) Plugging the highly leaking fracture section and continuation of emplacement of supercontainers and distance blocks, 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 space in drifts is filled with water and the drift is plugged by the drift end plug, see e).*

Table 1. Table of KBS-3H design alternatives and key differences. The table continues on the next page.

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 requirements on the drift are mainly related to geometry, surface straightness and inflows of groundwater.	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
Compart-ment	Sections with inflow roughly from 1 to 10 l/min per supercontainer section (approximately 10 m long) 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 of success of groundwater control and procedures for pipe removal (DAWE design).	Preliminary design
Compart-ment plugs	Similar for all alternatives.	The function of the plugs need to be verified by testing. The lengths of plugged inflow sections might 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 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
Super-container (shell and bentonite buffer inside)	Inflow to supercontainer section ≤ 0.1 l/min.	Use of titanium as alternative material for the supercontainer shell. Integrity of the buffer during transport and installation.	Detailed design Mock-up super-container Tested at Äspö HRL
Filling blocks	Placed in positions with inflow > 0.1 l/min and < 1 l/min per supercontainer unit to resist erosion and support the function of distance blocks.	The inflow limits are preliminary and need re-evaluation. Lengths and dimensions need to be defined in more detail.	Schematic 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 inflow ≤ 0.1 l/min. The blocks swell, fill the voids and withstand full groundwater pressure (4–5 MPa).	Studies showed that the design is not robust and may not fulfill the requirements. Several critical issues related to buffer behaviour, such as build-up of groundwater pressure on block surface leading to displacements lead to the conclusion that the design was not robust.	Detailed design
Fixing rings	Positioned adjacent to distance blocks in positions with inflow > 0.01 l/min to prevent displacements 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 fulfill requirement.	Preliminary design

Key components	Note of important design requirements	Uncertainties and important issues	Maturity of design
		Components specific to the DAWE design alternative	
Distance block (loose gap of 42 mm)	Positioned in supercontainer sections with inflow ≤ 0.1 l/min. The distance blocks absorb water, swell and seal.	The behavior after wetting and development of swelling to prevent possible piping is uncertain and is to be verified. Uncertainties related to possible erosion during the emplacement of supercontainers need verification as well.	Preliminary design
Wetting and air evacuation pipes	Rapid wetting and removablity.	The wetting time (= 14 hours) is preliminary estimate. The number of watering pipes needs to be optimised. The removability needs further studies to confirm robustness.	Preliminary design Pipe removal tested in 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.	Behavior during and after wetting. Extent of possible piping, erosion and development of swelling are uncertain and need verification.	Preliminary design
Sealing rings	Facilitate swelling of distance blocks by allowing supercontainer sections to be filled with water before possible piping occurs.	The function of sealing rings is to be developed.	Schematic design

In order to prevent flow of water there must be a ring or very light sealing at each distance block. The development of STC designs was motivated because testing of distance blocks in the BD design alternative and modelling of distance block behaviour indicated that the distance blocks may not withstand the full hydrostatic 5 MPa water pressure. One solution to resolve the problem could be therefore to allow piping and erosion to some extent between the supercontainer sections before all the sections are filled with water.

Important issues which were resolved in the design work 2004–2007 were the uncertainties related to the behaviour of the bentonite in the supercontainer, distance blocks and the filling blocks. The resolution of these issues was a major challenge and the issues were studied comprehensively by testing. The main results from testing /Sandén 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. The erosion rate is time dependent and also dependent on the salt content. The longer the time or higher the salinity, the larger the erosion.
- For bentonite blocks enclosed in a constant volume with a water-filled gap with no access to additional water will swell and close the gap, the swelling pressure will remain at few hundred kPa after water has migrated to the central parts of the blocks.
- Piping of water past a distance block can only be avoided if the gap between the distance block and supercontainer (in BD alternative) is small, which would be technically very challenging. Build-up of a hydraulic groundwater pressure on the major area of a distance block end surface would be difficult or impossible to avoid during the period of emplacement of supercontainers in one compartment in the deposition drift and subsequent plugging.

Compartment plug is important novel part of the KBS-3H design, which was developed in the project. It is made of metal and will be used to seal off drift sections where inflows are higher than roughly 1 litre per minute after grouting. The attachment part of the plug are inserted before deposition starts and centre part is installed rapidly during deposition. The detailed design of the plug, plan for testing plug in full scale at Äspö and preparation of notches to fasten the plug were made in order to demonstrate that the plug can be constructed as planned and to verify the fulfilment of the design requirements for water tightness and tolerance to hydrostatic pressure of 5 MPa.

A specific issue concerning the DAWE design alternative is the removal of watering pipes, which was tested at the Äspö HRL by using a three metres long pipe. The results clearly indicated that the pipes can be removed as soon as the compartment is filled with water but also pointed out the need for further testing.

One of the key issues in the KBS-3H project was to excavate, two deposition drifts at the Äspö Hard Rock Laboratory during the period October 2004 to February 2005. One horizontal drift was 15 m in length and one 95 m in length at depth of 220 m below the surface. The main conclusion of work was that 95 m long drifts can be excavated according to requirements and the technology would also be applicable for 300 m long drifts, provided that technology for drilling straight enough pilot holes is developed and confirmed.

As part of the project, the supercontainer design and the emplacement technology were developed. Two full-scale supercontainers were assembled at the Äspö HRL to achieve experience for future development. The work concluded that further optimisation and development will be needed. It was also proposed that the buffer should be placed inside the steel shell before emplacing the canister, which is also desirable with respect to requirements for radiation shielding. Deposition equipment, including a deposition machine based on a water cushion technology, were designed and manufactured. Full scale tests in the 95 m long drift verified that the technique is feasible for emplacement of supercontainers and distance blocks. Further tests are needed to show that the buffer maintains its overall integrity during handling and transportation, expecially important is that the buffer will not come in contact with water during emplacement. Preliminary studies were made on the operational safety and feasibility of reverse operation and retrievability, and the environmental impacts were preliminarily assessed as well. All these issues call for further development.

The site-specific layout for the KBS-3H was made using the same site data as used for the layout adaptation of the KBS-3V design to the Olkiluoto site. It was estimated that 25% of the site would not be suitable for disposal within the actual bedrock resource at Olkiluoto.

The amounts of residual materials (construction and stray materials remaining in the closed repository) were estimated as part of the work because these may have 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. The difference in quantities, between the BD alternative and the DAWE design alternatives is mainly related to 10% less steel in the DAWE design alternative due to the absence of fixing rings in the DAWE design.

The KBS-3H design is sensitive for groundwater flow into the deposition drift during the operational phase and different means and strategies to manage inflows were developed in the project. An important challenge in the project was to design and manufacture a Mega-Packer grouting equipment for testing at Äspö, which was initiated in the autumn 2007 at the –220 m level. Preliminary results using Silica Sol as grout were promising and indicate that inflows can be significantly reduced.

The conclusion of the evaluation of BD and DAWE alternatives was that BD design was judged to be technically complicated and not robust because the massive distance blocks are to be emplaced rapidly with small gaps followed by rapid installation of fixing rings. There were also significant uncertainties in functional behaviour in cases with severe inflow situation. Testing and modelling of the distance blocks in the BD alternative indicated that the distance blocks may not withstand the full hydrostatic 5 MPa water pressure without being displaced. Therefore the general conclusion was that the DAWE alternative is more robust and can be implemented with better reliability, it has more favourable buffer swelling characteristics after wetting and should hence be considered the most viable alternative for future development. The proposed STC alternative has, however, interesting beneficial features and is also regarded as a possible future alternative, however, the design is on a lower maturity level and should be developed further before it can be evaluated at same level as current BD and DAWE alternatives.

After the work 2004–2007 there are a number of important issues and uncertainties to be resolved:

- *Supercontainer shell.* Selection of a suitable metal. (All design alternatives.)
- *Division of drifts into compartments.* (All design alternatives.) The uncertainty is both conceptual and site-specific.
- *Compartment plugs.* (All design alternatives.) It is likely that demonstration of a compartment plug at the Äspö HRL will result in further development of the design, manufacturing and installation methods of the plug. The design of the plug is also dependent of 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 and some of these relate to the uncertainties in 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 to prevent thermal spalling as well as to the probability of occurrence and the acceptability of it.
- *Buffer evolution related to internal piping.* There is uncertainty whether piping or not 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 are evidences methodology is available for drilling straight pilot holes but verification is necessary.

Contents

1 Introduction

1.1 Background

This document provides a description of the most current design of a KBS-3H repository. KBS-3H is a repository alternative in which multiple canisters containing spent nuclear fuel are emplaced in parallel, approximately 100–300 m long deposition drifts (see Glossary in Appendix A for KBS-3H specific words), slightly inclined toward the transport tunnel. SKB and Posiva are engaged in a research, development & demonstration (RD&D) programme with the overall aim of developing the KBS-3H as a feasible alternative to KBS-3V, in which single canisters are emplaced in individual vertical boreholes drilled in the floor of the deposition drift.

A comprehensive evaluation of different repository alternatives was carried out in PASS-project between 1991 and 1992 /SKB 1992/. The conclusion of the evaluation indicated that a KBS-3V and an alternative design based on 200 m long horizontal deposition drift, called Medium Long Hole (MLH) concept, were considered more feasible than other alternatives.

The evaluation of alternatives was continued by comparing MLH and Short Horizontal Hole (SHH) and KBS-3-2C (two canisters in one KBS-3V deposition drift) alternatives. The conclusions in 1996 indicated that there was potential for the future development of MLH design alternative if motivated by cost and long-terms safety benefits, which were not evident at the time /Autio et al. 1996/.

The evaluation continued in 1996 when project JADE was initiated with the aim to evaluate if there was enough potential in some of the design variants to justify future development /Sandstedt et al. 2001/. It was noted in the conclusion of JADE project in 2001 that KBS-3V should be kept as the reference repository design and MLH alternative should be studied further with the aim of clarifying the technical feasibility of emplacement and the means of handling water inflow.

An R&D program was presented in late 2001 /SKB 2001/ with the aim to carry out preliminary study in 2002 of horizontal deposition in 200–250 m long deposition drifts followed by preliminary design in 2003 and demonstration of the repository concept during 2004–2007. As the R&D work started, the name of the alternative eventually was changed from MLH to "KBS-3H alternative".

The summary of the work carried out during the KBS-3H basic design phase in 2003 was reported by /Thorsager and Lindgren 2004/. In December 2003 it was decided to continue the development of KBS-3H alternative with the present step which started in early 2004 and was focused on development of a design based on Olkiluoto site, manufacturing and demonstration of the method at Äspö HRL as well as a safety case based on Olkiluoto site data.

During the early development of the basic design in 2004 it was concluded that there were several problems related to the presented KBS-3H design. Several of these problems related to the behaviour of KBS-3H design and scope of future research and development work were addressed in the seminar in Stockholm 9th February 2005. The designs were reviewed and assessed to contain significant uncertainties and problems. The most significant functional uncertainties and problems were related to uneven saturation, piping and rupturing of buffer mainly caused by heterogeneous groundwater inflow environment.

Therefore the design basis was developed further and two candidate designs were developed in the spring 2005: 1) Basic Design (BD) was developed more robust and tolerable to inflows. Parallel to that, a novel 2) DAWE design with drainage, air evacuation and Watering and was developed to function robustly at various inflow situations. This document describes the design developed in the period during 2004–2007.

The testing of the buffer design in laboratory scale has been ongoing since 2002 and demonstration and testing of different drift components and equipment have being carried out at Äspö since the excavation of KBS-3H deposition drifts at Äspö in late 2004.

The modification of design basis and the development of new candidate designs in 2005 started parallel to the long-term safety assessment in order to fulfil the timetable. This caused challenges in the work since the changes and modifications made during design development needed to be taken into account in the safety assessment. Generally the safety assessment is carried out after the design work has been finished.

1.2 Development phases of KBS-3H design

The development of candidate designs BD (Basic Design) and DAWE (Drainage, Artificial Watering and air Evacuation) started in spring 2005. The first document describing the intermediate state of the design was the DD-2005 /Autio 2007/, which described the design based on the work carried out mainly in 2005. The design was further developed in steps and the designs were presented in DD-2006 and eventually in this document DD-2007. Since the testing and demonstration has been running throughout the reporting phase and will be continued by finishing of reports, most important information and results from these have been included in the preceding reports.

The DD-2005 presented the candidate designs for the first time and was based on the following approach:

- Utilizing the knowledge of site conditions to divide the deposition drifts into compartments and adapting the drift layout in rock to utilize the rock heterogeneity in design by using suitable sections for deposition and by plugging the unsuitable sections.
- Reducing the operational time-dependent problems by dividing the drifts into compartments.
- Increasing the robustness of the buffer and plug design by allowing local technical optimisation and by controlling, if necessary, the initial state of saturation by using drainage, artificial watering and air evacuation.
- Using several different groundwater control techniques in different phases.
- Developing a research and development plan to verify the feasibility of the designs. Research is a significant part of the development of designs because all the design solutions and alternatives are novel in a sense that there are practically no applicable standards or design guidelines. Therefore research and development should be evaluated parallel to design work and should be focused on the reduction of several significant uncertainties in the engineering design.

This approach aimed to resolve the problems related to unsatisfactory behavior of buffer during the saturation phase, caused mainly by piping and possible distance block displacement or rupture.

The DD-2005 was followed by the DD-2006 /Autio et al. 2007/. The main objective of this document was to provide a description of the state of the design at that time for the KBS-3H long-term safety studies. The candidate alternatives presented in 2005 included several options for certain design components. The continued development of the candidate designs has resulted in several changes, modifications and added details to the designs presented in the DD-2005. The number of alternative technical design solutions was reduced and more information was obtained regarding some of the identified uncertainties, which were presented in the DD-2006. Additionally, the design of some components was developed further, most significantly the steel compartment plug and distance blocks in Basic Design. The design presented in the DD-2006 included the following issues when compared to the DD-2005:

- The canister spacing was evaluated and accurately specified.
- The thermo-mechanical behaviour of rock adjacent to KBS-3H deposition drift walls was re-evaluated and the results indicate significant susceptibility to spalling, which then concerns the design.
- The long-term safety requirements with an impact on the design and the effects of the rate of increase in groundwater pressure were evaluated resulting in changes to the design basis.
- The design of the steel compartment plug was established and the design was modified to withstand loading from both sides of the plug.
- Drip and spray shields were tested at Äspö and estimates were made of the engineered material quantities.
- The analysis of engineered and other residual materials was performed.
- A new updated layout, based on the new Olkiluoto bedrock model, was produced.
- The grouting techniques were developed (mainly the Mega-Packer technique) and the amount of residual grouting material in the rock was estimated.

The results of the KBS-3H long-term safety studies based on the DD-2006 are presented in several reports /Gribi et al. 2007, Smith et al. 2007ab, Neall et al. 2007/ and summarised in a long-term safety assessment report /Smith et al. 2007c/. The present DD-2007 document includes the following new issues and modifications to earlier design descriptions:

- Evaluation of DAWE and BD candidate designs and selection as DAWE for future development.
- Preliminary description of novel design alternative called STC (Semi Tight Compartment).
- Modelling of distance block behaviour in the BD alternative.
- Comprehensive description of operation.
- Groundwater control and Mega-Packer technique.
- Description of operation equipment.
- Excavation of deposition drift.
- Steering of pilot boring.
- Improved illustrations.
- Design details in general (e.g. deposition niche).
- More detailed description of filling components.
- Operational safety.
- Environmental assessment.
- Removal of pipes.
- Supercontainer design.
- Alternative materials and design for supercontainer design.
- Retrievability and delayed reverse operation.

In addition to this report there are several other important reports, the most important ones being the Summary report of Safety assessment for a KBS-3H spent nuclear fuel repository at Olkiluoto /Smith et al. 2007c/ and the Summary of the KBS-3H Project 2004–2007 /Posiva/SKB 2008/.

1.3 Objectives and scope of KBS-3H design work

The general main objective of the KBS-3H project was to demonstrate that the KBS-3H repository design is technically feasible and that KBS-3H fulfils the same long-term safety requirements as KBS-3V. The most important milestones and deliveries specified in the subproject plan for 2005–2007 to fulfil this objective were:

a) Production of two design alternatives (BD and DAWE) and required development of design basis.
b) Verification of the functioning of the most important design components by reporting of design.
c) Description of means to handle groundwater inflow including Mega-Packer device by reporting of design.
d) Plan for and Evaluation of testing the Mega-Packer and compartment plug.
e) Design of retrieval techiques.
f) Olkiluoto specific layout adaptation.
g) Finalisation of the designs.

To reach the objectives of the project, resolve the uncertainties and carry out the required R&D work the following main activities were included in the subproject:

1. Development of KBS-3H repository candidate designs to produce a design description of the alternatives for final reporting.
2. Development and design of steel components.
3. Development and design of buffer components including comprehensive laboratory testing.
4. Development and specification of groundwater control including Mega-Packer development.
5. Evaluation of steering technique for boring of pilot holes of KBS-3H deposition drifts.
6. Evaluation of engineered and other residual materials.
7. Layout adaptation of the repository at Olkiluoto site.
8. Development of necessary excavation techniques for e.g. improving drift quality and notches for steel components.
9. Mechanical engineering of e.g. distance block emplacement technique and pipe systems.
10. Thermo-Mechanical (TM) modelling of rock behavior adjacent to drift surface.
11. General planning of tests to support the design in laboratory and at Äspö in horizontal demonstration holes at –220 m level.

The following additional work described in this report which was not included in design subproject was included in demonstration and technical development subprojects:

- Excavation of two deposition drifts with a length, which verifies that the technology is sufficient
- Detailed design and manufacturing of deposition equipment.
- Tests of the deposition equipment
- Design and construction of a plug made of low-pH shotcrete (part of EC project ESDRED.
- Design of supercontainer
- Environmental assessment
- Use of alternative materials to steel for supercontainer
- Design of retrieval technique
- Operational safety.

2 General description of the KBS-3H alternative

2.1 General description of the KBS-3H alternative

The KBS-3H design is a variant of the KBS-3 method and an alternative to the KBS-3V design. The KBS-3H design is based on horizontal emplacement of several spent fuel canisters in a drift whereas the KBS-3V design calls for vertical emplacement of the canisters in individual deposition drifts, see Figures 2-1 to 2-3. Under Posiva's current plans, the repository is to be located at the depth of –420 m below sea level at Olkiluoto. These conditions serve as the basis for the reference design presented in this report. The design of the KBS-3H repository includes both one-storey and two-storey alternatives as in the case of the KBS-3V repository as well.

The general KBS-3H repository layout based on SKB's design is outlined in Figure 2-2. 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 8. The buffer and spent fuel canister are assembled into one unit, a so called supercontainer consisting of a canister surrounded by bentonite clay and a perforated shell see Figure 2-2, which then is pushed into the deposition drift.

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). The access to the deposition areas and general design of the deposition areas are different for the SKB and Posiva KBS-3 repositories, partly due to different regulations in Sweden and Finland and partly due to that optimisation led to different results, however, these differences are not particular for the KBS-3H.

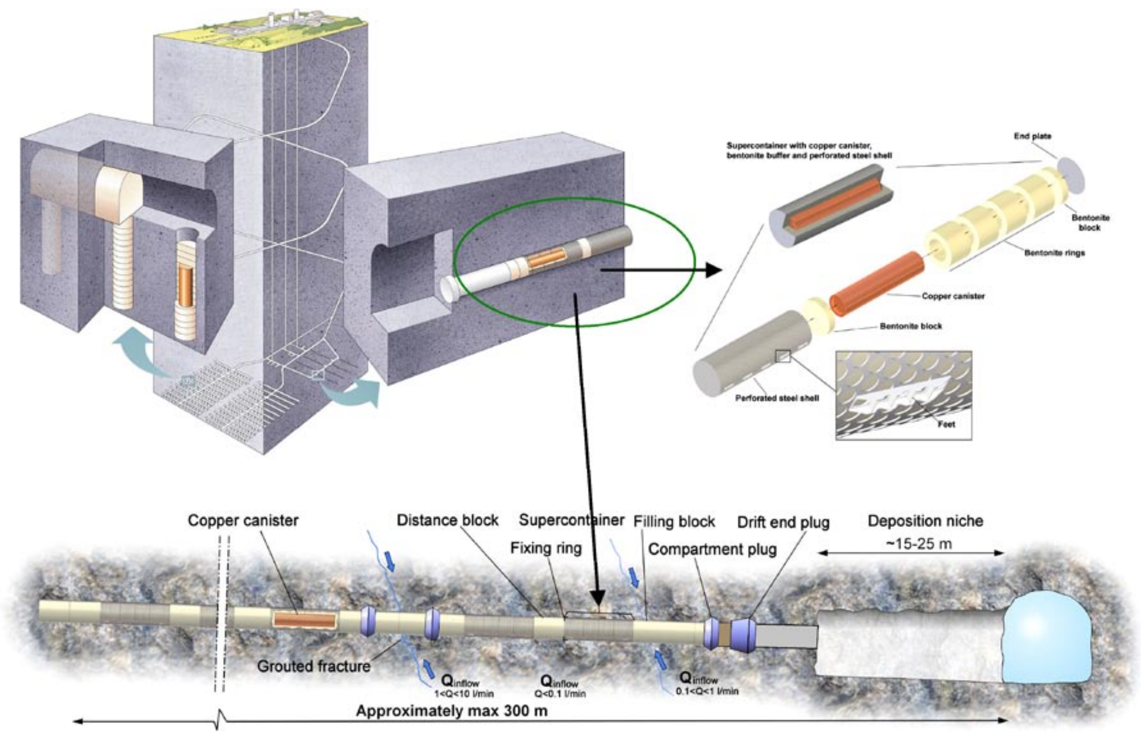


Figure 2-1. *Principles of the KBS-3V (upper left) and KBS-3H (upper right) repository designs and a more detailed illustration of the KBS-3H design (lower) and the supercontainer (upper right).*

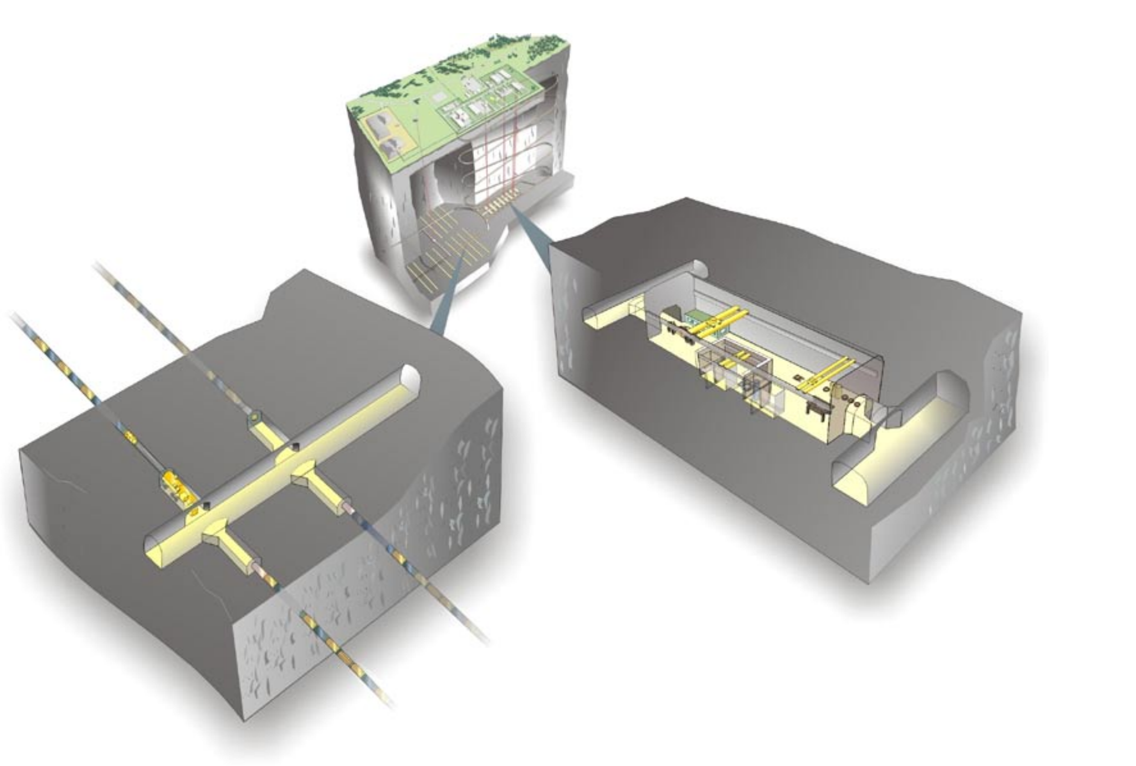


Figure 2-2. *General KBS-3H layout (top) with the reloading station (right) and deposition area with the transport tunnel, main tunnel, the deposition niche and deposition drifts (left). Main tunnel, deposition niches, and deposition drifts.*

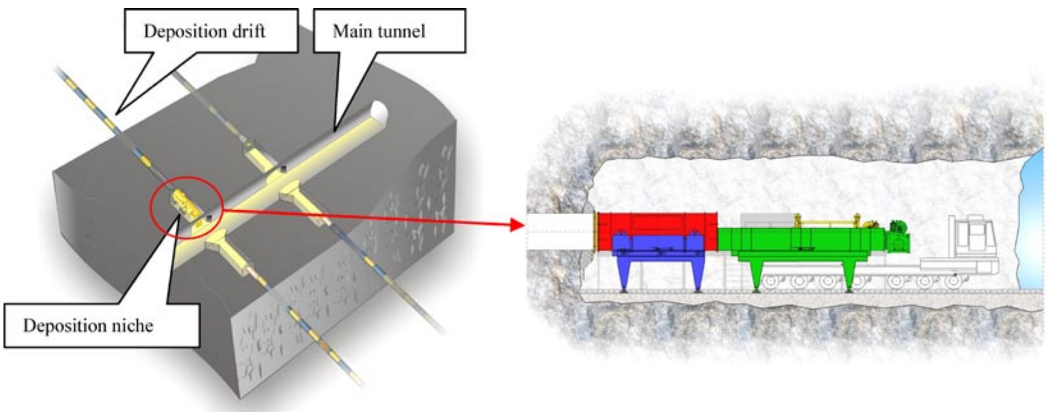


Figure 2-3. *Main tunnel, deposition niche, and deposition drifts in the KBS-3H repository design. See Figure 8-6 for present estimate for dimensions of the deposition niche.*

The access to the SKB deposition area is through one transport tunnel, whereas the Posiva design assumes that two transport tunnels with separate functions. Another important difference is how to ensure that the temperatures at the canister surface are not too high to impair the buffer functions. The optimisation work at SKB led to the result that the deposition drifts are separated by 40 m and the Posiva design that the drifts are separated by 25 m. A total of around 45,000 m of deposition drifts are needed with a total volume for deposition drifts being around 120,000 m^3 for the Swedish programme assuming 4,500 canisters and around 46,000 m of deposition drifts for the Finnish programme assuming 2,840 canisters. By having the 40 m distance SKB can put the canisters closer in a drift than the Posiva design. Up to 28 canisters will be deposited in each drift for the Swedish fuel, and layout principle at Forsmark site. For Olkiluoto with Finnish spent fuel and layout adaptation principle the estimated canister per drift is about 16–18. The results for KBS-3H design, also accounting for the site-specific thermal properties of the rock are that the nominal length of the distance block is 5.475 mm for the Posiva reference conditions and about 2.5 m for the expected SKB reference conditions, however, the design presented in this report is based on Posiva's design data because it was used as basis for safety assessment for a KBS-3H repository at Olkiluoto.

A general feature concerning the layout is the different types of spent fuel elements in use, depending on the reactor type. Posiva e.g. has to consider three types of fuel elements, 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 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.

Although most repository parts other than the deposition drifts and deposition niches are similar in principle, there is a difference between KBS-3V and KBS-3H in the design of the reloading station. The following functions are incorporated in the KBS-3H design:

- 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 placement in the supercontainer inside the shielded handling cell.
- Assembly of the supercontainer inside the transport tube within the shielded handling cell; the transport tube will later be transferred from the reloading station to the deposition area.

In the KBS-3H design, if necessary, drifts sections that are suitable for the emplacement of the spent fuel assemblies are compartimentalised to isolate them from sections that are not suitable due to water inflow. The division into compartments is accomplished through the use of compartment plugs. The canister and buffer are placed in a perforated steel shell and the entire assembly is called supercontainer and it is emplaced in the horizontal drift. A distance block of compacted bentonite, a key component in the design, is positioned between each supercontainer to obtain proper thermal spacing and isolation. One of the most important functions of the distance block is to seal the drift section between the supercontainers to prevent flow and advective transport along the drift. The sealing and plugging is assumed to occur when the distance block absorbs water, swells and obtains proper swelling pressure.

Two KBS-3H repository candidate designs called Basic Design (BD) and design based on Drainage, Artificial Watering and air Evacuation (DAWE) were developed in KBS-3H project based on two different functional principles. At later phase of the project the BD alternative was found not to be robust in drifts with several large inflows of the order of 0.1 l/min or less and therefore a third less mature alternative called Semi Tight Compartments design (STC) was introduced to function in these conditions. As a result there are three different variations (candidate designs) of the KBS-3H design. These alternatives are described in Chapters 5, 6 and 7. The development during 2005–2007 was mainly focused on BD and DAWE alternatives. However, the significant uncertainties related to feasibility of BD alternative motivated the introduction of the novel STC design after mid 2007.

The different design alternatives BD, DAWE and STC, see Figure 2-4, have several similar design components, the most important ones being the deposition drift, compartment, supercontainer, compartment plug, drift end plug and distance blocks. The similar components, differences in design and maturity of these are summarised in Tables 2-1 to 2-3. The maturity reflects the status of work on that specific component and focusing of limited design resources on issues which were assessed as being critical for the technical feasibility of the design alternatives. The maturity of these designs is presented in three different levels: a) Schematic design describes the conceptual design principles (lowest level of details) made in schematic design phase, b) Preliminary design describes the design made in design development phase after schematic design. This is used to estimate roughly e.g. material types, quantities and structural composition, c) Detailed design describes the design in sufficient details to be implemented (highest level of details). Some important features of different candidate designs are presented in Sections 2.2, 2.3 and 2.4.

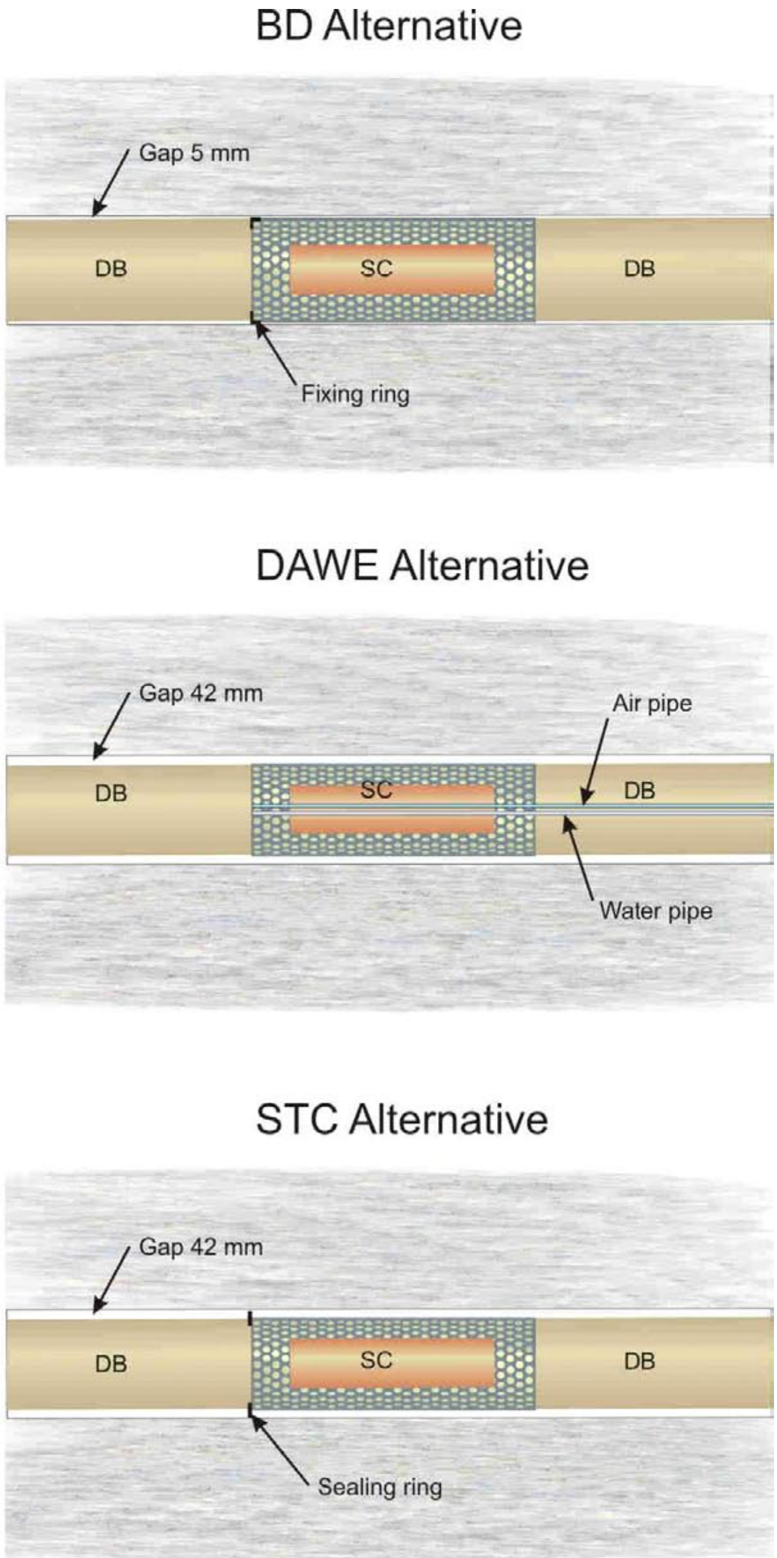


Figure 2-4. *A section containing a supercontainer (SC) with adjoining distance blocks (DB) in different KBS-3H design alternatives: Basic Design (BD) (on top), Drainage, Artificial Watering and air Evacuation (DAWE) design (in the middle) and Semi Tight Compartment (STC) design (on bottom). Note that the pipes in DAWE alternative are removed during operation.*

Table 2-1. Table of design components similar in all KBS-3H design alternatives. The maturity of these designs is presented in three different levels: a) Schematic design describes the conceptual design principles (lowest level of details), b) Preliminary design describes the design made in design development phase after schematic design, c) Detailed design describes the design in sufficient details to be implemented (highest level of details).

Design component	Maturity of design	Note of key requirements	Uncertainties and important issues
Deposition drift	Detailed design.	Requirements are mainly related to geometry, surface straightness and inflows.	The drift acceptance criteria are to be developed. Assumed drift length range 100–300 m may be optimized depending on layout and site-specific features. Technique to produce straight pilot holes is to be verified.
Deposition niche	Schematic design.	Host and allow operation of the deposition equipment.	Dimensions and shape are to be optimized.
Compartment	Preliminary design.	Sections with inflow roughly from 1 to 10 l/min per supercontainer section (approximately 10 m long) are isolated by using compartment plugs.	The inflow limit criterion is rough and needs to be evaluated more thoroughly. The length of compartments is to be optimized based on e.g. on groundwater control and pipe removal technique.
Drift end plug	Preliminary design.	The plug should take a full hydrostatic water pressure of 5 MPa and swelling pressure from buffer.	Alternative designs and materials available. Needs to be tested. The total length of the drift end plug and filling components is to be defined more thoroughly.
Compartment plugs	Detailed design.	The plug should take a full hydrostatic water pressure of 5 MPa.	The assembly and function is to be tested at Äspö to verify the design and give guidelines for further development. The length of plugged inflow section may be overly conservative and should be evaluated.
Spray and drip shields	Detailed design.	The drip shields should prevent spraying of water on buffer, which may cause erosion.	Has been tested at Äspö.The number of drip shields is site-specific.
Supercontainer	Detailed design.	Positioning criteria is inflow of 0.1 l/min or less in supercontainer section.	Has been manufactured and has been tested at Äspö by using low strength concrete. Test using buffer blocks are to be carried out.
Supercontainer shell	Detailed design.	To keep the canister and buffer in one package during emplacement.	Manufactured and tested at Äspö. The replacement of steel in the supercontainer shell is evaluated for long-term safety reasons. The degree of perforation of end plates is still to be adjusted.
Bentonite in supercontainer	Detailed design.	General requirements for bentonite buffer.	Initial water content and dry density depends on design alternative and resolution of critical issues.
Filling blocks	Schematic design.	Filling blocks are placed in positions where inflows are larger than 0.1 l/min and less than 1 l/min. The blocks support the function of buffer.	The inflow limit estimate is rough and needs to be evaluated more thoroughly. The limiting distances to inflows may need adjustments. The lengths and dimensions could be defined in more detail to improve efficiency.
Filling material	Schematic design.	Resist erosion and support the function of distance and filling blocks.	The dimensions are open and may be overly conservative in the design.

Table 2-2. Table of design components and differences in KBS-3H design alternatives. See caption in Table 2-1 for different levels of maturity.

Design component	BD	DAWE	STC	Maturity of design	Note of key requirements	Uncertainties and important issues
Distance block BD (tight gap between of about 5 mm)	x			Detailed design.	Bentonite buffer requirements apply to distance blocks. These are positioned in supercontainer sections where inflow is equal to or less than 0.1 l/min.	The tests showed that the design is not robust and may not fulfill the requirement in all situations.
Fixing rings	x			Preliminary design.	The fixing rings are placed adjacent to distance blocks in positions where inflow is larger than 0.01 l/min. Fixing rings have to prevent the movement of distance block under full groundwater pressure.	The inflow limit criterion is rough and needs to be evaluated more thoroughly. The tests showed that the design is not robust and may not fulfill the requirement in all situations.
Distance block DAWE (loose gap of about 42.5 mm)		x		Preliminary design.	Bentonite buffer requirements apply to distance blocks. These are positioned in supercontainer sections where inflow is equal to or less than 0.1 l/min.	The behavior after wetting and development of swelling to prevent possible piping is uncertain and is to be verified.
Distance block STC(loose gap of about 42.5 mm)			x	Preliminary design.	Bentonite buffer requirements apply to distance blocks. These are positioned in supercontainer sections where inflow is equal to or less than 0.1 l/min.	The behavior during and after wetting, possible piping, erosion and development of swelling to prevent possible piping is uncertain and is to be verified.
Sealing rings			x	Schematic design.	The sealing rings facilitate the swelling of distance blocks by allowing the supercontainer section to be filled with water until possible piping occurs	The sealing rings are to be designed in more detail in order to evaluate their functionality and conceptual principle.

2.2 Basic Design (BD) alternative

BD design alternative is based on assumption that the distance blocks will seal the wet supercontainer sections after emplacement stepwise in sequence independently of each other. The main idea with the BD design is to hydraulically isolate every supercontainer section from each other immediately after installation. During the installation of a deposition drift there will be no water flow from one supercontainer section to another. This is mainly achieved by the rapidly sealing distance blocks, which are designed in order to prevent all water flow between the supercontainer sections during the installation and also during the following saturation phase. Important design features specific to BD design alternative are the small, about 5 mm, gap between the distance blocks and the rock surface, requirement for a small gap between the supercontainer and the distance block and need for fixing rings to keep the distance blocks from moving when exposed to hydraulic pressure.

2.3 Drainage, Artificial Watering and air Evacuation (DAWE) alternative

In DAWE design alternative the empty void space in the gaps between the drift wall and the buffer inside a sealed compartment will be artificially water filled by using watering pipes. The length of the compartments is maximum the length of the deposition drift but can be shorter depending on inflow of groundwater. For the DAWE design the length of the compartment will

Table 2-3. Table of operational features and differences in KBS-3H design alternatives. See caption in Table 2-1 for different levels of maturity.

Operation	BD	DAWE	STC	Maturity of design	Note of key requirements	Uncertainties and important issues
Deposition equipment	x	x	x	Detailed design. Has been tested at Äspö using concrete blocks as dummies for distance blocks.	To emplace supercontainers according to design specifications.	The effectiveness and operational reliability of the equipment is being tested at Äspö using concrete blocks as dummies. To be tested using buffer. The need for additional devices for protection from water is to be evaluated during operation.
Emplacement of distance blocks	x	x	x	Preliminary design based on using concrete blocks with the deposition equipment.	The blocks should not deform or be damaged during emplacement.	The emplacement of distance blocks in BD alternative by using deposition equipment is not proven and is assessed as not being robust.
Emplacement of filling blocks	x	x	x	Schematic design based on using deposition equipment.	The blocks should not deform during emplacement.	The filling blocks are assumed to be similar as the distance blocks in all alternatives. This should be re-evaluated during detailed design.
Installation of fixing rings		x		Schematic design of installation.	Key requirements in operation are the installation time and operational safety.	Detailed design is required for further evaluation.
Installation of sealing rings			x	Schematic design of installation.	Key operational requirements are the installation time and operational safety.	Detailed design is required for further evaluation.
Use of wetting pipes		x		Preliminary design.	Removal is key requirement. Required wetting times are rough estimates.	Removal is to be tested in full scale. The pipe system (e.g. number of pipes) is to be optimised. The possibility to allow natural wetting in certain situations is to be evaluated.
Use of air evacuation pipes		x		Preliminary design.	Removal is a key requirement.	Removal is to be tested in full scale.

also depend on the feasibility to remove the pipes. The wetting is made rapidly in order to accelerate the swelling of the distance blocks and the void spaces around the supercontainers and the distance blocks. Buffer will swell and isolate the supercontainer sections almost simultaneously because all open connected void space in the DAWE design is filled with water at hydrostatic groundwater pressure, there will be no significant pressure gradients right after water filling that could be the driving forces for flow between the supercontainer sections. Hydraulic pressure differences between the neighbouring supercontainer sections that could potentially lead to buffer erosion by water flow and to mechanical displacement of the supercontainers and distance blocks are thus prevented during the operational period of a drift compartment. Furthermore, although the hydraulic pressure differences may still develop between the drift sections, the fact that they are water filled means that tighter drift sections do not provide sink volumes for potential water flow from the drift sections intersected by transmissive fractures, at least for an initial period following artificial watering and air evacuation. The watering time is expected to be about 14 hours at most for a 150 m long drift compartment. It should be noted that only about one third of the total void space (including bentonite pores) will be filled with water in this way, the remaining voids being less readily saturated. The system remains, therefore, in a partially saturated state even after artificial watering. All supercontainer sections will be filled simultaneously to avoid axial water flows that could give rise to bentonite erosion and redistribution along the drift.

In the case of DAWE design, like in BD, fractures that could give rise to significant water flows to adjacent unsaturated drifts or transport tunnels will be avoided as supercontainer emplacement locations. The drainage of inflowing water along the floor of the drift during operations in the DAWE alternative is achieved by inclining the drift towards its entrance. There is a gap of ca. 42 mm between the distance blocks and the drift walls, which is larger than in the BD (roughly 5 mm) and should prevent any contact with the water flowing along the bottom of the drift. Furthermore, a higher initial-water-content bentonite is used to prevent humidity-induced fracturing of the distance blocks. Drainage of inflowing water along the drift floor is expected to continue until the drift or the drift compartment is plugged. Following sealing of the compartment, artificial watering takes place simultaneously with evacuation of air to avoid gas pressurisation. Steel pipes along the surface of the drift are used for watering and air evacuation. The air evacuation pipe is lead 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 operations. Nozzles, which are directed downwards in the watering pipes are distributed along the drift in each supercontainer section to ensure uniform inflow and minimise any axial water flow in the drift that could give rise to bentonite erosion. Water is not directly injected in the sections where the distance blocks are positioned, again to avoid possible erosion.

2.4 Semi Tight Compartment (STC) alternative

The testing of distance blocks in the BD design alternative and modeling of distance block behavior indicated that the distance blocks may not withstand the full hydrostatic 5 MPa water pressure. One solution to resolve the problem could be therefore to allow limited piping and erosion between supercontainer sections before all sections are filled with water.

In the STC design, each section will be sealed with distance blocks and sealing rings that temporarily prevents water from flowing from one section to another before the section is filled with inflowing water. When the section is filled with water the distance blocks cannot withstand the high water pressure so there will be piping and flow of water into the next section. Since there are no demands on the distance blocks and sealing rings except than sealing off the groundwater from a supercontainer location, the blocks can be made with the same 42 mm gap between the distance blocks and the drift walls as in DAWE alternative. To prevent the flow of water, there must be a sealing ring or very light sealing at each distance block section. This sealing can be made without any demand on strength or as a gasket. Figure 2-5 shows the layout of distance blocks and sealing rings in the STC design.

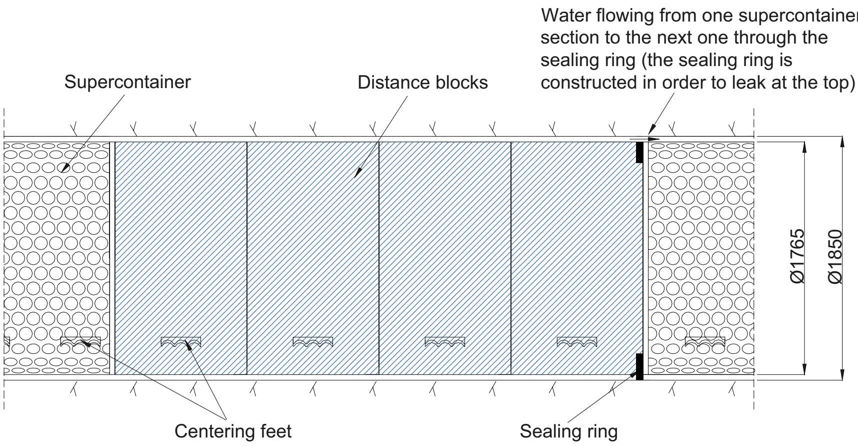


__Figure 2-5.__ Layout of Semi Tight Compartment (STC) design. The "sealing ring" only needs to withstand a couple of meters water head. This ring is not designed but only outlined.

3 Design basis

3.1 General

The basis for design is divided into the following categories:

- Functional requirements: specify how the buffer system must perform.
- Environmental boundary conditions: describe the properties of the bedrock where the buffer system must perform according to the functional requirements.
- Technical prerequisites: specify the aspects of the technical design that are fixed and cannot be changed (e.g. the diameter of the deposition drift).
- Design guidelines: describe the advice, instructions, opinions and proposals offered by experts to be followed to fulfil the functional requirements.

The requirements mentioned above, along with other general functional requirements, environmental boundary conditions, technical prerequisites, general design guidelines, and candidate design specific guidelines for developing a repository design were presented earlier by /Autio 2007/. Subsequently, several important changes in the design basis were realized:

a) The long-term safety requirements were revised resulting in some significant new requirements particularly with respect to canister positioning, which affects drift utilisation degree.

b) The maximum rate of increase in groundwater pressure was evaluated and increased from 100 kPa/h to a few MPa/h.

c) The supercontainer end plate structure was modified from perforated to solid. It was previously assumed that the supercontainer design is fixed, however, it was necessary to alter the end plate structure to obtain the required sealing functionality.

d) The operational times depend on the design of distance blocks. The emplacement technique presented earlier by /Autio 2007/ is not valid for "tight distance blocks" in the BD alternative and therefore a new technique was developed. The technique used for emplacement of distance blocks in the DAWE alternative is assumed as fixed and remains as previously described /Autio 2007/.

e) The long-term safety consequences of the interaction between the steel components and the bentonite surrounding the canisters are still under investigation; no quantitative restrictions for the use of steel have been specified thus far.

3.2 Safety functions and how they are provided in the current design

The long-term safety requirements are presented in /Smith et al. 2007a/ and include both qualitative and quantitative requirements for various system components. The description in this section is reproduced from /Smith et al. 2007a/ to highlight the most important long-term safety related requirements with respect to design.

3.2.1 Safety functions in KBS-3H

The canister, the buffer (i.e. the bentonite material originally inside the supercontainers, together with the distance blocks) and the host rock are the main KBS-3H system components that together ensure isolation of the spent fuel and containment of radionuclides according to the safety concept. Other system components, including the filling blocks, the compartment and drift end plugs, the steel supercontainers, fixing rings and other structural materials, have not been assigned safety functions. They are, however, designed to be compatible with, and support the safety functions of, the canister, the buffer and the host rock.

The main safety function of the canisters is to ensure a prolonged period of complete containment of the spent nuclear fuel as in the case of KBS-3V. 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.

The safety function of the canister is common to the KBS-3V. Safety functions of the buffer are (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. The current KBS-3H design includes the use of steel components external to the canisters that will corrode over time and give rise to potentially porous or fractured corrosion products. These may interact chemically with adjacent bentonite and the slow formation of an altered zone with perturbed mass-transport properties at the bentonite / rock interface at supercontainer locations cannot be excluded. A final safety function of the KBS-3H buffer (or, more specifically, the distance blocks) is, therefore, (c), to separate the supercontainers hydraulically one from another, thus preventing the possibility of preferential pathways for flow and advective transport within the drifts through the corrosion products or altered buffer.

The safety functions of the host rock are again the same as for the KBS-3V. They are (a), to isolate the spent fuel from the biosphere, (b), to 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 (c), to limit and retard both the inflow of harmful substances[1] to the engineered barrier system and radionuclide releases to the biosphere.

3.2.2 Design requirements to support the safety functions

(i) Design requirements related to mutual compatibility of the system components

A requirement common to all engineered system components, including not only the canister and the buffer, but also the filling blocks, the compartment and drift end plugs, the steel supercontainers shells and other structural materials, is that they should be mutually compatible. Although all components will inevitably undergo physical and chemical changes over time (e.g. due to chemical alteration or corrosion, saturation, swelling), none should evolve in such a way as to significantly undermine either the long-term safety functions or the design functions of the others. Thus:

- no component should contain any chemical constituents that lead to significant negative effects on the performance of the others,
- no component should generate gases at rates that could lead to a build-up of potentially damaging gas pressure (taking into account the gas permeability of the other components),
- no component should give rise to mechanical stresses that could lead to significant damage to the canisters or host rock,
- no component should undergo volume changes (due, e.g. to swelling, compaction, corrosion or alteration) that could lead to significant changes in density of the adjacent buffer.

The degree to which the current reference design meets these requirements is discussed in /Smith et al. 2007a/. In particular:

[1] Including the chemically toxic components of spent fuel, as discussed in the report /Neall et al. 2007/.

- the significance of interactions of iron and cement with the buffer and (in the case of cement) the host rock,
- the issue of gas generation and pressurisation of the drift,
- the potential for buffer swelling pressure and gas pressure to damage the rock,
- the stability of the canister under isostatic loading.

Scoping calculations of potential buffer density changes during the early phase of evolution are discussed in detail in /Gribi et al. 2007/ and in /Smith et al. 2007a, Appendix B.4/. The range of densities compatible with the buffer fulfilling its safety functions taking into account the evolution of groundwater and buffer porewater salinity (1,890 to 2,050 kg/m^3) is also discussed in /Smith et al. 2007a/ and in Appendix A.5 of the present report.

The following sections describe design requirements over and above the general requirement of mutual compatibility, which are intended to support the safety functions, and indicate how they are met in the current design.

(ii) Design requirements to support the safety function of the canister

This 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 the 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 system but the safety assessment must address less likely situations as well.

In order to achieve its design lifetime, canisters are required to have:

1. a low probability of occurrence of initial penetrating defects,
2. corrosion resistance,
3. mechanical strength.

The probability of occurrence of initial penetrating defects is still under investigation. In the current design, corrosion resistance is provided by the copper canister shell, and mechanical strength primarily by the cast iron insert.

The minimum design lifetime also implies a number of design requirements on repository layout (avoidance of fractures that may undergo shear movements that could damage the canisters and the buffer).

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.

(iii) Design requirements to support the safety functions of the buffer

The first safety function of the buffer (a, Section 3.2.1) is to protect the canisters from external processes that could compromise their safety function of the complete containment of the spent fuel. Corresponding design requirements on the buffer are that it should be:

- sufficiently plastic (or ductile) to protect the canister from small rock movements, including shear displacements smaller than 10 cm at canister locations (see Figure 3-1),
- sufficiently stiff to support the weight of the canisters and maintain their central horizontal positions in the drift in the long term,

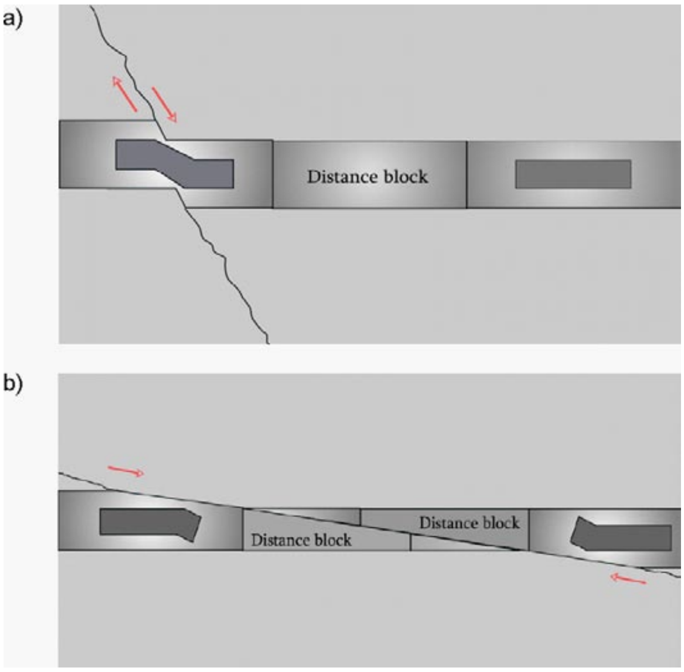


Figure 3-1. Shear movements on a), a subvertical and b), a subhorizontal fracture intersecting a KBS-3H drift /Smith et al. 2007a/.

- dense enough that microbes are metabolically barely active in the buffer and thus do not give rise to unfavourable chemical conditions at the canister surface,
- sufficiently impermeable, once saturated, that the movement of water is insignificant and diffusion is the dominant transport mechanism for corrosive agents present in the groundwater that may reduce the lifetime of the canisters.

A further safety function of the buffer (b, Section 3.2.1) is to limit and retard the release of any radionuclides from the canisters, should any be damaged. This implies design requirements that the buffer be:

- again impermeable enough, once saturated, that the movement of water is insignificant and diffusion is the dominant radionuclide transport mechanism;

and have:

- a sufficiently fine pore structure such that microbes and colloids are immobile (filtered) and microbe- or colloid-facilitated radionuclide transport will not occur.

It also implies a self-healing capability of the buffer, 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 are rapidly closed.

These safety functions are common to the KBS-3V and KBS-3H. In addition, for the KBS-3H design the final safety function of the buffer (c, Section 3.2.1) is to separate the supercontainers hydraulically one from another. This implies a design requirement that the buffer should provide:

- tight interfaces with the host rock within a reasonable time.

Competing requirements on buffer density are balanced in the design process. For example, excessive density would lead to a correspondingly high swelling pressure and to a risk of damage to the rock. It would also offer less protection of the canisters from rock movements. On the other hand, insufficient density would lead to the possibility of colloid-facilitated radionuclide transport. The choice of MX-80 bentonite as a buffer material with a design target for saturated density of 2,000 kg/m^3 is made with a view to balancing these various requirements.

The filling blocks are not considered part of the buffer and are not assigned any long-term safety functions – i.e. they are not required to contribute directly to the isolation of the spent fuel and containment of radionuclides. On the other hand, in the current design, they have the same properties as the buffer as they are likely, in practice, to contribute to the limitation and retardation of the release of any radionuclides from the canisters, should any canisters be damaged.

During the saturation of the repository, high hydraulic pressure gradients and gradients in buffer swelling pressure may develop along the drifts, which could potentially lead to phenomena such as piping and erosion of the buffer and displacement of the distance blocks and supercontainers. The distance blocks and filling blocks, together with the compartment and drift end plugs, have the important design function of keeping the adjoining buffer in place, and not allowing any significant loss or redistribution of buffer mass by piping and erosion during the operational period and subsequent period of buffer saturation. In the BD alternative the fixing rings also have the short-term safety-related design function of preventing displacement of a distance block while the adjoining components are installed. The distance blocks and filling blocks have a low hydraulic conductivity at saturation and will develop swelling pressure against the drift wall, such that friction will resist buffer displacement. Furthermore, each compartment plug is designed to stay in place under the applied loads (i.e. no significant displacement are allowed) until the next compartment is filled and a further compartment plug or drift end plug installed. Likewise, the drift end plug is designed to stay in place under the applied loads (no significant displacement allowed) until the adjoining transport tunnels are backfilled.

The temperature of the buffer is kept below 100ºC to avoid significant chemical alteration of the buffer that could undermine its ability to satisfy the above requirements. This in turn imposes requirements on buffer layout and dimensioning.

(iv) Design requirements to support the safety functions of the host rock

Unlike the engineered components of the repository, the implementer has no control over the undisturbed properties of the host rock, except in as far as by grouting of intersecting transmissive fractures during construction to avoid drawdown of surface waters and upconing of saline groundwaters, and by adaptation of the depth and layout of the repository, for example, to avoid unacceptable features (see /Smith et al. 2007a/). It should be noted, however, that grouting also affects the rock mass properties. Futhermore, it should be noted, however, that backfilling and sealing of the repository cavities 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 the inadvertent human intrusion to the repository more difficult. Requirements on the host rock related to site selection are similar to those for the KBS-3V design and will not be further discussed here.

(v) Design requirements related to the issue of repository gas

The repository must be designed so as to avoid the build-up of potentially damaging pressures due to repository-generated hydrogen gas from corrosion of supercontainer steel shell and structural components, and after canister failure also corrosion gases formed due to corrosion of the cast iron insert. This does not imply that the drifts and access tunnels need to be gas permeable, provided gas can escape to from the drift by other routes, e.g. via transmissive fractures in the rock. The issue of gas pressurisation in the repository near field is discussed in /Gribi et al. 2007/ and in /Smith et al. 2007a/.

3.2.3 Use of safety function indicators in safety assessment

To assess the performance and safety of a KBS-3H or KBS-3V repository, it is necessary to assess the conditions under which the identified safety functions will operate as intended, and the conditions under which they will fail, or operate with reduced effectiveness. Following the methodology adopted in the Swedish SR-Can safety assessment /SKB 2006ab/, KBS-3H safety studies make use of the concept of safety function indicators and associated criteria. One or more safety function indicators are 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. If the safety function indicators fulfil certain criteria, then the safety functions can be assumed to be provided. If, however, plausible situations can be identified where the criteria for on one or more safety function indicators are not fulfilled, then the consequences of loss or degraded performance of the corresponding safety function must be evaluated in the safety assessment.

It is important to distinguish design requirements from the criteria on safety function indicators. In general, design requirements refer to 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. Repository design also aims to ensure that the criteria on the safety function indicators are fulfilled over the required time frames, but this is seen as a target, rather than as a design requirement.

Adherence to design requirements is primarily the concern of design studies, whereas safety studies focus more on the fulfilment of safety function indicator criteria, taking into account the associated uncertainties. It is emphasised that, if there are plausible situations where one or more criteria on safety function indicators are not satisfied, this does not imply that the system as a whole is unsafe. Such situations must, however, be carefully analysed, for example by means of radionuclide release and transport calculations, as described in /Smith et al. 2007b/.

The following description of safety function indicators is based on the Evolution Report for the KBS-3H long-term safety assessment /Smith et al. 2007a/. The canisters, mineral alteration of buffer, freezing of buffer and indicators to host rock except rock shear and inflow rates are not addressed below but are described in /Smith et al. 2007a/.

Safety function indicators and criteria for the buffer

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

The loss or redistribution of buffer mass due, for example, to piping and erosion by flowing water could in principle lead to:

- 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 increased 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 buffer hydraulic conductivity, which, if sufficiently high, could lead to 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 affect),
- 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),
- 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 than 10 cm.

Consideration of the all three possible modes for loss or degradation of the buffer safety functions (loss or redistribution of buffer mass, mineral alteration of the buffer, or freezing of the buffer) leads to the safety function indicators and associated criteria that are summarised in Table 3-1. Most are taken directly from SR-Can. It should be noted that the criterion that there is a negligible impact on the rheological and hydraulic properties of the buffer due to mineral alteration subsumes the SR-Can criterion for a Swedish KBS-3V repository that buffer temperature remains below 100°C. The potential chemical processes that may occur at elevated temperature are, for example, silica dissolution, transport and precipitation of silica or aluminosilicate minerals. But neither experimental nor natural analogue studies have shown that there processes will actually occur. The effect of buffer cementation due to silica precipitation is, however, an issue for further work. The present criterion takes account of the concern that the buffer of a KBS-3H repository may be more affected by certain chemical interactions, and particularly those between the corrosion products of steel components external to the canisters and bentonite and those between cementitious materials and bentonite, than is the case for a KBS-3V repository.

Safety function indicators and criteria for the host rock

Safety-related aspects of the hydraulic properties of fractures intersecting a drift at canister and buffer emplacement locations are discussed in /Smith et al. 2007a, see Appendix A.4/, as well as the host rock safety function indicators and associated criteria.

One important safety function indicator, which has impact on design is limited rock shear at canister/distance block locations in deposition drift. The criterion for this is < 10 cm and the rationale is to avoid canister failure due to rock shear in deposition drift. This has site-specific impact on the selection of supercontainer positions and drift utilisation degree.

In terms of the transport barrier provided by the geosphere, a 10 m long transport path having a transmissivity of about 3×10^{-9} m^2/s provides a transport resistance in the order of 10,000 years per metre, which corresponds to an effective geosphere transport barrier for many safety-relevant radionuclides.

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

Safety function indicator	Criterion	Rationale
Bulk hydraulic conductivity	< 10–12 m/s	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 interaction 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 alternative since, in KBS-3H, the weight of the canister is distributed over a larger horizontal area compared to KBS-3V.

From the evaluation of the hydraulic properties of fractures intersecting a drift at canister and buffer emplacement locations, it is concluded in /Smith et al. 2007a/ that a transmissivity limit of about 3×10^{-9} m^2/s for fractures intersecting the drift at canister and buffer emplacement locations is desirable from the point of view of long-term safety. This is corresponds roughly to a maximum inflow of 0.1 litre per minute during saturation, which is the present rough estimate for the maximum inflow if the possibility of piping and erosion is to be avoided. This criterion is derived in the first place from considerations of the geosphere transport barrier. In practice, however, it is unlikely that selecting locations for canister and buffer is based on transmissivity directly, but largely on observations made at the drift wall, and other quantities including inflow, that can be measured directly.

3.3 Groundwater pressure increase rate

The research and development of distance block design in the BD alternative demonstrated the possibility that flow channels ("piping") might form through the distance block adjacent to the rock interface if the distance block design is not adequate /Börgesson et al. 2005/. This phenomenon was specified as a critical issue for resolution and is addressed in current buffer tests. The development of a proper design is apparently very sensitive to inflow rate (Q) from the surrounding rock into the open volume (V, on the order of a few cubic meters) between supercontainer sections (i.e. filling time of the open volume), rate of pressure increase, and time until the full hydrostatic pressure is reached after the volume was filled with water (Figure 3-2).

Appendix B in /Autio et al. 2007/ provides assessments of the rate of increase in groundwater pressure in a sealed supercontainer section. To the extent possible, these estimates were based on Olkiluoto-specific hydrological data. The estimates for the pressure increase from initial atmospheric pressure to a full hydrostatic pressure of 4 MPa with time in the supercontainer section were derived from two simplified cases. The first case evaluates a closed supercontainer section allowing for no escape of air, and the second case considers the increase in hydraulic pressure after the escape of air. Input inflows were in the range of 0.1 l/min to 1 l/min. These estimates were primarily derived for the planning of buffer tests to begin during 2006 and 2007 with the rate of pressure increase being one significant test parameter.

For the closed, supercontainer section scenario (first case), assuming the initial void space to be equal to the open space between the supercontainer and the drift wall, the maximum groundwater pressure build-up rate is 1.6 MPa/h at an inflow of 1 l/min or 0.16 MPa/h at an inflow of 0.1 l/min.

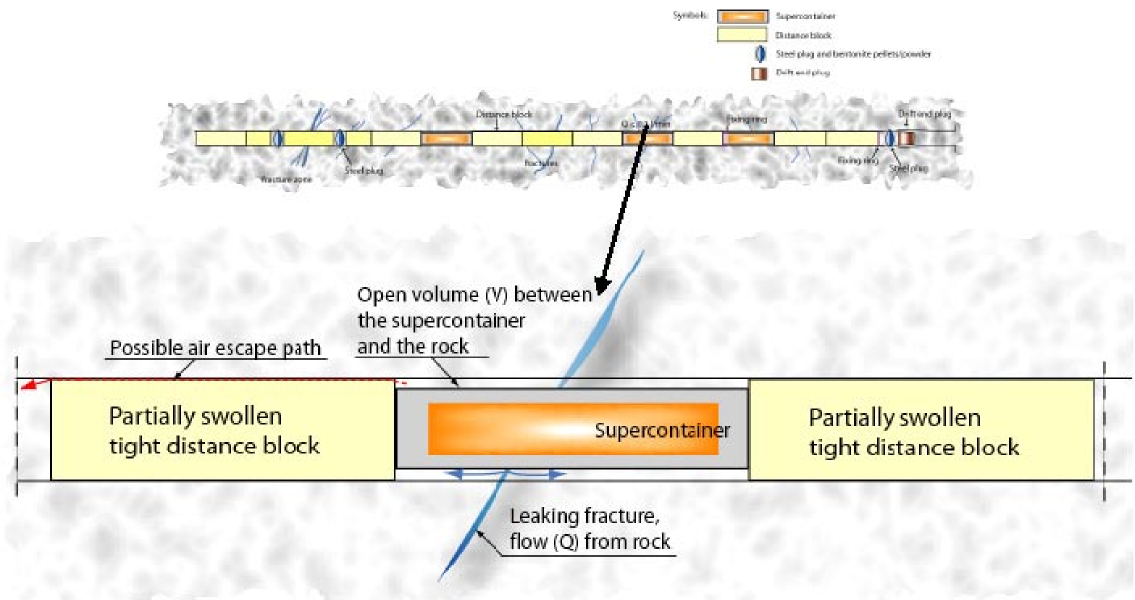


Figure 3-2. Groundwater inflow into the supercontainer section in the KBS-3H design.

For the scenario concerning hydraulic pressure after the escape of air (second case) the rate of increase is based on the solution to Theis's equation and, assuming radial flow, depends on the storativity to transmissivity ratio S/T, which is assumed to be in the range from 1 to 1,000. In the case of S/T equal to 100, a value relevant for the drifts considering the estimated storativity and possible transmissivities of the fractures, the maximum pressure build-up rate can be as high as 25 MPa/h. At smaller S/T ratios the pressure build-up rate increases and, conversely, at larger S/T ratios value, i.e., lower transmissivities, the pressure build-up rate decreases. Site-specific storativity data is lacking and causing uncertainties in the estimations. Furthermore, the analytic solution does not take into account the changing flow rate, which means that the resulting pressure increase rates are upper limits for a given S/T value.

The rate of pressure increase appears to change during the flooding of supercontainer sections. In the second case the pressure increase is very rapid after the escape of air, whereas in the first case where there is significant amount of trapped gas in the supercontainer section, the pressure increase starts significantly earlier but builds up at a slower rate.

The values of pressure increase rates presented above are rough estimates as they are based on simplified cases neglecting many phenomena, e.g., skin effects actually occurring in the drift, which may retard the actual pressure increase. Storativity values themselves are also quite uncertain. Nevertheless, the estimates are considered to give an idea of the possible range of the pressure increase rate.

Using the Discrete Fracture Network (DFN) modelling approach, /Lanyon and Marschall 2006/ also estimated the rate of pressure increase. Their results indicate the rate is largely controlled by the geosphere inflow and the assumptions concerning the storage term associated with the super-containers and distance blocks. In models where no storage is associated with the drift sections, the pressure rises very quickly with derivatives greater than 1 MPa/hr. In the models containing greater storage, either due to trapped air or the use of a larger storage term, the highest gradients are only associated with high transmissivity features located in blank (no supercontainer) or sealed sections. Typically, pressures rise faster around the distance blocks, as these have been associated with smaller storage terms. The effect of the storage term for a drift section intersecting a 0.1 l/min feature (transmissivity 2.65×10^{-9} m^2/s) is clearly seen in Figure 3-3 where for storage term (CT value) greater than 8×10^{-8} m^3/Pa the pressure derivative is below 100 kPa/hr.

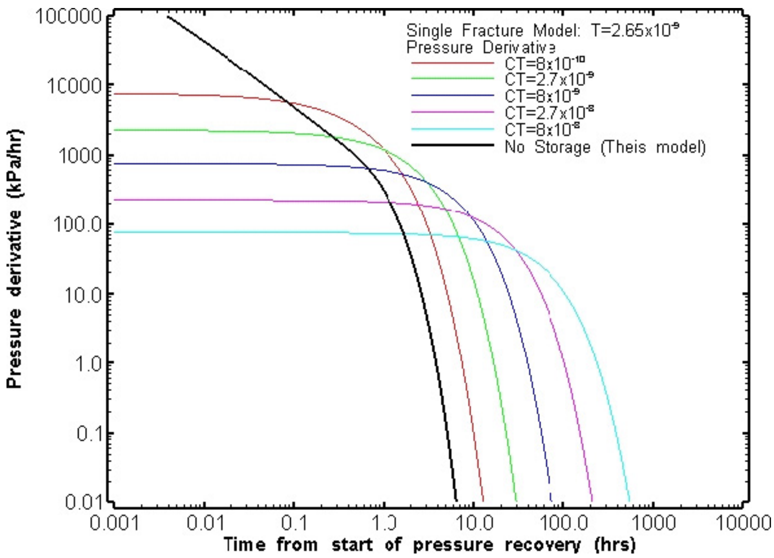


Figure 3-3. *Effect of storage term (CT in m^3/Pa) on pressure derivative (rate of pressure increase in kPa/hr) in a drift section intersecting a leaking fracture (inflow = 0.1 l/min, T = 2.65×10^{-9} m^2/s) using nSights models /Lanyon and Marschall 2006/.*

3.4 Drift quality

The present distance block designs in the BD alternative is based on having a tight part with no gap and loose part having a 15 mm wide gap between the distance block and drift surface. The presently defined nominal gap width between the rock surface and supercontainer is 42.5 mm. In the final state, this gap will depend on the geometric tolerances (e.g., straightness and surface roughness) of the drift and the size of the supercontainer. During operation the canister will be lifted and lowered stepwise, and the free gap will be reduced to something closer to 20 mm.

The drift geometry and quality requirements in the deposition drift for demonstration at Äspö are displayed in Figure 3-4. According to specification see Appendix G in /Autio et al. 2007/, the nominal drift diameter is 1,850 mm with an allowed decrease of 10 mm at a length of 300 m as a consequence of the expected wear and tear in the cutting head of the boring machine. Additionally, stepwise unevenness and roughness were specified with tolerances up to 5 mm each.

Further quality requirements in the KBS-3H drift, which originate from transport technique of the supercontainers are as follows:

- The maximum allowed deviation of the floor of the drift from ideal cylindrical shape including all sources of error, is ± 5 mm over the length of the canister (6 m).
- The maximum allowed deviation from the theoretical centre line of the tunnel at the end of the deposition drift (300 meters) is ± 2 meters in total (note that the deviation requirement in Figure 3-4 differs from that), which includes all horizontal and vertical deviation components.
- The maximum allowed waviness is R = ± 2.5 mm for the pilot hole over the length of the canister (6 m), see Figure 3-4.
- The maximum allowed roughness is 5 mm over a length of 1 meter.
- The deposition drift must have an inclination angle of 1.5–2.0 degrees upwards towards the end of drift; the larger inclination is favourable for muck flushing.

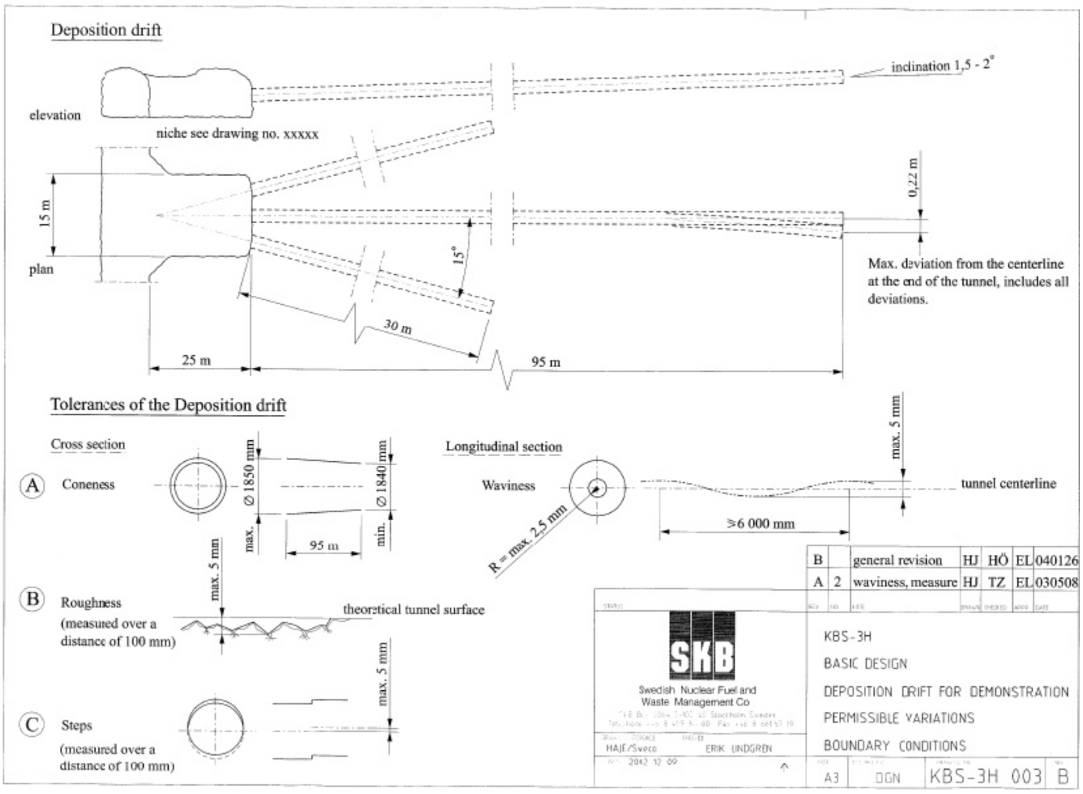


Figure 3-4. *Drift geometry and quality requirements in the deposition drift for demonstration at Äspö Hard Rock Laboratory.*

The 10 mm-reduction in drift diameter due to the cutter wear of deposition drift boring machine is the largest diameter variation expected. Additional reduction in effective diameter is caused by waviness and roughness, the maximum allowable deviation being ±2.5 mm (total 5 mm) in all directions at wavelength of 6 m or more (see Figure 3-4). A stepwise deviation of 5 mm was defined in vertical direction. This would result in a situation where the largest effective diameter reduction in vertical direction at the length of 300 m would be 20 mm, consisting of 10 mm diameter reduction, 5 mm waviness reduction and 5 mm stepwise deviation. The corresponding reduction of diameter in horizontal direction would be 15 mm, assuming that the stepwise deviation is excluded.

It should be noted, that to fulfil the requirements, it has been assumed that the ends of possible rock bolts and other permanent structures should be sunk e.g. by chamfering the rock surface.

3.5 Olkiluoto bedrock model

The KBS-3H design and analysis of long-term safety is based on Olkiluoto bedrock model 2003, as shown in Figure 3-5 /Vaittinen et al. 2003/. A new bedrock model was recently completed /Paulamäki et al. 2006, Ahokas and Vaittinen 2007/ and was used in the KBS-3H layout adaptation 2007 /Johansson et al. 2007/, as shown in Figure 3-6. The new bedrock model included some changes in the fracture zones and new hydraulic conductivity data for fractures and fracture zones.

The development of the new bedrock model has not resulted in any significant changes to the KBS-3H design itself. The direction of deposition drifts, number of compartments, etc has not changed, however, the adjustments in fracture zones produced some differences in the appearance of layout. Additionally, the new bedrock model and new data on hydraulic conductivity enabled a new layout adaptation (see Chapter 12).

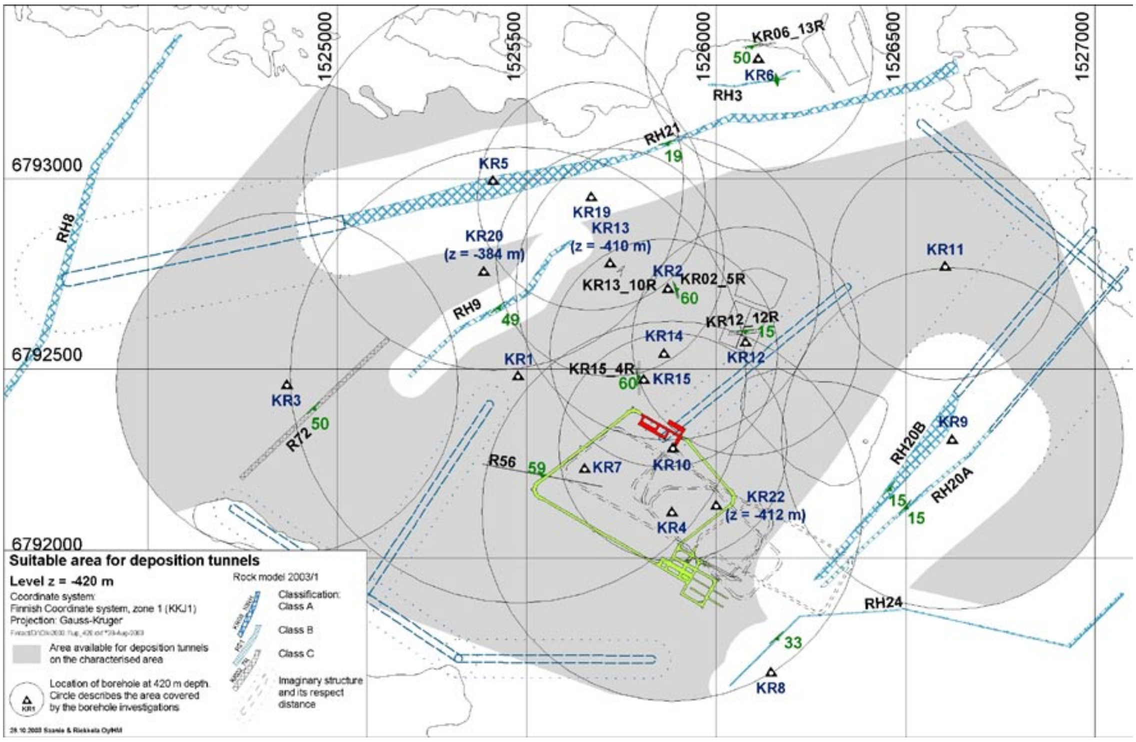


__Figure 3-5.__ Olkiluoto bedrock model 2003, level –420 m /Vaittinen et al. 2003/.

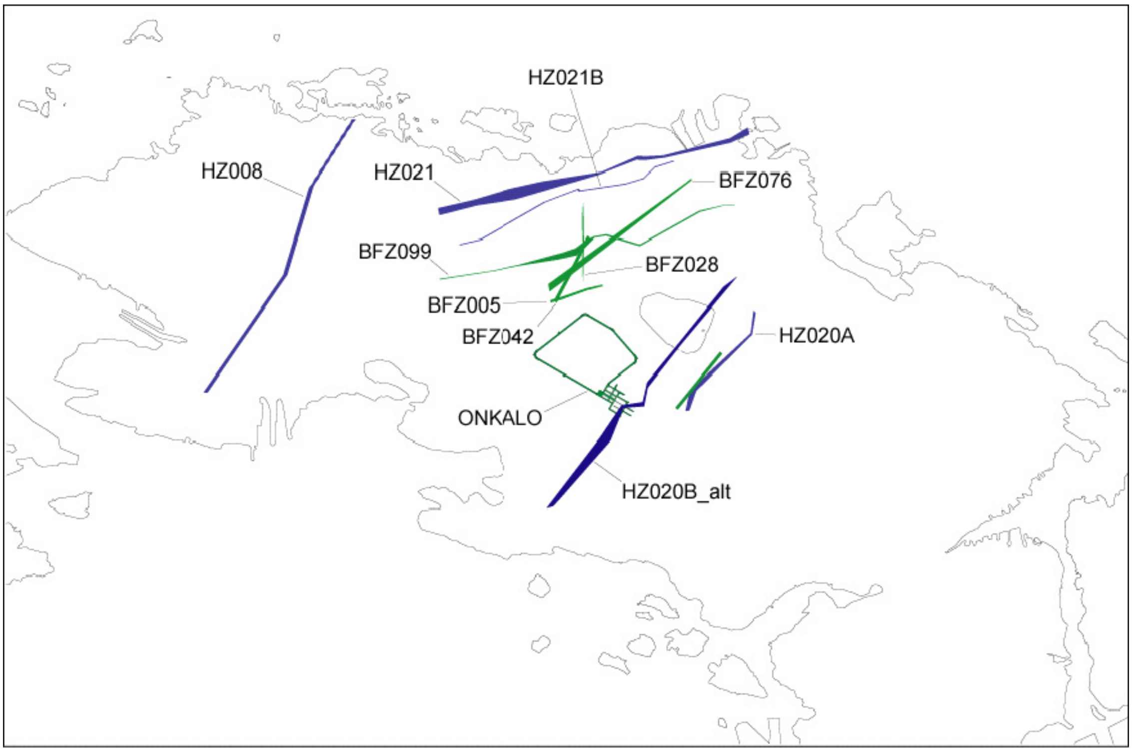


Figure 3-6. *Bedrock model 2006, level –420 m at Olkiluoto showing the layout determining fractures and also the location of ONKALO and the shoreline of Olkiluoto island /Kirkkomäki 2006/. The model is based on /Paulamäki et al. 2006/.*

3.5.1 Number of compartments and inflows

The hydraulic description of the bedrock at Olkiluoto has been given by /Hellä et al. 2006/ on the basis of flow-log borehole data. The focus of that report was to define the number of fracture intersections in a KBS-3H deposition drift and leakage rates. The number of compartments and several other features were also evaluated by /Lanyon and Marschall 2006/ using DFN-modelling.

The present estimate is that, in an average 300 m-long deposition drift, the following features will be encountered /Hellä et al. 2006/:

- There are long “dry” sections without visible leakage.
- The drift is intersected by 1–3 local fracture zones.
- The drift is intersected by approximately three fractures or fracture zones (one per 100 m).
- There are six 5 m long sections (length of supercontainer or distance block) with inflow larger than 0.1 l/min.
- There are four to five 10 m-long sections with inflow larger than 0.1 l/min.

/Hellä et al. 2006/ acknowledge that there may be significant local variations from average conditions. The main results with respect to design presented by /Lanyon and Marschall 2006/ are:

- The geometric simulations indicate a consistent layout across all the geosphere model variants and realisations.
- Typically, each 300 m drift is divided into 2 compartments by a compartment plug pair (regarded as a single seal).
- Each drift on average contains 23 supercontainers with 3–4 blank sections (sections where filling blocks are positioned instead of supercontainers).

- Total average inflow to the compartments (prior to grouting) within a drift is about 1.5 l/min.
- Average inflow to a single compartment (prior to grouting) is below 1.0 l/min.
- Approximately 18 % of drifts exceed the suggested 30 l/min limit without grouting. If grouting can be successfully performed (reduction to 10–8 m^2/s) the maximum inflow should be reduced to about 15 l/min with less than 1% of drifts exceeding 10 l/min. Inflow estimates are likely to be conservative (see /Lanyon and Marschall 2006/.

3.5.2 Hydraulic characteristics

Hydraulic pressure in neighboring supercontainer sections during the first years after emplacement

One critical issue in distance block design and related testing is the filling of the open volume by inflowing groundwater and the subsequent rapid development of hydraulic pressure. The filling and pressure development has been evaluated by /Lanyon and Marschall 2006/ and is found to be heterogeneous for the majority of supercontainers not intersecting transmissive fractures. Within these sections no significant pressure rise is predicted within the first years as any water inflow is taken up by the bentonite.

Furthermore, there are indications that only a fraction of the supercontainers may become pressurised during the first year of operation. The result will be a system of neighbouring supercontainers and distance blocks with full hydrostatic pressure on one side of the distance block and none on the other. This situation is graphically represented in Figure 3-7 where filling time and pressure are analysed with respect to inflow and position in a 300 m long deposition drift. Large pressure gradients and forces over the distance blocks are expected. The effect may be different between the DAWE and BD alternatives.

Influence of excavation of adjacent drifts

The excavation of several deposition drifts at the same time may form flowpaths between drifts and also other tunnels, which reduces the hydraulic pressure. The results from DFN-modelling by /Lanyon and Marschall 2006/ suggest that pressure disturbances due to the excavation of adjacent drifts may be large (~2 MPa) and rapid. Typically the most transmissive features react most quickly, but drawdown is seen in almost all intervals intersected by transmissive features.

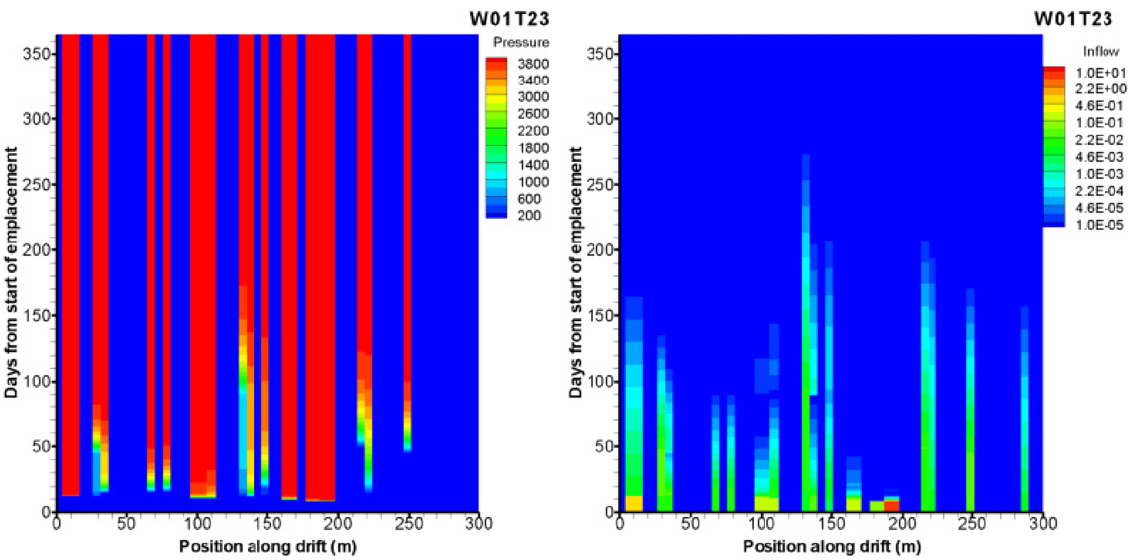


Figure 3-7. *Example of pressure (on left) and inflow (on right) as a function of time and position along a drift /Lanyon and Marschall 2006/. The heterogeneity along a 300 m long drift with respect to pressure is significant.*

Time to fill gap volume

The results from DFN-modelling by /Lanyon and Marschall 2006/ suggest that some of the supercontainer gap volumes will be filled within 10–20 days after the start of emplacement. This situation conforms to the supercontainer positioning criteria requiring inflow less than or equal to 0.1 l/min into an open volume of 1.342 m^3 around the supercontainer and results in a maximum filling time of roughly 10 days.

A filling time of 200 days or more is expected in sections where the transmissivity of features is below 10^{-10} m^2/s. In tight sections with no transmissive fractures, the filling time will clearly be longer.

4 General Design and common design components

4.1 General description of the KBS-3H repository

4.1.1 General

The KBS-3H repository design is based on emplacement of spent fuel canisters in the horizontal direction (see Figures 4-1 and 4-2). There are three different variations (called candidate designs) of KBS-3H design: a) Basic Design (BD), b) design based on Drainage, Artificial Watering and air Evacuation (DAWE) and 3) Semi Tight Compartment (STC) design, see Sections 2.1–2.4.

Deposition drifts start from deposition niches off the main tunnel, and those sections of the drift that are suitable for the emplacement of supercontainers are called compartments. The design of the deposition niches is considered preliminary and remains a work in progress. Compartment plugs are used to isolate suitable sections of the drift from certain water-bearing fracture zones as substantial water inflow may have detrimental effects on buffer material. Inflow limits are used to determine zone suitability. Inflow limits are also used to establish supercontainer and filling block positions. Filling blocks are placed in positions which are not suitable for supercontainers. Current estimates of inflow limits and their effect on repository design is presented in Table 4-1.

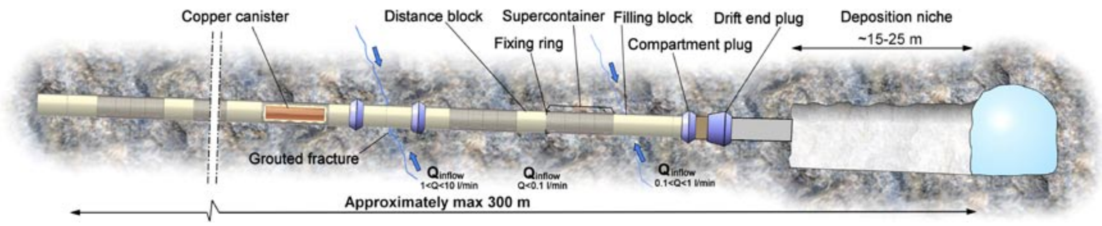


Figure 4-1. KBS-3H repository design alternative.

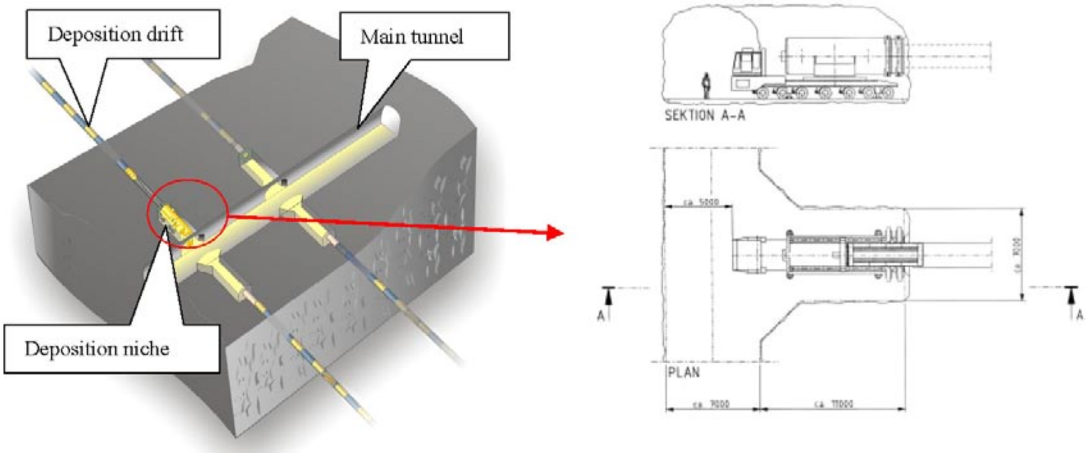


Figure 4-2. Main tunnel, deposition niches and deposition drifts in the KBS-3H repository design /Thorsager and Lindgren 2004, SKB 2001/. See Figure 8-6 for present estimate for dimensions of the deposition niche.

Table 4-1. Present estimates for inflow limits based on /Lanyon and Marschall 2006/ and corresponding effect on design.

Inflow (l/min) into a drift section of about 10 m assuming inflow from one fracture	Transmissivity (m^2/s) assuming one inflowing fracture [2]	Hydraulic aperture, e, microns	Design action	Reduction in drift utilisation degree
Inflow < 0.1	T< 2.65E-9	e < 15	Supercontainer sections (one unit is about 10 m).	No effect (a supercontainer can be located into the section).
0.1 ≤ Inflow < 1	2.65E-9 ≤ T< 2.65E-8	15 ≤ e < 32	Filling blocks, estimated length about 10 m.	A bentonite block of 10 m shall be located into the section. One unit reduces the utilisation degree by 4%.
1 ≤ Inflow < 10	2.65E-8 ≤T<2.65E-7 [3]	32 ≤ e < 69	The drift is divided to compartments and the inflow zone is isolated by using compartment plugs. The length of plugged zone is 20–30 m.	A compartment plug unit of 30 m [4] in total shall be located into the section. One compartment plug unit reduces the utilisation degree by 11%.

[2] Transmissivity calculated from inflow using Thiem's equation and assuming a constant head of 400 m at a radius of 50 m from the tunnel (radius 0.925 m), see Appendix B.
[3] If T ≥ 1E-7 m2/s, the section probably belongs to a Class A or B fracture zone and such sections should, therefore, not occur in the bedrock resource where the deposition drifts are located.
[4] 30 m = stabilization zone 10 m + fracture zone (conductive section) 10 m + stabilization zone 10 m.

As mentioned previously, the supercontainer consists of the copper canister with a surrounding buffer of compacted bentonite placed in a perforated steel shell (see Section 4.4). A distance block of compacted bentonite is emplaced between each supercontainer to obtain proper mutual thermal spacing and isolation.

One of the most important functions of the distance block is to seal the drift section between the supercontainers to prevent flow and advective transport along the drift, see Section 2.1.

4.1.2 Stepwise construction and operation

The stepwise construction and operation of the KBS-3H deposition drift is presented here briefly for the DAWE design alternative in a storyboard manner. A more detailed description is presented in the following chapters. A description of the drift lengths and supercontainer numbers can be found in Chapter 12.

The construction of the deposition niche and drift starts during investigation phase, see Figure 4-3, by drilling an investigation hole in the centre line of the drift. If the investigations verify the suitability of the position for deposition drift, a deposition niche is excavated and a pilot hole is bored to be used later to guide the boring of full diameter drift. The investigation hole can be used for grouting transmissive fracture zones, however, it is likely that the larger diameter pilot hole is more suitable because the fracture intersection is larger than in investigation hole, see Chapter 9 more detailed description of groundwater control.

During the excavation of the drift, the transmissive fracture zones identified by investigations can be sealed by removing the boring equipment from the drift and carrying out pre-grouting e.g. by LHHP cement or Silica Sol through several holes drilled inside the perimetre of the drift (see Figure 4-4).

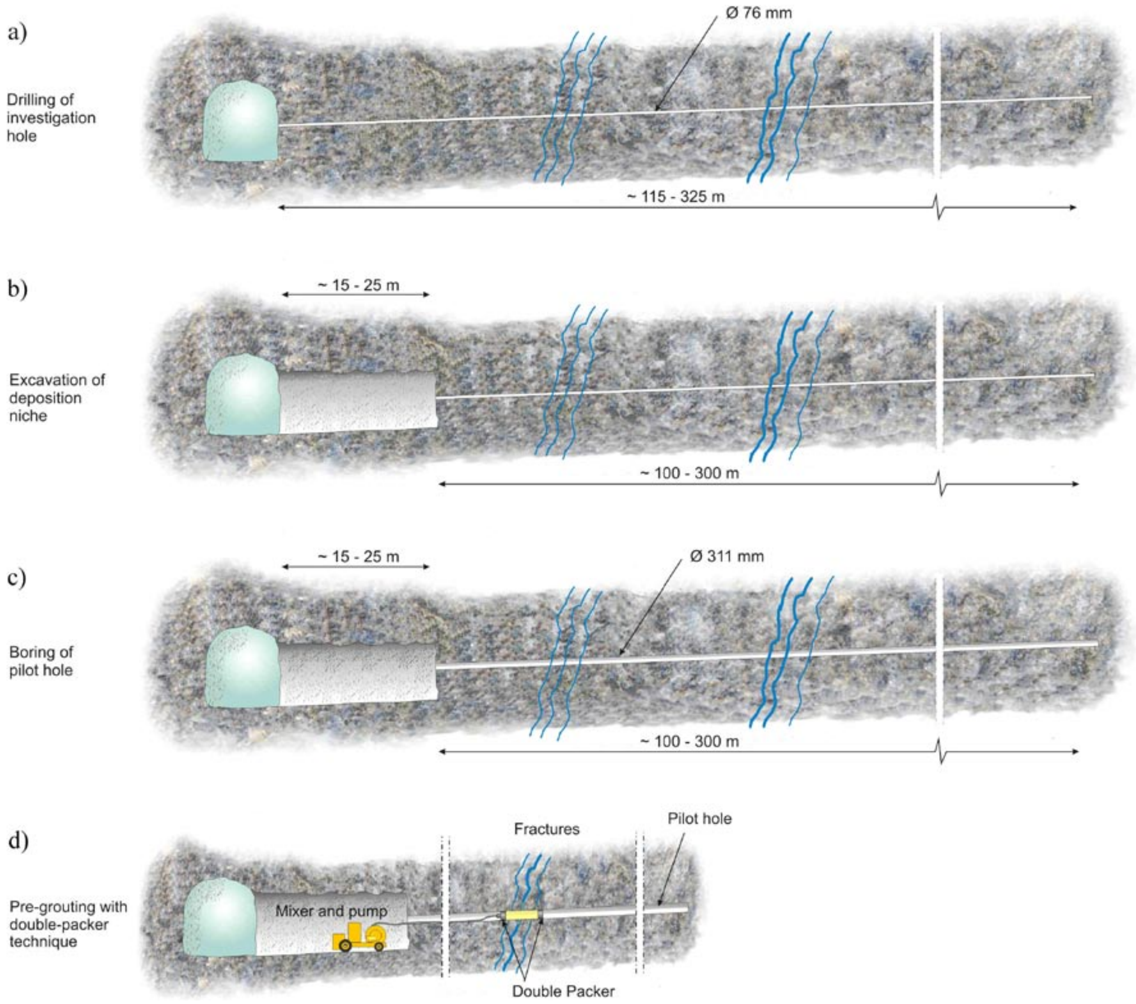


Figure 4-3. The phases before drift excavation: a) investigation hole, b) excavation of deposition niche, c) boring of pilot hole for drift excavation and d) rock sealing by using a double packer arrangement.

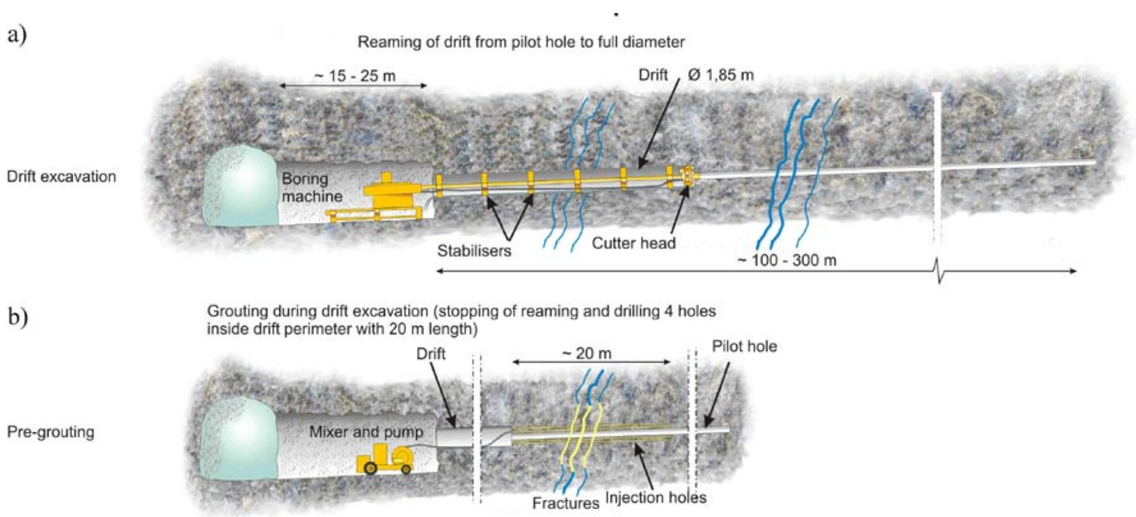


Figure 4-4. The phases during drift excavation: a) excavation of the drift by using boring machine, b) pregrouting of transmissive fracture zones during boring.

After excavation the drift is prepared for operation by surveying it carefully and grouting the possible leakages by using a Mega-Packer unit /Börgesson et al. 1991/. The preparatory work includes also excavation of notches for compartment plugs, drift end plugs and possible other design components. The attachments to compartment plugs and other components are also installed during this phase. Spraying or dripping water leakages are covered with drip shields and wetting and air evacuation pipes are installed on the walls (only in case of DAWE alternative), see Figure 4-5.

The operation of the drift starts by emplacing supercontainers and distance blocks in the first compartment in a series, see Figure 4-6. After all the supercontainers and distance blocks have

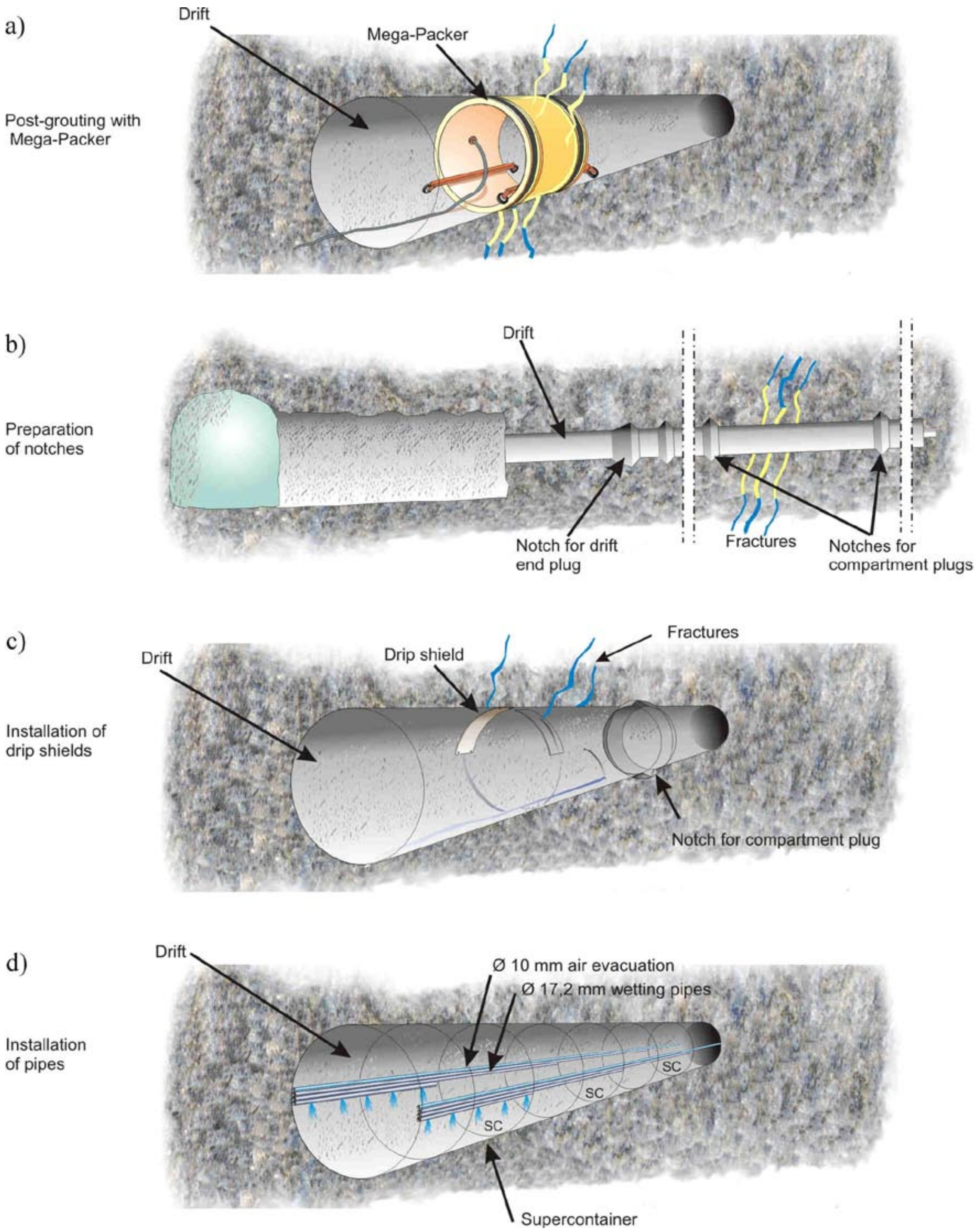


***Figure 4-5.** The phases after excavation to prepare the drifts for operation: a) post-grouting by using Mega-Packer, b) excavation of notches for compartment plugs and other possible components, c) installation of drip shields and attachments to e.g. compartment plugs and d) pipes (only DAWE alternative).*

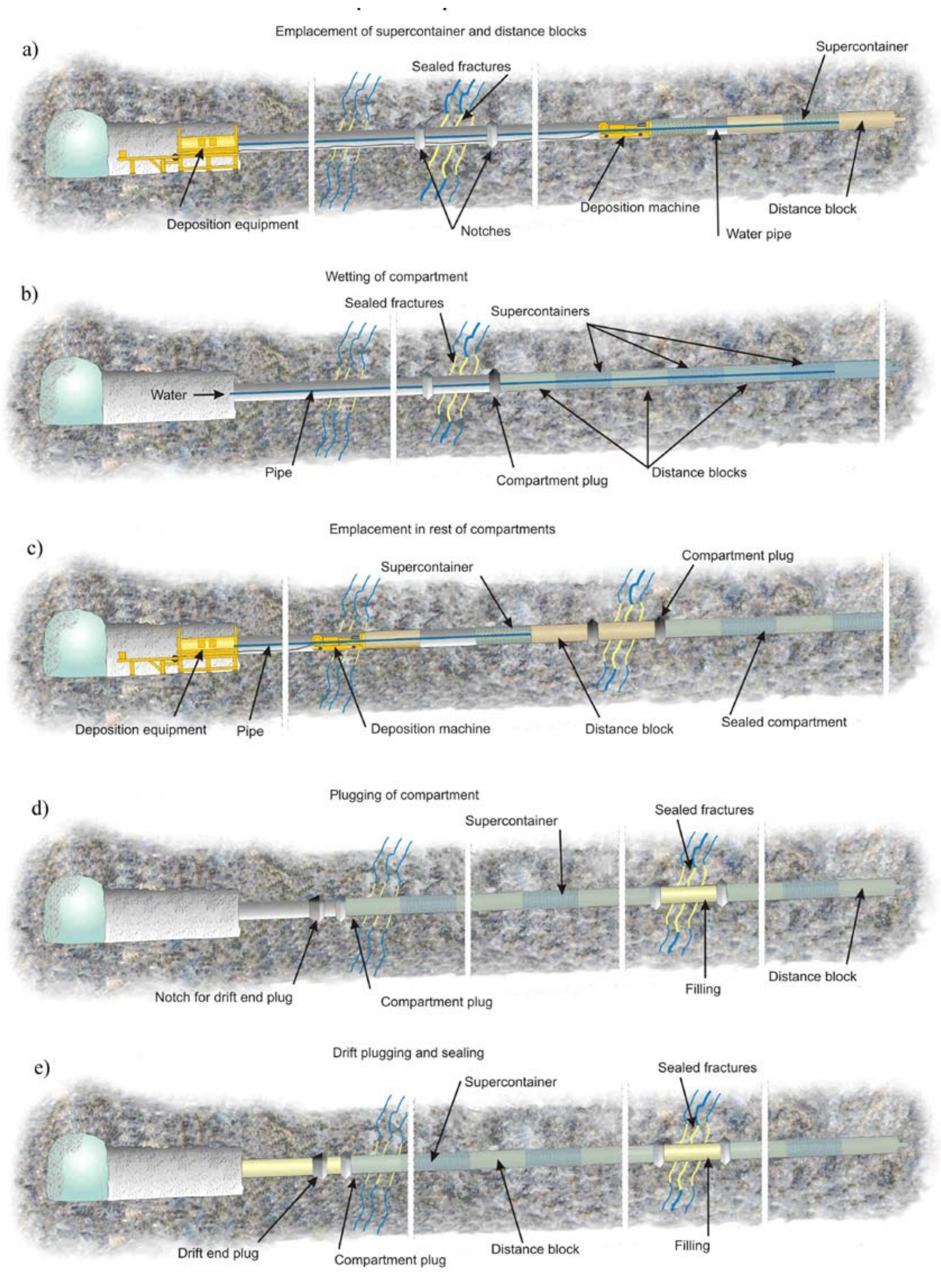


Figure 4-6. *The operation phases: a) installation of supercontainers and distance blocks in the first compartment, b) plugging of the first compartment, filling it with water and removal of pipes (only DAWE alternative) c) plugging the highly leaking fracture section and continuation of emplacement of supercontainers and distance blocks, 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 space in drifts is filled with water and the drift is plugged by the drift end plug, see e.)*

been emplaced, the filling components are emplaced and drift is plugged by using a compartment plug and filled with water. During water filling the trapped air is removed and the pipes are removed. After removing pipes, the filling components are placed between the two compartment plugs and the second compartment plug is installed rapidly. After the second compartment plug is in position, the operation starts again by emplacing distance blocks and supercontainers. After the last distance block is in position, the filling components next to compartment plug are installed followed by the installation of compartment plug, wetting of the drift, removal of pipes and construction of the drift end plug.

4.1.3 Design components common to both alternatives

The design components, which are similar to both BD and DAWE alternatives, are:

- Deposition drift.
- Supercontainer.
- Buffer material inside supercontainers.
- Length of distance blocks.
- Compartment plugs.
- Drift end plug.

The deposition drift geometry and tolerances were presented in Section 3.4. The drift design is considered fixed and is identical for both the BD and DAWE alternatives, however, it is possible that the requirements for the BD alternative are stricter than for the DAWE.

The supercontainer design is presented in Section 4.4 and is considered fixed with the exception of the modification of end plates from perforated to solid (see Section 4.4.2). The dimensions and properties have been presented in Section 4.4 and drawing in Appendix D.

The buffer material inside supercontainers has been assumed to be the same in BD and DAWE alternatives. The design parameters have been presented in Section 4.4.3.

The length of distance blocks is the same for BD and DAWE alternatives and fixed for Olkiluoto design and for different type of canisters. The nominal length is 5.465 mm based on Posiva BWR 1,700 W type fuel and having 5 mm gaps on both sides of distance block between supercontainers.

The design components common to all design alternatives are presented in the following sections. Drift end plug and drip shields are presented in the same chapter merely for reporting purposes without generic coupling.

4.2 Drift end plug and drip shields

4.2.1 Drift end plug

The drift end plugs are not assigned safety functions, but are designed to be compatible with, and support the safety functions of, the canister, the buffer and the host rock (Appendix B.2).

The drift end plugs can be composed of steel, low-pH concrete, or both. Steel compartment plugs can be installed in relatively short time whereas concrete structures will evidently require a minimum hardening time of two weeks until the structure can be loaded. Steel is favoured over concrete as material because short plugging and sealing time is favourable to the behaviour of buffer under saturation and increases its efficiency.

From the long-term behaviour point of view there are significant differences between plug options, as discussed below.

Compartment plug:

- the steel will expand as it corrodes,
- corrosion will produce hydrogen gas,
- after a long period of time the steel converts to impermeable magnetite and other corrosion products,
- the expected lifetime of a steel structure is shorter than that of concrete.

Concrete plug:

- a directly applicable low-pH concrete mixture may not be available today, however, it will most likely be available in the near future,
- concrete will dissolve in groundwater after a long period of time. The rock aggregate will remain in the position of the former structure and therefore the volume will shrink,
- after concrete dissolution, the hydraulic conductivity of the volume may increase,
- the expected lifetime of concrete structure is longer than that of steel structure.

To satisfy operational and long-term safety requirements, an integrated plug with a short-term steel compartment plug and long-term concrete component (as illustrated in Figure 4-7) was selected. The compartment 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 hardens, which is estimated to take a few weeks. Based on Olkiluoto data, it is likely that there will be several sufficiently dry deposition drifts allowing for the use of concrete-only plugs. In the case of the BD alternative, a concrete-only plug may be able to plug the drift entrance in most cases, however, in the case of the DAWE alternative incorporating artificial wetting, the compartment plug is expected in all cases. The use of both steel and concrete plug in series is considered a robust alternative at this phase of design because it functions properly in all situations.

Concrete drift end plug

Conventional low-pH concrete plugs (see Figure 4-8) can be of three different designs:

- Low-pH shotcrete friction plug.
- Low-H steel reinforced cast concrete plug positioned in a notch.
- Low-pH steel reinforces cast concrete wedge shaped plug positioned in a notch.

Estimated material quantities for these plug alternatives are presented in Table 4-2.

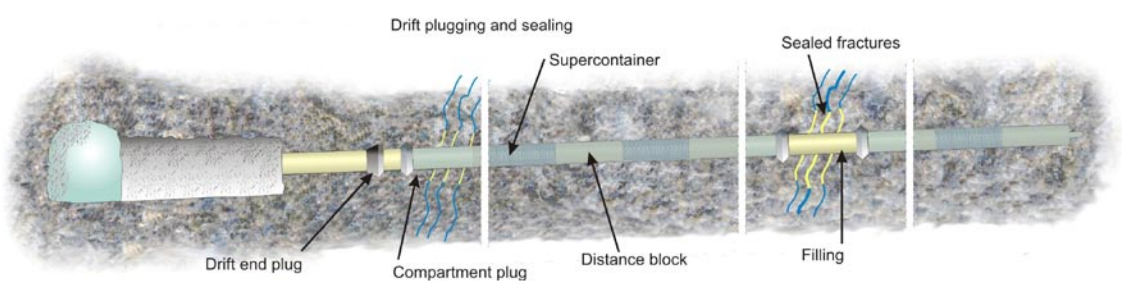


Figure 4-7. *The drift end plug arrangement based on a rapidly installed compartment plug and a final concrete plug. Extra filling blocks are installed adjacent to plugs to compensate the possible density reduction in future.*

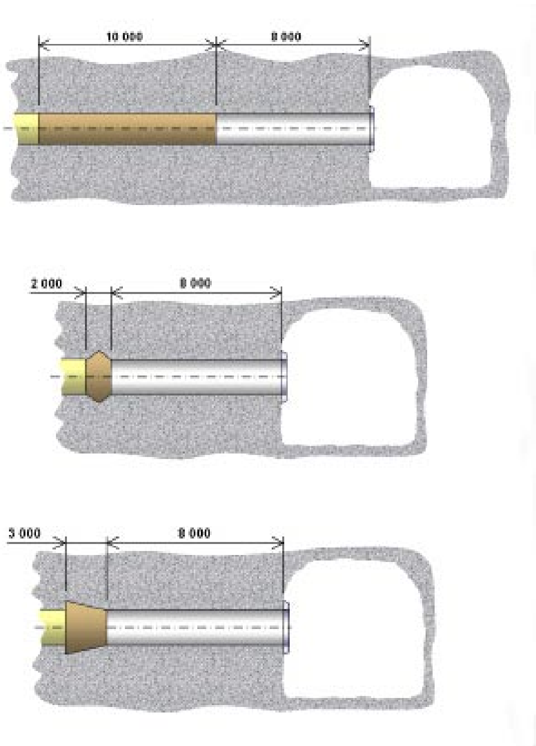


Figure 4-8. Concrete plug alternatives: Friction plug (top) similar to shotcrete plug, steel reinforced plug positioned in a notch (middle) and steel reinforced wedge shaped plug positioned in a notch (above) /Thorsager and Lindgren 2004/.

Table 4-2. Material quantities in different plugs. The material quantities are based on /Autio et al. 2007, see Appendix G/ and have been adjusted from 1.75 m drift diameter to 1.85 m diameter.

Plug type	Friction plug*	Steel reinforced	Steel reinforced wedge shaped	Rock plug
Length, m	11	2	3	2
Concrete, m^3	30	8	11	1.2
Steel reinforcement, kg	1,860	860	550	200
Rock, m^3	-	-	-	4.5
Cooling and grouting pipes, m	430	123	168	-

*made of concrete of shotcrete

Cement-grouted rock drift end plug

An alternative plug design based on using a rock kernel is illustrated in Figure 4-9. The kernel is slightly wedge shaped. The amount of concrete in the design is clearly smaller than in other alternatives. Therefore the possible chemical disturbance caused by concrete is smaller than in other alternatives and the potential open void resulting from the long-term dissolution of concrete is also smaller. The design is quite preliminary and has not been tested.

Reference design of drift end plug

The drift end plug reference design (steel reinforced concrete plug positioned in a notch) is shown in Figure 4-10. It was selected on the basis of its technical feasibility and concrete minimization potential. The cement-grouted rock plug is an attractive alternative due to the small quantity of concrete required, but the design is novel and needs to be properly verified. A compartment plug can be positioned adjacent to the concrete plug when necessary for rapid sealing during the hardening of concrete.

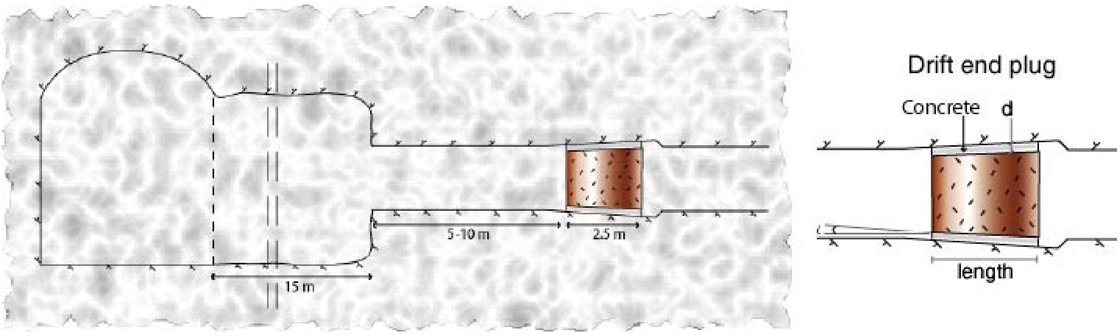


Figure 4-9. A draft of a rock plug grouted in the drift.

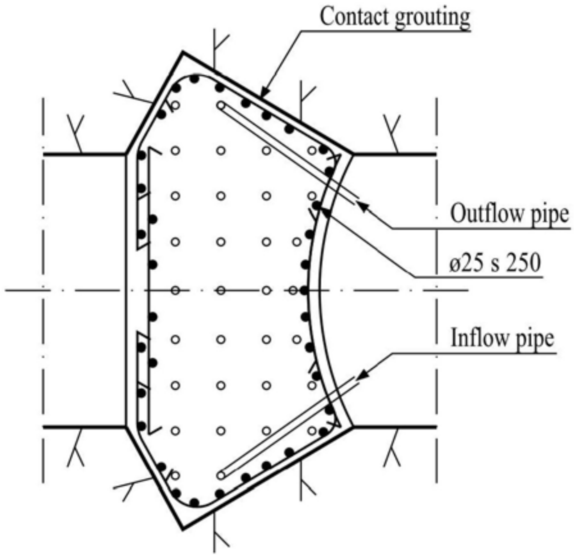


Figure 4-10. The steel reinforced plug positioned in a notch (see Appendix G for details in /Autio et al. 2007/). The pipes are for cooling during hardening of the concrete.

Low-pH concrete

The concrete plug design is based on the use of low-pH cement. The exact composition of the concrete remains to be developed, but there is reason to believe the design basis will be valid due to several different research and development efforts. For example, the composition of the Low Heat High Performance Concrete (LHHPC) used in the Tunnel Sealing Experiment in Canada at AECL's Underground Research Laboratory URL is presented in Table 4-3 /Martino et al. 2002/.

The composition of the LHHPC is regarded as a potential reference example of possible concrete to be used in the drift end plug because the composition has been specified adequately and it is designed to ensure a very low hydration heat and very good performance in a repository environment.

The LHHPC cement is sulphate-resistant Portland cement (in Canada Type 50) and the silica flour is the filler from grinded quartzite with a very low pozzolanic reactivity. The particle size distribution is 1–100 µm for a silica content of 99.8%, this obtained from US Silica in Illinois in is Sil-Co-Sil 53. The silica fume is product from SKW (Silica Becancour) with an average grain diameter of 0.25 µm. The superplasticiser used in the mixture is naphthalene sulfonate, liquid form, and the aggregates are of type rounded aggregates, 98% from magmatic rock and some limestone, screened directly at the URL, dried and bagged at the Winnipeg Lafarge plant before the final mix. The gravel particle size is between 4.5 and 12.5 mm and sand is ASTM C33 (9% passing 150 µm sieve) with fineness modulus of 2.66.

Table 4-3. Composition of the low-pH concrete called Low-Heat High Performance Concrete (LHHP) used in the Tunnel Sealing Experiment in Canada at AECL's Underground Research Laboratory URL /Martino et al. 2002/.

Constituents (kg/m³)	
Cement	97.0
Silica fume	97.0
Silica flour	193.8
Sand	894.7
Coarse aggregates	1,039.6
Superplasticisers	10.3
Water	97
Principal properties	
E/C ratio	0.98
Slump (mm)	170
Density (Mg/m³)	2.424
% mineral addition	80
Compressive strength MPa (28 days)	75
Elastic modulus (MPa)	36,000
Hydraulic conductivity (m/s)	$< 10^{-14}$

4.2.2 Drip and spray shields

The spraying, dripping, and squirting of groundwater (see Figure 4-11) onto the buffer material during the operation phase is prevented by placing metal spray shields over inflow points. At single inflow points the shielding can be implemented through the use of stud type nipples (e.g. penny shaped disk attached on the rock surface in the center of inflow point). Inflow coming from the roof of the deposition drift will be redirected towards the lower half of the drift.

The material alternatives for the shields are copper or steel. Steel is preferred because the structures are thin (in mm range), their number is small, and the steel completely corrodes in a relatively short period of time when compared to the supercontainers. The shields are fastened mechanically with screws into small holes drilled in the rock. Round "penny" type washers are placed in positions of single flow points. The sheets are shaped to follow the rock surface tightly. The drip shields shown in Figure 4-12 were tested in the KBS-3H demonstration drift at Äspö HRL.

The weight of the drip shields that was tested was 220 g on the average. It is possible that two shields are required in leaking fracture intersections with several inflow points on both sides of drift wall and the mass of shields and attachment bolts is less than or equal to 600 g. The estimated number of shielded sections is 4–5 per drift.

4.3 Compartment plug

4.3.1 Design

Steel compartment plugs are used to isolate water-leaking fractures or fracture zones, which are unsuitable for deposition of canisters, from more suitable sections of the drift.

A list of design bases as input parameters to be used in the detailed design of steel compartment plug is presented in /Autio et al. 2007, see Appendix G/. The compartment plugs are not assigned safety functions, but are designed to be compatible with, and support the safety functions of, the canister, the buffer and the host rock (Appendix B.2). Testing of the compartment plug is planned to take place at Äspö in 2008.

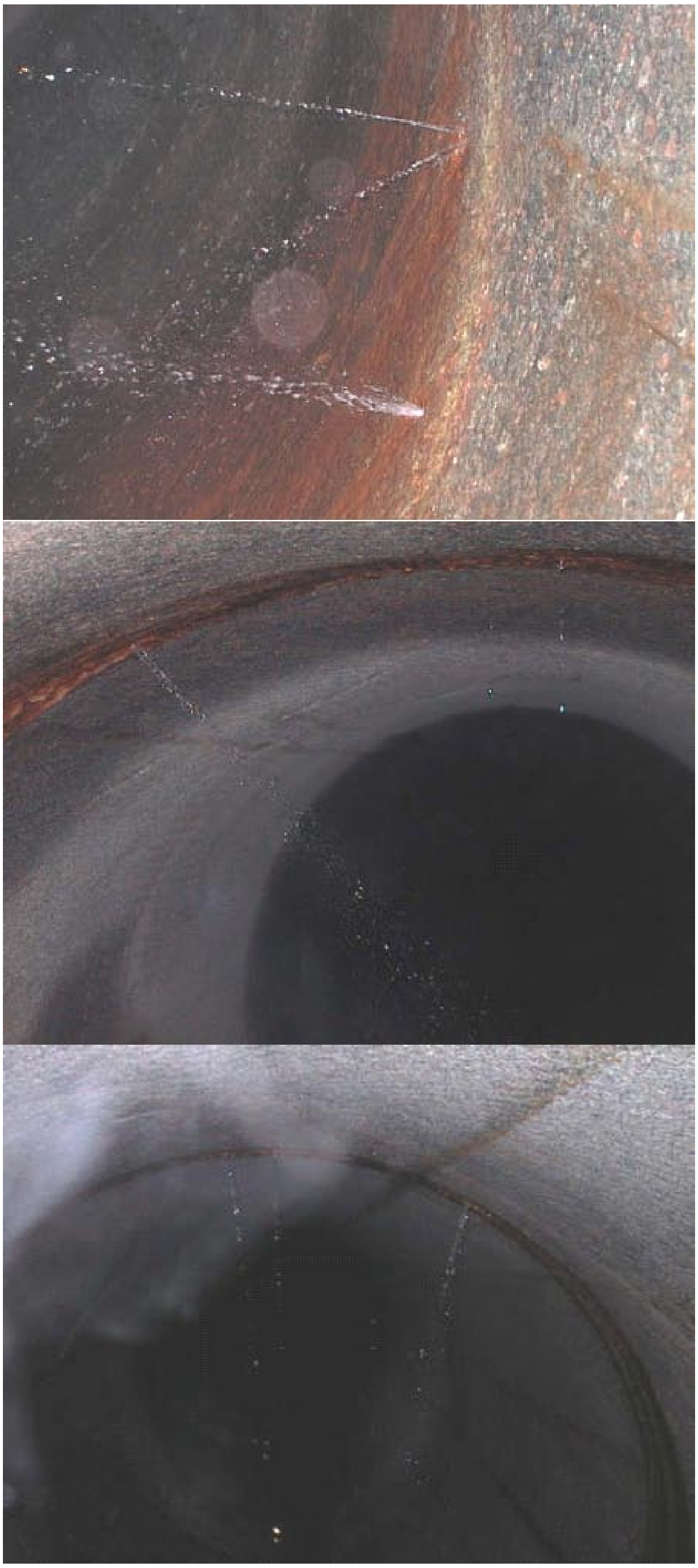


Figure 4-11. *Example of spraying inflow points in the KBS-3H demonstration drift at Äspö. Photo by J Autio.*

Figure 4-12. Principle of using drip shields (top) and as attached to the demonstration drift at Äspö (above right) and after detachment on the floor (above left). Photos by H. Wimelius.

The design of the steel compartment plug entails installation of a steel collar structure in the rock before the start of deposition operations. The fastening ring is attached to the rock surface and sealed during installation with concrete. This procedure allows the centre part of the plug to be rapidly installed during deposition operations.

The functional purpose of the compartment plug is to isolate "good quality" deposition compartments from "bad quality" water-bearing fracture zones, which may have detrimental effect on the distance blocks and supercontainers during saturation. In general, the design requirements are as follows:

a) Provide an adequate drift seal, which prevents flow through the plug and rock plug interface, to avoid erosion of buffer. The flow should be reduced to the same order of magnitude as the flow through the rock. The plug is positioned in good quality rock sections in the drift.

b) The plug is capable of supporting a full hydrostatic pressure of 5 MPa after installation.

c) Form a confining surface to maintain the supercontainers and other components (e.g. buffer) in position during operation of each drift. It is assumed that these forces will be equal to or less than hydrostatic pressure during operation.

The basic design of the compartment plug is the same for the BD and DAWE design alternatives, with the exception of perforations for the pipelines found only in the DAWE alternative.

The plug can be used to withstand the groundwater pressure from one or both sides. The plug is composed of one or two caps depending on the direction of the force.

The plug consists of a V-shaped groove excavated to the drift, a steel-fastening ring, a collar mounted against the ring, and a cap installed on the collar. The space between the ring and the rock is grouted (see Figures 4-13 to 4-17). The design has been described in /Autio et al. 2007, see Appendix H/.

The cap is in the shape of a dome attached to a flange. The shape of the cap has been chosen so that the stress distribution in the cap is as even as possible. The height of the cap is 400 mm and the diameter 1,650 mm.

Construction of a two-sided plug configured with the least possible number of parts, requires a symmetric groove in the rock and a symmetric fastening ring and collar. These components behave similarly in either of the two possible directions of the acting force.

In this construction all, or almost all, of the joints in the steel assembly are sealed by welding. The fastening ring and collar components are welded together, and the collar itself is welded to the fastening ring. The rear side cap, which is installed first, may be fastened with bolts, but the front side cap, under current plans, is fastened and secured by welding. The assembly is subject for automation in future. The preliminary design of automation can be made after the proper functioning of design has been verified by field tests at Äspö.

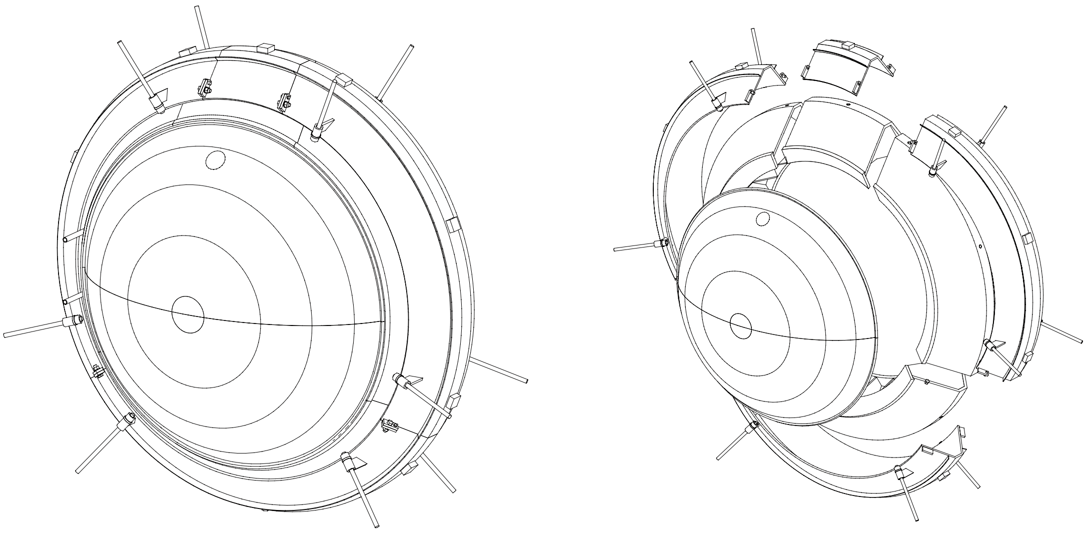


Figure 4-13. *The steel compartment plug as seen from the high-pressure side with a break down to pieces.*

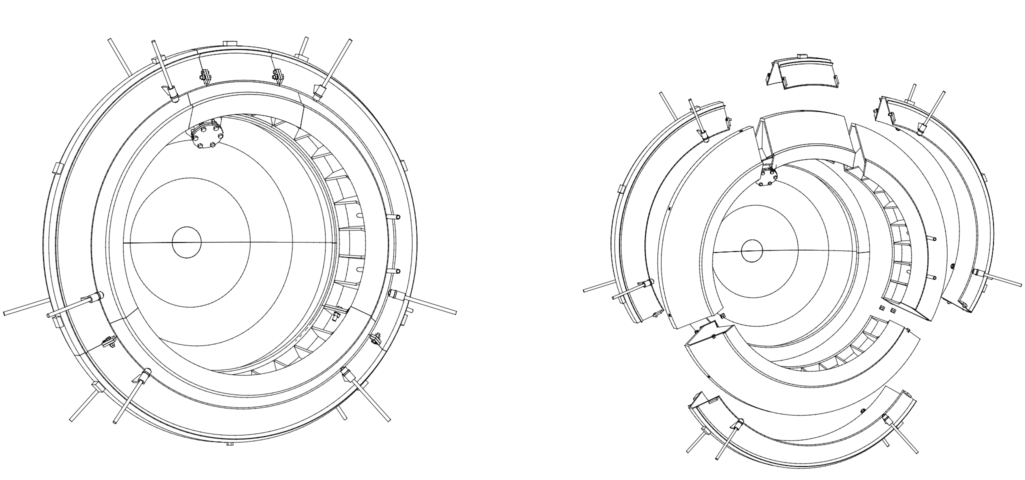


Figure 4-14. *The steel compartment plug as seen from the low-pressure side with a break down to pieces.*

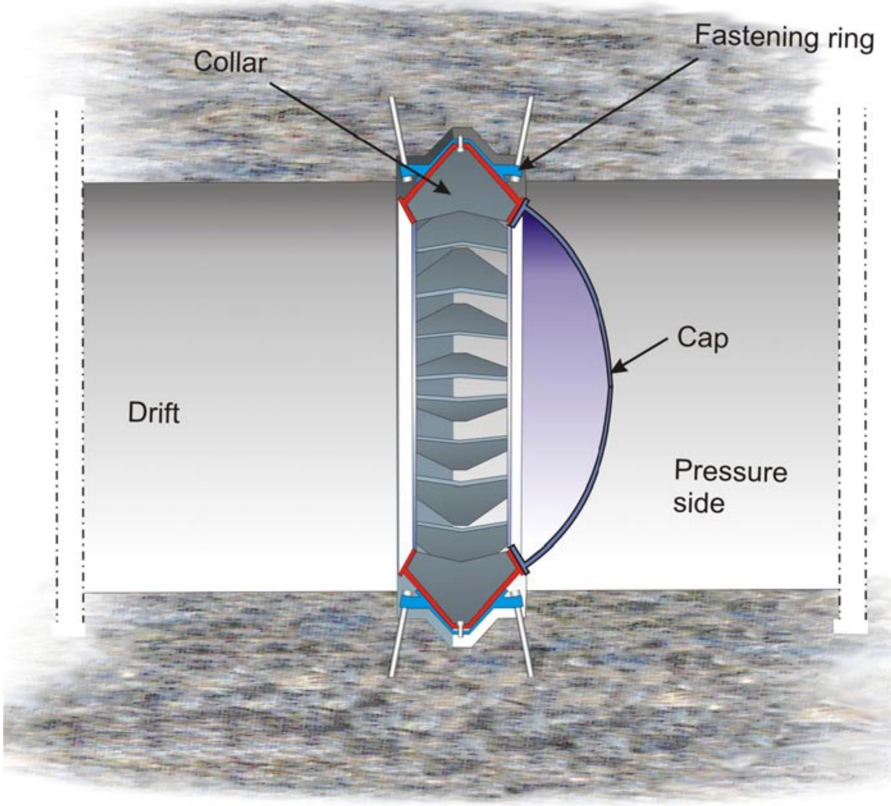


Figure 4-15. *The steel compartment plug and main structural parts.*

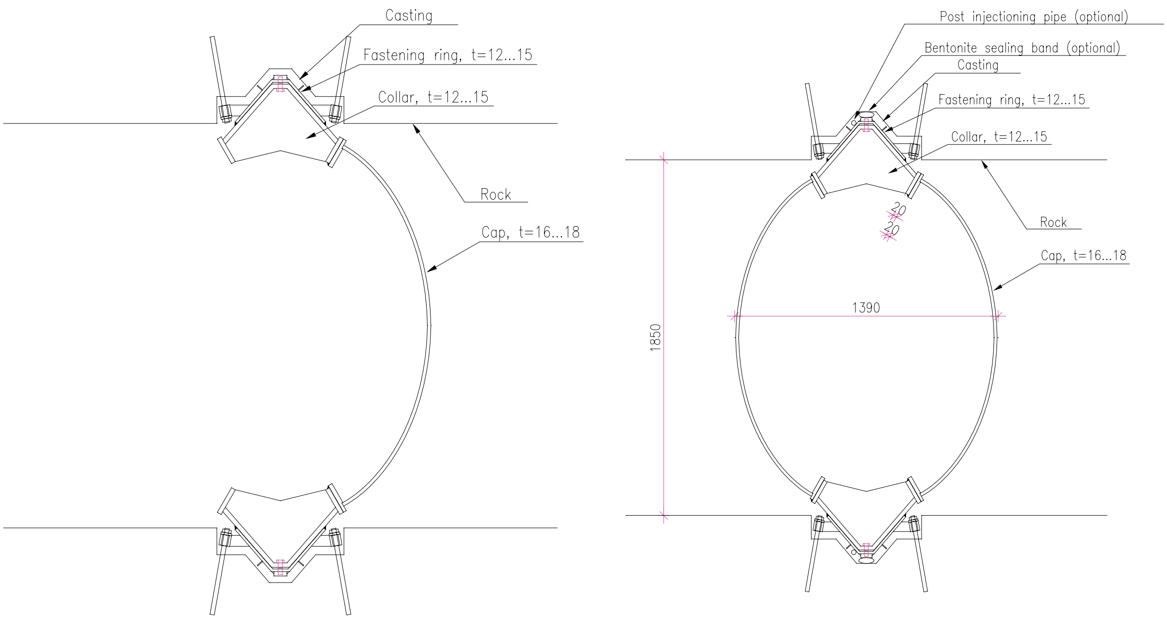


Figure 4-16. *Cross section of the compartment plug: one-sided with one cap (left) and two sided with two caps (right) dimensioned to withstand pressure from one or both sides respectively.*

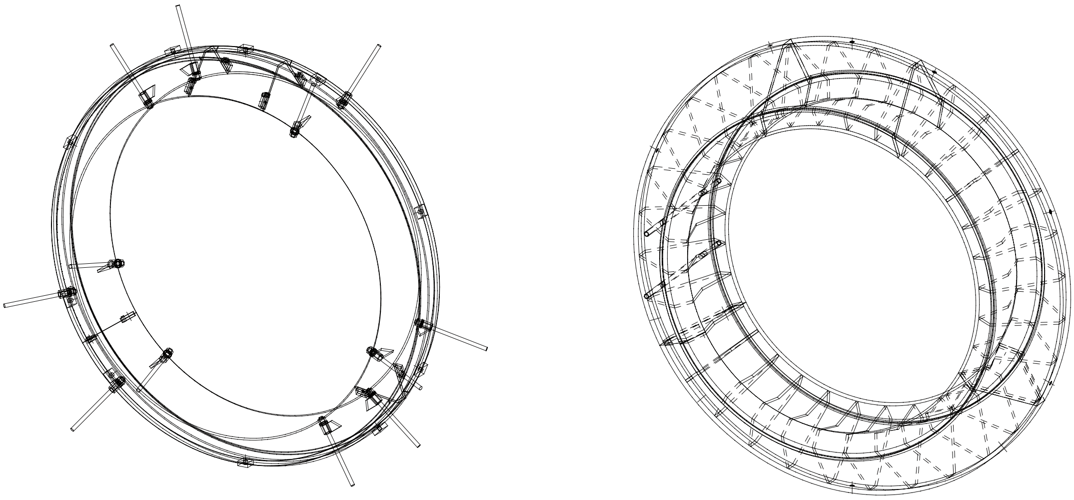


Figure 4-17. Fastening ring (left) and collar (right). The fastening ring is installed in the drift before operation starts.

The final steel weights of the fabricated parts are:

- Fastening ring 400 kg.
- Collar 1,250 kg.
- Cap 440 kg.

The required amount of concrete for casting the space between the ring and rock is approximately 190 litres.

The approximate total steel weight of a one-sided plug without bolts is 2,090 kg. The bolts add ca. 20 kg to the weight. The grade of the steel used is general structural steel S355J0.

The notch excavation was tested at Äspö HRL in 2007, see Figures 4-18 and 4-19. The excavation was made by sawing altogether 14 parallel cuts with varying depths creating a V-shaped notch with a flat bottom. The slabs were later broken by wedging. A special rail was built to allow sawing the cuts along the circumference of the drift.

4.3.2 Modeling of plug behaviour

The deformation of the plug under pressure was analysed using the general FEM (Finite Element Model) program Algor. The structure was modelled with either 8- or 6-noded brick elements. Due to symmetry considerations, only a quarter of the plug was modelled. The modelling is fully described in /Autio et al. 2007, see Appendix I/.

The basic load acting on the surface of the cap is 5 MPa, which corresponds to the groundwater pressure at 500 m of depth. The direction of the load is perpendicular to the surface. A load safety factor of $\gamma = 1.35$ and a material safety factor $\gamma = 1.1$, in accord with Eurocode 3, were used (see Table 4-4). The calculation strength of the steel is $f_d = 355$ MPa / 1.1 = 323 MPa.

The load on the dome is defined as a surface load acting perpendicularly to the top surface of the dome. Only one load case, with a pressure load of 5 MPa and a load factor 1.35, was considered. The modelled structure includes all of the steel components, the rock surface, and the concrete cast between the rock surface and the steel assembly. The model geometry is shown in Figure 4-20; the different colours correspond to different structural aspects. Contact surfaces were defined between the various structural aspects, allowing for parallel movement between them. The interface between the concrete casting (grey colour) and rock surface is an exception, as adhesion was assumed and a fixed connection defined. Symmetric boundary conditions were applied to the cut planes of the model and a fixed boundary condition was applied to the outer surface of the rock.

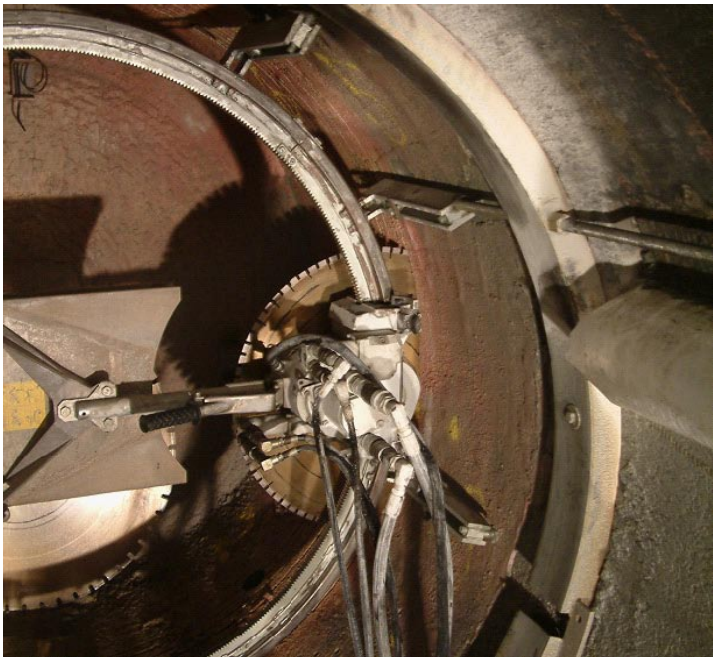


Figure 4-18. Sawing of a notch for the compartment plug by a specially developed rig.

Figure 4-19. Template for verifying the shape of the notch for the compartment plug.

Table 4-4. Summary of the design data for modeling of the steel compartment plug.

Design data		Geometry	
Pressure	5 MPa	Diameter of the cap	1,650 mm
Load safety factor	1.35	Height of the cap	400 mm
Material safety factor	1.1	Thickness of the cap	16 mm
Material	Steel S355	Collar main plates thickness	20 mm
Grout elastic modulus	35.5 GPa	Thickness of the grout layer	40 mm
Rock elastic modulus	50 GPa	Thickness of the rock layer	60 mm
Steel elastic modulus	205 GPa		
Poisson's coefficient	0.3 (0.15 grout)		

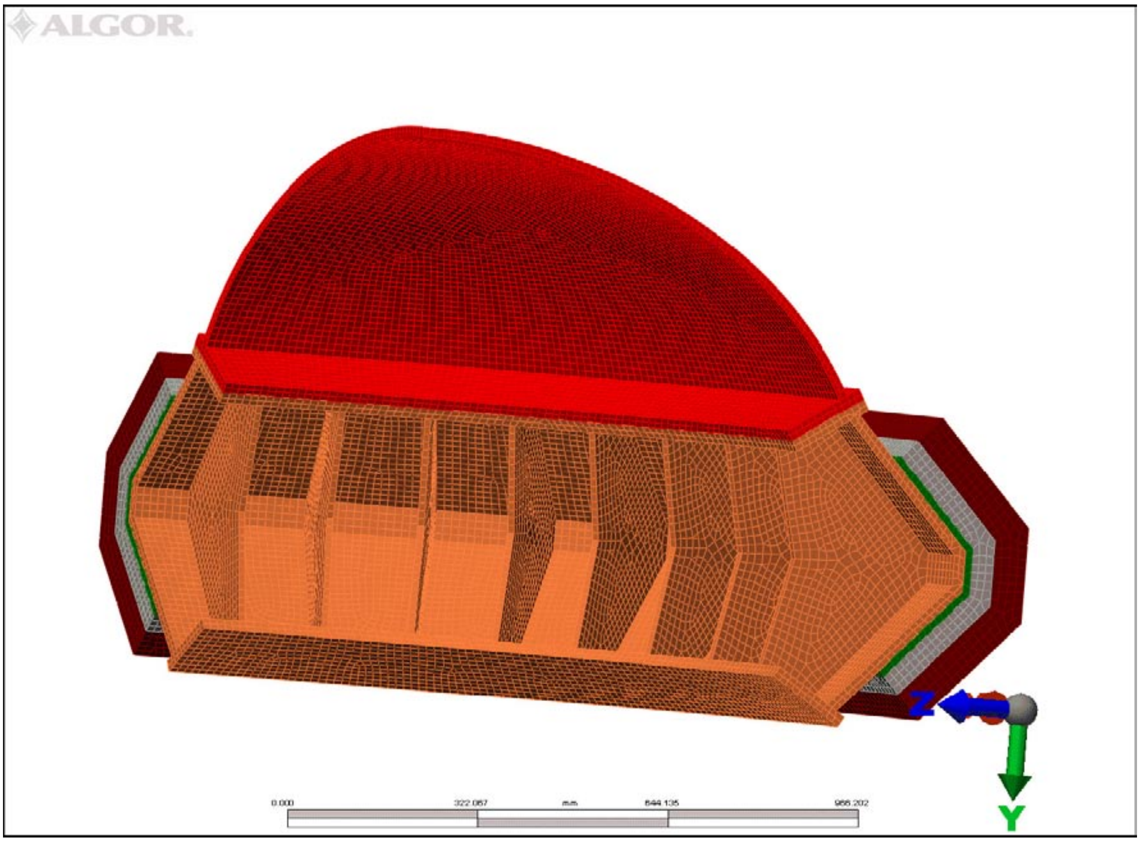


Figure 4-20. *Model geometry of the steel compartment plug.*

The von Mises stress distribution is shown in Figure 4-21 and displacements of the dome in Figure 4-22. As can be seen in Figure 4-21, the highest stresses occur at the centre of the dome. Some stress concentration can be seen at the perimeter of the dome, where there is a fixed boundary condition. The von Mises stresses are below the calculation strength f_d = 323 MPa, and hence the stresses are on an acceptable level. The maximum displacement at the centre of the dome is 1.4 mm with a load factor of 1.35, and thereby the displacement with the nominal load of 5 MPa is ca. 1 mm.

The displacements and stresses of other parts of the structure are shown in Figures 4-23 and 4-24. The load factor 1.35 is included in the values. The displacements outside the dome are of a magnitude of tenths of millimetres. Outside the dome, which is covered by the distinct model, highest stresses appear in the stiffening ribs. The stress level (maximum stress 230 MPa) is, however, well below the calculation strength of the steel.

Compression stresses in the concrete cast were also analysed. Stress peaks can be seen at the intersection points of the collar profile and stiffening ribs. The maximum stresses in general are approximately 100 MPa. Stress peaks are somewhat higher, but the area where stresses above 100 MPa occur is negligible. The compression balances out rapidly in the base of the concrete cast. In the rock, at the bottom of the groove, the highest compression stress values are approximately 32 MPa. The stresses are shown in Figure 4-25.

Resistance against snap-through (sudden failure of plug) was evaluated with a non-linear Mechanical Event Simulation solver and the load was applied stepwise.

A two-phase approach was used to examine the effect of eventual shape imperfections produced in the manufacturing process (see Appendix I in /Autio et al. 2007/). The results indicated that minor deviations (less than 5 mm) in shape do not cause excessive stresses.

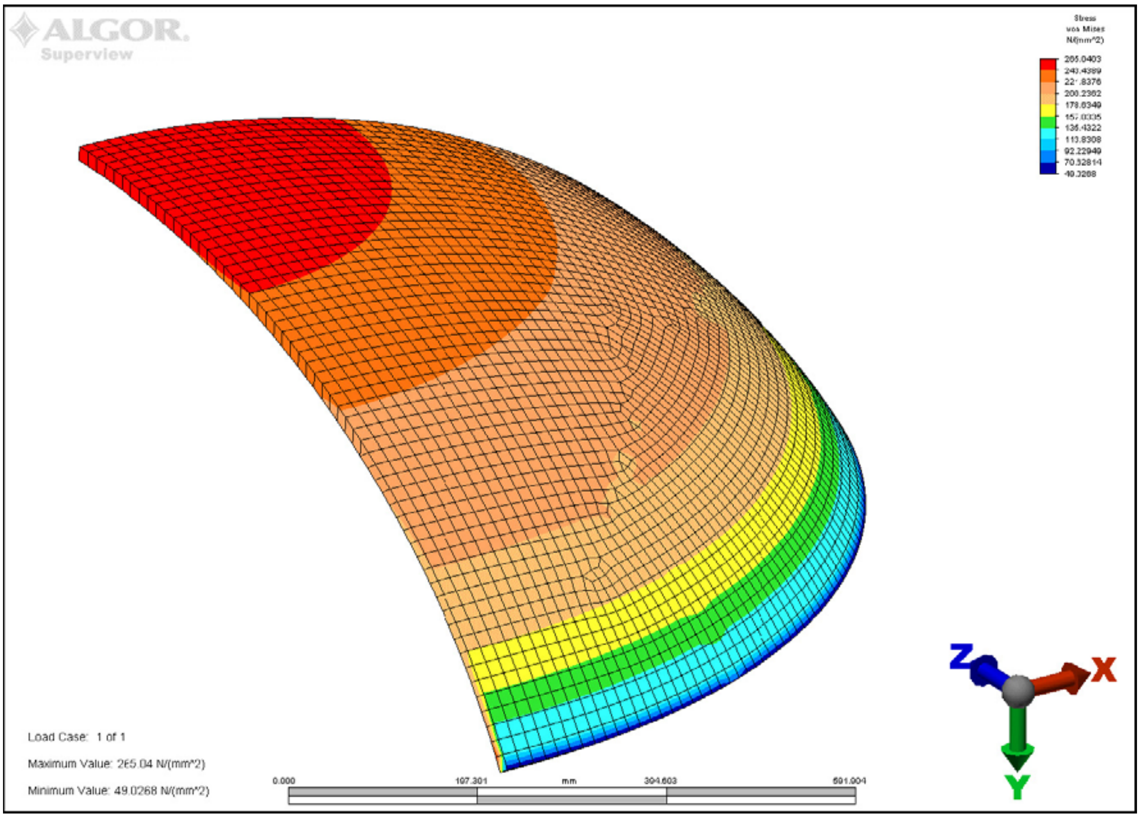


Figure 4-21. *The von Mises stress distribution in the steel compartment plug.*

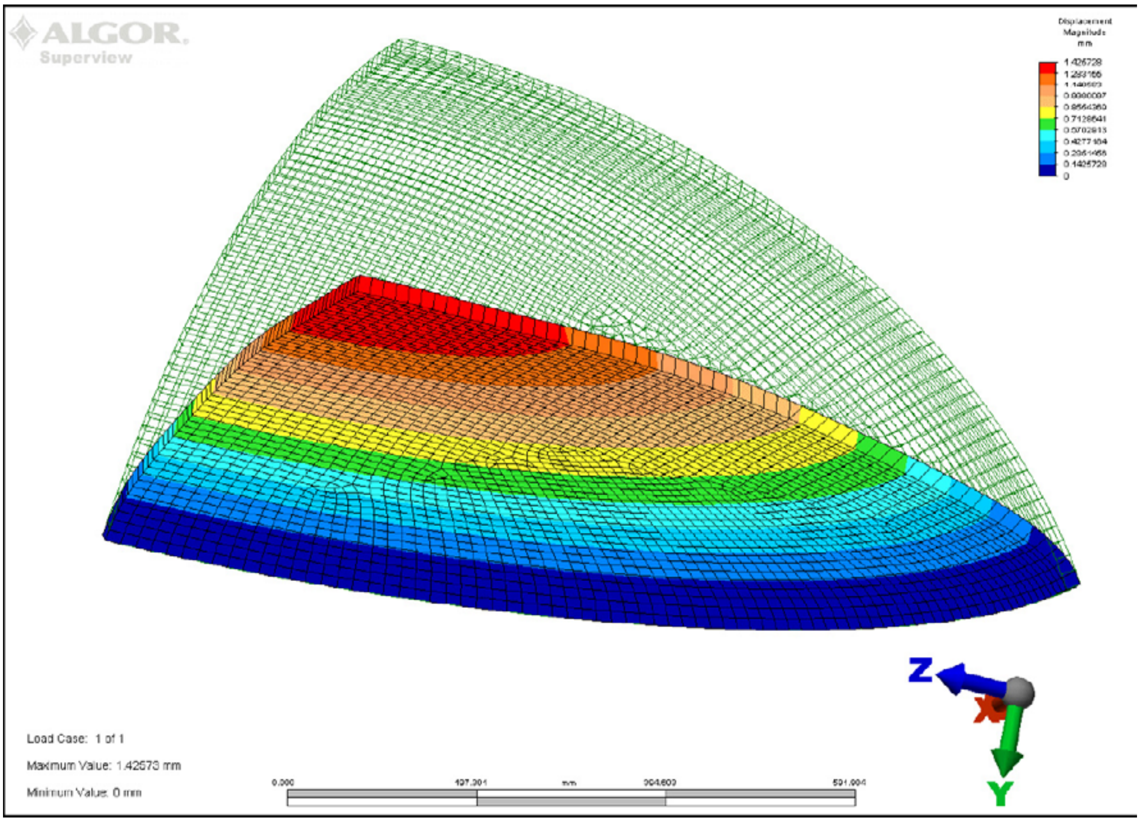


Figure 4-22. *Displacements in the steel compartment plug.*

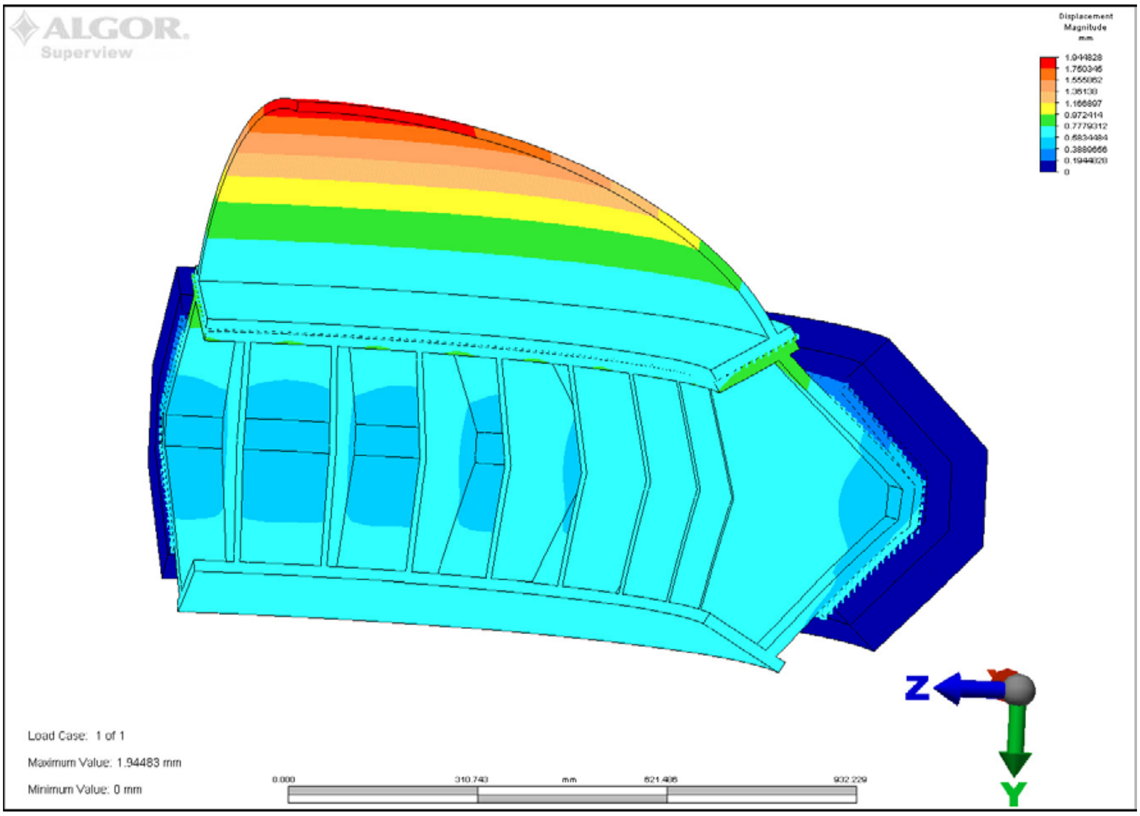


Figure 4-23. *Displacements of the steel compartment plug.*

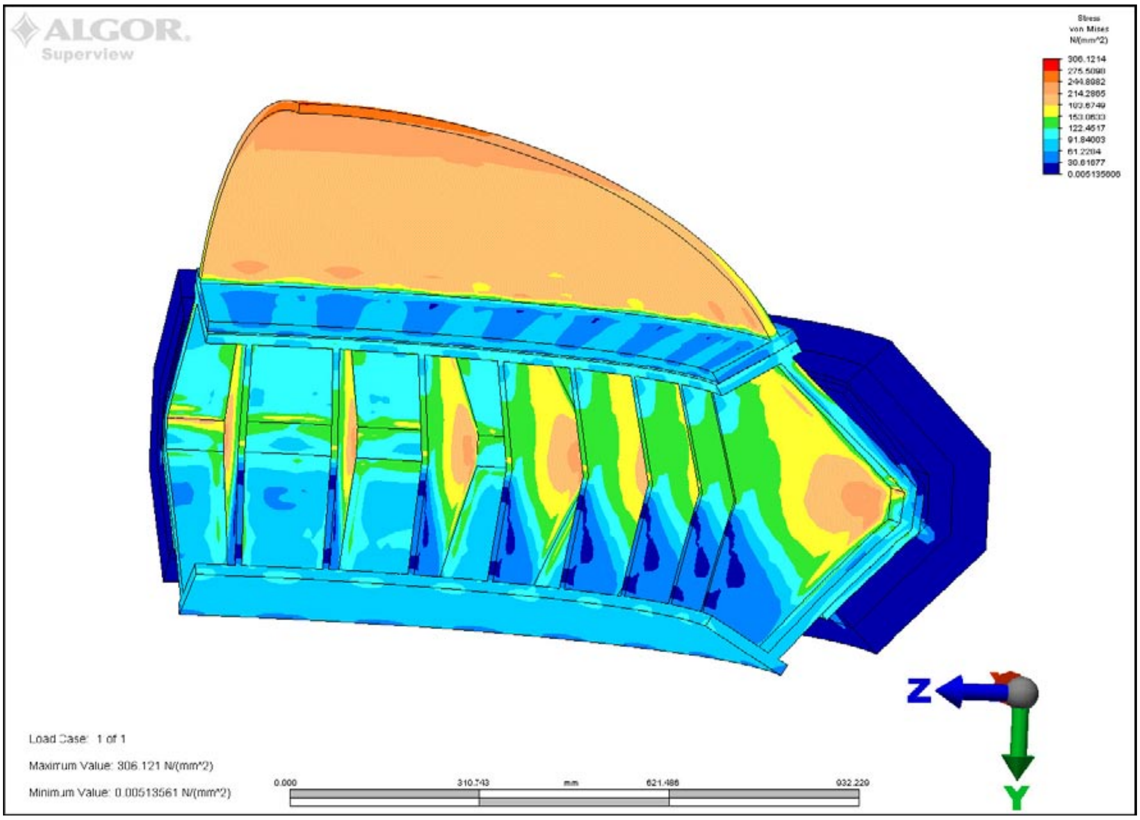


Figure 4-24. *Von Mises stress in the steel compartment plug.*

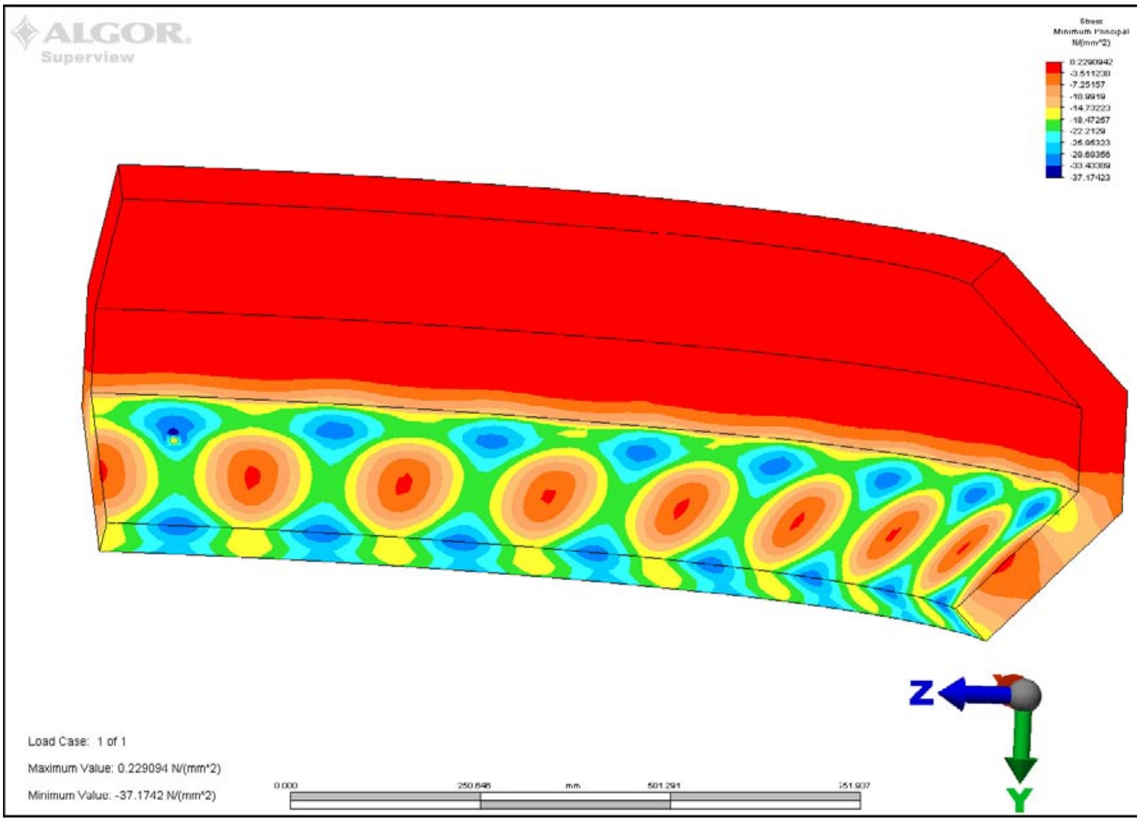


Figure 4-25. *Minimum principal stress in rock at the bottom of the groove.*

4.4 Supercontainer shell

4.4.1 Design

The supercontainer is depicted in Figure 4-26, showing the spent fuel canister surrounded by a bentonite buffer and the perforated steel shell.

The engineering drawing of the supercontainer (see Figure 4-26) is presented in Appendix D and includes SKB's BWR 1,700 W canister (length = 5,560 mm) in the design. All of the relevant dimensions are tabulated in Appendix C, the outer diameter of the carbon steel shell of supercontainer is 1,765 mm, the length of Posiva's BWR 1,700 W canister (reference design) is 5,525 mm, the weight, including feet, is 1,071 kg without feet and 1,108 kg with feet. The steel cylinder is 8 mm thick with a perforation of 60% /Börgesson et al. 2005/ with 100 mm diameter holes, see Figure 4-27 for detailed dimensions.

The shell is provided with five pair of feet with a height of 42.5–45 mm (to provide nominal gap of 42.5 mm) and 73.5° spacing (centre of feet).

Table 4-5 shows the dimensions with manufacturing tolerances and weights on components for SKB's supercontainers with PWR and BWR canisters.

The supercontainer end plate was previously specified to the same degree of perforation as the cylinder. This end plate specification was found to be problematic because the use of perforated material results in an increase to the effective gap size between the supercontainer and distance block. The gap size is a critical issue especially for BD design as it is key to ensuring that the hydraulic pressure exerted on the distance blocks can be reasonably and technically managed. Therefore, the design of the end plates was modified so that they will not be perforated.

The supercontainer is designed with regards to the most unfavourable load conditions due to tolerances in the deposition drift. The worst-case scenario is when the deposition drift has a "step" near the outermost parking foot at each end of the supercontainer.

The supercontainer was analyzed using the general FEM program ANSYS (see Figure 4-28). The model was simplified to one quarter of the supercontainer. Contact element was used in the model to allow for simulation of gaps and contact, as well as friction, between all surfaces. The bentonite has in the model the capability of both cracking and crushing. The steel was modeled as elastic-ideal plastic.

The supercontainer is designed with regards to the most unfavourable load conditions due to tolerances in the deposition drift.

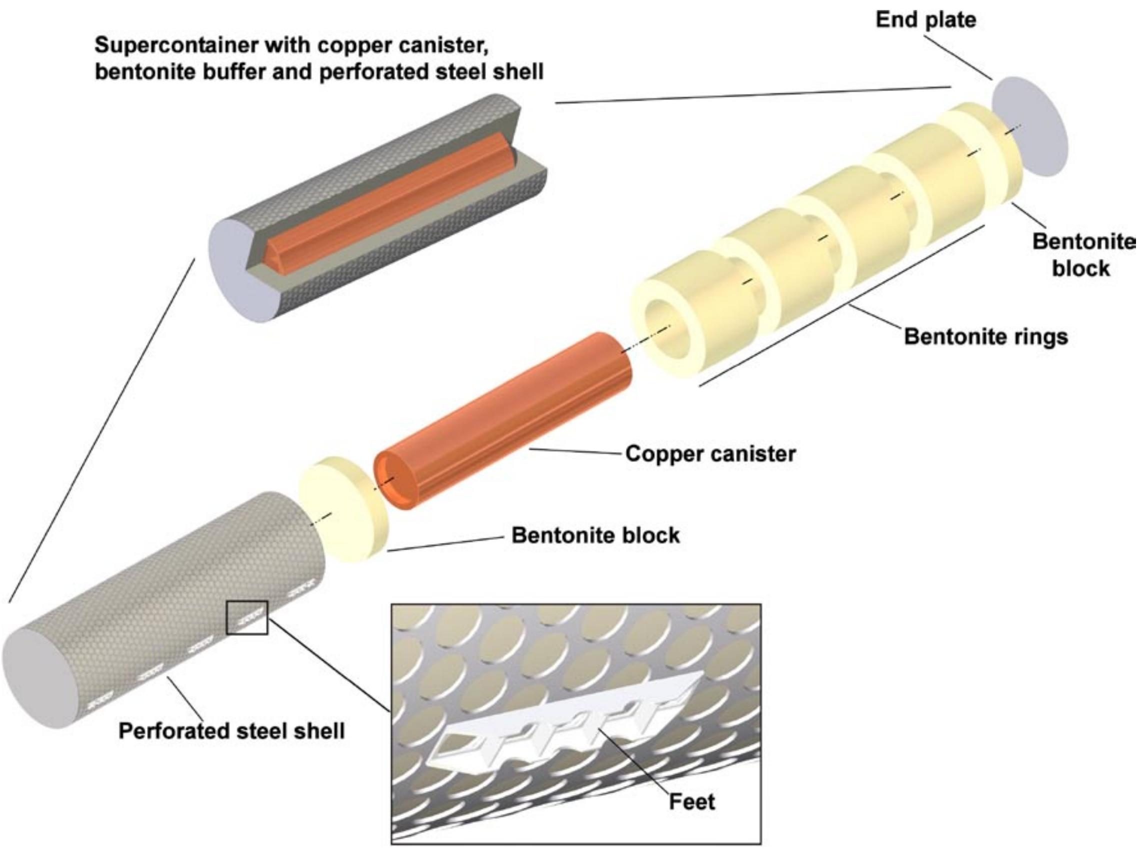


Figure 4-26. *The supercontainer and different components in it.*

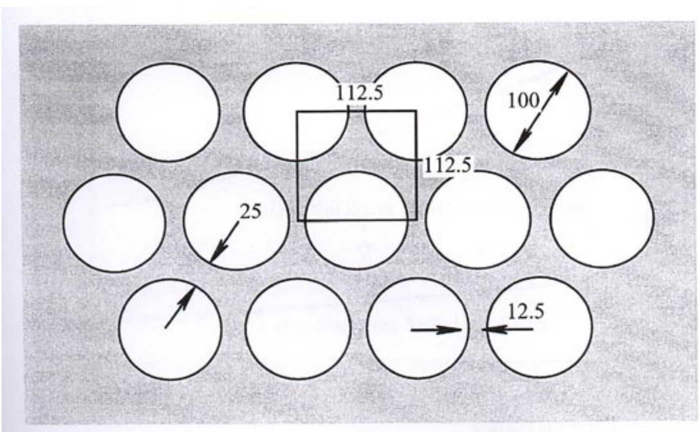


Figure 4-27. *Section of supercontainer cylindrical shell surface, showing dimensions [mm] of the perforations.*

Table 4-5. Dimensions with manufacturing tolerances and weights on components for SKB's supercontainers with PWR and BWR canisters and Posivas BWR canister (reference design).

Component	OD (mm)	ID (mm)	Length (mm)	Approx. weight (kg)
Steel shell (SKB)	1,765 $^{0}/_{-2}$	1,749	5,556 $^{+5}/_{0}$	890
Steel shell (Posiva)	1,765 $^{0}/_{-2}$	1,749	5,525 $^{+5}/_{0}$	1,071
Bentonite rings (SKB)	1,740 $^{+1}/_{-2}$	1,058 $^{+1}/_{-1}$	1,211 $^{+1}/_{-1}$	3,720
Bentonite rings (Posiva)	1,739 $^{+1}/_{-2}$	1,058 $^{+1}/_{-1}$	1,202.5 $^{+1}/_{-1}$	-
Bentonite block (SKB)	1,740 $^{+1}/_{-2}$	-	350 $^{+1}/_{-1}$	1,707
Bentonite block (Posiva)	1,739 $^{+1}/_{-2}$	-	350 $^{+1}/_{-1}$	-
Canister (SKB PWR loaded)	1,050 $^{+2.35}/_{-2.35}$	-	4,835 $^{+2.85}/_{-2.35}$	26,910
Canister (SKB BWR loaded)	1,050 $^{+2.35}/_{-2.35}$	-	4,835 $^{+2.85}/_{-2.35}$	24,600
Canister (Posiva BWR loaded)	1,050 $^{+2.35}/_{-2.35}$	-	4,800 $^{+2.85}/_{-2.35}$	-
Assembled SKB PWR supercontainer	1,765 $^{0}/_{-2}$	-	5,560 $^{+6}/_{-6}$	46,094
Assembled SKB BWR supercontainer	1,765 $^{0}/_{-2}$	-	5,560 $^{+6}/_{-6}$	43,784
Assembled Posiva BWR supercontainer	1,765 $^{0}/_{-2}$	-	5,525 $^{+6}/_{-6}$	-

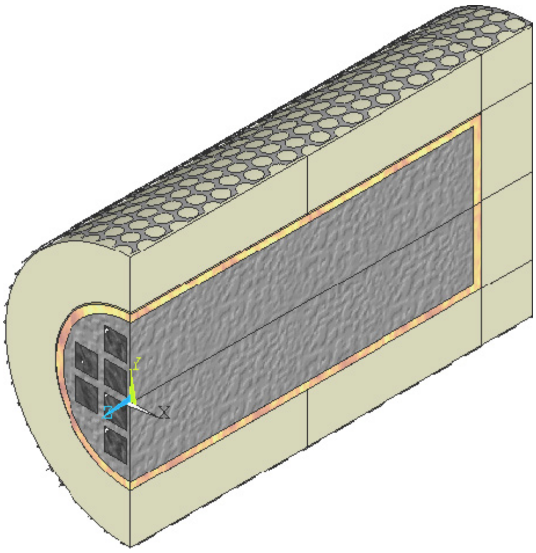


***Figure 4-28.** FEM-model of the supercontainer.*

4.4.2 Alternative supercontainer shell materials to steel

Alternative materials have been investigated for the supercontainer shell because of the potential long-term safety consequences of the interaction between the iron in the steel shell (or its corrosion products) and the bentonite surrounding the canisters.

The present supercontainer design uses the general structural steel S235JRG2 with a minimum tensile strength of 235 MPa. Potential alternative materials should at least have the same minimum strength as the existing material or the design must be re-evaluated.

The following materials have been evaluated:

- Copper alloys.
- Nickel based alloys (Monel, Alloy 625).
- Titanium alloys.
- High performance Stainless Steels (duplex ss).

It has been concluded that copper alloys would require redesign of the supercontainer and definitely increased material thicknesses due to the limitations in strength compared with the existing material. Copper is not either potential alternative for other design components as the compartment plug.

Nickel based alloys and high performance stainless steel (duplex) has also been considered due to the slow corrosion rates. Nickel based alloys, duplex stainless steel and titanium alloys have all enough strength and can be used without redesign of the supercontainer. Since the tensile strength is higher than the original material there is a possibility to decrease the wall thickness proportional to their higher strength values. These materials are also potential alternatives for other design components. One disadvantage of the nickel based alloys is the high nickel price. In addition, the nickel-bentonite interaction is poorly known.

Aiming for reduction of needed material volume for the manufacturing of the supercontainer, using a material with higher strength, for example higher grades of titanium or duplex stainless steels, is recommended.

Considering the tensile strength and cost, the most likely cost effective solution if smaller contents of iron can be accepted will be to use a duplex stainless steel for example LDX 2101. Titanium is considered for the safety case point of view as the only alternative if iron cannot be allowed. The alternative material for the supercontainer is still open and to be decided later. Potential interaction about the proposed alternative materials and the bentonite should be addressed further.

The manufacturing of the supercontainer shell should be taken into account when selecting the alternative material. Bending of plates and making of holes in materials with higher tensile strength demand more of the equipment but this will be taken care of with qualified manufacturers working with qualified procedures.

Welding of these alloys can successfully be performed with rather conventional welding methods. Special care must, however, be adjusted to each grade of material and be performed in accordance with qualified procedures to keep the good mechanical properties even in welded conditions.

Based on a first preliminary evaluation of the long-term safety aspects of nickel and titanium based alloys both of the alloys considered appear to have advantages with respect to carbon steel slow corrosion rates and lower production of hydrogen gas. Of these alloys the greatest probability of bentonite alteration appears to result from Ni(II) whereas the impact of titanium on bentonite is expected to be minimal and it is recommended that titanium should be considered futher as an alternative material for the supercontainer and associated metal components. Further evaluation on the long-term impact of the titanium is, however, warranted.

4.4.3 Buffer blocks in supercontainer

General

A main part in the KBS-3H alternative is the use of a supercontainer. Bentonite blocks will be installed inside the supercontainer, surrounding the copper canister. The bentonite blocks inside the supercontainer will be of the same quality (density and initial water ratio) for the different design alternatives. The final average density at saturation of the blocks after having swelled through the perforated steel supercontainer and filled the volume between the supercontainer and the rock should be between 1,950–2,050 kg/m^3 (dry density 1,481–1,637 kg/m^3). Two types of block will be installed: ring shaped blocks around the canister and cylindrical blocks at each end of the supercontainer. The initial density of the blocks, before emplacement, will vary depending on block type.

The current buffer material inside the supercontainer is MX-80-type sodium bentonite with 10% initial water content. The outer diameter of the bentonite blocks is 1,740 mm and the thickness of the end blocks 350 mm. The initial dry density of the ring shaped blocks is 1,887 kg/m^3 (1,789–1,977 kg/m^3). The density after swelling and saturation is 2,000 kg/m^3 (1,950–2,050 kg/m^3) and the estimated swelling pressure 7–8 MPa. The properties of the buffer end blocks differ slightly from those of the ring blocks (see Appendix C).

Initial conditions of blocks in supercontainer

The suggested design requires blocks with high initial density depending on the rather large slots that should be filled. Table 4-6 show the dimensions used for the calculations and also the calculated dry density of the blocks for Olkiluoto BWR OL1-2 spent fuel. In Figure 4-29 the dry density of the blocks is plotted vs. the saturated density after swelling and homogenization. The tolerances of the dry density on the manufactured blocks are rather large (1,791–1,979 kg/m^3 for the ring shaped blocks and 1,665–1,841 kg/m^3 for the cylindrical end blocks) to obtain an average density at saturation between 1,950–2,050 kg/m^3 in the drift.

Sensitivity for variations of the tunnel diameter

The calculations are done using the nominal diameter of the deposition drift i.e. 1,850 mm. The diameter will, however, vary and this will influence the density at saturation in the system. The diagram in Figure 4-30 shows how the density at saturation will vary with different tunnel diameters. The figures in the diagram assume a density at saturation of 2,000 kg/m^3 at the nominal tunnel diameter (1,850 mm).

Table 4-6. Table showing the dimensions used in the calculations. The table also shows the calculated dry density of the blocks that will be used in the supercontainer.

Dimensions	
Rock	
Diameter tunnel, mm	1850
Super container	
Outer diameter, mm	1765
Inner diameter, mm	1749
Thickness of container and end plate, mm	8
Degree of perforation	62%
Length, mm	5546
Canister	
Outer diameter, mm	1050
Ring shaped block	
Outer diameter, mm	1739
Inner diameter, 1060	1060
Cylindrical end block	
Outer diameter, mm	1739
Calculated block data	
Ring shaped block	
Target average density at saturation, kg/m³	2000
Initial block dry density, kg/m³	1885
Initial block void ratio	0.480
Cylindrical end block	
Target average density at saturation, kg/m³	2000
Initial block dry density, kg/m³	1753
Initial block void ratio	0.592

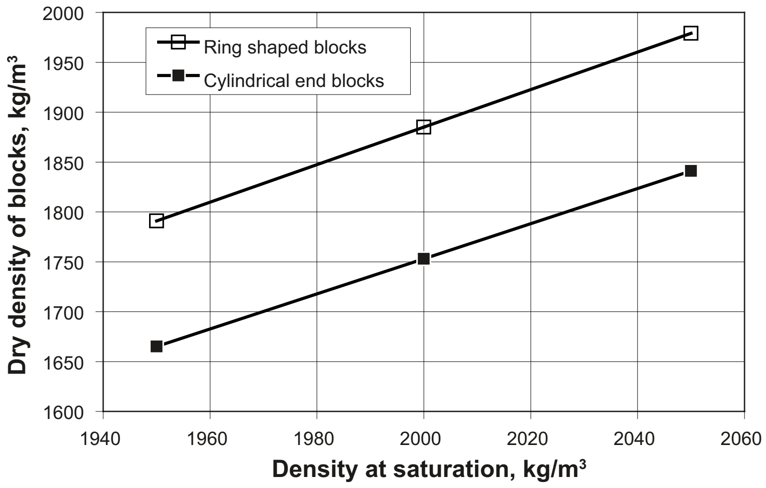


Figure 4-29. Diagram showing the dry density of the blocks (dimensions according to Tables 4-5 and 4-6) plotted vs. the density at saturation in the tunnel after swelling and homogenization. The two different block types in the supercontainer (ring shaped and cylindrical) are shown in the diagram.

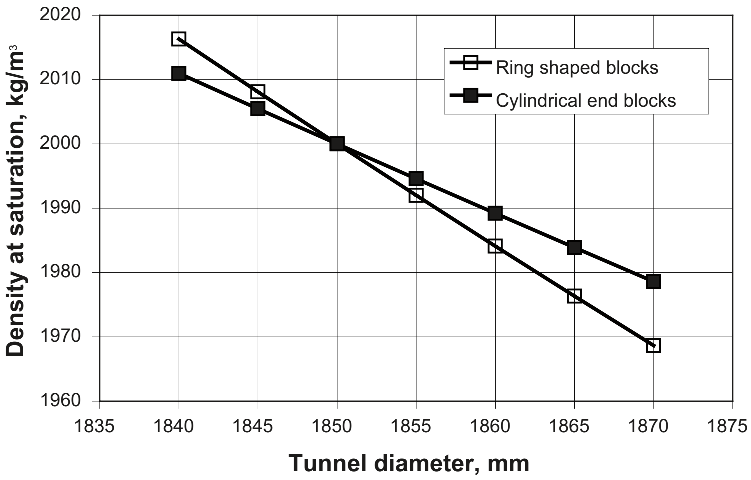


Figure 4-30. Diagram showing the density at saturation in the tunnel after swelling and homogenization (intended density at saturation 2,000 kg/m³) plotted vs. various tunnel diameters. The earlier calculations are done using the standard diameter 1,850 mm, but there will probably be variations in the real case.

Sensitivity for corrosion of the supercontainer

Investigations are going on regarding the behavior of the steel in the supercontainer during corrosion. In order to investigate the final saturated density of the bentonite and its sensitivity for a possible volume change of the corroded steel, calculations of some extreme mechanical effects of complete corrosion have been done for three different cases:

1. The volume of the emplaced steel is the same after corrosion (hypothetical reference case).
2. The volume of the corroded steel is zero (hypothetical reference case).
3. The volume of the emplaced steel has been doubled after corrosion (a doubling of the volume is the expected case due to conversion to magnetite, which has half the density of the original metal.

The calculations made assume radial swelling only. Axial swelling/homogenization is not taken into account. In Table 4-7 the results from the calculations are shown for both block types.

The influence is limited for the bentonite rings but larger for the end blocks depending on the rather large end plate of the supercontainer.

Table 4-7. Table showing how corrosion of the supercontainer influences the final average density of the buffer. The three different cases described have been calculated: the steel volume is the same after corrosion, the steel has no volume and the steel volume is doubled.

Block type	Saturated density for the different volume cases		
	Same volume kg/cm³	No volume kg/cm³	Double volume kg/cm³
Ring shaped block	2,000	1,991	2,009
Cylindrical block	2,000	1,982	2,016

4.4.4 Assembly of supercontainer

The assembly of the two supercontainers manufactured for the full-scale tests and demonstrations carried out on the KBS-3H alternative at Äspö HRL is presented including experiences and potential improvements that can be considered for future development.

For test purposes were the supercontainers mock-ups with concrete instead of bentonite as buffer material.

The assembly sequence, which is illustrated in the Figures 4-31 and 4-32 below, was carefully addressed during the planning phase due to the narrow tolerances. The nominal radial space between components is approximately 3–4 mm. The concept is based on building the supercontainer around the canister placed in a vertical position.

The only way to handle the supercontainers after assembly is with the transport tube. The supercontainer is therefore assembled on top of the transport tube gamma gate. Thereafter, the transport tube is connected to the gamma gate. After connection, the transport tube with the supercontainer can be lifted and tilted to a horizontal position, see Figure 4-33.

The challenges for the assembly that were discussed during the planning phase due to the narrow tolerances were shown to be controllable and the assembly was easily performed in one day during the demonstration at Äspö excluded welding of end plates. The main problem that occurred during the demonstration was the welding of the "lower" end plate placed on the gamma gate and the bending of the end plates due to weld stresses. It is obvious that the bending of the end plates can be eliminated if the welding and welding method is optimized in the future.

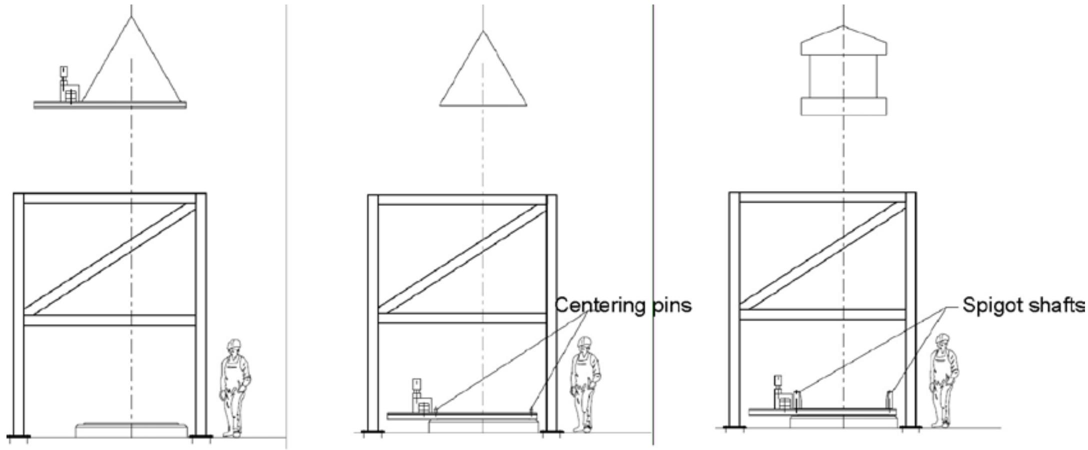
The welding and the subsequent weld inspection of the end plate were difficult to perform because of the limited space toward the gamma gate. Possible solutions are to redesign the gamma gate for better access or to weld the end plate to the steel shell before placing on the gamma gate.

However, welding the end plate to the cylindrical steel shell, as the first work step, requires changing the whole assembly sequence. This means that the buffer should be placed inside the steel shell before placing of the canister. According to the tests performed, this seems to be possible. To reduce the risk for jamming when placing the buffer inside the steel shell all edges on the buffer should be provided with chamfers. Placing of the canister after placing of the buffer is also desirable with regards to requirements for radiation shielding in the actual repository.

4.4.5 Alternative designs of the supercontainer

Alternative designs were made to evaluate the possibility to design the supercontainer without the steel shell to reduce the amount of corrodable steel and related possible detrimental effects and therefore better fulfill the long-term safety requirements as regards the amount of corrodable materials. The main assumptions for this study were:

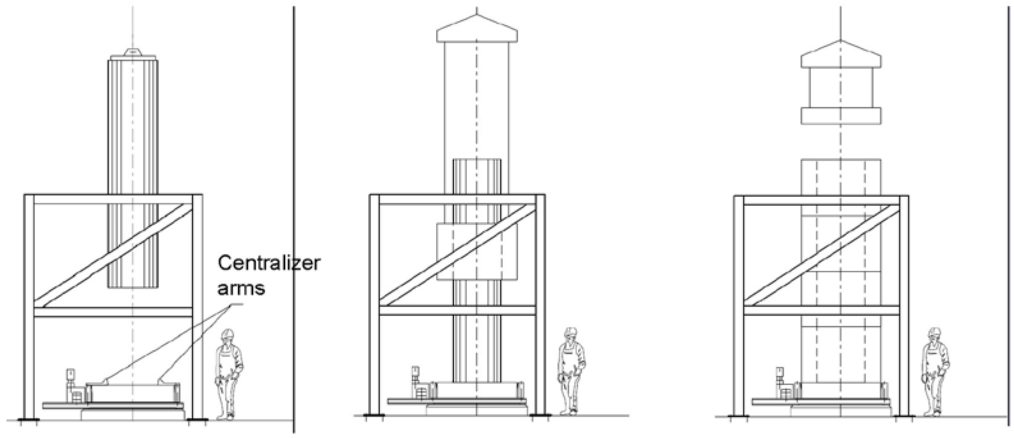
- The amount of steel should be minimised.
- The present deposition machine should be used for transporting of the supercontainer. The supercontainer should therefore be provided with feet.
- The buffer and the spent fuel canister should be transported as one package for radiation shielding purposes.



1. Placing of heavy gamma gate

2. Placing of supercontainer end plate

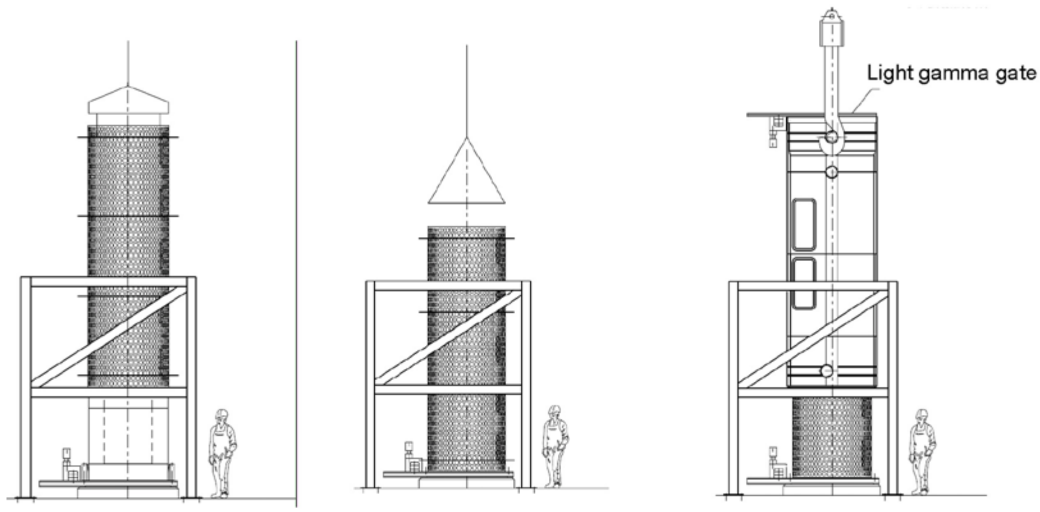
3. Placing of lower buffer block



4. Placing of canister

5. Placing of buffer rings

6. Placing of upper buffer block



7. Placing of supercontainer shell, welding of lower supercontainer end plate

8. Placing and welding of upper supercontainer end plate, dismantlig of fixture plates

9. Placing of transport tube, assembly of heavy gamma gate. Lift of complete transport tube with supercontainer

Figure 4-31. *Assembly of supercontainer at Äspö.*

***Figure 4-32.** Supercontainer assembly at Äspö.*

Figure 4-33. The supercontainer is placed into a transport tube for transportation down to the underground test site at Äspö HRL.

The original supercontainer shell is used to hold the bentonite blocks together, which is vital for the transportation and for the buffer behavior after the final placement. If the shell is removed or partly removed the blocks must be kept together with other means. A number of different alternatives have been evaluated.

If the steel shell is completely removed can the buffer be kept together with tie rods, this is illustrated in Figure 4-34. The tie rods can be made of titanium.

The feet, which are vital to allow for transportation with the present water cushion principle, can be attached to the buffer in the same way as for the distance blocks alternatively can the feet be connected to a "cradle" fully or partially covering the length of the supercontainer. These feet arrangements are illustrated in Figures 4-35 to 4-37.

An alternative to have the feet connected with screw directly to the buffer is to use "straps" that are keeping the feet in place during the transportation. The "straps" are after the final placement released and removed. The principle with "straps" is illustrated in Figure 4-38.

One other evaluated alternative is to use a mechanical casing surrounding the "supercontainer" during the transport. After the final placement of the supercontainer is the mechanical casing released and removed with the deposition machine. The casing will during the transportation act as a protection. The principle with mechanical casing is illustrated in Figure 4-39.

The alternatives with straps and casings requires, however, changes of the present deposition machine.

One more alternative for the feet arrangement is the use of foot beams which are not connected with the buffer. During transportation the foot beam will be guided by the slide plate. The principle with foot beams is illustrated in Figure 4-40.

The study has presented several possible alternatives to the present supercontainer concept. One should, however, have in mind that the presented alternatives put higher demands on the buffer with regards to structural strength when no shell is used.

The presented alternatives involve a high risk that pieces from the buffer might fall causing problems for the transportation. It is only the alternative with a mechanical casing which can prevent this.

The presented alternatives must be developed further especially as regards the effects the alternatives will have on the present deposition equipment and therefore are additional research and development required.

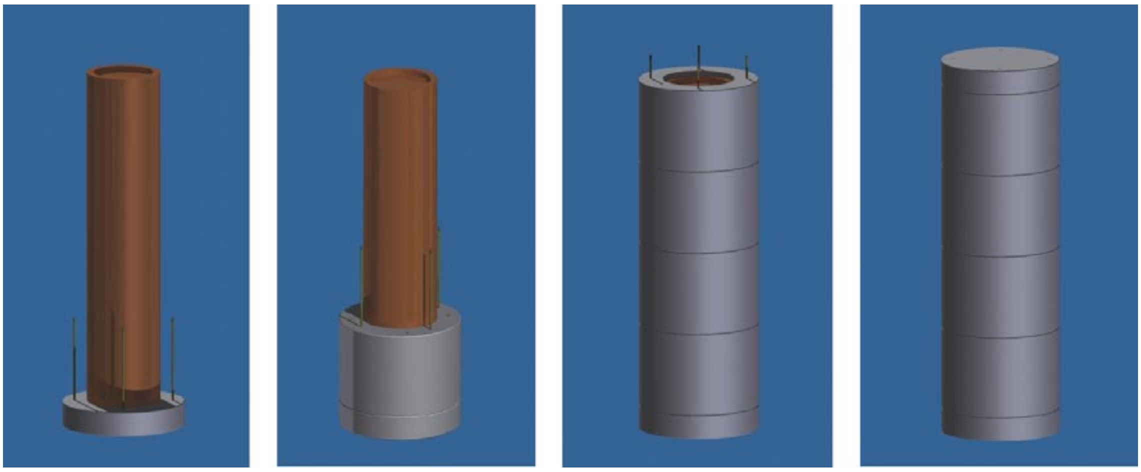


***Figure 4-34.** Illustration showing the assembly using tie rods.*

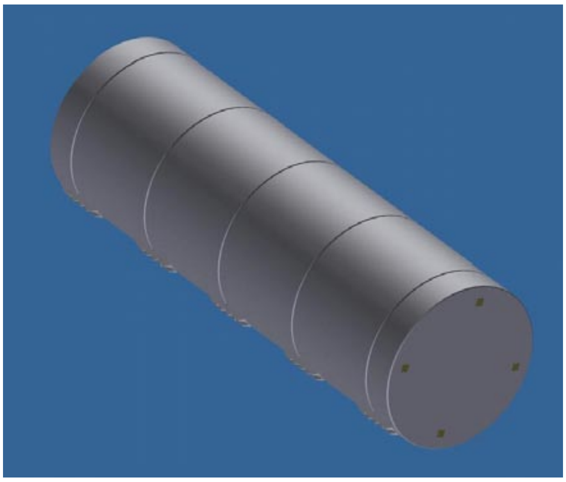


***Figure 4-35.** Feet attached directly to the buffer.*

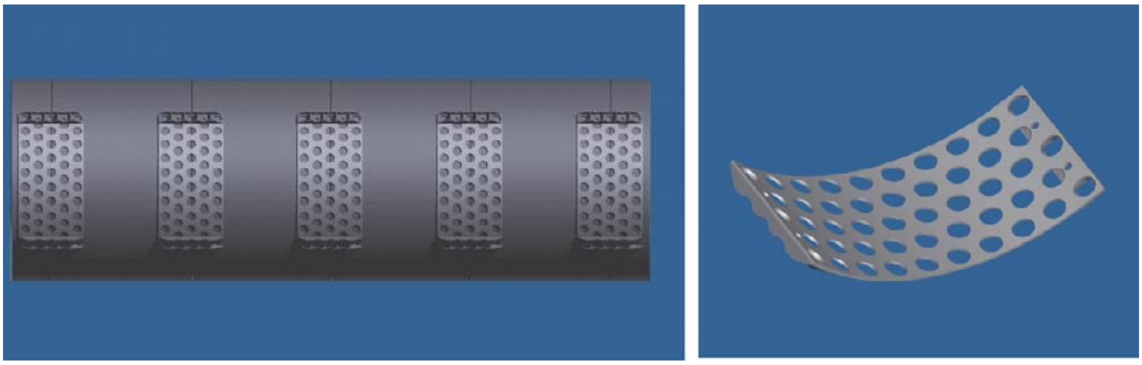


***Figure 4-36.** Feet mounted to a ”cradle”.*

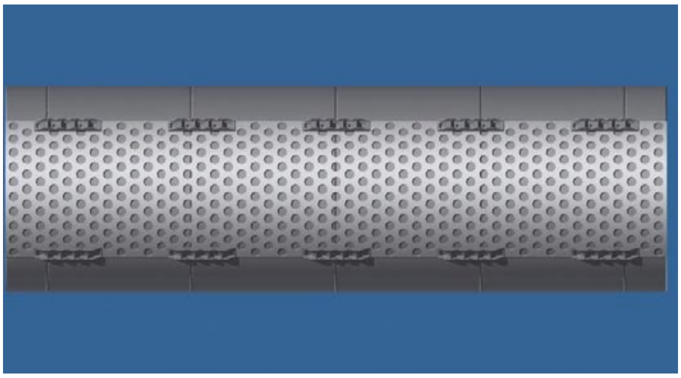


Figure 4-37. *Feet mounted to a ”cradle” covering the full length.*

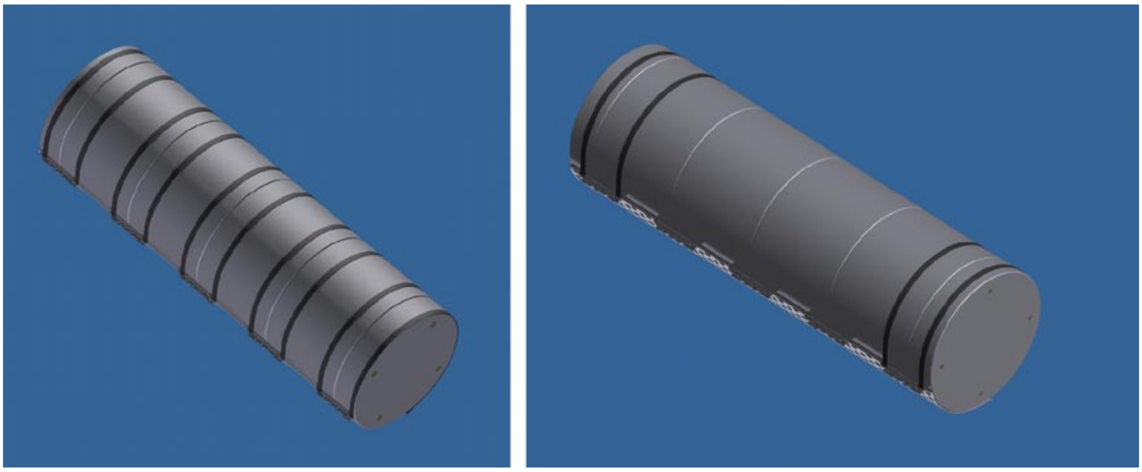


Figure 4-38. *Feet attached to the buffer with ”straps”.*

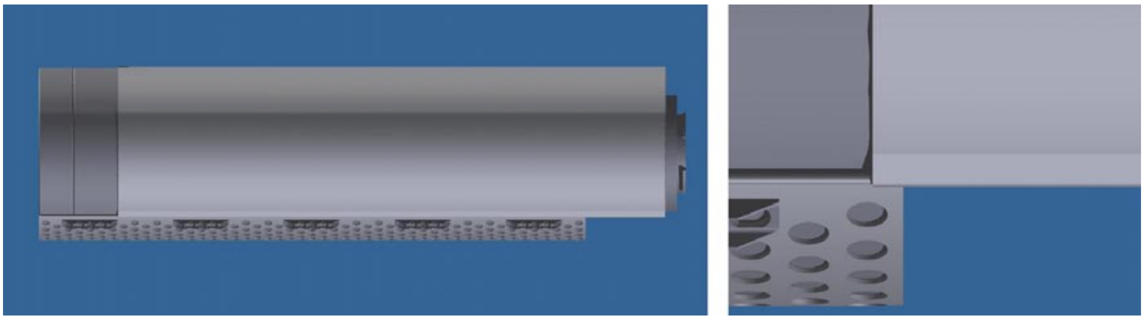


Figure 4-39. *Mechanical casing.*

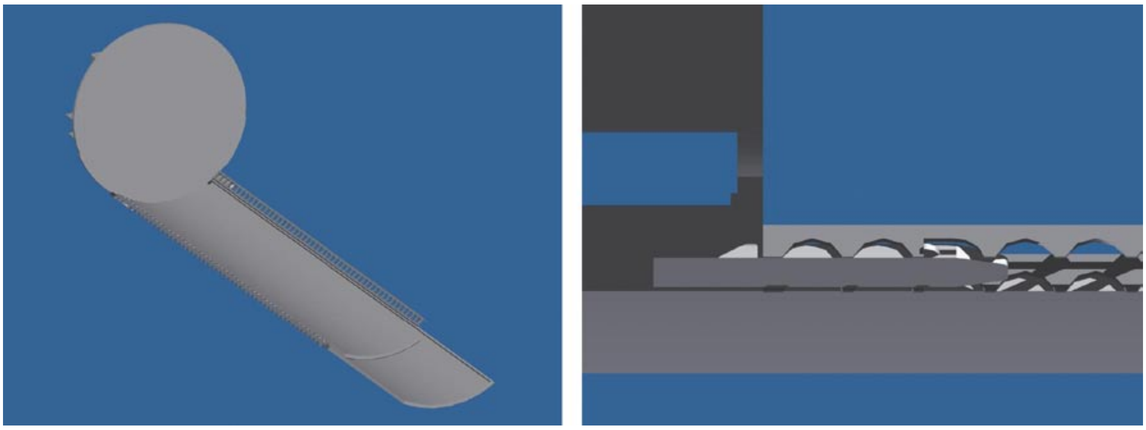


Figure 4-40. Foot beams are supported by the slide plate (left), the foot beams are during transport connected to the radiation shield with grippers (right).

4.5 Deposition drift

4.5.1 Excavation

The deposition drift of the KBS-3H is excavated by mechanical boring using rotary crushing, called reverse raiseboring or push-reaming /Bäckblom and Lindgren 2005/, see Figure 4-41. Key component of the system are: raiseboring machine, cutter head, drill string, stabilizers, and flushing system, see Figures 4-42 to 4-46. The principle is same as in boring of deposition holes in KBS-3V and in box-hole raiseboring. The removal of muck is based on water flushing instead of vacuum suction in KBS-3V deposition hole and gravity in box-hole boring. Water flushing is facilitated by the slight inclination upwards of the drift which enables the gravity flow. Another available and tested technique is cluster boring. The technique was tested and found technically feasible, however, the push-reaming was selected as the reference technique /Bäckblom and Lindgren 2005/.

The technique was tested and demonstrated by reaming or excavating two KBS-3H deposition drifts of diameter 1.85 m at the Äspö Hard Rock Laboratory from late 2004 to early 2005. The drifts were excavated in good quality rock similar to that in expected repository sites. One of the horizontal drifts was 15 m long and the other one 95 m in length.

The requirements specified for the drift quality, e.g. surface evenness, (see Section 3-4) were in principle fulfilled except the requirement for the straightness of the hole. Examples of different type of surface unevenness found in the KBS-3H demonstration drifts at Äspö are shown in Figures 4-47 and 4-48.

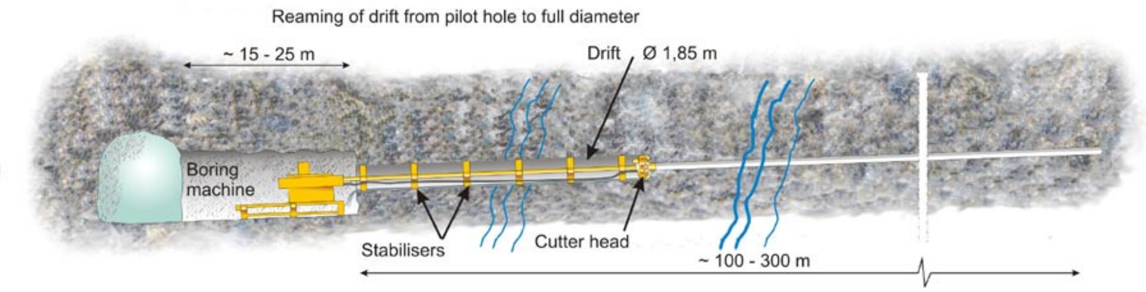


Figure 4-41. Principle for boring the KBS-3H deposition drifts by reaming the pilot hole using rotary crushing.

Figure 4-42. *The cutter head at site (left) and during operation (right).*

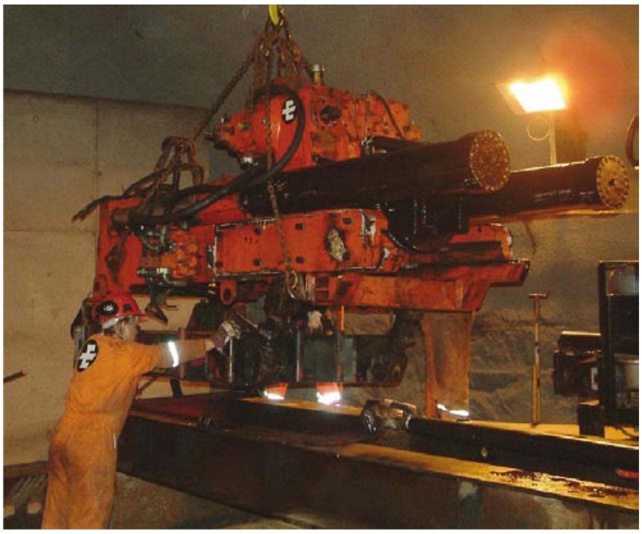


Figure 4-43. *The boring machine being installed.*

Figure 4-44. *The start of reaming the pilot hole to full diameter.*

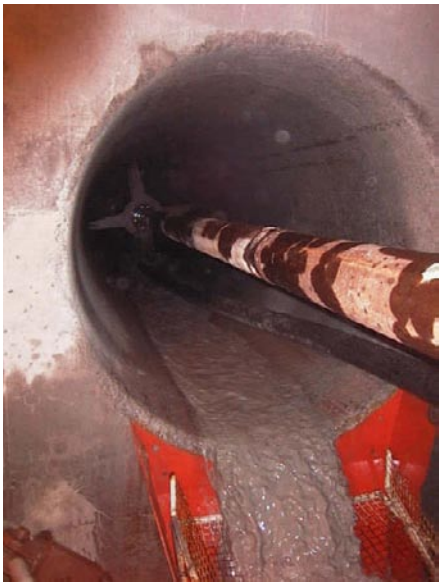


Figure 4-45. *The removal of muck and flushing is based on water flow.*

Figure 4-46. *Stabilizers used to support the drill string.*

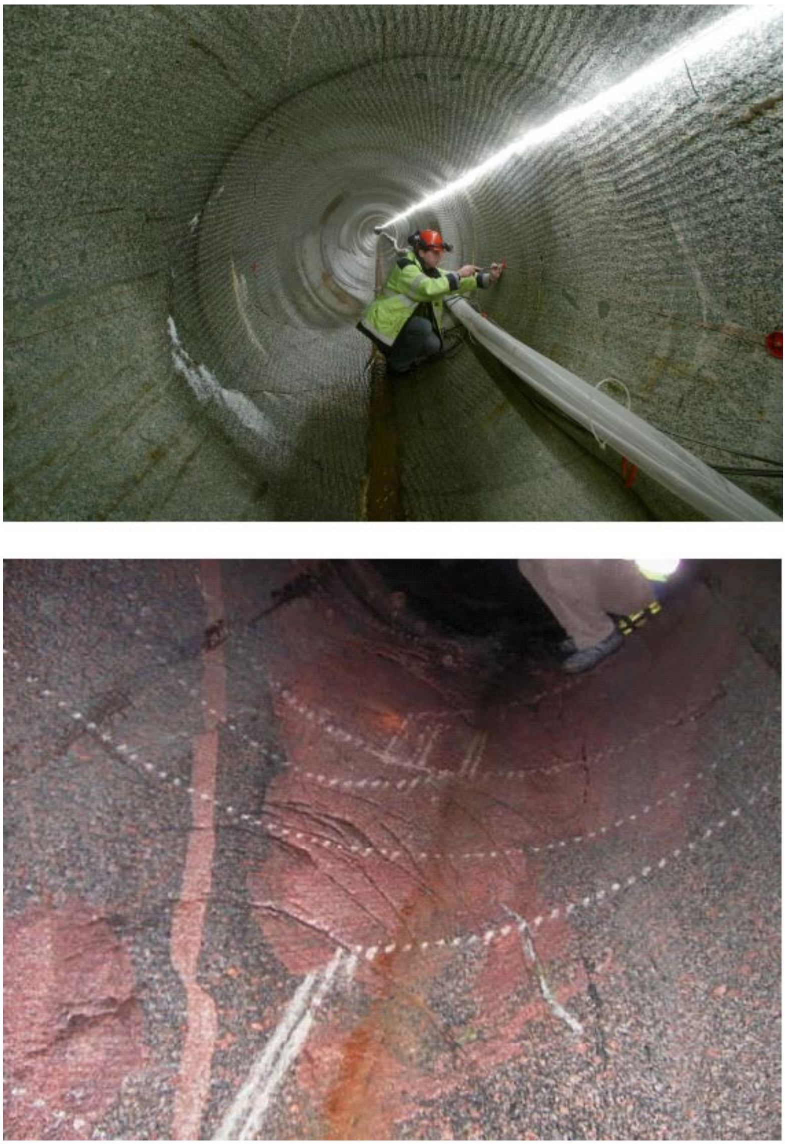


Figure 4-47. *Some typical types of surface unevenness in deposition drift: rifle type grooves on the drift wall (top) and notches at fracture intersections on the floor (above). Note that some of the surface unevenness are due to rock fractures and not related to the excavation method.*

Figure 4-48. *Some typical types of surface unevenness in deposition drift: cavities on the drift roof (top) and rims shaped grooves and a notch (above). Photos by J Autio.*

Standard boring equipment was modified for this specific application. The boring performance of the boring equipment was modest, being about 6 m per 12 hours; however, there are several ways to improve the performance in a production-type boring equipment.

The results indicated that the technique is technically viable for producing 300 m long deposition drifts.

The results emphasize the need for developing adequate steering system during drilling of the pilot hole and further optimisation of requirements for the quality of the drift.

The drift quality can be improved if needed. One alternative is to smooth the surfaces and adjust the drift diameter through treatment of the surface of the holes after excavation. This alternative can be accomplished by using rotary boring type equipment with a finishing cutter head or by use of a novel finishing machine. An illustration of a possible technique is shown in Figure 4-49, however, the technique is on conceptual level based on existing tools and has not been used or tested.

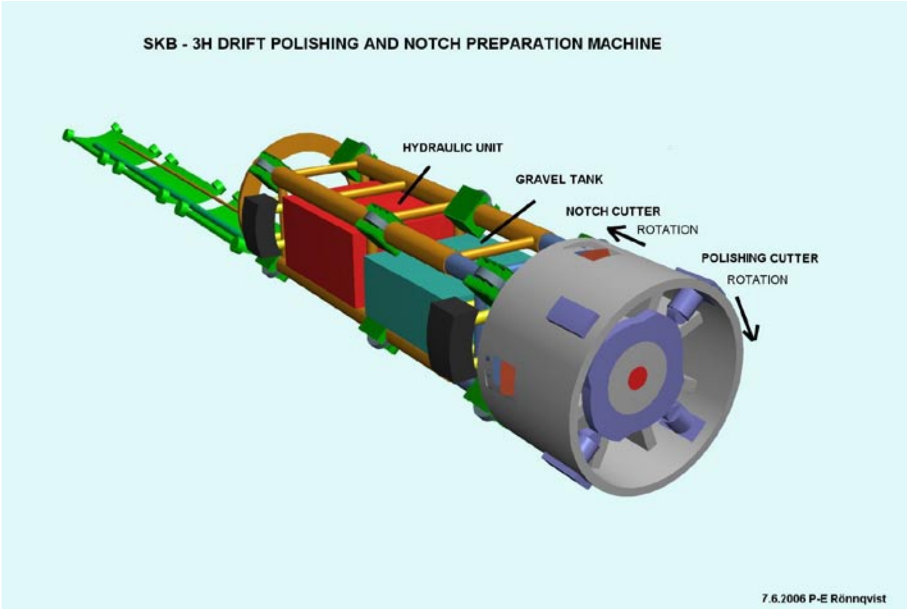


Figure 4-49. *Illustration of a possible machine to be used to smoothen deposition drift surfaces and to produce constant diameter.*

An important aspect of fulfilling the quality requirements for the pilot boring of deposition drifts is to produce a pilot hole with the required straightness and waviness. The pilot hole is used to guide the cutting head of the boring machine. Achieving the waviness requirements seems to be more of a challenging task than deviating from the theoretical straight axis and, therefore, development work on the steering of pilot boring is described separately in the following chapter.

4.5.2 Steering of pilot boring

A straight pilot hole is the prerequisite for successful excavation of a deposition drift fulfilling the strict geometrical requirements presented in Section 3.4. Thus the requirements for the pilot hole are highly related to the final quality of the deposition drift. The quality requirements are as follows /Autio et al. 2007/:

1. The maximum allowed deviation including all sources of error is ± 5 mm over the length of the supercontainer (6 m). This requirement is in line with the calculations conducted with the supercontainer.
2. The maximum allowed deviation from the theoretical center line of the tunnel at the end of the deposition drift (300 meters) is ± 2 m (total deviation including horizontal and vertical deviation components).
3. The maximum allowed waviness is R = ± 2.5 mm for the pilot hole over the length of the supercontainer (6 m).

The requirement of the straightness of the pilot hole for the boring of demonstration drifts at Äspö was such that the end of the pilot hole for the 95 m drift should be within ± 1 m of the theoretical centerline. An additional more rigorous requirement was set to a deviation of ± 0.22 m, which was meant to entitle the drilling contractor to bonus compensation. According to the measurements the deviation in the vertical direction was 61 cm (downwards) and 11 cm (to the right) in the horizontal direction. This demonstrates that the straightness of boreholes is a crucial matter in all kinds of drill holes/boreholes. Absolutely straight holes cannot be drilled with the present technology, but there are some means how to improve the straightness of the holes.

Managing a straight hole requires that:

- Professional team is employed in the work.
- Drilling rig is aligned accurately with the target path of the hole.
- Equipment is optimal for drilling straight holes.
- Positioning of the drilling bit/hole can be measured to ensure that the hole is on the target path.
- Equipment for smooth correction/re-orientation of the hole in case the hole has deviated from the planned path.

There are uncertainties and errors involved with all requirements listed above. The most important factor causing uncertainty is connected with the determination of the accurate position of the hole (distance from the target path) by deviation survey tools. Deviation is caused by several factors, e.g. rock conditions and drilling/boring equipment used. All present deviation survey tools have their limitations causing some uncertainty, and determining of the most accurate tool available on the market is difficult, if not infeasible. This is because there is no impartial test data available on the accuracies between the different survey tools under the same rock conditions.

In general the best accuracies in vertical direction is on the order of 0.1% and 0.15% in horizontal direction in relation to the hole length. Consequently, the measuring accuracy for a 300 m long drift would between 0–300 mm in vertical direction and between 0–450 mm in horizontal direction along the pilot hole. This means that one cannot detect deviation changes in the end of the hole, which are below these limits. This does not meet the present requirement, which is ± 5 mm over the length of the supercontainer. However, the requirement of ± 2 m for the total deviation of the 300 m long pilot hole is feasible with the commercially available deviation survey tools connected with directional core drilling. However, the uncertainty related to deviation surveys can be minimized by using more than one survey tool and by repeating the survey runs to achieve better statistical reliability. Another way to decrease uncertainty is to decrease the measuring interval (distance between the measuring stations).

Continuous control of deviation and technique to guide the hole back to its planned path (trajectory) within given tolerances are the most critical issues when drilling or boring straight holes. The idea of active steering is by far the most promising due to continuous deviation control and the subsequent corrective re-orientation of the hole.

The Rotary Steerable Drilling Systems (RSS) are preferred tools in oil and gas industry primarily because the tools can follow the planned well path without stopping (active steering). Several service companies offer Rotary Steerable Drilling Systems.

The Rotary Steerable System developed by Smart Drilling GmbH was demonstrated at Äspö for active steering of a 95 m long pilot hole (Ø 152 mm) made with rotary crushing drilling related to excavation of two KBS-3H drifts in 2004–2005 /Bäckblom and Lindgren 2005/. Unfortunately the RSS-tool failed to prove its capability to comply with the given requirements, both with respect to deviations as well as durability. One weakness of this tool (a probable reason for the problems encountered) was that it has mainly been used in soft rock conditions and the hard rock references are very few. Although the stated requirements were not met the pilot hole was straight enough for reaming it to the final drift size 1,850 mm for other planned demonstrations.

/Bäckblom and Lindgren 2005/ analyzed the results of the drift excavation project and concluded e.g. that a strategy for drilling a 300 m long pilot hole would be needed and it is also necessary to develop and demonstrate technology for guidance and active steering of the pilot hole over a distance of 300 m. The plan for the demonstration that failed, was aimed to drill first a Ø 152 mm hole, which would then be enlarged to Ø 279 mm.

As stated before the accuracy of the deviation survey methods do not necessarily fulfill the strict requirements set for the KBS-3H pilot holes and deposition drifts. All deviation survey tools (Flexit, Maxibor, etc.) have their own limitations. SKB manufactured (prepared by Geocon) a special measuring device for the drift demonstration at Äspö to make independent checking of the deviation measurements carried out by the contractor. The device with a prism in the center (Figure 4-50) is inserted into the pilot hole and the accurate position of the centre point of the hole can be measured by standard survey technique with theodolite. The prerequisite is of course that the drill string is removed and the hole is straight enough so that the prism can be hit by laser beam from the theodolite at the entrance of the hole /Bäckblom and Lindgren 2005/.

Potential techniques to drill/bore straight pilot holes for KBS-3H deposition drifts have been investigated. The technique should include an active steering system or a system, which can be used to re-orient the hole back to the planned path. Although the demonstration of active steering by Smart Drilling failed at Äspö the feasibility of other RSS systems e.g. Geo-Pilot by Halliburton should be examined in more details.

In addition to further clarification of the RSS techniques, a two-phase pilot drilling test starting with a Ø 76 mm core drilled pre-pilot (investigation) hole is proposed. Figure 4-51 shows the equipment of a 76 mm core-drill rig as it was installed in ONKALO, the underground characterisation laboratory in Olkiluoto. Devico has developed their own directional drilling system (DeviTool™ family) for this hole size (NQ). To manage the strict requirements set for the straightness of the pilot hole survey technique, like the one (Geocon) used at the Äspö experiment, could be used, if seen feasible (the small hole diameter might restrict the use of this method). After drilling the pre-pilot hole it can be reamed (see Figure 4-52) to the diameter of 311 mm. The pilot hole is reamed to the final drift size (Ø 1,850 mm) using horizontal push-reaming technique, see Figure 4-41. Although the proposed system is not exactly active steering it is believed to result in a straight pilot hole, which is the prerequisite for the geometrically acceptable deposition drift.

Figure 4-50. *Device used for measuring the straightness of the pilot hole in the demonstration at Äspö /Bäckblom and Lindgren 2005/.*

Figure 4-51. *In ONKALO the drill rig installed on a truck has been used to core drill up to 200 m long investigation holes along the planned access tunnel.*

Figure 4-52. *Pre-pilot hole could be reamed with a special pilot bit equipped with a guiding pin /Bäckblom and Lindgren 2005/.*

5 Basic Design (BD) alternative

5.1 Specification of the functional structure and design components

The main idea (see Sections 2.1 and 2.2 for background and introduction) with the Basic Design (BD) is to hydraulically isolate every supercontainer section from each other immediately after installation. During the installation of a deposition drift there will be no water flow from one supercontainer section to another. This is mainly achieved by the distance block sections, which are designed to prevent all water flow between supercontainer sections during the installation and also during the following saturation phase.

The functional groundwater-related requirements for the distance blocks, based on the Olkiluoto site, are as follows:

- should withstand a maximum water pressure of 5 MPa,
- a maximum pressure increase rate of 1–5 MPa/h,
- a maximum water inflow rate of 1 l/min (corresponding to a filling time of 24 hours of one supercontainer section), even though the largest allowed inflow in a supercontainer section has been specified as 0.1 l/min.

In the following discussion, it is assumed that the application of proper techniques, which will not be further elaborated, has reduced groundwater inflow. Additionally, deposition drift, canister, and supercontainer functions are only briefly described here as they are considered as fixed design aspects.

The design is based on the following functional components:

- *Prevention of buffer erosion by spray and drip shields.* Direct water flow on buffer surface will cause surface erosion. Spraying, squirting and significant dripping of groundwater on supercontainers and distance blocks is prevented by using shields.
- *Isolation of compartments from water-bearing fracture zones by plugs – compartment formation.* Isolation of deposition compartments from water-bearing fracture zones, which may have detrimental effect on the distance blocks and supercontainer during saturation, will be accomplished through the use of plugs.
- *Sealing of the drift entrance by plugs.* The deposition drift is sealed and plugged after emplacement of supercontainers and distance blocks. The plugging will partly prevent possible displacement of buffer components and groundwater inflows out from the drift. The plug will support hydrostatic pressure in the drift after operation and retain the supercontainers and other components in position. The plug will be exposed to both hydrostatic pressure and swelling pressure from the buffer. The plug is positioned so that flow from the drift into the surrounding open tunnels is small enough to prevent detrimental erosion effects.
- *Interruption of operations by plugs.* The emplacement of supercontainers can be stopped temporarily if the drift is plugged rapidly before the distance blocks start to swell into the open tunnel. Such interruptions are feasible after the plugging of one compartment. The interruption may be caused by failure in operation and swelling of already emplaced buffer.
- *Hydraulic isolation of supercontainers by distance blocks.* Hydraulic isolation of successive supercontainer sections from one other during the saturation phase by using distance blocks. In this manner each supercontainer section is saturated by groundwater inflow from bedrock without flow from one supercontainer section to another.
- *Thermal spacing of canisters in the drift by distance blocks.* Adequate thermal spacing between successive canisters is obtained by using a distance block of required length.

- *Prevention of displacement of distance and filling blocks by fixing rings.* Steel fixing rings will be installed, where necessary, to avoid displacement of the distance blocks prior to the installation of compartment and drift end plugs. Such displacements could otherwise arise as a result of large hydraulic pressure differences along the drift due to heterogeneous water inflow. Displacement in case of limited pressure exertion over the end face of a distance block can be prevented during compartment operation by the fixing rings that are installed along the drift. A high hydrostatic pressure in the supercontainer section will act on parts of the cross section area of the distance blocks and the displacement of the blocks is partly counteracted by the friction between bentonite and rock and also by the support from the neighbouring section in addition to fixing rings.
- *Sealing of unsuitable sections by filling blocks.* Positions that are not suitable for emplacement of a supercontainer, because of larger-than-accepted water inflow or other reasons, are packed with filling blocks. The objective of the blocks is to provide extra sealing capacity between neighbouring distance blocks and to reduce the hydraulic pressure induced force exerted on distance blocks adjacent to supercontainer sections.
- *Compensation of local density reductions by filling blocks with extra swelling potential.* Density reductions may be caused by dissolving cement from drift plug or compaction of lower density filling adjacent to compartment plugs.
- *Drainage* of major inflows during operation from volume between plugged compartments by permeable low compressibility filling and swelling partially permeable filling. Sections with significant water leakage, which are not suitable for deposition, are isolated from other sections of the drift by installing two plugs, one on each side of the inflow section. The volume between compartment plugs is backfilled and drained until the second plug is in place.

Deposition drift and supercontainer design are assumed as fixed part of system and are not considered as design components in this context. The BD – Design Components (BD-DC) shown in Figures 5-1 and 5-2 are:

- BD-DC1 Spray and drip shield.
- BD-DC2 Distance block.
- BD-DC3 Fixing rings to support distance blocks.
- BD-DC4 Coupling between supercontainer and distance block.
- BD-DC5 Compartment plugs.
- BD-DC6 Filling blocks.
- BD-DC7 Drift end plug.
- BD-DC8 Permeable filling.
- BD-DC9 Partially permeable filling.

5.2 Distance block reference design

5.2.1 General

Several distance block designs were evaluated, however, one design was to be selected to be referred to in several other studies (e.g. safety assessment work). One of the several alternatives (alternative 3) was selected as the so called reference design for the distance block. However, this is not to be confused with the KBS-3H reference design. There were uncertainties in all design alternatives and thefore the other laternatives are laso described in later sections.

A distance block is positioned between supercontainers to prevent water flow between the supercontainer sections. The purpose of the distance block, according to the requirements is to maintain the integrity of the canisters for at least 100,000 years by protecting them from

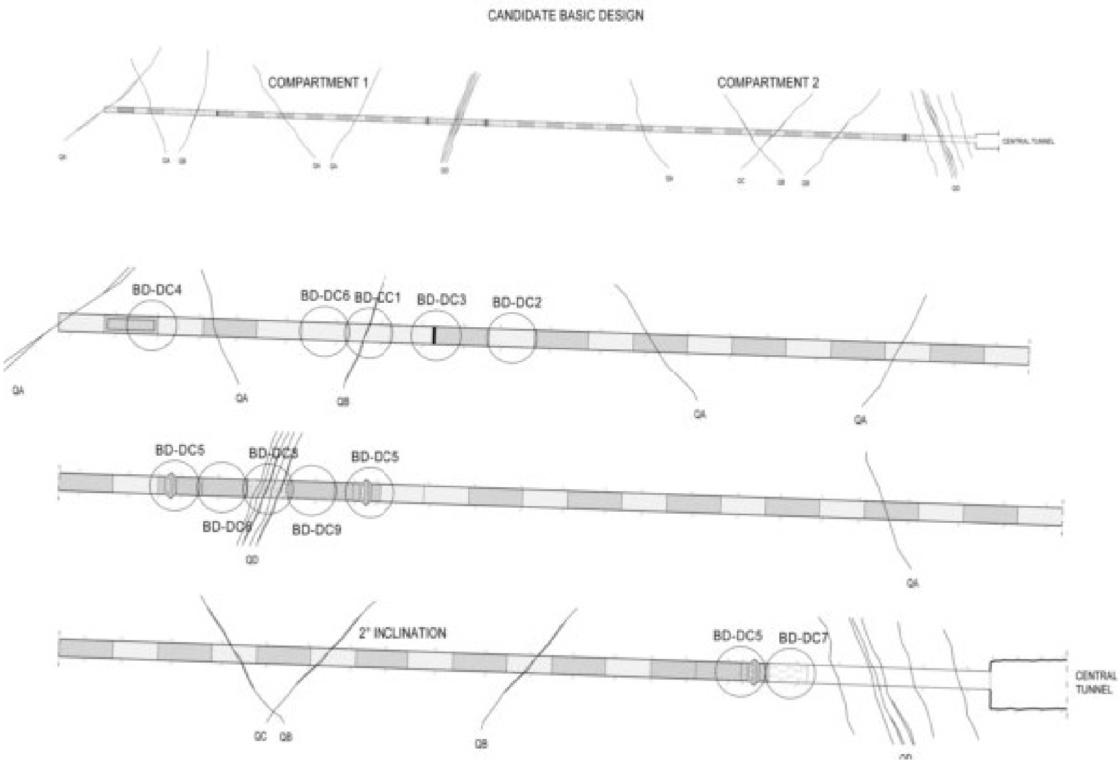


Figure 5-1. *Components of the Basic Design alternative (QA, QB, QC refer to fractures with different inflow rates).*

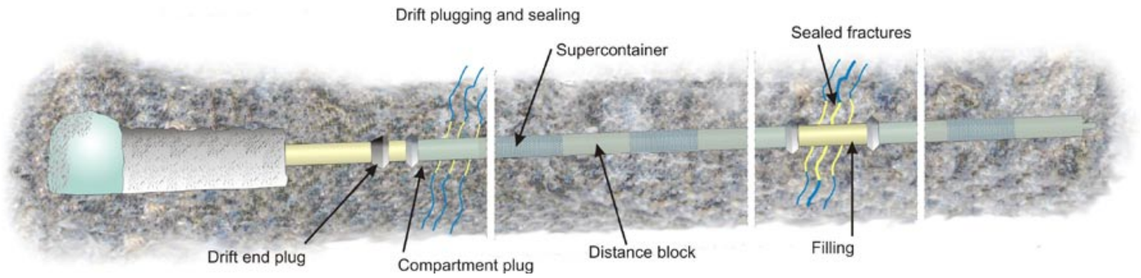


Figure 5-2. *Main components in the design.*

detrimental THMBC processes, and to limit and retard the release of any radionuclides from any damaged canisters. The distance blocks also separate the supercontainers hydraulically one from another, thus preventing the possibility of preferential pathways for flow and advective transport within the drifts through the corrosion products or altered buffer. Furthermore, the distance blocks maintain spacing between the canisters along the drifts ensuring that temperatures are maintained at acceptable levels. The distance blocks are required to provide a nearly impermeable, once saturated, tight interface with the drift rock wall within a reasonable time.

5.2.2 Critical design issues

Several significant uncertainties related to the behaviour of distance blocks and buffer materials were identified in /Autio 2007/. The most important issues to be resolved were included in an extensive buffer test plan. These critical issues to be resolved to produce viable designs were:

1) *Humidity induced swelling.* The process of humidity induced swelling and possible cracking has an effect on the early behaviour of distance blocks before water saturation is achieved. The magnitude of this effect depends on the design alternative(s) selected and is evidently more significant in case of DAWE design.

2) *Erosion of filling blocks and buffer.* The physical erosion of buffer, distance blocks and filling blocks results in transport of bentonite and variation in the buffer density within the deposition drift. Erosion may take place as the result of free–flowing water in the drift between the blocks and the rock, as channelled "piping" type flow or as the result of flow along fractures.

3) *Saturation of distance blocks.* The saturation process of distance blocks in heterogeneous inflow environment has significant effect on the sealing ability and piping resistance. The nature of this effect is different in DAWE and BD design. In the case of DAWE design artificial wetting is used to speed up saturation and possible later drying and possible shrinkage is an important process and needs to be studied. In BD design the saturation takes place by natural inflows and the situation right after plugging of the compartment is very different from DAWE alternative. In BD alternative heterogeneity in wetting and swelling is much larger. The redistribution and migration of water e.g. in one distance block or buffer inside a supercontainer could be caused either by the thermal output of the nearby supercontainer or suction-induced water redistribution from the outer perimeter to the drier interior regions of the distance block.

4) *Piping through distance blocks.* In the BD design alternative the distance blocks are supposed to prevent water flow between supercontainer sections. The design of the distance blocks should thus be such that no piping will occur but the influence of the rock hydraulic conditions are strong and more tests are needed to develop a better understanding of how this process works (see Figure 5-3). If piping occurs, transport of bentonite may take place depending on the intensity of the process and this could adversely affect system performance.

5) *Hydraulic pressure on distance block end surface.* The extent and distribution of hydraulic pressure on the inner end face of the distance blocks remains uncertain. The magnitude and distribution of the pressure-induced load on the distance blocks is important since it will affect the movement of these blocks and determine the dimensioning of the fixing rings in the BD design. The main 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 possible that the pressure is exerted on the whole surface.

As a result from testing two design factors /Börgesson et al. 2005, Sandén et al. 2008/ were found to be critical to the function of distance blocks:

- In order to prevent piping in the slot between distance blocks and rock, the width of the slot must be very small because the bentonite has a very short time (from 24 hours to 10 days) to swell and seal before the full water pressure could occur.
- The area of the vertical surface of the distance block on which the water pressure can act on is very important. If the area is large, the forces on the fixing ring will be very high and it will not be possible to prevent displacement of the blocks and consequent piping.

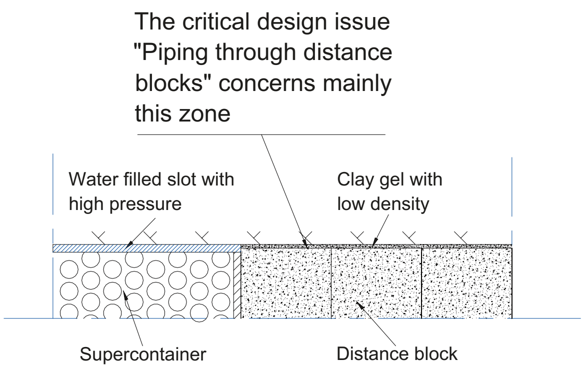


Figure 5-3. *Figure showing a schematic drawing of the critical issue "piping through distance block".*

5.2.3 Groundwater pressure increase and inflow rate in testing and design

The research and development of distance block design in the BD alternative demonstrated the possibility that flow channels ("piping") might form through the distance block adjacent to the rock interface if the distance block design is not adequate /Börgesson et al. 2005, Autio 2007, Sandén et al. 2008/. This phenomenon was specified as a critical issue. The development of a proper design is apparently very sensitive to inflow rate (Q) from the surrounding rock into the open volume (V, on the order of a few cubic meters) between supercontainer sections (i.e. filling time of the open volume), rate of pressure increase after the open volume is filled with water, and time until the full hydrostatic pressure is reached after the volume was filled with water (Figure 5-4).

The reference case in testing corresponded to following inflow and pressure increase rates:

- Inflow rate of 0.1 l/min in a supercontainer section.
- When the inflow was stopped, a water pressure increase rate of 0.1 MPa/h up to maximum 2 MPa.

The pressure increase rate is highly uncertain. It was evaluated using several different methods and there were indications that it could be clearly higher than the 0.1 l/min assumed for the refence case /Autio et al. 2007/. Therefore, additional test were performed simulating these extreme cases, which thus deviate from the reference case:

- Inflow rate of 1 l/min in a supercontainer section.
- When the inflow was stopped, a water pressure increase rate of 1 MPa/h up to maximum 5 MPa.

Four different alternative distance block designs to fulfill the above mentioned inflow conditions are presented. The recommended design to be referred to is design alternative 3 (discussed below). The three other designs are presented in Section 5.3.

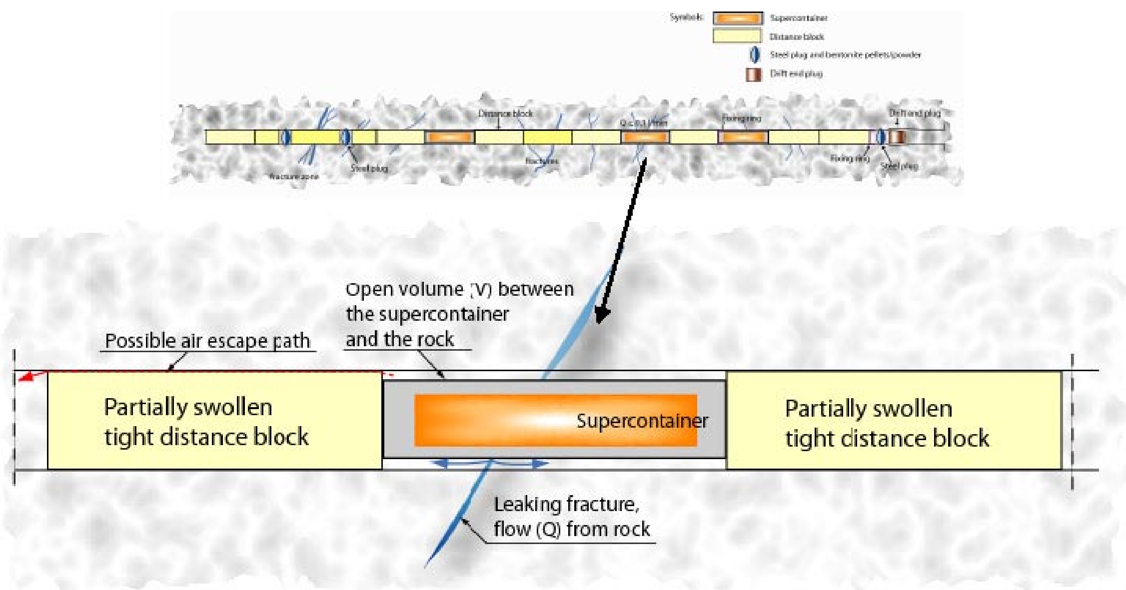


Figure 5-4. *Groundwater inflow into the supercontainer section in the KBS-3H design.*

5.2.4 The reference design: Design alternative 3 (distance block split in three parts)

Several distance block designs were evaluated. The selection of design alternative 3 as reference design was based on experimental observation of sealing ability and also operational aspects such as emplacement technique and time. There was sufficient experimental evidence from previous and ongoing studies /Börgesson et al. 2005/ to assume that the sealing ability of the proposed design was adequate.

Design alternative 2 was evaluated to function technically well. Due to the disadvantages concerning the rather difficult and time consuming installation with this design alternative, design alternative 3 (or 4) was chosen as reference design. The design is proven to withstand the extreme conditions (1 l/min and 1 MPa/h) and the installation is judged to be feasible. Another advantage is that the design is likely to resolve the possible spalling problem. The design could be motivated in all distance block sections. It is also possible to combine the two design alternatives i.e. install distance blocks according to design alternative 3 but also install a drainage tube. The advantages of pre-wetting i.e. filling all empty space with water are seen in several laboratory tests. This will of course extend the installation time somewhat mainly due to the fact that the drainage tube has to be retrieved which is supposed to take some days. The retrieval technique is currently being tested in laboratory but could probably be improved.

The reference distance block design alternative 3 is based on using two different components in series; a "tight" block and a "loose" block as shown in Figure 5-5. The bentonite used in the distance blocks is MX-80-type with an initial water content of 24%, a final saturated density of 1,950–2,050 kg/m^3 and a dry density of 1,481–1,637 kg/m^3.

The surfaces of the segments in "tight" blocks are inclined so that the parts can be pushed in position and the bentonite will be in contact with the rock surface. This design could be used for the entire length of the distance block if required.

The first unit is a one-meter long, fixed length "tight" fit block, which is emplaced in contact with the rock surface providing a gap on the order of the surface roughness of a few millimetres. This component provides for rapid sealing. The overall design is flexible because the length of the "loose" block can be modified to fit different canister spacings. The surface quality of the drift in distance block positions will be improved by mechanical grinding, if necessary, to obtain a constant diameter and a smooth surface to reduce the gap. The "tight" block can be put together in two ways. In both, the block is emplaced in slices (see Figure 5-6) and the number of slices is defined by the final required thickness of the block (see Figures 5-7 to 5-11). The number of cylindrical slices, which are composed of smaller blocks, in a 1 m long "tight" distance block is only two. The length of the unit can be adjusted to different canister spacings by adding or subtracting "loose" component blocks, as the "tight" sealing length remains constant.

The "tight" distance block can be composed of three large slightly wedge shaped blocks (see Figures 5-7 and 5-11), which are pushed in place by using the equipment shown in Figure 5-8. As an alternative, the "tight" block can be made of a cylindrical large centre block and a number of small wedge-shaped blocks as shown in Figures 5-9 and 5-10. The longer "loose" block is installed adjacent to the "tight" block by using a different and more efficient technique with a nominal gap of 15 mm. The block is centralized to obtain a constant gap over the whole perimeter by using small, steel feet. An alternative design, which makes use of rock as centralizing material is also under consideration.

Table 5-1 shows the dimensions and block data. In Figure 5-12 the dry density of the blocks is plotted vs. the average density at saturation after swelling and homogenization. The tolerances of the dry density on the manufactured blocks are rather large (1,513–1,673 kg/m^3 for the design with 10 mm gap and 1,481–1,637 kg/m^3 for the design with split block) to obtain an average density at saturation between 1,950–2,050 kg/m^3 in the tunnel.

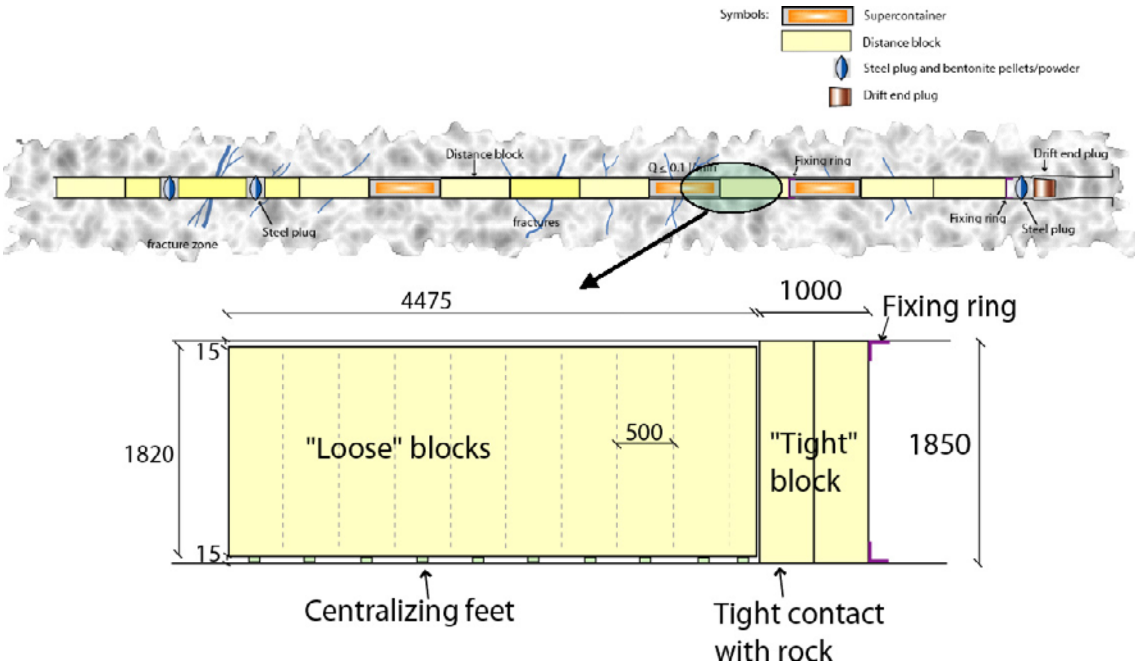


***Figure 5-5.** The distance block section is composed of "tight" and "loose" components in the BD alternative, initial gaps between block and drift surfaces range from 15 mm to a few mm.*

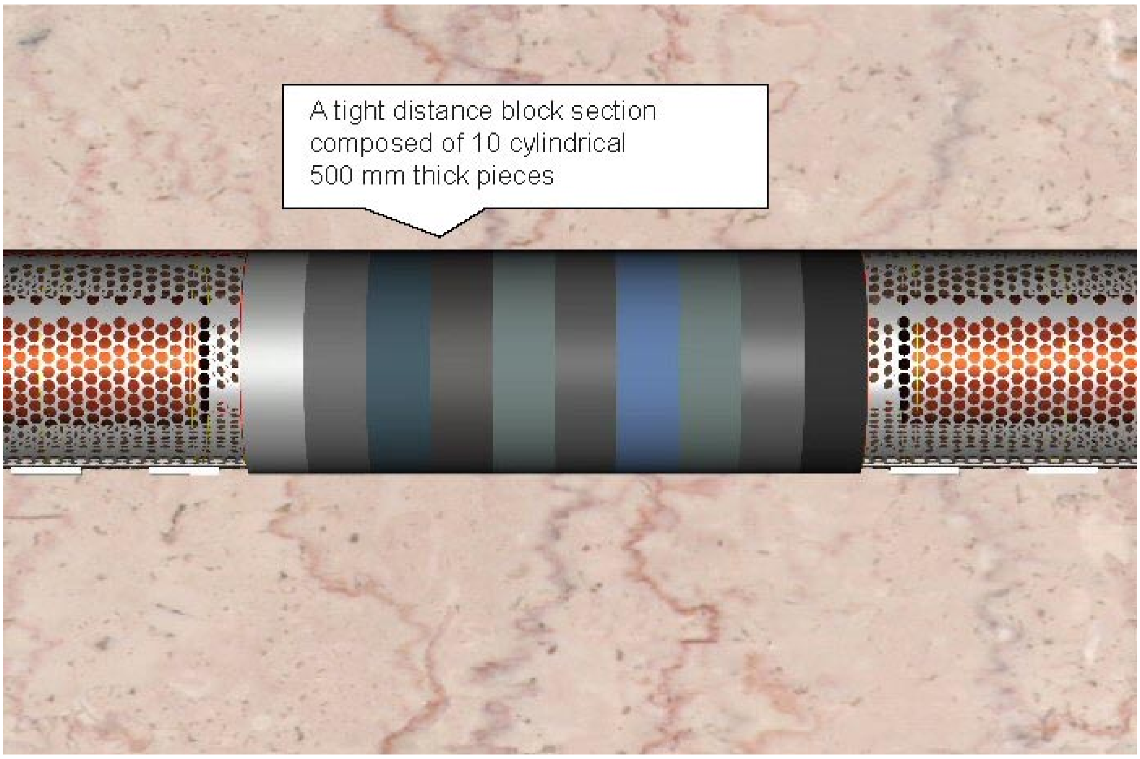


***Figure 5-6.** The "tight" component of distance block section is composed of slices of thickness of approximately 500 mm.*

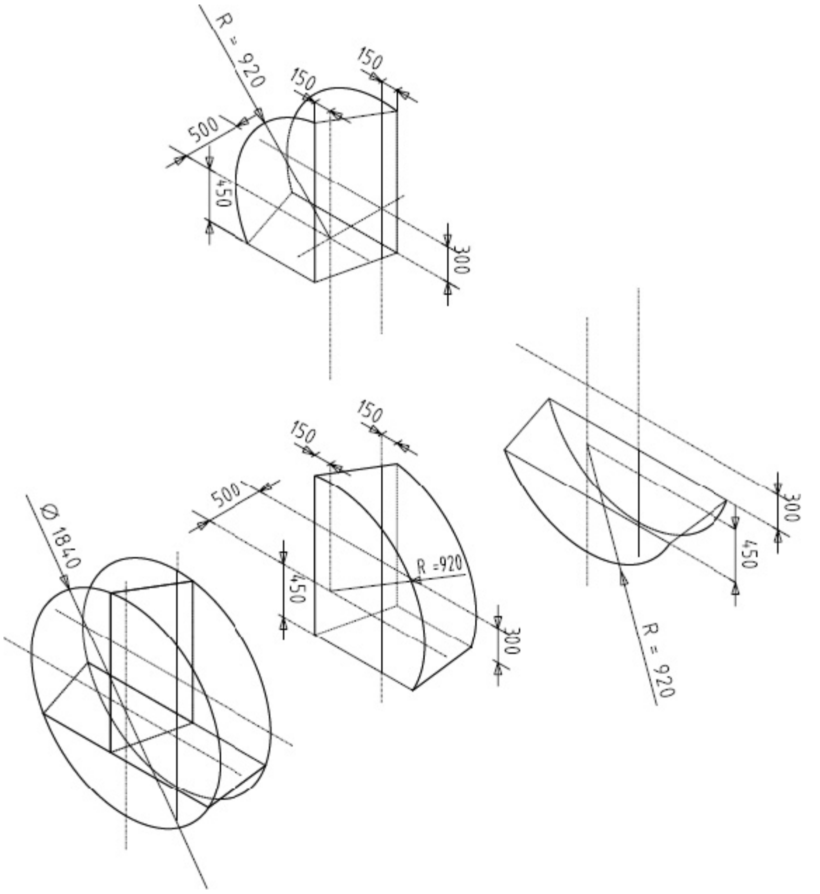


Figure 5-7. *The "tight" component of distance block sectiont based on three pieces in BD alternative.*

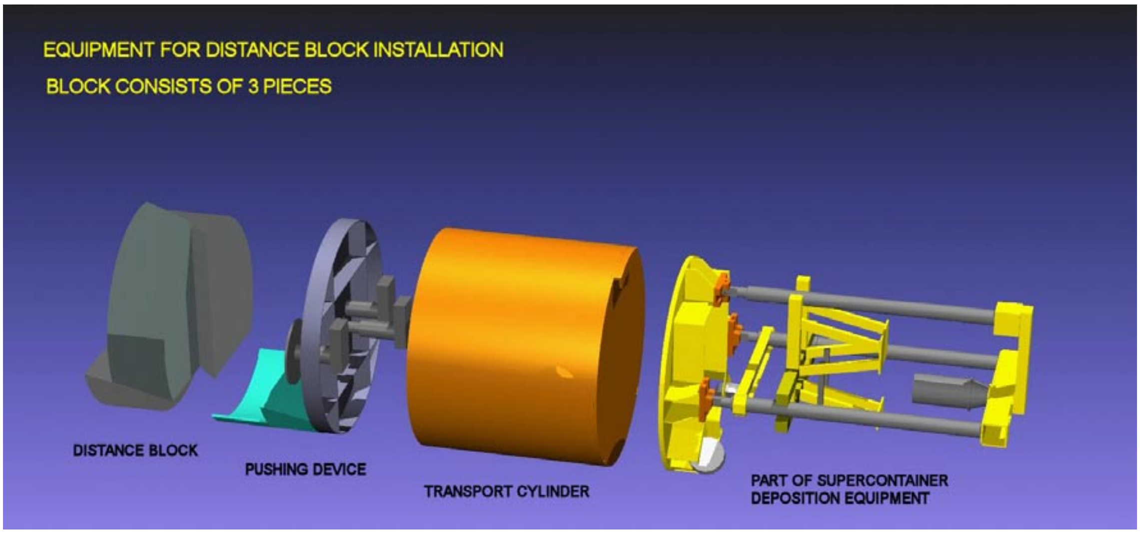


Figure 5-8. *The principle of emplacement of "tight" distance block section based on three pieces.*

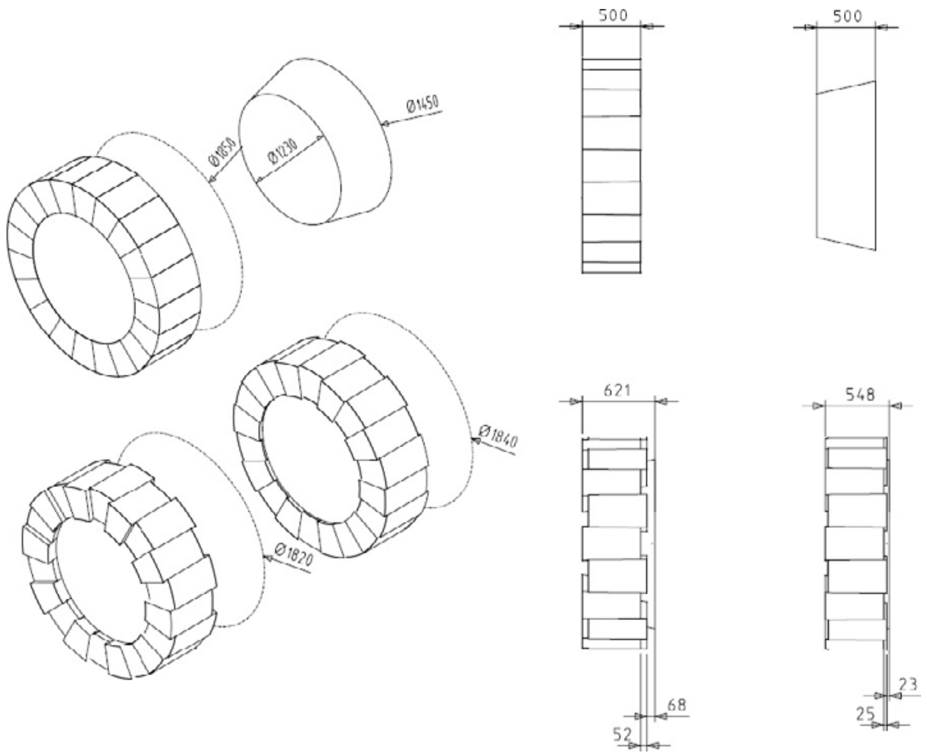


Figure 5-9. The dimensions of the "tight" component of the distance block section based on a central cylinder and small blocks in the BD alternative.

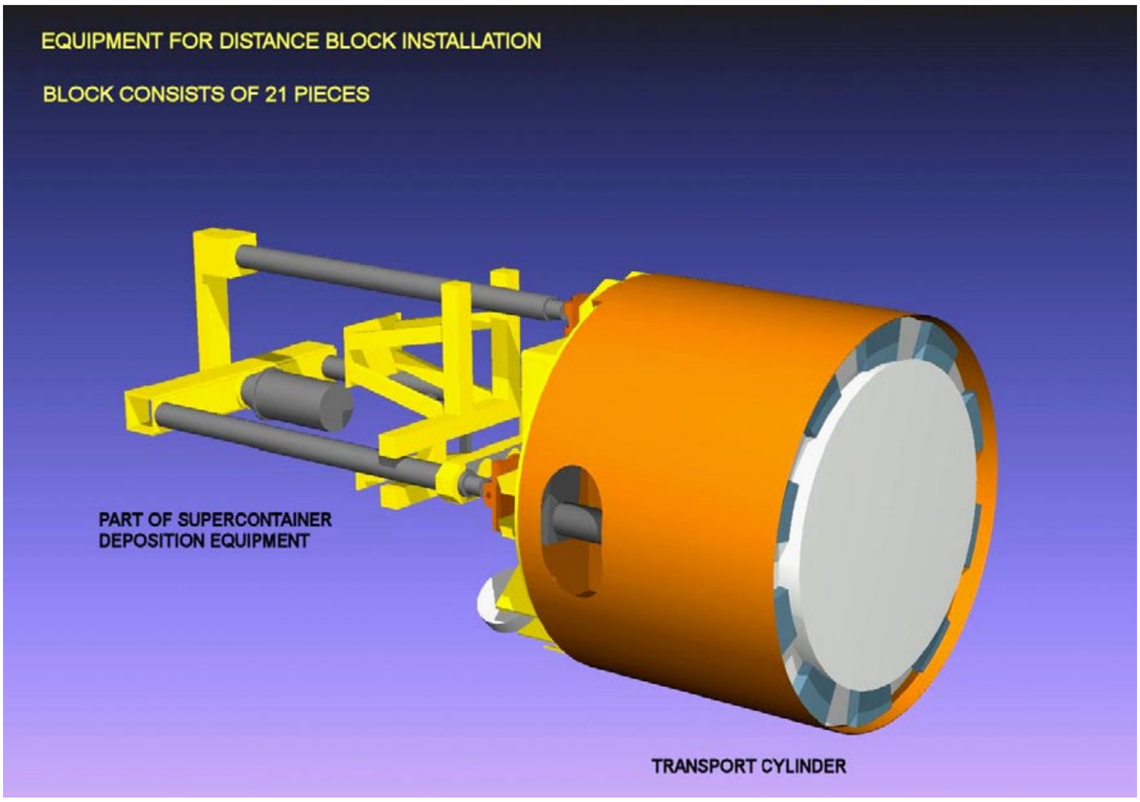


Figure 5-10. The principle of emplacement of "tight" component of distance block section based on a centre cylinder and small blocks in BD alternative.

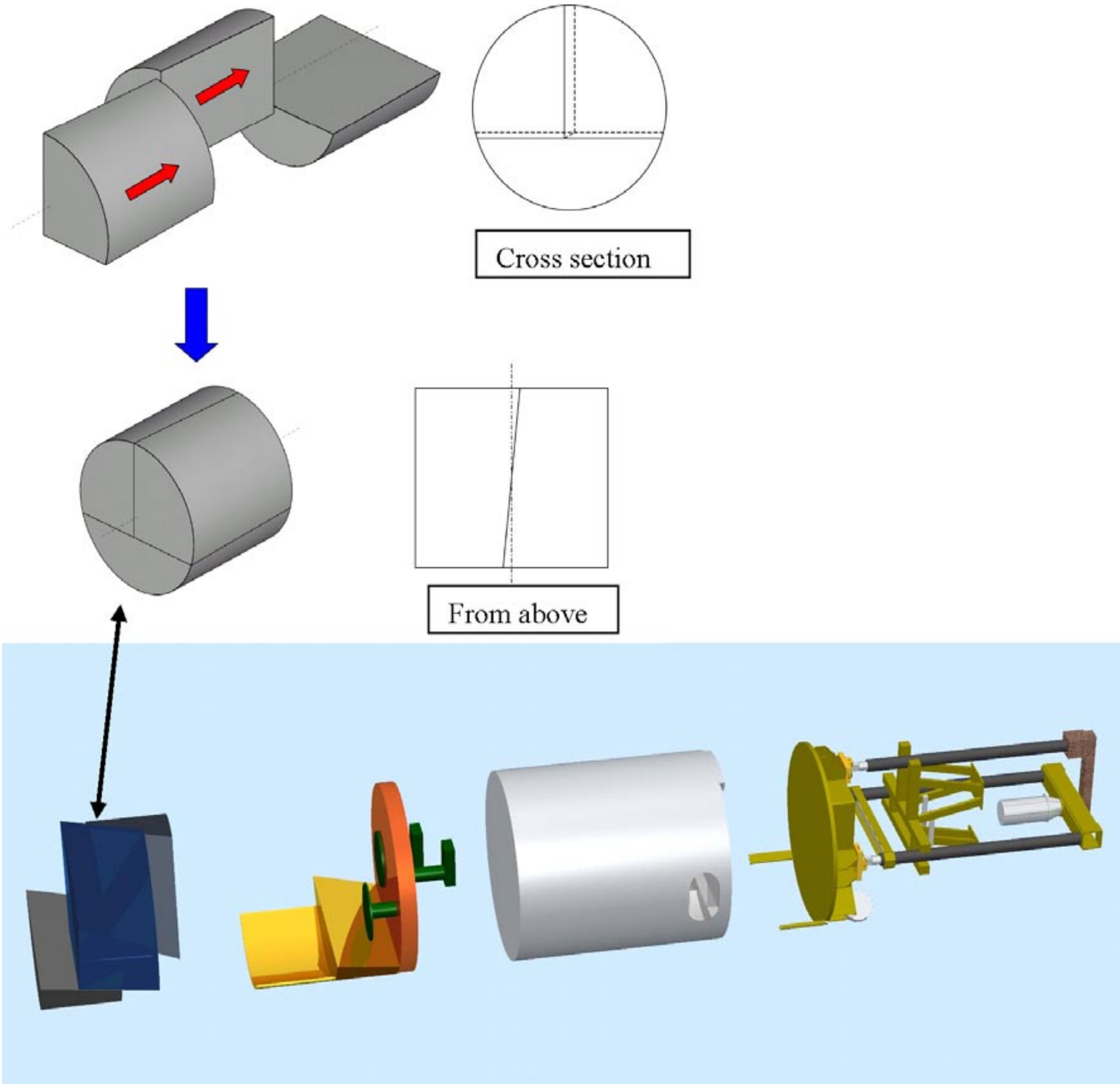


Figure 5-11. *Figures showing a schematic drawing of alternative 3. The picture shows the divided block to the left and an example of special designed installation device.*

Table 5-1. Table showing the data used in the calculations of average density after swelling and saturation. The table also shows the calculated dry density of the distance blocks for the suggested designs.

Dimensions	
Rock	
Diameter tunnel, mm	1850
Tight distance block, 5 mm gap (Alt. 1)	
Outer diameter, mm	1840
Tight distance block, 10 mm gap (Alt. 2)	
Outer diameter, mm	1830
Tight distance block, split block (Alt.3 and 4)	
Outer diameter, mm	1850
Calculated block data	
Tight distance block, 5 mm gap (Alt. 1)	
Target average density at saturation, kg/m³	2000
Initial block dry density, kg/m³	1576
Initial block void ratio	0.771
Tight distance block, 10 mm gap (Alt. 2)	
Target average density at saturation, kg/m³	2000
Initial block dry density, kg/m³	1593
Initial block void ratio	0.752
Tight distance block, split block (Alt.3 and 4)	
Target average density at saturation, kg/m³	2000
Initial block dry density, kg/m³	1559
Initial block void ratio	0.790

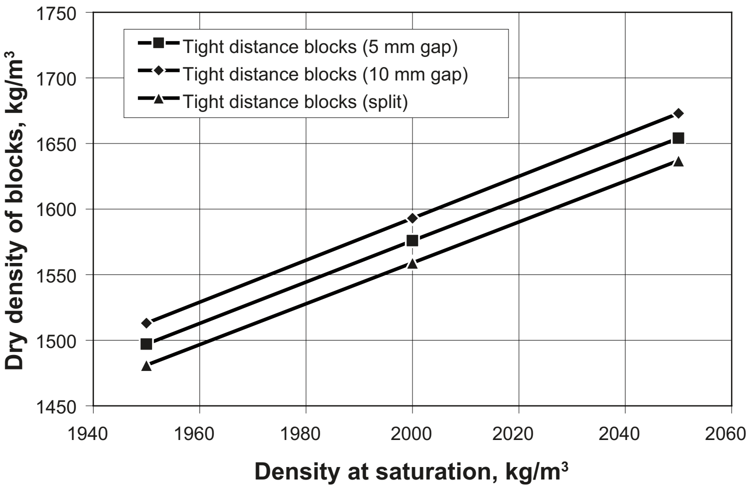


Figure 5-12. Diagram showing the dry density of the blocks (dimensions according to Table 5-1) plotted vs. the average density at saturation in the tunnel after swelling and homogenization. Data for two of the suggested designs are plotted in the diagram.

5.2.5 Sensitivity for variations of the tunnel diameter

The required block densities are calculated using the nominal diameter of the deposition drift i.e. 1,850 mm. The diameter will, however, vary and this will influence the final density in the system. The diagram in Figure 5-13 shows how the average density at saturation will vary with tunnel diameter. The diagram assumes an average density at saturation of 2,000 kg/m³ at the nominal tunnel diameter (1,850 mm).

5.3 Other distance block design alternatives

5.3.1 Design alternative 1 (5 mm slot)

A number of tests have been performed in scale 1:10 (diametrical) and with a test length of 1 metre. In the test series several parameters have been varied such as slot widths, centered and non centered blocks, pellets filling in the slot and also a pre-wetting of the slot. The results showed that a slot of 5 mm can be accepted under these conditions if the slot is pre-wetted. A design that seems to work for these extreme conditions is shown in Figure 5-14. Tests with this design and conditions were repeated three times in the laboratory.

Design principles:

- Centered blocks with 5 mm slot to the rock.
- Pre-wetting of the slot.
- 3.5% salt in the water.

The layout demands that special sealing's are made around the inner distance block against the supercontainer and also at the outermost block against the supporting ring due to the pre-wetting of the gap bentonite/rock. The sealing's can be rather simple, perhaps made of bentonite, since its only purpose is to withstand the pressure from the water when filling up the slot (the pre-wetting).

The difference in diameter between the deposition drift and the distance blocks is only 10 mm. The small gap and the demand to centre the block radially could be a problem for the installation. The laboratory experiments indicate that this is the maximum gap that can be allowed for these extreme conditions without controlling the water pressure.

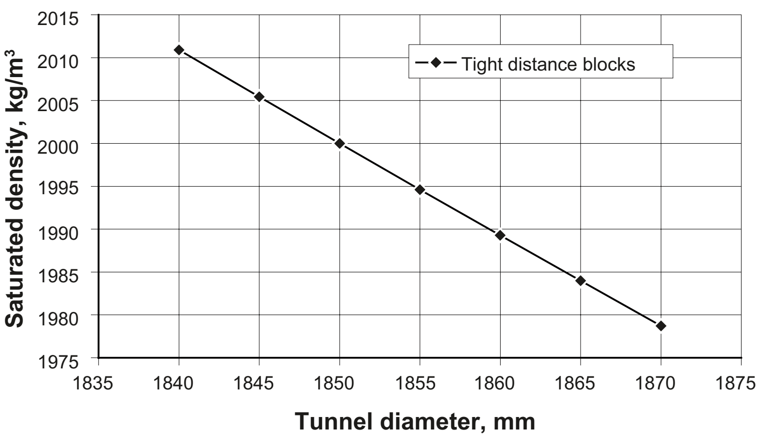


Figure 5-13. Diagram showing the average density at saturation in the tunnel after swelling and homogenization (target density at saturation 2,000 kg/m³ at the tunnel diameter 1,850 mm) plotted vs. various tunnel diameter.

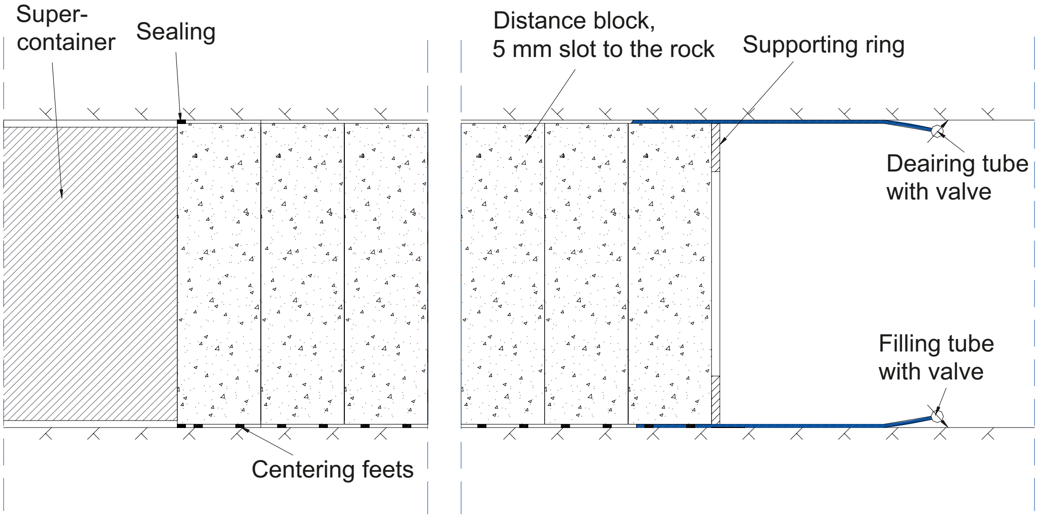


Figure 5-14. Figure showing a schematic drawing of layout alternative 1.

5.3.2 Design alternative 2 (10 mm slot and controlled water pressure)

Tests have also been made in a similar test device with the test length 3 meter. In this device a design with artificial control of the water pressure inside the distance blocks was tested. A drainage tube leading into the supercontainer section was installed in the slot under the distance blocks, see Figure 5-15. This drainage tube made it possible to control the water pressures in the supercontainer section and by that also give the bentonite more time for maturation (water uptake and swelling). This technique has also made it possible to increase the slot width from 5–10 mm which will facilitate the installation of the distance blocks.

An issue discussed with this layout has been the retrieval of the drainage tube. This was also tested with good results. The technique used was to pull the tube out in steps (Tested with 1 meter/step and 24 hours) giving the bentonite time to seal the remaining volume. This design has been repeated two times in the laboratory at these extreme conditions.

Design principles:

- Centered blocks with 10 mm slot to the rock.
- Pre-wetting of the slot.
- 3.5% salt in the water.
- Drainage tube through the distance blocks into the supercontainer section to control the water pressure.

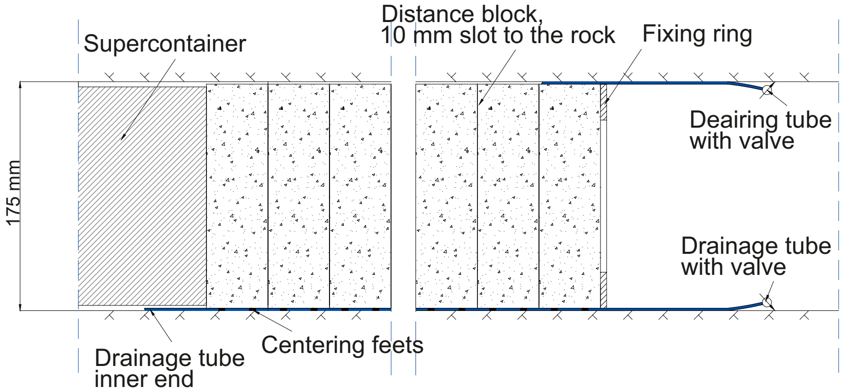


Figure 5-15. Figure showing a schematic drawing of alternative 2.

A temporary sealing is needed around the outermost block facing the fixing ring. The sealing can be rather simple, perhaps made of bentonite, since its only purpose is to withstand the pressure from the water when filling up the slot (the pre-wetting).

The difference in diameter between the deposition drift and the distance blocks is in this layout increased from 10 mm (Layout alternative 1) to 20 mm. This will facilitate the installation of the distance blocks but it is still rather tight. The layout is rather time consuming. The bentonite needs about 14 days before it can withstand 5 MPa including withdrawal of the tubes. This time can perhaps be decreased if the technique is optimized.

5.3.3 Design alternative 4 (block divided in one central part and an outer ring)

This design is a variation of design alternative 3.

Design principles:

- The same idea as alternative 3 with tight fitting blocks, but the distance block consists of a central, somewhat conical block, with a number of outer minor fitting blocks placed in contact with the rock, see Figure 5-16. This solution means that the sealing ability is high since the block is mainly in contact with the rock.
- The outer block is proposed to be made with a thickness of 1 m. The distance blocks inside can be made with a slot of 5 cm to the rock, which facilitates their installation.
- The fitting blocks will be made slightly larger than the slot and the jutting part after installation will be cut off.

5.4 Fixing rings to support distance blocks in BD alternative

In all probability, there will be supercontainer sections that will stay dry for relatively long periods of time immediately next to sections that will saturate and rapidly obtain full hydrostatic pressure. Saturation times may differ by two orders of magnitude or more from one section to the next. For example, the empty volume in one supercontainer section can fill and the bentonite swell to fill the open gap in 10 days whereas the neighbouring section in tight rock may fill and the buffer swell over 200 days or more.

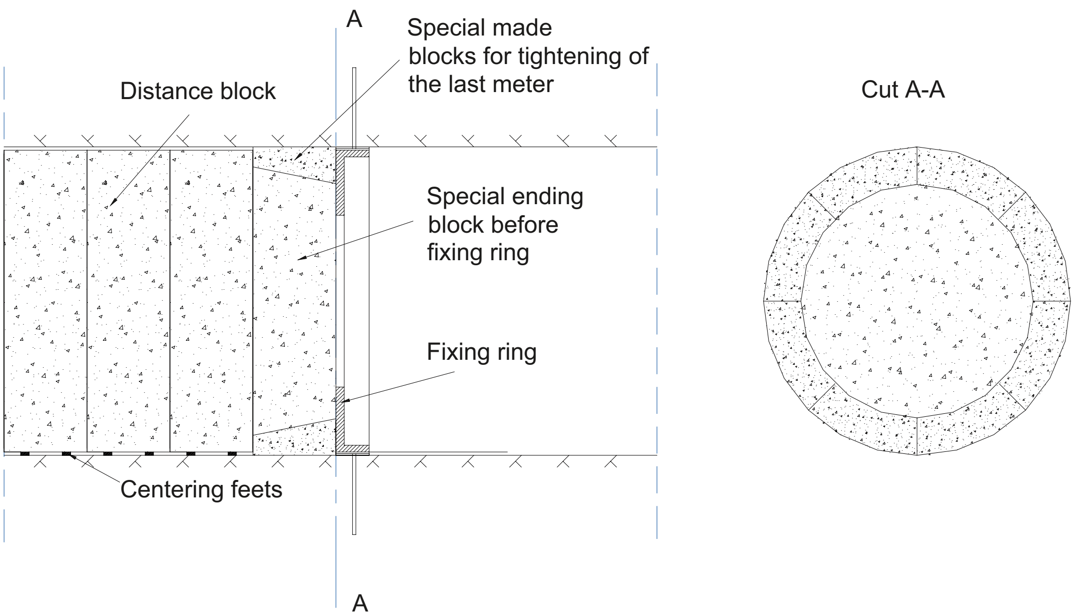


Figure 5-16. *Figure showing a schematic drawing of layout alternative 4.*

The distance blocks must maintain their sealing ability between large hydrostatic pressure differences. If there is full hydrostatic pressure on one side of the distance block and no pressure on other side, the resultant force may displace the block (see Figure 5-17). As a result, piping of water flow through the distance block and bentonite erosion may occur.

The displacement of the block is counteracted by the friction of the block against the rock surface and support from the next supercontainer section. Additionally, the use of a supporting structure, which will fix the distance block mechanically in the desired position (Figure 5-17), aids in preventing displacement of distance blocks. This supporting structure will be positioned on one side of the distance block to prevent one-way movement.

Fixing rings are installed in every position where the inflow in the supercontainer section is larger than 0.01 l/min after sealing. This inflow limit is a rough estimate and needs to be verified.

The fixing ring design is based on the following design requirements:

- The ring shall be constructed in one shift (7 hours).
- The fabrication material is steel, similar to that of the supercontainer.
- The ring is dimensioned to withstand a one-way hydrostatic pressure of 4 MPa exerted on a surface area at the face of a distance block from a drift surface of 10 cm inwards. The surface area in question is 0.55 m^2 yielding a total force of 2.2 MN (220,000 kg). The basis for this estimate is presented in Section 9.4 in /Börgesson et al. 2005/.
- The thickness of the steel in the ring is optimised to obtain corrosion gas generation times similar to those expected from the supercontainer and to prevent the development of any new significant time dependent corrosion processes. The target thickness is on the same order as the thickness of the supercontainer steel, which is 8 mm.
- The ring is composed of smaller size segments, which can be handled and transported inside the drift.
- The ring should fail in a controlled way if the strength is exceeded.

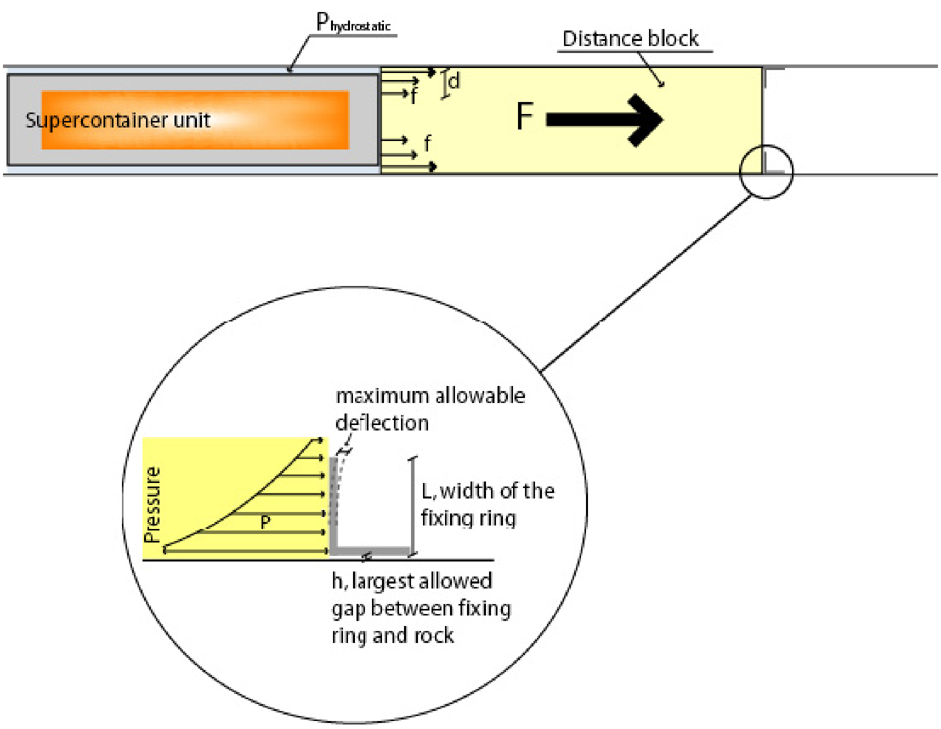


***Figure 5-17.** Fixing ring principle and dimensioning parameters for BD alternative.*

The preliminary design of the fixing ring is shown in Figures 5-18 and 5-19. The ring is based on the following elements:

- Indentation in rock, which is excavated before operation starts.
- A collar attached in the rock surface before operation starts. The collar should be positioned in the required position with a tolerance of 50 mm.
- Rigid fixing ring installed during operation.

The fixing rings are installed using bolts or welds. The weight of the fixing ring is 600 kg if it is made of a 10 mm steel plate. The amount of cement to grout the fixing ring in rock is approximately 15 l, which is equal to about 23 kg of low-pH cement.

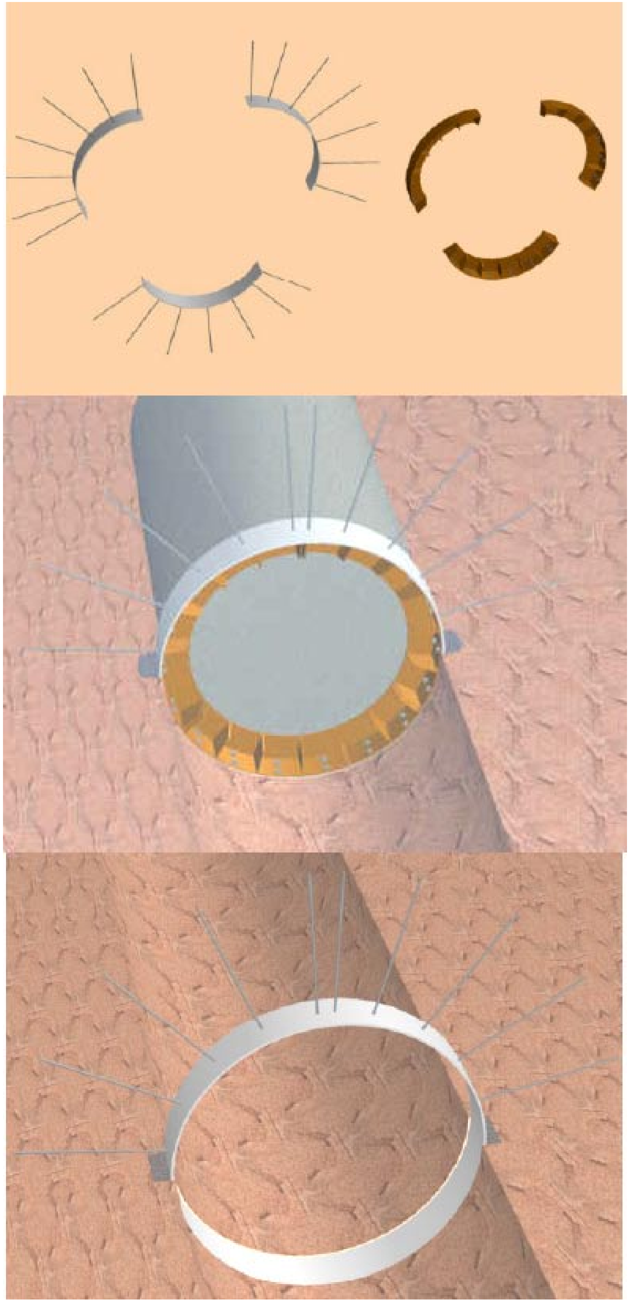


Figure 5-18. *3D-visualization of the fixing ring (middle) showing all components (top). The light grey shaded collar (above) is installed before operation starts.*

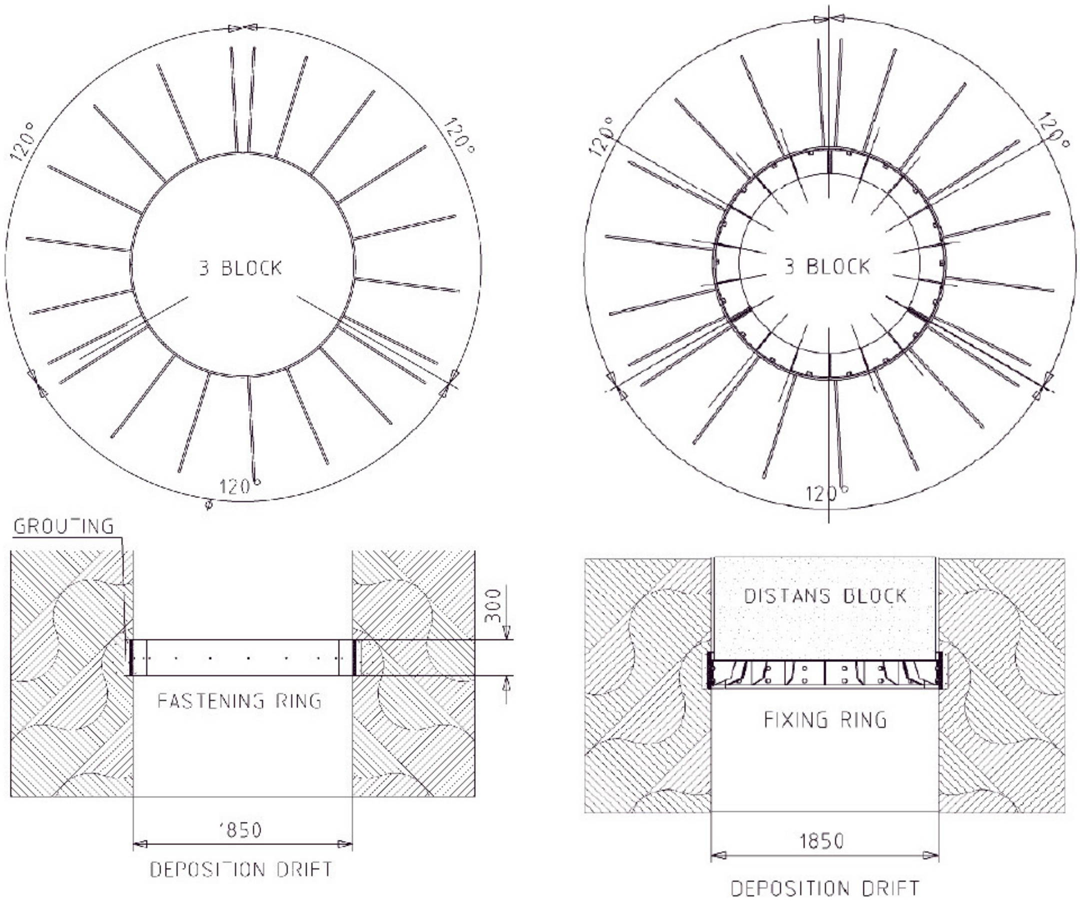


Figure 5-19. *Cross section of the fastening ring of the fixing ring (left) and the fixing ring (right).*

5.5 Contact between supercontainer and distance block

The contact between supercontainer and the neighboring distance block in BD alternative (see Figure 5-20) is an important design factor, because according to tests it has impact on the extent of hydraulic forces acting on the top face of distance block. Therefore the contact between supercontainer and distance block is designed to ensure that the distance blocks will be exposed to only partial hydrostatic pressure.

The massive steel fixing rings, intended to minimise the movement of distance blocks when full hydrostatic pressure has been exerted on the whole top surface area, have been assessed as being technically and economically unfeasible. The amount of steel used in the fixing rings can be reduced significantly, and the rings made lighter, if it is assumed that full hydrostatic pressure is not exerted on the entire face of the distance block.

Tests indicate that if the contact (see Figures 5-20 and 5-21) between the distance block and supercontainer is tight (on the order of 7 mm), the pressure is exerted on a limited circular surface area between the rock surface and outer surface of the supercontainer and about 10 cm radially. The total gap is between the distance block and supercontainer is composed of deviations in planarity between the supercontainer end plate and distance block face, gap increase due to the use of perforated material, and the gap between the supercontainer end plate and internal buffer. The theoretical total initial gap is at present calculated to be in the order of 5–6 mm at minimum.

Tests performed in an earlier phase of the project /Börgesson et al. 2005/ have indicated that with an initial gap between distance block and supercontainer of 7 mm, the pressure will be exerted on a limited circular surface area between the rock surface and the outer surface of supercontainer and about 10 cm radial inwards from that. These early tests were, however, performed at the

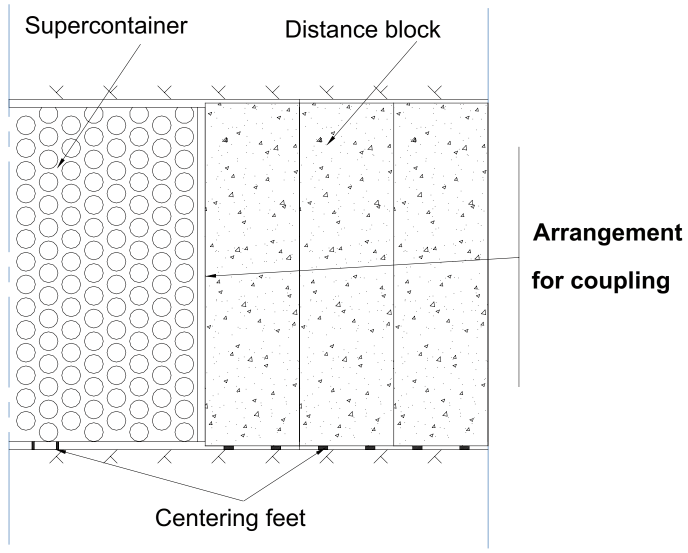


Figure 5-20. The coupling between the distance blocks and the supercontainer can be arranged in several ways all having the same objective to minimize the initial gap to prevent exposure to full hydrostatic pressure on whole surface area.

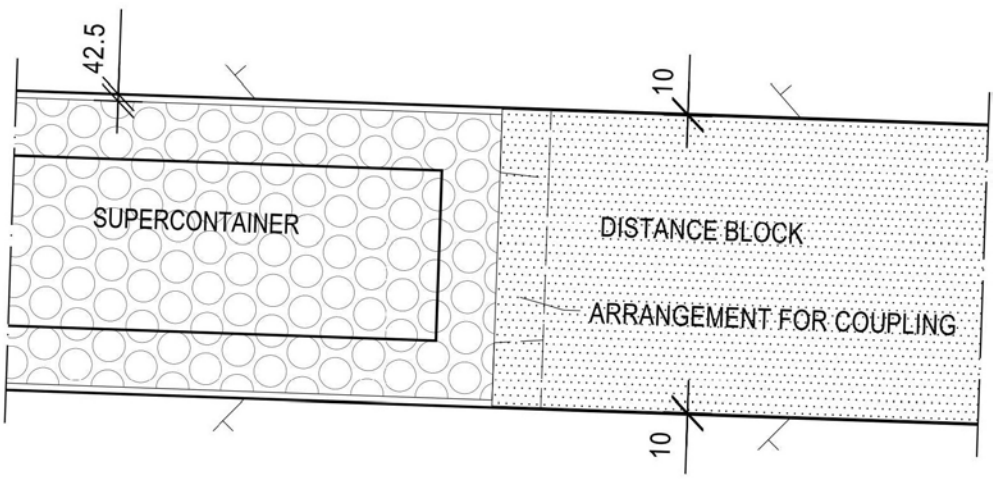


Figure 5-21. The contact between the distance block and supercontainer can be arranged in several ways all having the same objective to minimize the gap to prevent exposure to full hydrostatic pressure on the whole surface area. Note: the gap between rock and block has not been fixed, here it has been assumed to be 10 mm, it is, however, 15 mm in the reference design.

present reference conditions (water inflow rate of 0.1 l/min and supercontainer section, water pressure increase rate of 0.1 MPa/h up to a maximum water pressure of 2 MPa). New tests have been performed /Sandén et al. 2008/ simulating tougher conditions (water inflow rate of 1 l/min and supercontainer section, water pressure increase rate of 1 MPa/h up to a maximum water pressure of 5 MPa). These tests showed that at these conditions the maximum allowed initial gap between supercontainer and distance block was 2 mm to obtain a tight sealing and limit the radial water penetration to 10 cm. This required also that the bentonite had a time for swelling of about 10 days (could be arranged by the use of a special drainage tube leading out water from the supercontainer section through the distance blocks and the fixing ring).

One conclusion from the tests is that in the BD it is very important to minimize the initial gap between supercontainer and distance block. It will probably be necessary to design a special coupling to secure that the gap is as small as possible. The coupling may not be a design component in itself but it is one important part of the distance block design and is therefore regarded as separate component integrated to distance block design. A good contact may be ensured by e.g. measuring the drift and supercontainer top surface geometry after installation and modifying the first section of distance block to fit in the position tightly. The priority for this design work is, however, low depending on the status of development of the BD (see Section 5.6 and 5.8).

The issue of contact between the supercontainer and the distance block is of less importance for the other design alternatives (DAWE and STC) since no hydrostatic pressure will be built up during the installation phase. It is, however, favorable to have a small gap initially to minimize the development of an axial swelling pressure which can lead to displacements of the distance blocks.

5.6 Modelling the effect of gap between distance blocks, supercontainer and drift surface on fixing rings

5.6.1 General

In the original version of the BD the distance block is required to withstand a water pressure of 5 MPa and a pressure increase rate of 1–5 MPa/h at a water inflow rate 0.1 l/min without leaking water through the distance block. There are two critical processes related to those demands:

1. the contact between the distance block and the rock must be minimised with a "tight" distance block design and with the fixing ring to prevent piping,
2. the force on the fixing ring caused by water pressure on the vertical surface of the distance blocks must not be too high to prevent bentonite displacement.

The effect of hydraulic pressure on distance blocks and behaviour of gaps between supercontainer and distance blocks were identified as one critical issue to be resolved by testing. Based on previous experience from basic design phase it was assumed in design that the gap should be less than or equal to 7 mm and the pressure would affect a ring shaped surface section of width of about 10 cm /e.g. Börgesson et al. 2005/. The behaviour of gaps and pressure has significant impact on the design of the fixing rings, which are supposed to prevent bentonite displacement.

In order to design fixing rings, a number of Finite Element Model calculations have been made at the end of May 2007 as described in Section 5.6.2. The modelling showed that the elastic deformations of the blocks when exposed to a high water pressure will be rather large. The deformations will lead to widening of the gap between the supercontainer and the distance block, which will give the water access to larger surfaces and full hydraulic pressure will be exposed on the whole end surface area of the distance block. This effect is due to the lower elastic-module of the buffer blocks in light of the low water content (10%wt). Furthermore, the water intrusion in the gap will increase the gap even more in a progressive and self-sustaining fashion.

The demanding hydraulic conditions make it impossible for the distance blocks to withstand 5 MPa water pressure without a strong full plug (similar to a compartment plug). The design must thus allow piping and erosion between supercontainer sections before all sections are filled with water. One way to solve the problem is to use the DAWE technique where the deposition drift is kept open and free drainage allowed. A problem with this design is that it is difficult to guarantee that there will be no bentonite slurry flowing along the drift floor out to the part of the drift where the installation takes place, since both water dripping on the blocks and humidity induced cracking of the blocks may take place and cause erosion of bentonite.

5.6.2 Finite Element Model (FEM) modelling

Beside laboratory tests also FEM modellings have been performed to study the effect of demand (2) above and to design the fixing rings. Not only is the force on the fixing ring of interest but also the required radial extension of the ring. The limited strength of the bentonite blocks requires that the fixing ring has a sufficient extension.

The results of the FEM calculations are presented below. The calculations show as expected that high water pressure on a large area can be a problem for the integrity of the distance block. The required width of the fixing ring depends very much on the radial depth of the water penetration and the applied water pressure.

At the compressive strength 8 MPa of the bentonite block the fixing ring only needs to be 0.1 m wide unless the water pressure penetrates deeper than about 0.2 m. However, at the compressive strength 4 MPa the ring needs to be 0.4 m for the same case. Since the distance blocks for the basic design need to fill up almost the entire drift (only a few mm slot to the rock surface) the dry density of the block must be lower than the blocks used for earlier tests. In addition blocks at low density have a better integrity if their water ratio is high so it is foreseen that the water ratio of these blocks will be 24–26% yielding a degree of saturation higher than 95%. Additional modelling has been done taking these factors into account.

Figure 5-22 shows a drawing of the situation that is modelled. The water pressure is assumed to penetrate radially into the block joint and act with full water pressure on a ring shaped vertical surface, which is located at the rock surface with the radial extent dr_w. The fixing ring is also vertical and ring shaped with the radial extent dr_f. Three different water penetration depths dr_w and three different fixing ring widths dr_f have been modelled. The length L = 1 m has been used in the FE-model.

Case 8 (water penetration to the radial depth 10 cm and a fixing ring with the radial extension 40 cm) has been modelled with a few changes that takes the low density of the blocks in consideration. The following changes have been done:

E = 50 MPa (E-modulus),

N = 0.45 (Poisson's ratio),

q_f = 2 MPa (Compressive strength).

Three different boundary conditions between the bentonite block and the rock surface have been used:

- Case 8b: Contact rock/distance block with no friction.
- Case 8c: No contact rock/distance block.
- Case 8d: Contact rock/distance block with friction angle 10°.

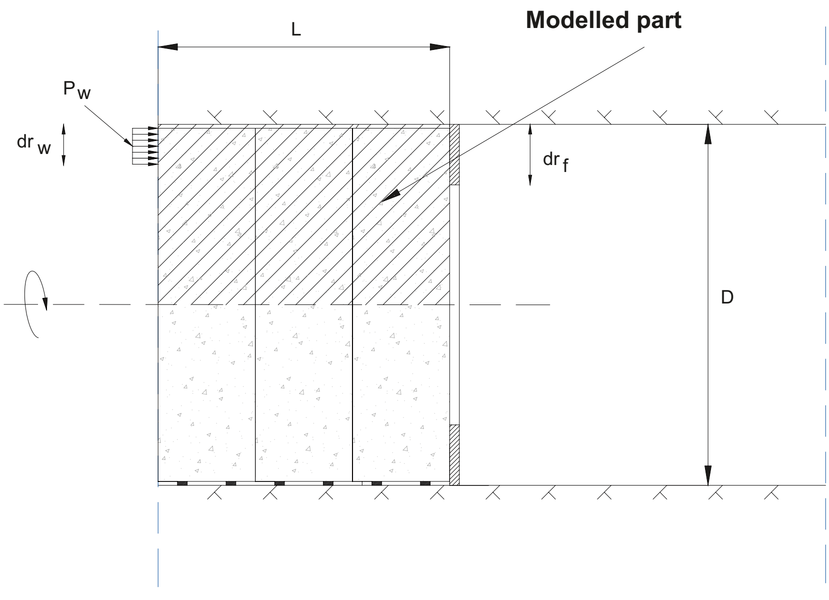


***Figure 5-22.** The basic geometry modelled (hatched area). Axial symmetry is assumed around the drift centre axis.*

Case 8b has the same block/rock interaction as case 8 and all other cases. Case 8c assumes that the slot between the block and the rock is so large that the block will not come in contact with the rock surface. Case 8d is the same as case 8b but with a friction angle of 10 degrees between the block and the rock surface.

Case 8b

Figure 5-23 shows the von Mises stress distribution at full water pressure 5 MPa for case 8b.

The figure shows that the stresses are quite high at the fixing ring, where local yielding takes place. The figure also shows that high stresses with yielding takes place close to the high water pressure. In addition the figure shows that the displacements are very large (although magnified 50 times).

The axial displacements are shown in Figure 5-24. The figure shows that the displacements are more than 7 mm at the point where the water penetrates. This is mainly elastic deformations caused by the low E-modulus.

Case 8c

The situation is even worse for case 8c where there is no contact between the block and the rock. Figure 5-25 shows the displacement plot. Due to plastisication the calculation stopped at the water pressure 3.75 MPa but the axial displacements are already at this water pressure more than one cm.

Case 8d

If friction is introduced between the block and the rock the displacements will be slightly smaller but it does not help very much. Figure 5-26 shows the results from this calculation.

In spite of the friction the displacements at the point of water penetration is more than 6 mm.

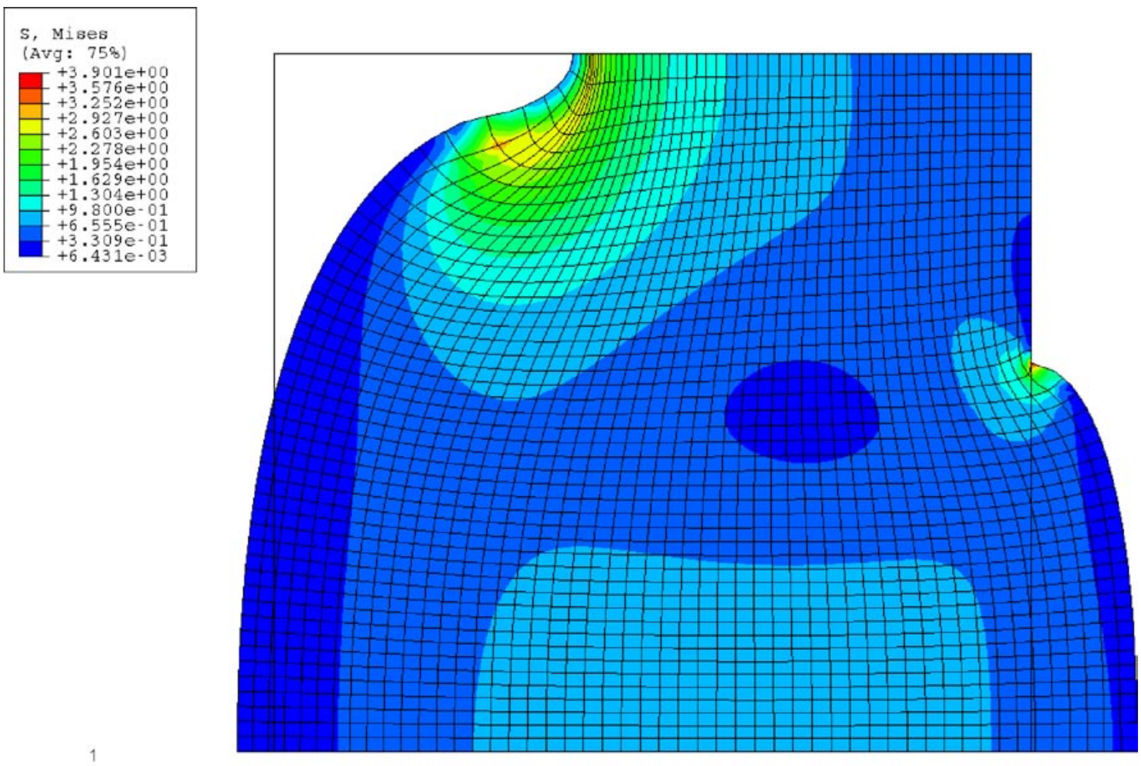


Figure 5-23. *Von Mises stress at full water pressure 5 MPa for case 8b. Displaced element mesh with the displacement magnification factor 50.*

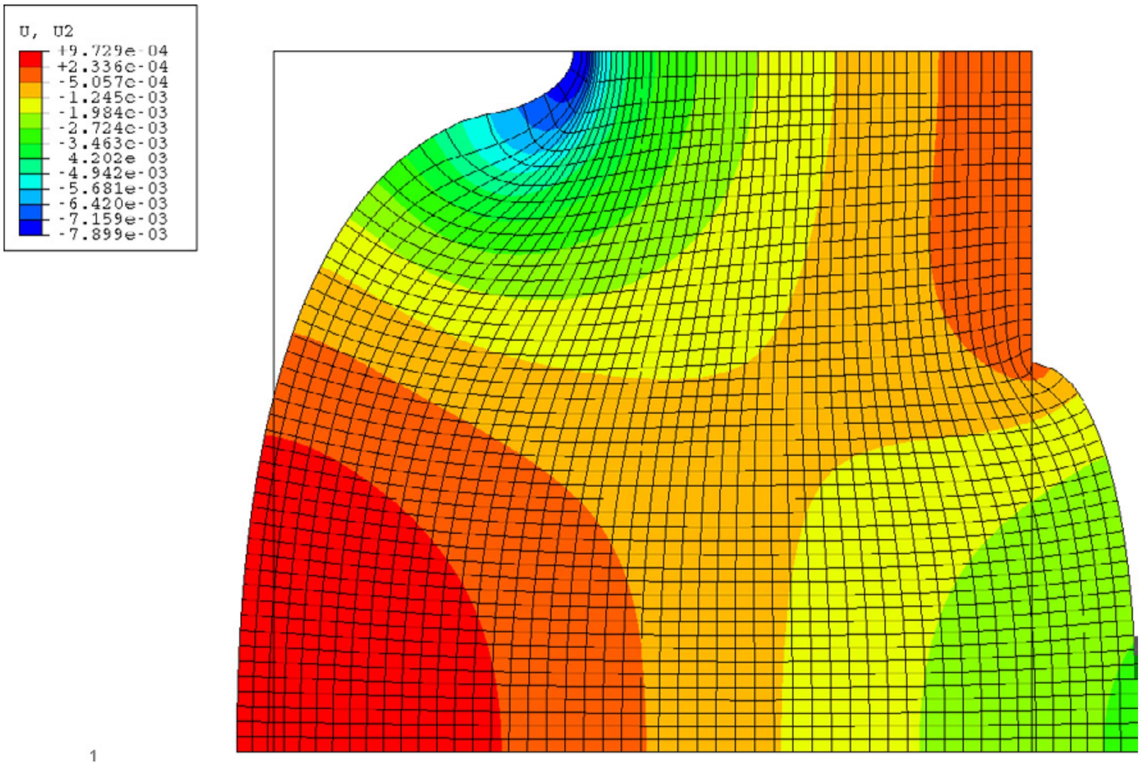


Figure 5-24. *Axial displacements (m) at full water pressure 5 MPa for case 8b.*

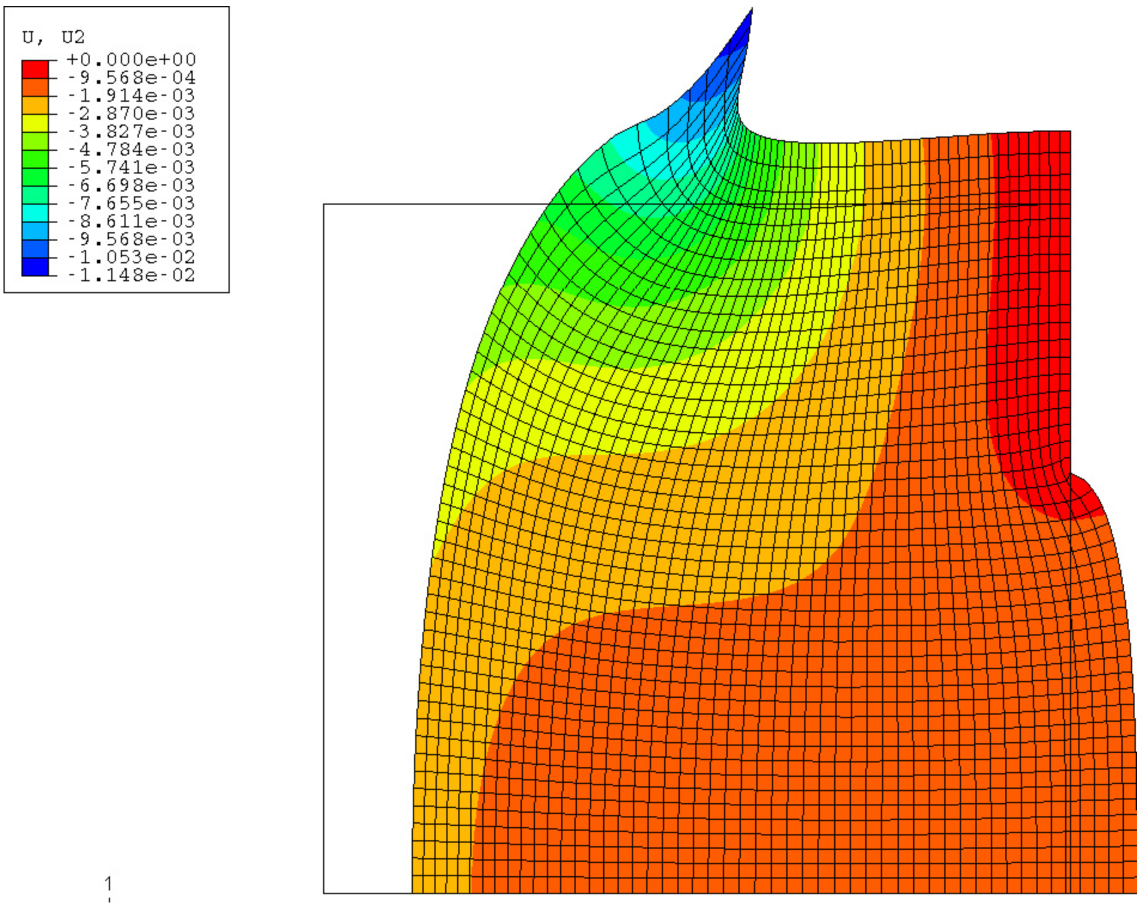


Figure 5-25. *Axial displacements (m) at the water pressure 3.75 MPa for case 8c.*

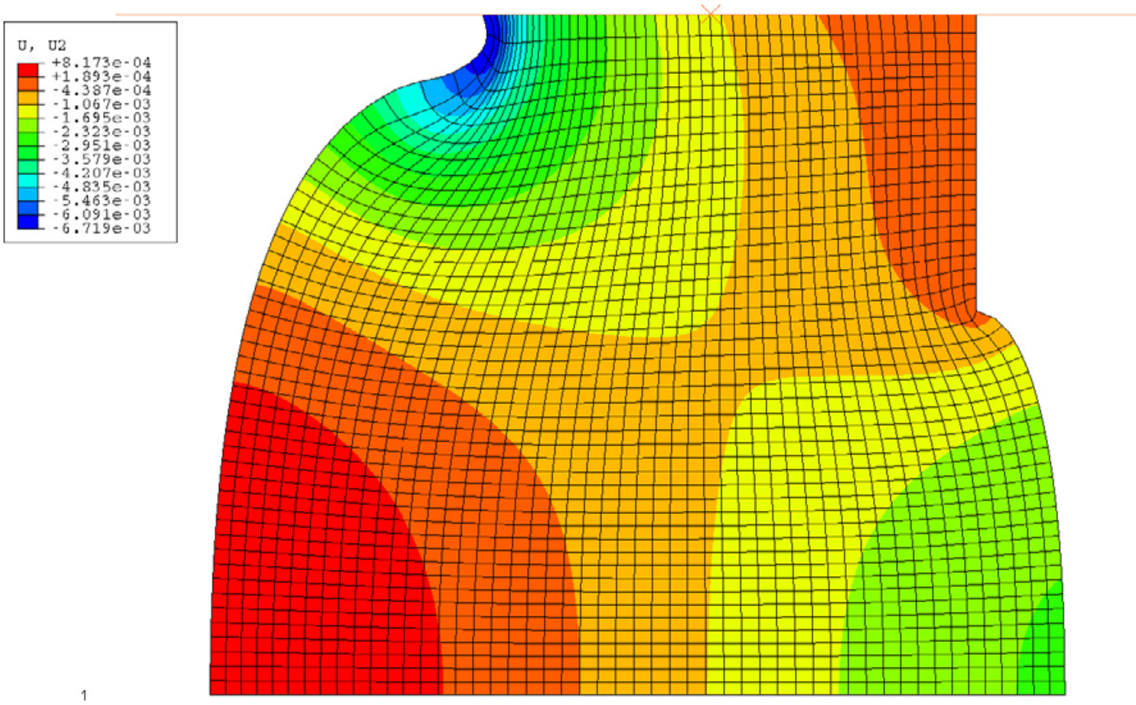


Figure 5-26. *Axial displacements (m) at full water pressure 5 MPa for case 8d.*

5.6.3 Conclusions from the FEM modelling

The calculations show that independent of the block/rock interaction the elastic displacements of the bentonite block are 5–10 mm. Since the pressure will also act inwards the displacements may well be doubled. In addition the displacements will be larger in reality since the distance block in the calculations is only 1 m thick while they will be 3–5 m in total in the real concept.

Since the demand on the slots between the blocks is very strong (only a few mm allowed) the large displacements will open up the slot and thus make the water penetrate deeper. This is a progressive process that most probably will lead to that the entire block surface is subjected to full water pressure. Other conclusions of these calculations are that the same process may take place radially since the blocks are 1.85 m in diameter and the same high elastic strains will occur in this direction the process can only be tested in full scale since the elastic displacements are proportional to size.

The modelling results therefore indicate strongly that the BD will not perform as expected unless a rigid compartment plug (as opposed to a fixing ring) is inserted to withstand the full hydraulic pressure.

5.7 Filling components

5.7.1 General

Filling components are to be used as massive sealing elements in positions, which are not suitable for supercontainer positioning or to compensate for the potential reduction of buffer density. The reduction of buffer density may be caused by the filling of open volume resulting from the dissolution of compartment or drift end plugs or by open volume adjacent to compartment plugs or fixing rings left in the drift during operation.

The filling components have not been designed in detail and the design principles presented here reflect the present ideas and will be developed further.

The filling components will inevitably undergo physical and chemical changes over time due to mineral transformations, shrinkage, swelling, erosion, etc. However, it is required that these processes will not involve volume changes that could lead to significant changes in buffer density (mainly distance blocks). The range of densities compatible with the buffer fulfilling its safety functions taking into account the evolution of groundwater and buffer porewater salinity (1,890 to 2,050 kg/m^3) is discussed in Appendix B.5.

Additional void space and density reduction can be formed in the drift system by the dissolution of cement from concrete drift plugs, compression of permeable crushed rock filling by swelling buffer, and compression of lower density filling adjacent to compartment plugs. This density reduction should be compensated by additional swelling capacity and density in the filling components.

The following types of filling designs may be used in a drift:

1) Filling adjacent to steel compartment plug:
   - between steel compartment plugs,
   - on the drift entrance side of compartment plug,
   - in the drift end side of compartment plug,
2) Filling blocks in drift positions with water leakages.

The use of filling components is related to water inflows. 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 equalt to 1 l/min after sealing the section cannot be used for deposition of a canister and must be filled with filling element similar to buffer. If the inflow into a supercontainer section after sealing is roughly from 1 to 4 l/min per supercontainer section (approximately 10 m), the leakage zone is isolated by using compartment plugs.

One critical issue in the design of filling components is the filling of open volume by inflowing groundwater and the subsequent rapid development of hydraulic pressure. The filling and pressure development has been discussed in Section 3.5.2. Within the majority of supercontainer sections not intersecting transmissive fractures, no significant pressure rise is predicted within the first years as any water inflow is taken up by the bentonite. Furthermore, there are indications that only a fraction of the supercontainers may become pressurised during the first year of operation. The result will be a system of neighbouring supercontainers and distance blocks with full hydrostatic pressure on one side of the distance block and none on the other.

It assumed that the distance block in the BD alternative will seal that drift section when exposed to water. The maximum filling time of the open volume in a supercontainer section is roughly 10 days according to the supercontainer positioning criteria (inflow less than or equal to 0.1 l/min). A filling time of 200 days or more is expected in sections where the transmissivity of features is below 10^{-10} m^2/s. In tight sections with no transmissive fractures, the filling time will clearly be longer. The time to obtain significant swelling pressure on the compartment plug is yet unknown, however, if the distance blocks function according to plans and the inflow rates are according to estimates, the time will likely be in range of several months.

5.7.2 Filling adjacent to the outer side of the compartment plug

The material used to fill the open volume next to plugs is expected to be composed of MX-80-type bentonite pellets and additional crushed rock, if necessary. The pellets cannot be in direct contact with the first distance block since the pellets section has a very low density and will be compressed by the neighbouring bentonite blocks. There must thus be a transition zone between the distance blocks and the pellets, which after equilibrium will have a gradient in density. This section should be designed so that the density is the same as the density of the distance block at that side and then be reduced with distance from this section until it has the same density as the compressed pellets section at the contact with the pellets. The bentonite will not be homogeneous mainly due to friction between the bentonite and the rock surface. The required length of the transition zone is a function of the length of the pellets filled zone and the properties of the material inside the plug. The length can be estimated by a rather simple equilibrium calculation and by Finite Element Modelling.

In addition to the pellets and transition zones there is probably the need for a separating section between the pellets and the first bentonite block in the transition zone to be able to backfill with pellets, see Figure 5-27. The section could be a wall if necessary, and could be made of several different types of materials, such as copper, titanium, steel or thin low-pH concrete beams.

The key elements in the preliminary design (Figure 5-27) are:

- filling section,
- transition section,
- separating section between these.

The dry bulk density of the individual pellets is about 1,830 kg/m^3 and the dry bulk density of the emplaced pellets is about 950 kg/m^3. The transition blocks are similar to the "loose" component of distance blocks.

5.7.3 Filling between compartment plugs

The filling material for use between steel compartments plugs has not been completely defined. The filling material is not assigned safety functions, but should be designed to be compatible with, and support the safety functions of, the canister, the buffer and the host rock (Appendix B.2).

The key design requirements for the filling between compartment plugs are:

- The filling at the high inflow zone should be made of material that allows for easy drainage during filling operations.
- A bentonite material is required at the contact zone between the compartment plug and the rock to seal possible leakages.
- A filter zone separates the drainage material from the bentonite.
- One or more separating walls between the different filling materials are probably required for operational purposes.

The fill placed in a section with very high water inflow between the compartment plugs is not designed to seal but to let water pass through it. Figures 5-28, 5-29 and 5-30 show the design components, general design principle and proposed design of the compartment fill respectively.

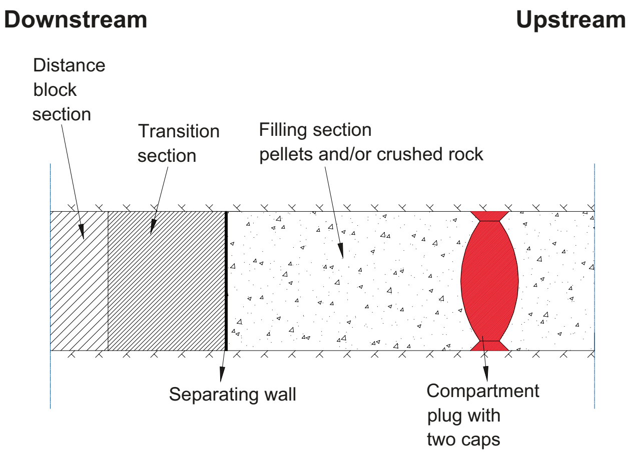


Figure 5-27. *Schematic design of the filling outside the outer compartment plug.*

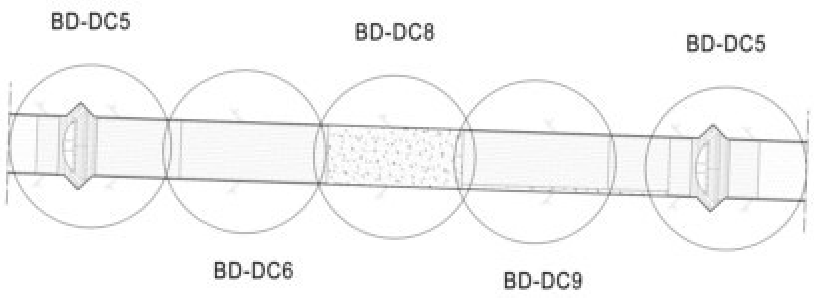


***Figure 5-28.** Schematic illustration of compartment plug system showing the filling components. The drainage material consisting of permeable filling (DC-8) is positioned in the leaking fracture intersection. The leakage is conducted out from the intersection through a partially permeable filling (DC-9). The upstreamand downstream sides of the leakage are filled with filling (DC-6 and DC-9) consisting of pellets and/or crushed rock.*

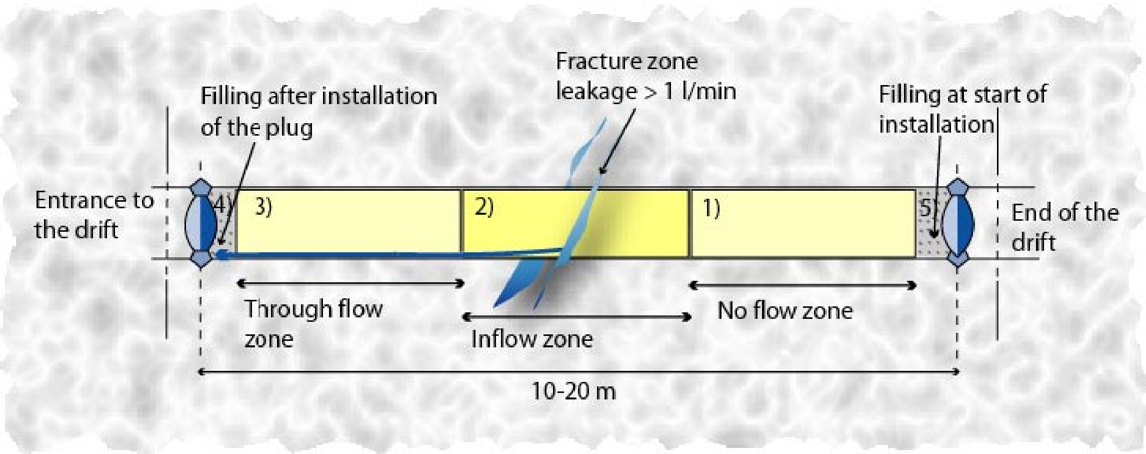


***Figure 5-29.** Conceptual design of filling between steel compartment plugs.*

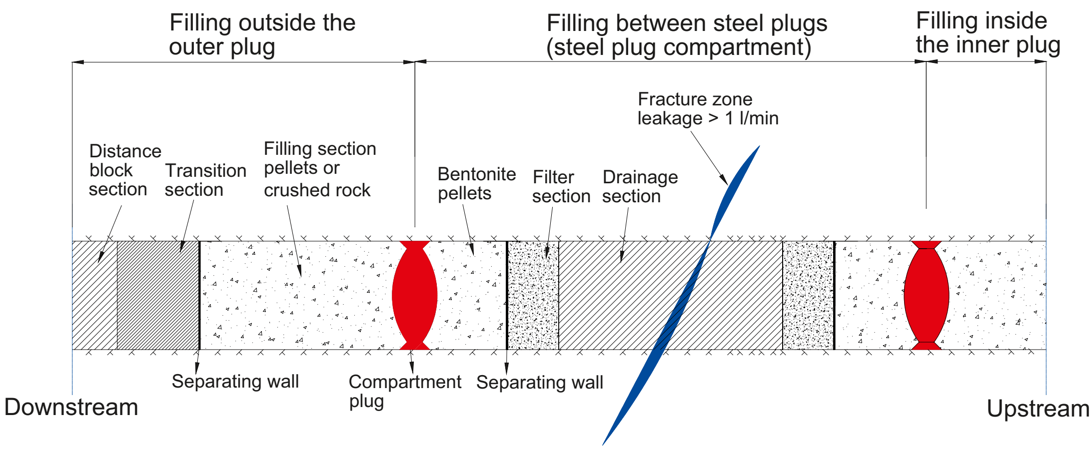


***Figure 5-30.** Preliminary schematic design of the different filling between and adjacent to compartment plugs.*

The filled section between two plugs should look like the schematic provided as Figure 5-30. The drainage zone with free-draining filler material needs to extend across the region intersected by the fractured zone. Beyond this is a filter zone (at least one, perhaps two), occupied with a filter material that can resist intrusion of bentonite into it and similarly will not enter into the drainage material. The filter material can be part of the drainage section or a separate component composed of crushed rock with proper grading for filtering.

Separating walls may also be needed between the different materials. Finally a zone with bentonite pellets in contact with the compartment is included.

5.7.4 Filling inside the inner side of compartment plug

There are two preliminary designs for two different cases for the filling inside the inner compartment plug based on the general design presented in Figure 5-31:

1) The further end of plugged compartment is the drift end (i.e. rock). The pellet-filled zone can be reduced to about 0.5 m, when compared to case 2).
2) The further end of plugged compartment is another compartment plug. In that case the filling inside the inner compartment plug needs to mirror the type of filling done outside, as described in Section 5.7.2, see also Figure 5-32.

5.7.5 Filling blocks for use in drift positions with water leakage – filling block unit

Filling blocks (Figure 5-33), similar to distance block sections are emplaced in positions where the groundwater inflow is higher than is allowed for supercontainer installation (0.1 l/min before sealing of fractures) and lower than the limit for using compartment plugs (1 l/min after sealing). Two important requirements for filling blocks is that they keep the adjoining buffer in place and prevent significant loss or redistribution of buffer.

The filling blocks will be similar to reference design of distance blocks i.e. manufactured of bentonite and compacted to the same density. The unit length of one filling block is the same as length of distance block, however, the total length of filled section can be increased if necessary by placing several filling block components next to each other.

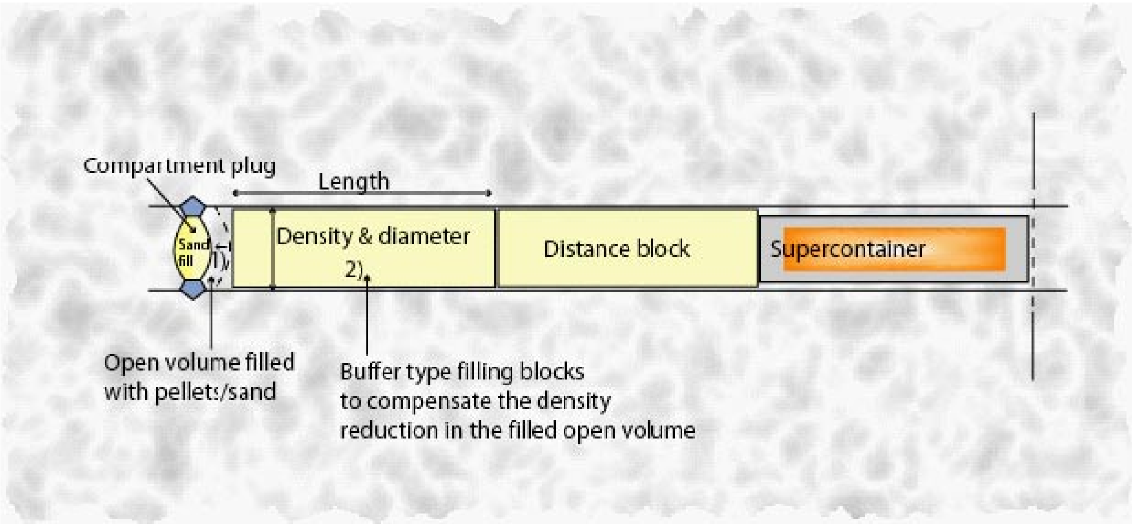


Figure 5-31. Conceptual design of filling adjacent to compartment plug (1) and transition block (2).

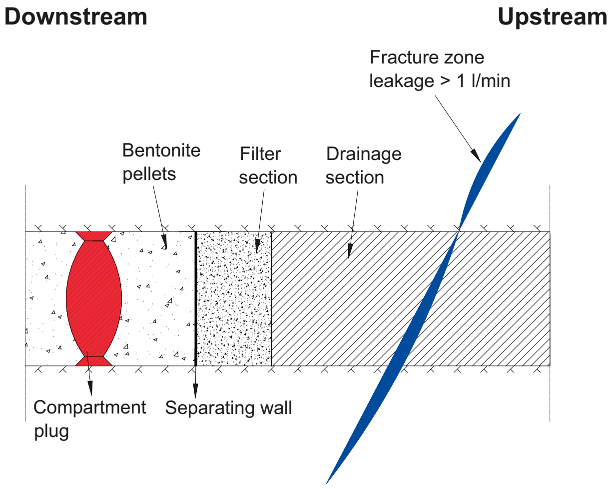


Figure 5-32. Schematic proposed design of the filling between two compartment plugs. The design is intended to be symmetric around the fractured zone. Downstream refers to direction towards the deposition niche, upstream referes to direction towards the dead end of the drift.

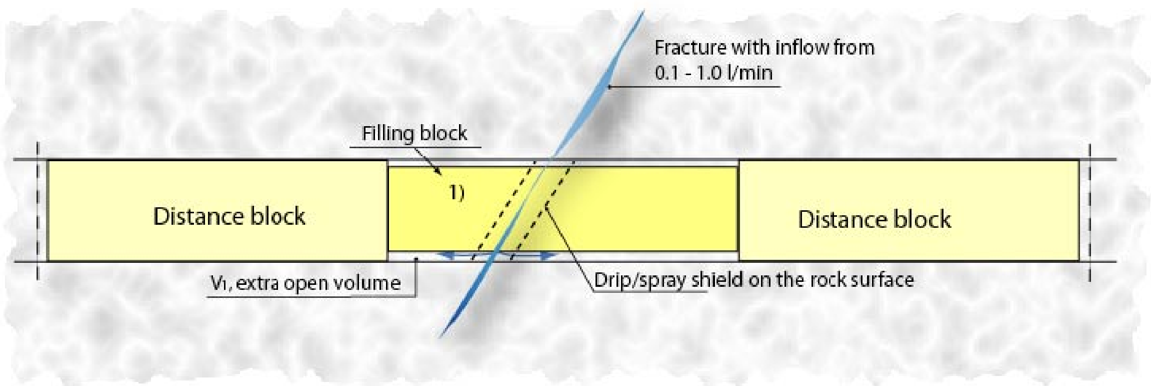


Figure 5-33. Filling block similar to distance block sections are emplaced in positions where water inflow is higher than 0.1 l/min, but less than 1 l/min.

5.8 Uncertainties and proposal for future work

The extent and magnitude of hydraulic pressure on the face of the distance block depends on the behavior of gap between drift surface and buffer, joints in bentonite and the gap between distance block and supercontainer. Current estimates are that the hydraulically-induced pressure will be exerted on a rim of about 10 cm width if the gap between distance block and supercontainer is 7 mm wide /Börgesson et al. 2005/. This was the basis for design of distance block in the Basic Design (BD) alternative presented in in this report and was also previously used in DD-2006 /Autio et al. 2007/.

The magnitude and extent of hydraulic pressure on the distance block face was identified as a critical issue needing to be resolved by testing /Autio et al. 2007/. The function of distance block reference design presented in Section 5.2 was studied by testing and modelling as described in Section 5.6.

The FEM modelling and laboratory tests have shown that there are significant uncertainties related to the functionality of distance blocks. The requirements specified for the buffer are not reliably fulfilled by the distance blocks and so they have been deemed to be unfeasible. The main issue encountered in both testing and modelling is that full hydrostatic pressure is generated on whole distance block vertical joint face in positions where inflows of 0.1 l/min or less occur (reference conditions). The hydrostatic pressure will cause compression of the distance blocks, increasing the gaps and as a result the hydraulic force is larger than can be accommodated by the fixing rings, resulting in unacceptable displacement of the distance blocks.

Calculations show that independent of the block/rock interaction, the elastic displacements of the bentonite block are 5–10 mm. Since the hydraulically-induced pressure will also act inwards, the displacements may well be doubled. In addition, the displacements in a field situation will be larger than the preceding estimate as the distance block used in the calculations is only 1 m in length while they will be 3–5 m in total in the repository. Although the gap between the distance blocks and supercontainer is only a few millimetres in thickness, it is expected that the hydraulic force will open the gap allowing water to penetrate deeper, increasing the area subjected to hydraulic pressure. This is a progressive process that most probably will lead to that the entire block surface being subjected to full water pressure. The result is likely a situation where the entire distance block is pushed by hydraulic pressure through the fixing ring, see Figure 5-34.

The distance block design, which is based on a small, millimetre size gap between rock and buffer, is also technically not robust because it doesn't meet the basic drift quality requirements specified in design basis (the required surface roughness is of the same order as largest allowed gap), without additional measures being taken. The emplacement time of the distance blocks requires a wetting period, which is of the order of week, while the basis assumed for design has been direct emplacement without any wetting. This would increase the operation time of one drift from the order of days to months. Therefore the distance block, a key component, in the Basic Design alternative has been assessed as being not robust and to contain severe functional uncertainties.

Several different alternatives for the distance blocks were evaluated and are presented in Section 5.3, however, none of these were judged to be viable. The problem encountered with these alternatives is the same as in the case of filling components and so the filling block design presented will not fullfill the design requirements or function properly in specified inflow environment. There are also several groundwater pressure related problems related to filling adjacent to compartment plugs that need to be resolved.

Therefore the general conclusion developed from the preceding discussion and information developed to date is that the Basic Design is not robust, includes severe functional uncertainties and should not be considered a viable design alternative. It is perhaps usable in cases where less severe inflow conditions exist but this has not been evaluated in this document.

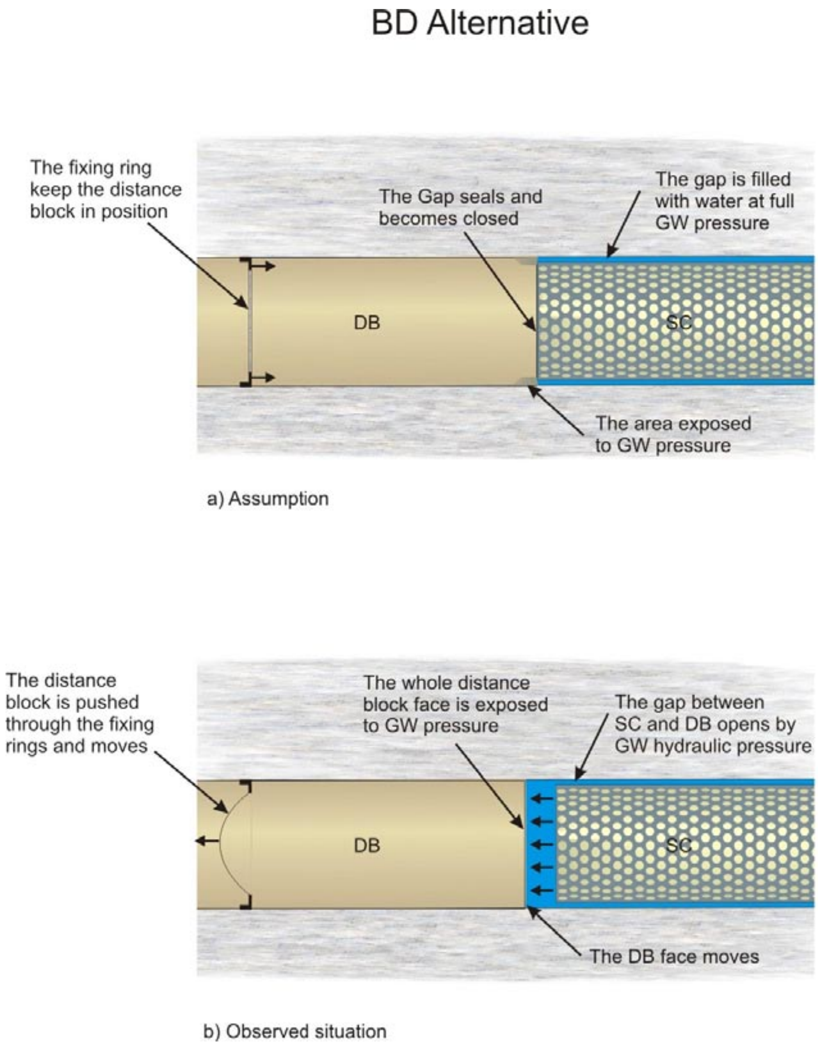


Figure 5-34. *Assumed and observed and modelled behaviour of the distance block due to the full hydrostatic pressure of 5 MPa in the Basic Design alternative.*

6 DAWE (Drainage, Artificial Watering and air evacuation) alternative

6.1 Specification of the functional structure and design components

In the Drainage, Artificial Watering and air Evacuation (DAWE) 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 saturation of the void spaces around the supercontainers.

Because the DAWE design calls for all open connected void space to be filled with water at hydrostatic groundwater pressure, there will be no significant pressure gradients right after water filling. This will avoid flow between supercontainer sections. Hydraulic pressure differences between neighbouring supercontainer sections that could potentially lead to buffer erosion by water flow and to mechanical displacement of the supercontainers and distance blocks are thereby prevented during the operational period of a drift compartment. Furthermore, although hydraulic pressure differences may still develop between drift sections, the fact that they are water filled means that tighter drift sections do not provide sink volumes for potential water flow from drift sections intersected by transmissive fractures, at least for an initial period following artificial watering and air evacuation.

As in the BD, fractures that could give rise to significant water flows to adjacent unsaturated drifts or transport tunnels will be avoided as supercontainer emplacement locations. Nevertheless, the criteria for identifying transmissive fractures that must be avoided are expected to be less stringent for DAWE compared to the BD design alternative. Operational criteria will also need to take into account of the possibility of having to drain potentially large water inflows along the drift without perturbing the buffer and thereby the possibility of internal erosion of the buffer after drift closure.

The drainage of inflowing water along the floor of the drift during operations is achieved by having the drift inclined to the rear of the drift, allowing for natural water flow towards the entrance. There is a gap of approximately 40 mm (37.5–42.5 mm) between the distance blocks and the drift walls, which is larger than in the Basic Design. This gap should prevent any contact of the distance block with water flowing along the bottom of the drift.

It is proposed that a higher initial-water-content bentonite be used to prevent humidity-induced fracturing of the distance blocks. Passive, gravity-controlled drainage of water along the drift floor is expected continue until the drift or drift compartment is plugged.

Following sealing of the compartment, artificial wetting takes place simultaneously with evacuation of air, thereby avoiding gas pressurisation. Steel pipes along the surface of the drift are used for watering and air evacuation. The sides of the drift are the preferred position for watering pipes to avoid possible damage during operations. Nozzles, which are directed downwards in the watering pipes are distributed along the drift in each supercontainer section to ensure uniform inflow and minimise any axial water flow in the drift that could give rise to bentonite erosion. Water is not directly injected in the sections where the distance blocks are positioned, again to avoid possible erosion.

The flows of water and air during the watering period are illustrated in Figure 6-1. It should also be noted that only about one third of the total void space (including bentonite pores) will be filled with water in this way, the remaining voids being less readily saturated. The system remains, therefore, in a partially saturated state even after artificial watering. All supercontainer sections will be filled with water simultaneously to avoid axial water flows that could give rise to bentonite erosion and redistribution along the drift. The maximum wetting time is expected to be about 14 hours per one 150 m long compartment at most.

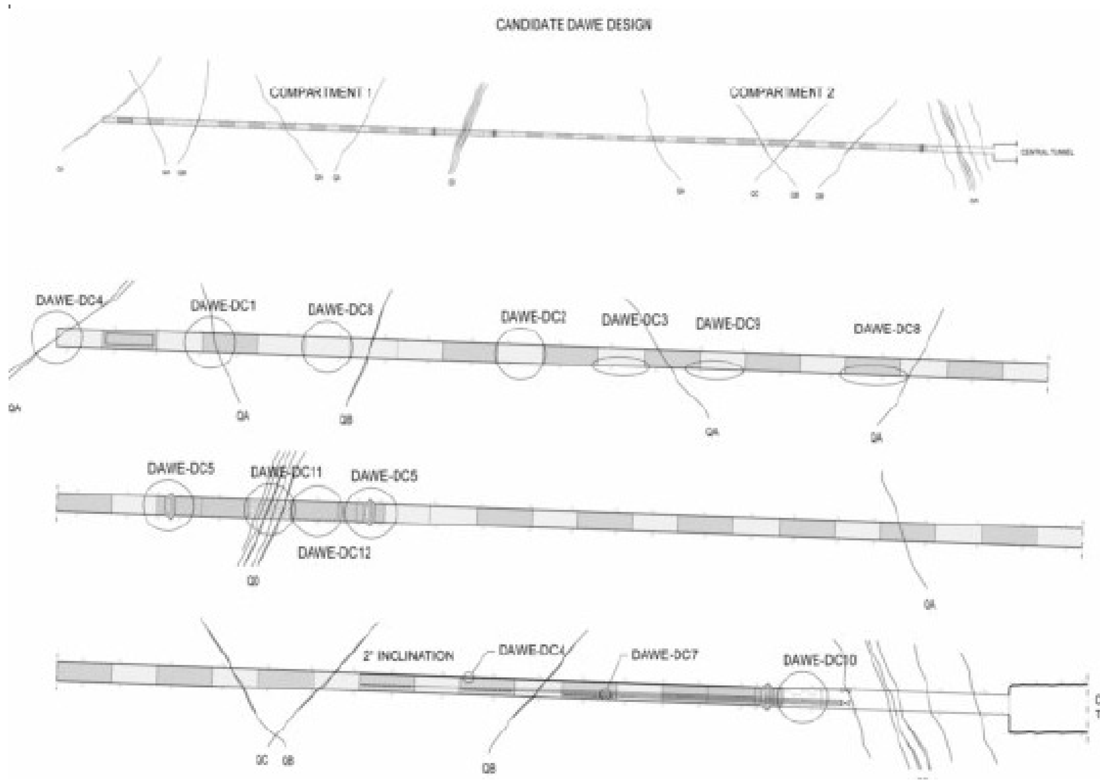


Figure 6-1. *The DAWE design in an illustrative vertical section with examples of positions of design components. The identifiers in fractures refer to different types of water leaking fractures. The watering and air evacuation pipes are shown only in the beginning of the drift.*

In the following discussion, it is assumed that the application of proper excavation and construction techniques have reduced groundwater inflow to acceptable or manageable rates. Groundwater control techniques are described in Chapter 9. Additionally, deposition drift, canister, and supercontainer functions are only briefly described here as they are considered as fixed design aspects. The DAWE design has the following functional requrements:

1) *Prevention of buffer erosion by spray and drip shields.* Direct water flow on buffer surface will cause surface erosion. Spraying, squirting and significant dripping of groundwater on supercontainers and distance blocks is prevented by using shields.

2) *Drainage on the bottom of the drift.* The water inflows are drained during operation so that buffer will not be in contact with water. The drift is inclined and therefore water flows naturally towards the entrance of the drift.

3) *The plugged drift is filled with water using artificial watering pipes.* The empty volume in the drift is filled with water to produce even initial wettening of buffer and diminish possible hydraulic pressure differences between supercontainer section, which may cause e.g. piping and detrimental transport of bentonite. All supercontainer sections are filled at the same time prevent axial flow along the drift. As a consequence of filling, bentonite will swell rapidly and seal the drift. The pipes are removed from the drift after watering.

4) *Air and gas is evacuated during filling by using air evacuation pipe.* Large volumes of air and gas are trapped in the drift after plugging. Highly pressurized gas acts as an energy accumulator, which may induce unfavourable flow in the drift and cause operational problems during removal of wetting pipes.

5) *Isolation of water-bearing fracture zones by plugs (same as in BD).* Isolation of deposition compartments by using plugs from water-bearing fracture zones, which may have detrimental effect on the distance blocks and supercontainer during saturation.

6) *Sealing of the drift by plugs (same as in BD).* The deposition drift is sealed and plugged after emplacement of supercontainers.

7) *Interruption of operation using plugs (same as in BD).* The emplacement of supercontainers can be stopped temporarily if the drift is plugged rapidly. The interruption may be caused by failure in operation and swelling of already emplaced buffer.

8) *Hydraulic isolation between supercontainers and adequate thermal spacing of canisters is obtained by using distance blocks (same as in BD).* Thermal spacing between successive canisters is obtained by using a distance block of required length.

9) *Sealing and filling of unsuitable sections by filling blocks (same as in BD).* Positions that are not suitable for emplacement of supercontainers, because of larger than accepted water inflow or other reasons, are packed with filling blocks. The objective of the blocks is to provide extra sealing against neighbouring distance blocks and to reduce the hydraulic pressure induced force exerted on distance blocks.

6.2 Specification of the design components

6.2.1 General

Design components, which are the same between the BD and DAWE designs, are described in Chapter 4.

The DAWE Design Components (DAWE-DC) shown in Figure 6-1 are:

- DAWE-DC1 Spray and drip shield.
- DAWE-DC2 Distance block.
- DAWE-DC3 Drainage system of inflowing water.
- DAWE-DC4 Air evacuation system.
- DAWE-DC5 Compartment plugs.
- DAWE-DC6 Filling blocks.
- DAWE-DC7 Artificial watering system.
- DAWE-DC10 Drift end plug.
- DAWE-DC11 Permeable filling.
- DAWE-DC12 Partially permeable filling.

6.2.2 Distance block

Distance blocks are positioned between the supercontainer sections of an emplacement drift. The purpose of the distance block is to provide sufficient thermal spacing between supercontainers and to hydraulically isolate the supercontainers during saturation. It is expected that the distance block will swell more rapidly than the buffer in the supercontainer and so will prevent the flow of water along the drift.

The distance blocks will have to be placed on feet (same as for the supercontainers) in order to permit a free flow of water on the tunnel floor.

Initial conditions of the blocks

The distance blocks in the DAWE alternative are assumed to have the same initial diameter as the supercontainer.

The initial gravimetric water content of bentonite in the distance block is 21%. The design length of distance block is 5.475 m and the diameter is the same as the supercontainer (1,765 mm), see Table 6-1. The initial dry density of the distance block is defined to be

Table 6-1. Table showing the dimensions used in the calculations. The table also shows the calculated dry density of the distance blocks for the DAWE design.

Dimensions	
Rock	
Diameter tunnel, mm	1850
Distance block	
Outer diameter, mm	1765
Calculated block data	
Distance block DAWE	
Target average density at saturation, kg/m³	2000
Initial block dry density, kg/m³	1712
Initial block void ratio	0.629

1,712 kg/m^3 and the final saturated density of the distance block is expected to be 2,000 kg/m^3 (actually ranging from 1,950 to 2,050 kg/m^3). The tolerances of the dry density on the manufactured blocks are rather large (1,627–1,798 kg/m^3) in order to get a density at saturation of between 1,950–2,050 kg/m^3 in the tunnel. Figures 6-2 and 6-3 provide information on the density and saturation conditions generated by various clearances and initial density conditions.

Sensitivity for variations of the tunnel diameter

The required block densities are calculated using the nominal diameter of the deposition drift i.e. 1,850 mm. The actual tunnel diameter will, however, vary and this will influence the final density in the system. Figure 6-3 shows how the average density at saturation will vary with tunnel diameter, assuming an average density at saturation of 2,000 kg/m^3 at the nominal tunnel diameter (1,850 mm).

6.2.3 Water supply system

Sealed drift compartments will be flooded using pipes. The open volume (air-filled macropores and gaps) in a supercontainer position is about 1.3 m^3 (42.5 mm gap and 5.56 m length). The open volume in the distance block position of length 5.46 m is 1.3 m^3 (42.5 mm gap). The largest possible total open volume in a supercontainer section (about 10 m) is then about 2.6 m^3. It is likely that the final volume will be smaller due to humidity induced swelling of bentonite. In order to artificially fill the total open volume including 15 supercontainers in one compartment in 14 hours, a flow rate of 45 l/min is required. This is equal to about 3 l/min per supercontainer section. Water is led to the drift evenly through several holes in every container section to avoid large inflows. If twenty holes are positioned in every supercontainer section, the inflow per hole is 0.13 l/min. The maximum time needed to complete water inflow is expected to be about 10–14 hours.

The flooding system described below is based on installation of several small diameter pipes positioned on the sidewalls of the drift before operation starts. Water is distributed evenly in the supercontainer sections through several (10–30) holes in these pipes.

The positioning of the pipes on the roof of the drift is preferred over the bottom of the drift in order to avoid possible problems with pipe removal. However, the clearance on the sides of the drifts is larger during operation and so vulnerability to damage from pipe removal is lower on the sides of the drifts. Therefore, the preferred position for pipe systems is along the sidewalls (see Figures 6-4 and 6-5).

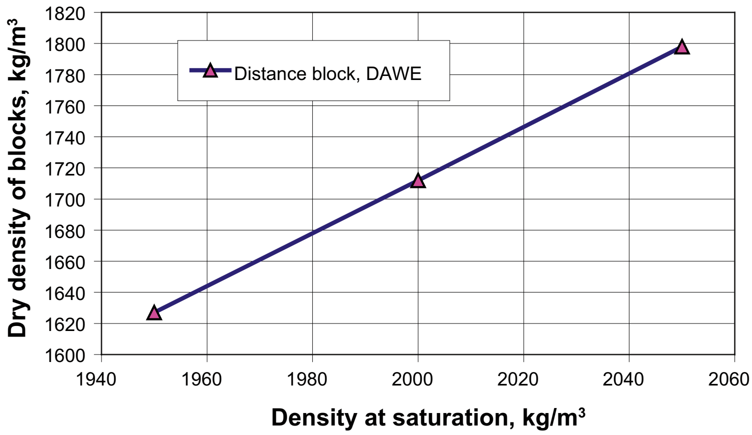


Figure 6-2. Dry density of the blocks (dimensions according to Table 6-1) plotted vs. the average density at saturation in the tunnel after swelling and homogenization.

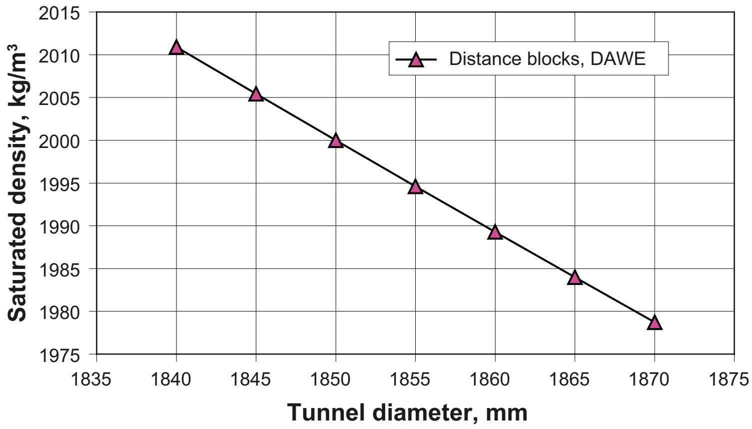


Figure 6-3. Average density at saturation in the tunnel after swelling and homogenization (intended average density at saturation 2,000 kg/m³) plotted vs. tunnel diameter.

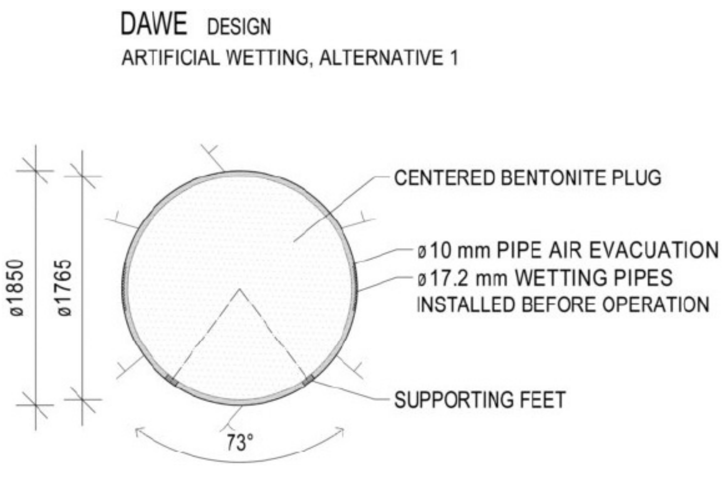


Figure 6-4. The artificial watering and air evacuation pipes in the DAWE design based on the use of several small 17 mm diameter pipes on the sides of the drift.

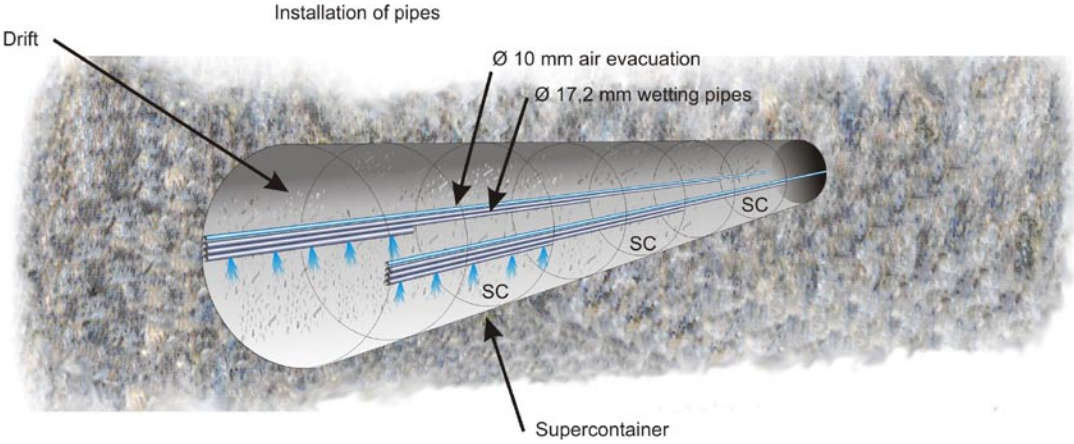


Figure 6-5. *The artificial watering and air evacuation pipes in the DAWE design.*

As a design principle, no pipes will be left in the drift. Nozzles in the water supply pipes are distributed along the drift in each supercontainer section to ensure uniform inflow and minimise any axial water flow in the drift that could give rise to bentonite erosion. Water is not directly injected in the sections where the distance blocks are positioned, again to avoid possible erosion.

Steel is the preferred pipe material because it will not introduce any new material in the drift and will corrode in case it is left in the drift as a consequence of deviation in operation. One 17.2 mm diameter, type DN 10 17.2x1.25 steel pipe of is required for every supercontainer section. The capacity is 30 l/min and tensile strength 80 MPa. The weight is 0.5 kg/m and the weight of water 0.17 kg/m. The pulling strength of the pipe is 5 kN with cross sectional area of 0.626 cm^2, which corresponds to removal of 747 m long pipe with friction coefficient of 1. The open gap between the supercontainers and adjacent rock faces is 20 mm under operation conditions. After operation the gap is 42.5 mm.

Installing pipes on both sidewalls, for redundancy purposes, doubles the number of pipes. The air evacuation pipes are installed on top of the wetting pipes. If a deposition vehicle were to collide with one set of pipes and render them non-functional, the redundant set on the opposite wall can be used. The number of pipes installed on each wall is about 15 (see Figures 6-4 and 6-5). The pipes are attached on the sidewalls of the drift in U-shaped brackets of weight about 50 g/piece with spacing of 5 m so that they can be pulled out separately. One collar seal is installed in the steel compartment plug for every pipe. The water is distributed through several small holes in the pipes to supercontainer cells.

The pipes are removed after a compartment has been isolated by installation of the steel compartment plug and filled with water, see Figure 6-6. A collar seal system is required in order to remove the pipe or pipes without loss of softened bentonite from the plugged drift. The collar system may be based on principles similar to as collar systems used in underwater drilling. Another alternative is to pressurize the drift during the removal period. This procedure would require a pressure of 0.3–0.5 bar at maximum (difference in hydraulic head between the ends of the drift) and will not prevent the leakage of groundwater at higher pressure. Bentonite mud can be pumped into the drift if necessary to fill the open volume left by the pipes during removal.

6.2.4 Air evacuation system

In order to facilitate air removal during artificial drift flooding, a pipe is installed on the top or sides of the drifts before operation (see Figure 6-4 and 6-5). The open end of the pipe is placed in the highest point at the far end of the drift, where air is trapped due to the slight upward inclination of the drift. The pipe is equipped with a filter to eliminate possible plugging.

Air is evacuated from the drift through a pipe with an inner diameter of 10 mm. Two pipes are installed for redundancy. The pipes are dimensioned to allow the same outflow of air as inflow of water (45 l/min). Steel or copper is the preferred pipe material as they will not introduce any

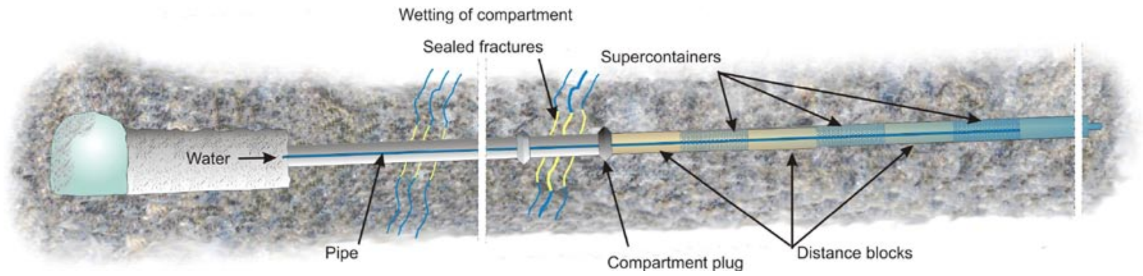


Figure 6-6. *The artificial watering and air evacuation pipes in the DAWE are removed rapidly after the compartment has been filled with water.*

new material in the drift. The pipes are removed after a compartment has been plugged with the steel compartment plug and filled with water. A collar seal system is required to remove the pipe without loss of softened bentonite from the plugged drift.

One copper pipe with an inner diameter of 10 mm is required for one compartment. The tensile strength of the copper pipe is 20 MPa. Its weight is 0.31 kg/m and the weight of water 0.08 kg/m totalling 0.318 kg/m. The pulling strength of the pipe (20 MPa) with cross-sectional area of 0.35 cm^2 is equal to 0.7 kN which corresponds to removal of 220 m long pipe with friction coefficient of 1. A steel pipe of 10 mm diameter would weight 0.27 kg/m and allow larger pulling force for removal. The pipes are attached to the sidewalls of the drift in U-shaped brackets, weighing about 50 g each, over spacings of 5 m so that they can be pulled out separately.

6.2.5 Plugs

The specification of compartment and drift end plugs in DAWE are similar to that in BD presented in Section 4.3. The only difference of DAWE to BD alternative is that the plugs are equipped with lead-through, valves and collar seals for possible drainage, wetting and air evacuation pipes.

6.2.6 Removal of pipes

The pipes used for watering and air evacuation are to be removed after the compartment has been sealed with a compartment plug and filled with water. The compartment plugs contain a hole for each pipe and are equipped with a collar seal system to prevent the outflow of water or softened bentonite from the water filled drift. The use of watertight collars is a proven engineering technique, which can be found, for instance, in underwater drilling operations. Another alternative is to pressurize the drift during the removal period. This procedure would require, at maximum, an overpressure of 0.3–0.5 bar at the removal end of the drift. Any open volume resulting from the pipe removal can be filled with bentonite mud if necessary.

The removal of the pipes is one important step of sealing the drift compartment because the steel pipes are not allowed to remain in the drift due to long-term safety aspects. The pipes are preferred to be removed before the swelling pressure of the bentonite increases and make the pipe removal more difficult. In order to develop a robust and viable system a removal test was launched in October 2007 at Äspö and completed early February 2008. A sketch design and the realized set-up are shown in Figures 6-7 to 6-9.

Analyzing of the results is still ongoing, but as clearly indicated by Figure 6-10 after a few days from the beginning the friction has increased quite steeply from 0.5 kN up to 2.2 kN in one month. The test shows that the pipes can be removed by the planned technology, but, as expected, it needs to be done as soon as possible after the compartment is filled with water.

Due to the swelling pressure from the bentonite and the friction between the bentonite and the steel tube a counter force will arise when pulling the tube. With a maximum allowable stress of

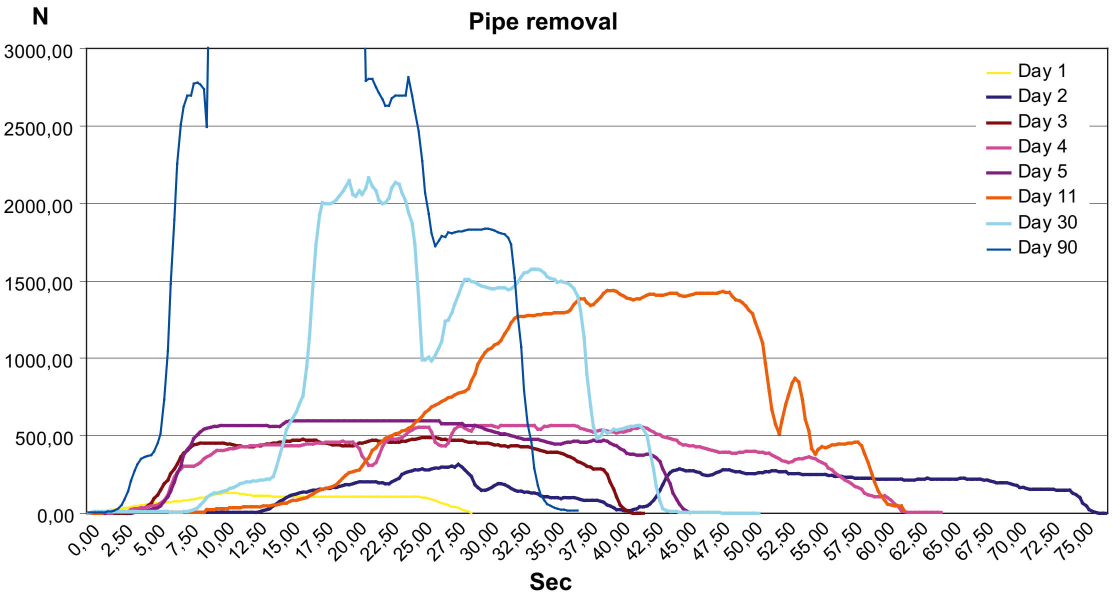


Figure 6-7. *Equipment for the pipe removal test.*

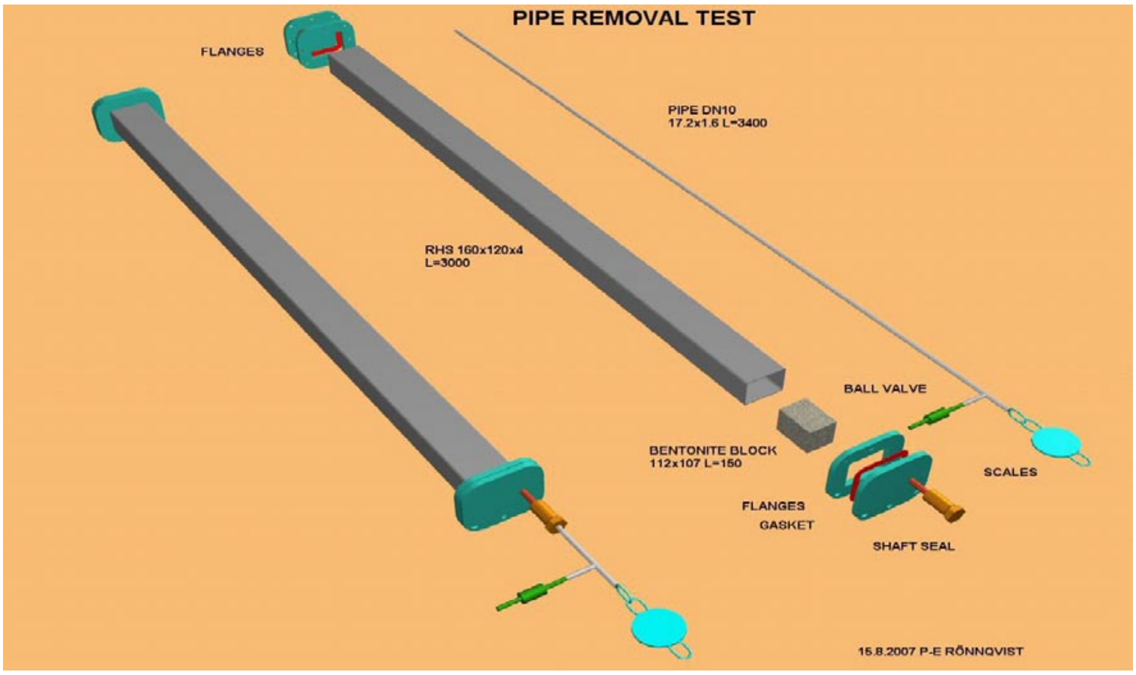


Figure 6-8. *Realized set-up of the test equipment for pipe removal.*

Figure 6-9. *Recording unit of the test equipment.*

Figure 6-10. *Development of pipe friction during a test period of three months.*

500 MPa for the stainless steel pipe (17.2 x 1.6 mm), the maximum force that can be applied is 40 kN. If the friction force is expressed in kN/m tube, the allowable force for the real case (150 m) will be 0.26 kN/m. This means that in the performed laboratory test, with a length of 3 m, the maximum allowable load is 0.78 kN.

In the performed test this limit was reached rather soon. After 5 days the measured load was 0.60 kN and after 10 days 1.44 kN. These measurements correspond to a swelling pressure of 10–25 kPa (friction angle of 20°) which is in the same range as the measured (during the test the swelling pressure was measured in two points). After three months the load already exceeded 3 kN, which was the upper limit of the measuring device.

After analyzing carefully the results obtained this far the tests will be continued with more specific studies on the friction between the pipe and the bentonite. More attention will also be put on developing the collar system and the joints of the pipes.

6.2.7 Filling blocks and other filling components

The filling blocks and filling components are of the same type in the DAWE alternative as described in Section 5.7 for the BD except for the filling outside the plug which is not necessary for the DAWE design.

The filling blocks should seal the section of drift where they are positioned and should resist erosion. The present DAWE design is based on using distance blocks as filling blocks, however, the properties of the blocks may be improved through increasing their resistance to erosion, improving swelling potential and hydraulic conductivity characteristics.

6.3 Spalling

For purposes of the current discussion, spalling (see Figure 6-11) is defined as the breaking of a rock surface into splinters, chips or fragments. The occurrence of spalling depends significantly on *in situ* rock stresses and rock strength and is, therefore, site-specific.

Spalling caused by thermal stresses adjacent to a KBS-3H deposition drift was addressed in Autio et al. 2007. Based on Olkiluoto site data it is likely to occur in distance block positions in DAWE and STC alternatives and in the position of supercontainers in all three alternatives over limited areas as a result of thermal loading from the fuel canisters if the buffer material exerts no counteractive swelling pressure on the affected rock surface. In the worst-case scenario, spalling will occur along an entire dry drift section. In the best-case scenario, spalling will occur at supercontainer locations only. Regardless, the development of swelling pressure at the rock surface is uncertain.

Spalling is not likely to occur after excavation. The detrimental effects of possible sparse spalling may be remedied by several engineering actions.

Spalling is both site and design dependent. It depends on the rock strength, state of stress, and the existence and length of dry sections. The results of the TM modelling are based on Olkiluoto data and the situation at other sites could be different.

In the event the buffer exerts some swelling pressure on the rock surface, there are significant uncertainties related to occurrence of spalling:

- the magnitude of the swelling pressure needed to eliminate spalling is uncertain,
- the swelling pressure of bentonite buffer in dry drift sections is unknown,
- the frequency and length of dry drift sections is not fully known.

The supercontainer sections are evidently most susceptible to spalling in dry drift sections in all alternatives, however, the distance blocks with a large gap in DAWE and STC alternatives are susceptible to spalling as well.

Figure 6-11. *Spalling at Äspö on the vertical surface of a full-scale deposition hole in the APSE experiment /Andersson and Eng 2005/.*

6.4 Uncertainties and proposal for future work

Most of the identified issues and uncertainties are related to the behaviour of buffer:

- Swelling of buffer after artificial wetting and redistribution of water in heterogeneous inflow environment which may induce pressure gradients giving rise to internal water flows from wet sections to dry sections, see Figure 6-12.
- Swelling pressure of buffer after artificial wetting and effect on spalling. After initial system wetting, the water will migrate to drier parts of buffer, which may desiccate the already saturated buffer adjacent to buffer outer surface. There are indications from laboratory and intermediate-scale tests that the gap between the drift wall and buffer will remain closed and some swelling pressure may be sustained. However, the magnitude of swelling pressure initially present at this interface is uncertain as is the pressure needed to prevent spalling.
- Cracking of the buffer surface adjacent to a perforated supercontainer shell during operation and subsequent dropping of particles to the drift floor, which may be eroded by inflows. The cracking of buffer surface is caused by the high humidity in the drift and absorption of moisture in the surface. Recent tests indicate that the quantity of falling particles could be quite small and the possible erosion rates low, however, more evidence is needed.
- The removal of pipes has been tested in the laboratory and is described in Section 6.2.6. The robustness of removal is critical to the method and should be verified also at full scale.
- The compartment plug is essential component in the DAWE alternative and has not yet been tested.

It is proposed that the testing focused on the resolving the uncertainties mentioned above are continued and also extended to large-scale test, such as Big Bertha scale (50%), see Figure 6-13. These types of tests should also be done at field-scale once these smaller-scale tests provide sufficient behavioural information to allow for designing the tests. Laboratory test results on the performance of the distance block in the KBS-3H alternative along with plans for future buffer studies are presented in /Börgesson et al. 2005, Sandén et al. 2008/.

The functionality of the compartment plug and removal of pipes should be tested in full scale in order to verify their suitability. Such tests should include the adjacent filling components that influence the sealing of plugs.

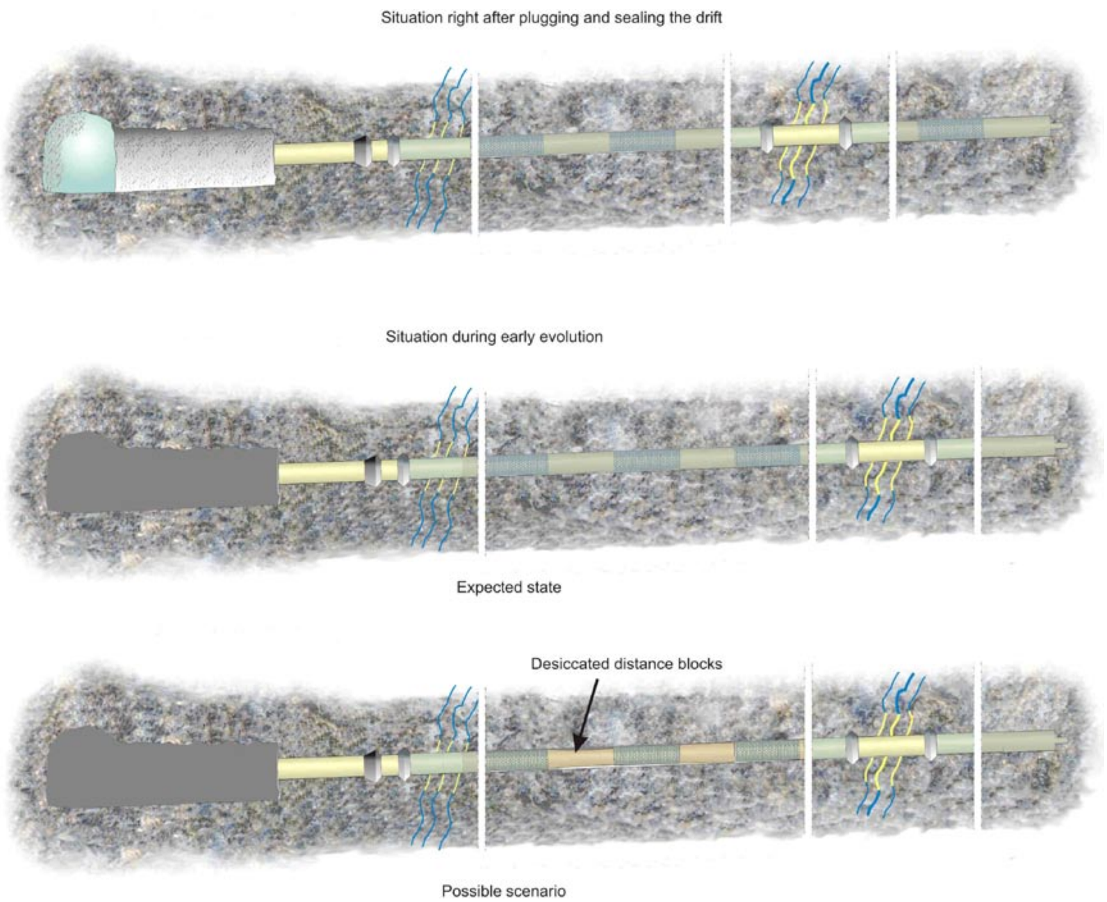


Figure 6-12. *Picture showing the ideal state after drift plugging and sealing the drift when buffer has fully saturated (top). If the there are very dry section in the drift, it could be possible that some of the buffer in the dry section desiccate as water migrates towards the inner parts of distance blocks. The migration is caused by gradient in water content, i.e. water will migrate from wet parts to dry parts. As the amount of water becomes smaller, the buffer dessicates.*

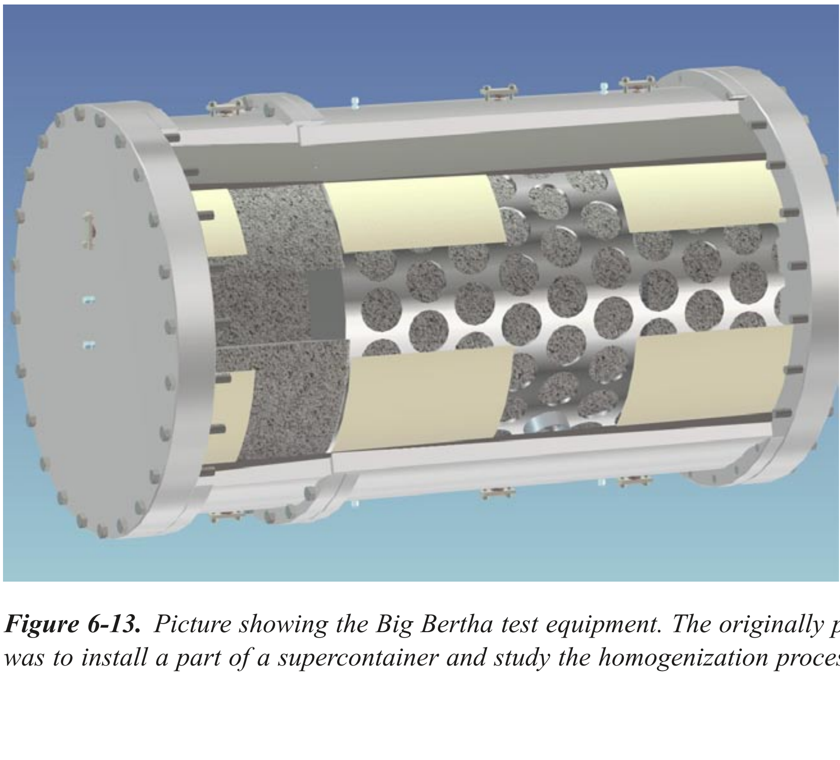


Figure 6-13. *Picture showing the Big Bertha test equipment. The originally plan with the equipment was to install a part of a supercontainer and study the homogenization process during long time.*

7 STC (Semi Tight Compartment) alternative

7.1 General

It was concluded in Section 5.8 that the Basic Design alternative was found to contain several uncertainties and was assessed as not being robust. In order to solve the problems related to piping and high hydraulic forces a new design called Semi Tight Compartment (STC) alternative was developed. The main change in the functional processes was allowing piping and erosion between supercontainer sections to occur before all sections are filled with water.

One way to solve the issue of piping and distance block displacement by hydraulic forces is to use the DAWE technique where the drift is kept open and free drainage allowed. A weakness with this design is that it is difficult to guarantee that there will be no bentonite slurry flowing along the drift floor out to parts of the drift where supercontainer installation is still occurring, since both water dripping on the blocks and humidity induced cracking of the blocks may take place and facilitate erosion of bentonite.

In the STC design each section will be sealed with distance blocks and sealing rings. These materials temporarily prevent water from flowing from one section to another before the section further away from the operational area is filled with inflowing water. When the section is filled with water the distance blocks cannot withstand the high water pressure piping and flow of water into the next section occurs. Since there are no demands on the distance blocks and sealing rings excepting to seal against only a few metres of hydraulic pressure, the blocks can be made with the same gap between rock and block as the supercontainer (as in DAWE). In order to prevent flow of water there must be a ring or very light sealing at each distance block section. This sealing can either be made similar to the fixing ring type structure in DAWE design alternative without any demand on strength or as a gasket. Figure 7-1 shows the design.

Since the sealing ring can withstand a small water head the supercontainer section is expected to be filled with water before it leaks into the neighboring section. Based on the empty volume between the bentonite blocks/rings and the rock surface it will take about 20 days before the entire section is filled with water if the water inflow to the section is equal to the maximum allowed water inflow for an emplacement section (0.1 l/min).

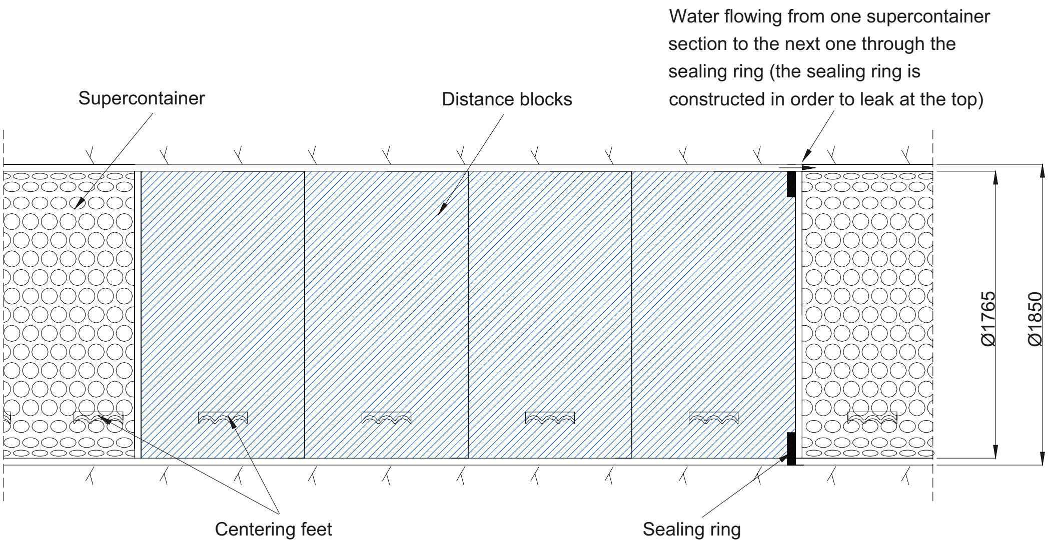


Figure 7-1. *Layout of STC. The "sealing ring" only needs to stand a couple of meters water head. This ring is not designed but only outlined.*

The temporary sealing and associated prevention of water flow along the drift at each section makes the drift rather dry at the location of each installation since less than 0.1 l/min will be flowing into the section of drift of concern. Just as for the original BD and DAWE, sections with water inflow larger than 0.1 l/min will not be used but filled with filling blocks or sealed with compartment plugs. The STC design ensures that during operation there will be no bentonite slurry flowing along the drift floor to the part of the drift where installation is taking place.

In order to evaluate two extreme cases for the impact of mass transport of bentonite from one drift section to another the following conditions were considered:

1) 0.1 l/min enters the inner section while all other sections are dry. This leads to a situation where the inner section will be filled with water after about 20 days. Then water is assumed to move via piping through the sealing and start filling the next section. After another 20 days this section is full of water and the third section will start filling and so on. Figure 7-2 illustrates the sequence.

The consequence of this scenario is that there will be the potential for considerable erosion of bentonite from the innermost section into the others. According to laboratory-scale tests the erosion may be between 0.1% and 1% of the weight of the eroding water /Sandén et al. 2008/. For a drift with the length of 150 m the total volume that will be filled in this way is 2.8 m^3 per section times 15 sections (assuming 10 m long sections), which yields a total water volume of about 41 m^3. The total amount of eroded bentonite will thus be 41–410 kg, which for the worst case may be taken as erosion occurring in a single section. Experience from laboratory- and small field-scale tests is that the erosion decreases with time and 0.1% will likely be a more realistic erosion rate, but this needs to be further investigated. Only half the reference tunnel length has been used in the preceding calculation since if the erosion case is as extreme as this, countermeasures or subdivide the drift. This extreme case can also be avoided by using filling blocks in the inner section which will reduce flow and erosion.

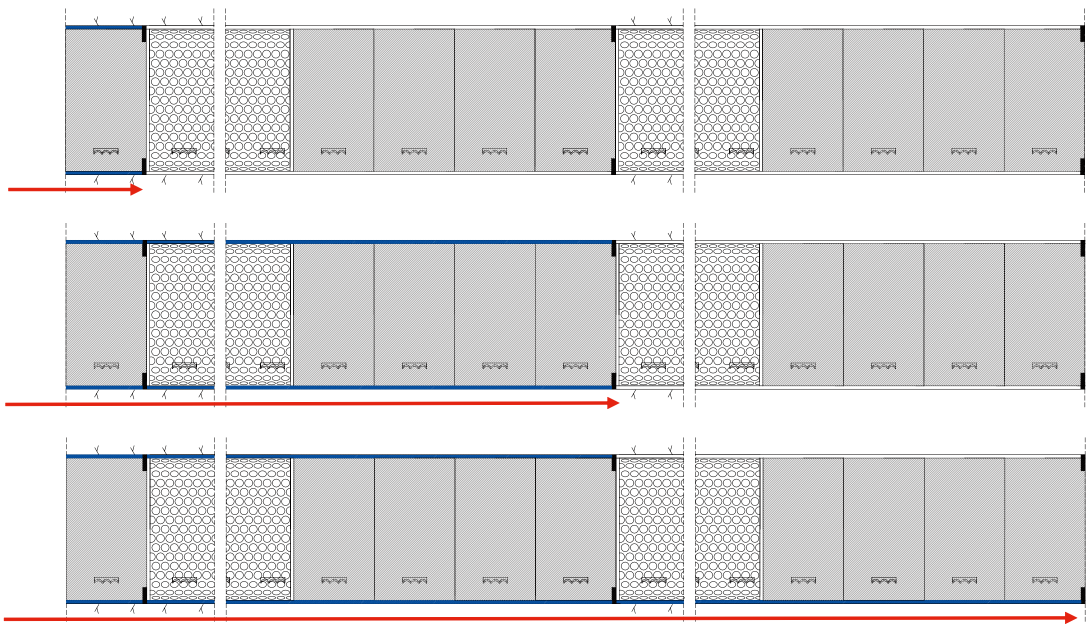


Figure 7-2. *Illustration of the sequential water filling of the supercontainer sections at the extreme case when 0.1 l/min flows into the inner section and all other sections are dry. The upper figure shows the situation after 20 days when the innermost section has been filled with water. The next figure shows the situation after another 20 days when the next section is filled with water. The lower figure shows the situation during filling of the third section.*

2) An even more extreme case is when all sections in the drift leaks 0.1 l/min. If the installation rate is one supercontainer section (with the total length of 10 m) per 2:d day the entire 300 m long drift with 30 sections will be placed in 60 days. This case does not allow for emplacement operations to function as proposed since water inflow will catch up with the installation location in about 36 days due to the consecutive flooding of the sections. For this extreme scenario either a plug has to be built every 70–80 meter, the installation rate increased or else the drift needs to be remediated to reduce total inflow down to manageable rates.

The STC design is very similar to the DAWE design, except that there is no artificial watering and no drainage tubes. There are, however, special sealing rings needed between each supercontainer section. In the STC design, each section will be sealed with distance blocks and sealing rings that temporarily prevents water from flowing from one section to another before the section is filled with the inflowing water. A detailed description of this process is provided in Section 2.4.

7.2 Specification of the functional structure

It is assumed in the specification that groundwater inflow has been reduced by applying proper techniques and therefore sealing is not included in functional structure below. The function of deposition drift, canister and supercontainer are only generally described here because they are considered to be fixed part of the design. The STC design is rather simple and requires fewer components than the other design alternatives e.g. is no special drip shields needed in the deposition. The design is based on the following functional elements:

1. *Hydraulic isolation between supercontainers and thermal spacing of canisters is obtained by using distance blocks (same as in DAWE).* Thermal spacing between successive canisters is obtained by using a distance block of required length.
2. *Sealing ring.* The sealing ring will be installed around the last distance block in every supercontainer section. The sealing ring will be designed to withstand a small water head which will prevent water from leaking into the neighboring section before the section is filled with water.
3. *Sealing of the drift by plugs (same as in BD).* The deposition drift is sealed and plugged after emplacement of supercontainers.
4. *Intermission of operation by plugs (same as in BD).* The emplacement of supercontainers can be stopped temporarily if the drift is plugged rapidly.
5. *Isolation of water-bearing fracture zones by plugs (same as in BD except for the filling outside the plug which is not necessary for the STC design).* Isolation of deposition compartments from water-bearing fracture zones which may have detrimental effect on the distance blocks and supercontainer during saturation by using plugs.
6. *Sealing and filling of unsuitable sections by filling blocks (same as in basic design).* Positions which are not suitable for emplacement of a supercontainer because of unacceptably high water inflow or other reasons are filled with filling blocks. The objective of these blocks is to provide extra sealing capacity to neighboring distance blocks and to reduce the hydraulically-induced force exerted on distance blocks.

7.3 Specification of design components

7.3.1 General

Deposition drift, supercontainer and other design components are kept fixed and are not considered in this context. The STC Design Components (STC-DC) are:

- STC-DC1 Distance block.
- STC-DC2 Sealing rings.
- STC-DC3 Filling blocks.
- STC-DC4 Compartment plugs.
- STC-DC5 Drift end plug.

7.3.2 Distance block

A distance block is positioned between the supercontainers. The objective of the distance block is to provide sufficient spacing between supercontainers to meet thermal requirements and to hydraulically isolate the supercontainer sections during saturation. The distance block is expected to swell faster than the buffer in the supercontainer and also to prevent flow along the drift.

The distance blocks in the STC design will be of the same quality as the distance blocks in the DAWE design. The total length is 5.475 m and the diameter is the same as for the supercontainer, 1,765 mm. The initial dry density of the bentonite is 1,712 kg/m^3 and the final saturated density is 2,000 kg/m^3 with range from 1,950 to 2,050 kg/m^3. The distance blocks will have an initial water ratio of 22%.

7.3.3 Sealing ring

A special sealing ring will need to be developed. The sealing ring will be installed around the last distance block in every supercontainer section. The sealing ring will be designed in order to withstand a small water head in order to prevent water from leaking into the neighboring section before it is filled with water.

7.3.4 Plugs and filling components

The specifications of compartment and drift end plugs are similar to those in the BD except for the filling outside the outer plug which is not necessary for the STC design.

Filling blocks, similar to distance blocks, are used next to plugs as massive sealing elements and to fill positions that are unsuitable for placement of supercontainers. The filling blocks will be of the same type as described for the Basic Design.

7.4 Advantages and disadvantages with STC

The STC design has several advantages compared to BD but also some disadvantages.

Disadvantages

- The obvious disadvantage of the STC design is the erosion that may take place before the drift is filled with water but the erosion will only be internal to the drift. No bentonite will leave the drift but the redistribution will, in the worst case, be 41–410 kg from one section. It is important for STC alternative to further study the erosion process.

- Another disadvantage is that some kind of sealing is needed that prevents piping before the supercontainer section is filled with water. The demands on such a seal are small and it should be possible to design and install such a seal.
- If water inflow 0.1 l/min takes place in all or almost all sections, it might be necessary to install additional compartment plugs in the drift since the installation rate of 1 section per two days is too slow.
- The operation efficiency is uncertain since the design is merely on schematic level. However, there are indications that it could be lower compared to DAWE alternative because of the installation of sealing rings and possible limitations to compartment lengths. This is to be evaluated in future after the design has been developed further.

Advantages

There are several advantages of the new proposal (compared to both BD and DAWE).

- By measuring the inflow in each supercontainer section before installation the consequences can be calculated and controlled by adapting the design to the inflow pattern.
- There will be no high water pressures in the drift before the end plug or internal compartment plugs, which have been designed to withstand 5 MPa water pressure, have been built.
- The water pressure increase rate (which is so difficult to predict) can be disregarded.
- There are no risks that bentonite slurry will flow on the drift floor during installation since each section will take care of the inflowing water until a plug has been built.
- No artificial watering associated with pipeline removal issues is needed.
- Cracking at high RH is not an issue (can be accepted).
- Since all distance blocks can be made with the same diameter as the supercontainer, the installation procedure is simple.
- The axial slot is not a big issue for this design since full water pressure can be accepted on the entire block surface when the plug is built.

There are therefore a number advantages with the proposed STC design, simplicity being the most obvious.

7.5 Uncertainties and proposal for future work

The most significant uncertainties in the STC design are related to the robustness of sealing material function and fulfilment of longterm safety criteria, both of which depend on rate of erosion and consequent redistribution of bentonite.

The estimated largest quantity of transported bentonite is 41–410 kg from one section, which will result in reduction of density in the affected section, however, this will be coupled with an increase of density in the section where bentonite is settled. The estimate of potential material relocation includes significant uncertainties related to erosion rates and expected inflows. The behaviour of sealing rings and possibility to obtain detrimentally high hydraulic pressure because of rapidly sealed distance blocks should also be evaluated.

The erosion process first needs to be studied at laboratory scale and later at full scale including the sealing rings. The longterm consequences of erosion should be further investigated as well as the water filling process inside the supercontainer sections.

8 Equipment for transportation of supercontainer and distance blocks

This section describes the equipment developed and manufactured during 2005 by CNIM, France for the deposition of supercontainers/distance blocks and the demonstrations carried out at Äspö HRL during 2007. The transportation equipment includes the following main components.

- Deposition machine.
- Start tube for deposition machine with transport support.
- Transport tube for supercontainer with transport support.

The development of the deposition equipment and the subsequent demonstration is included in the research and development programme called ESDRED ("Engineering Studies and Demonstration of Repository Designs") that is supported by the European Commission.

For demonstration purposes have the following simplifications been made on the equipment:

- The transport tube and the gamma gates are designed without consideration to radiation shielding.
- The start tube is just a "half" tube, in order to better observe the deposition machine during the demonstration. When handling a real supercontainer with a spent fuel canister the start tube will be closed for radiation shielding.
- The deposition drift has not been provided with a gamma gate.

8.1 Transport principle

The deposition equipment design is based on a transport principle where the supercontainer is moved stepwise. The supercontainer, which is provided with feet, as described in Section 4.4, is moved with help of a lifting cushion palett, see Figure 8-1, 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 pressure medium. The function of the water cushion is described in Figure 8-2.

Water as the pressure medium instead of air was chosen after performed mock-up tests, which shown that water is more energy efficient than air. The stepwise transport principle is described in Figure 8-3. The process is repeated continuously until the supercontainer is in the correct position in the deposition drift. The same principle is used for transport distance blocks according to the DAWE and STC alternatives.

The transport principle is chosen to reduce required forces needed to move the supercontainer, which will minimize the risk for damage of the surrounding steel shell and the bentonite buffer.

Figure 8-1. View of underside of the lift pallet during installation of water cushions.

Step 1
Prior to inflation, the load is solidly supported on landing pads. These pads protect the lifting cushion from being crushed when the load is at rest.

Step 2
When water supply is applied to the lifting cushion, the cushion inflates, creating a seal against the slide plate surface and raising the load approximately 10 mm.

Step 3
When the pressure within the cushion is sufficient to offset the load's weight, water slowly and evenly escapes between the flexible cushion and the slide plate. The load is literally floated on a thin, nearly frictionless cushion of water.

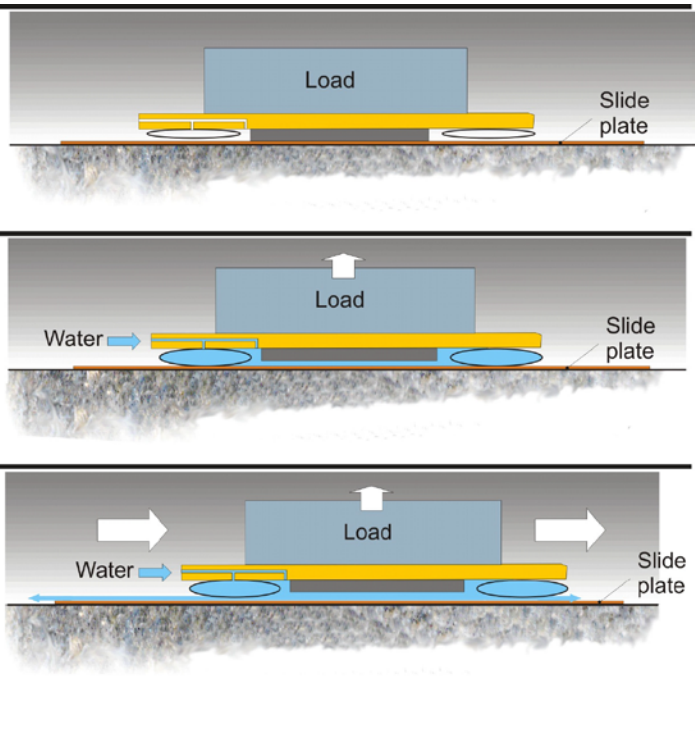


Figure 8-2. Schematic illustration of the lifting cushion principle.

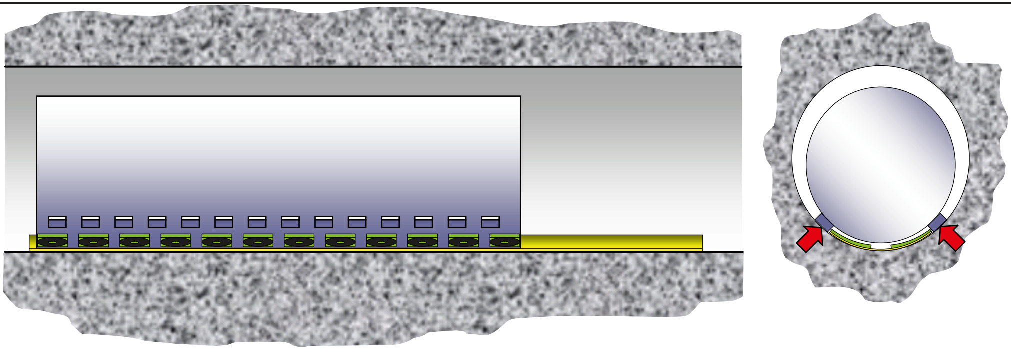
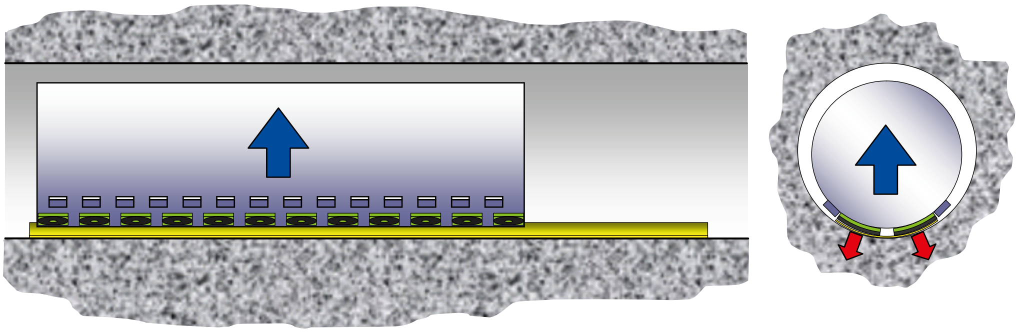
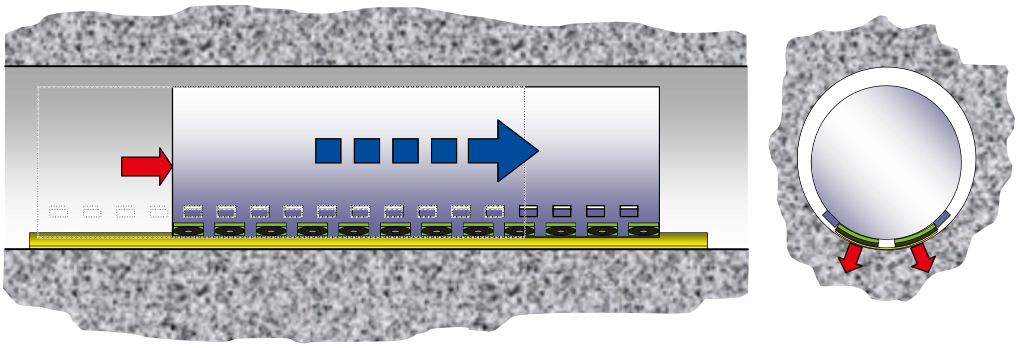
Step 1	
	The supercontainer is resting on its support feet (indicated with red arrows). The lifting pallett/slide plate located between the supercontainer feet is inactivated.
Step 2	
	When the lifting cushions on the pallettare activated (indicated with red arrows) the supercontainer is lifted. The supercontainer floats on a thin film of water.
Step 3	
	Floating on the water film the supercontainer is moved forward one stroke (1.5 m) on the slide plate. After fulfilled stroke the lifting cushions are inactivated and the supercontainer is lowered for support on the feet and the slide plate is moved forward to prepare for the nest cycle.

Figure 8-3. *Schematic of the chosen transport principle.*

8.2 Deposition equipment

The equipment needed for the deposition of supercontainers/distance blocks inside the drift consists of the following main components:

- Deposition machine.
- Start tube for deposition machine with transport support.
- Transport tube for supercontainer with gamma gates.
- Transport support for transport tube.

Figures 8-4 and 8-5 show the set-up of the equipment manufactured for the tests that have been carried out during 2007 at Äspö HRL level –220 to verify in full-scale that the KBS-3H transport alternative with water cushion technology is technically feasible for emplacement of supercontainers and distance blocks.

The buffer inside supercontainer was simulated in full-scale tests at Äspö by using low strength concrete instead.

The following minimum dimensions are recommended for the niche in front of the deposition drift for set-up of the equipment this is also illustrated in Figure 8-6. Note that the size of experimental niche at Äspö was made clearly larger to be able to excavate several depositon drifts from same niche.

- Length 22 m.
- Width 4.6 mm.
- Height 6 m.

The dimensions are based on the following reasoning.

A main assumption is that the set-up shall not interfere with transports in the main tunnel. If this not is a requirement the length of the niche can be reduced.

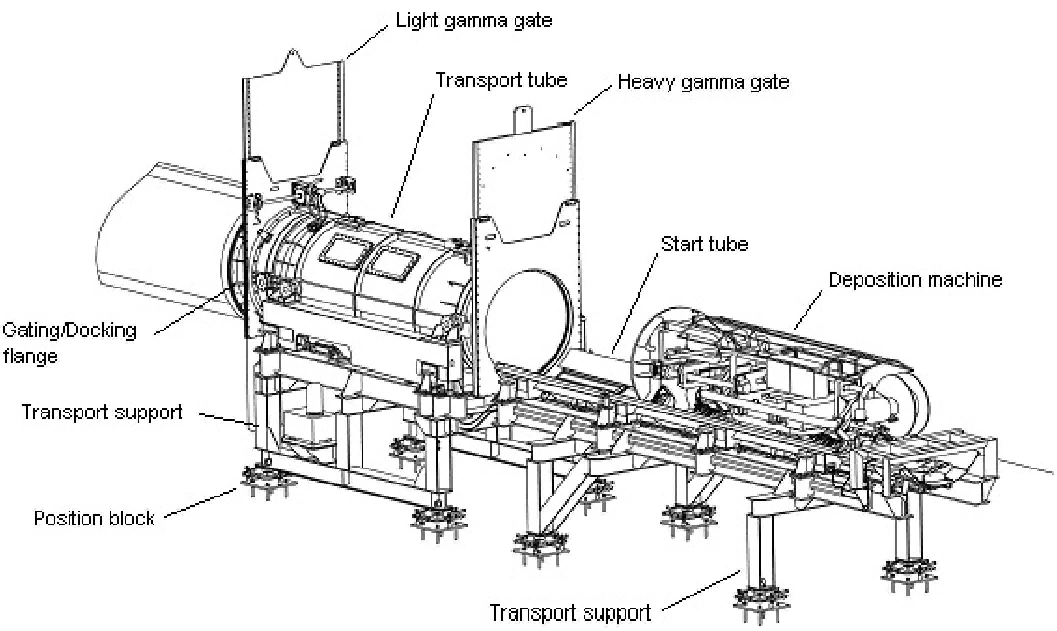


Figure 8-4. *3D-layout of deposition equipment.*

Figure 8-5. *Set-up of equipment at the test site at Äspö HRL, level –220 m.*

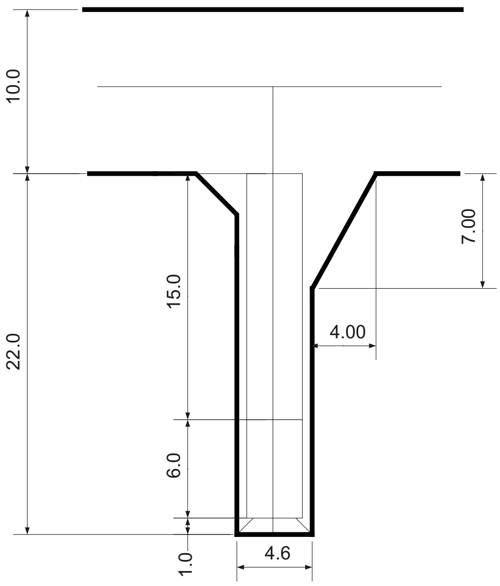


Figure 8-6. *Minimum dimensions of the niche (plan view).*

Presently, the test equipment consists of a slide plate and a water cushion pallett made demountable to allow them to be retracted underneath the machine to minimize the overall length during transport. This concept is, however, considered not advisable for the real repository. The installation and alignment of the slide plate and the pallett to the machine is critical for the function of the machine. The deposition machine should therefore ideally be transported in its full length approximately 15 m. The set-up time for the equipment will also be reduced.

The width of the niche (4.6 m) is based on that escape routes of minimum 0.6 m are available on each side of the equipment. It is also assumed that the width of the main tunnel is 10 m and that the control cubicle is located on the start tube or outside the niche in the main tunnel.

The height of the niche is based on that the deposition drift is located approximately 2.5 m above the floor and that the height of the present gamma gates is optimised and lowered approximately 500 mm.

The present manufactured deposition equipment is designed to be transported with one of the existing transport vehicles by SKB. The cabin on the vehicle will interfere with the traffic in the main tunnel, however, it is assumed that in the real repository the start tube/transport support for the deposition machine could be a self-propelling vehicle.

8.3 Deposition machine

The deposition machine, Figure 8-7, forms a complete unit with the sliding plate and the lift (water cushion) pallett. The main frame of the deposition machine consists of steel beams with rectangular cross sections. The deposition machine is wheel driven with electrical gear motors on all wheels. The wheel arrangements are mounted to the main frame with spherical bearings allowing for rotation between the frame and the wheel arrangements. The wheel arrangement allows for active steering of the wheels. The position of the wheels is controlled by inclinometers on the wheel support.

The slide plate on which the lift pallett is sliding on is made of stainless steel and is attached to the main frame. The front of the slide plate, see Figure 8-8 is equipped with two cameras with lighting facing forward and backwards. The slide plate is also equipped with sensors (forward and backward) for detection of obstacles in front of the deposition machine and for positioning of the supercontainer.

The lift pallett is attached to the radiation shield, which is connected to the deposition machine frame via three synchronized actuators allowing for the stepwise movement. The stroke of the actuators is 1,500 mm.

The lift pallett is guided on the slide plate to prevent rotation of the supercontainer during transportation, see Figure 8-9. The position/orientation of the deposition machine and the supercontainer is continuously monitored and adjusted by means of an inclinometer on the radiation shield and the movable ballast on the deposition machine.

For centering of the slide plate/pallett between the supercontainer feet is the radiation shield is equipped with "forks", see Figure 8-10.

The lift pallett, which is equipped with 24 water cushions in two longitudinal rows left/right, is shown in Figure 8-1.

The water cushions are inter-connected in pairs along each side, except for cushions in rows 1, 4, 7 and 10, which are cross-connected between the left and the right side to allow for cushion selection, in case of transport of distance blocks (whose weight is lower than that of the supercontainer). The cross-connected cushions in rows 4 and 10 are normally closed during transport of the supercontainer, which means there are only 20 out of 24 cushions active at a time. This set-up has been chosen with regards to the cushion pressure/load behaviour. It appeared in the previous cushion tests that the cushion lifting height is sensitive to load and/or pressure changes. The sensitivity is, however, less at higher pressure. The set pressure is 2.7 bars with 20 cushions.

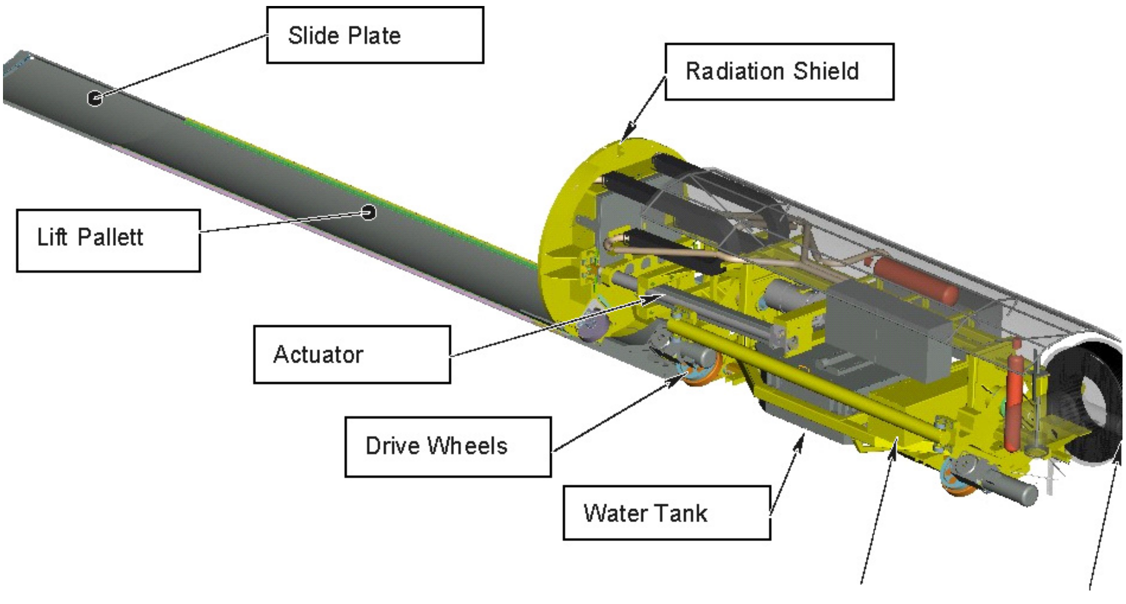


Figure 8-7. *3D-Illustration of the deposition machine.*

Figure 8-8. *Front of slide plate.*

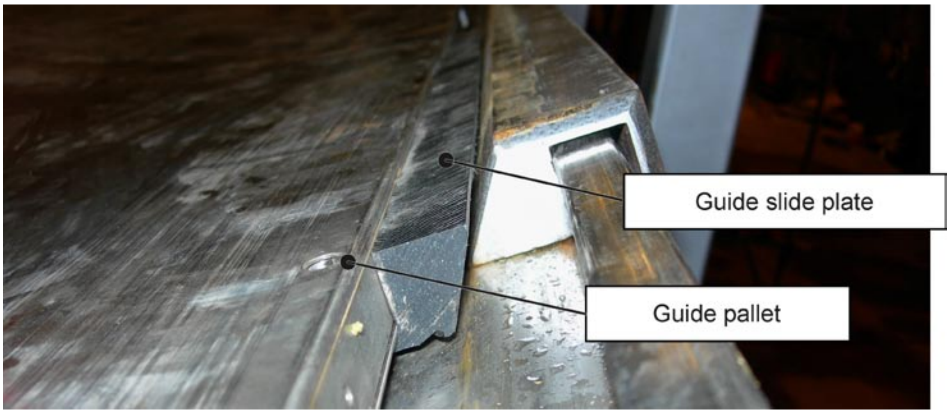


Figure 8-9. *Guides between the pallett and the slide plate.*

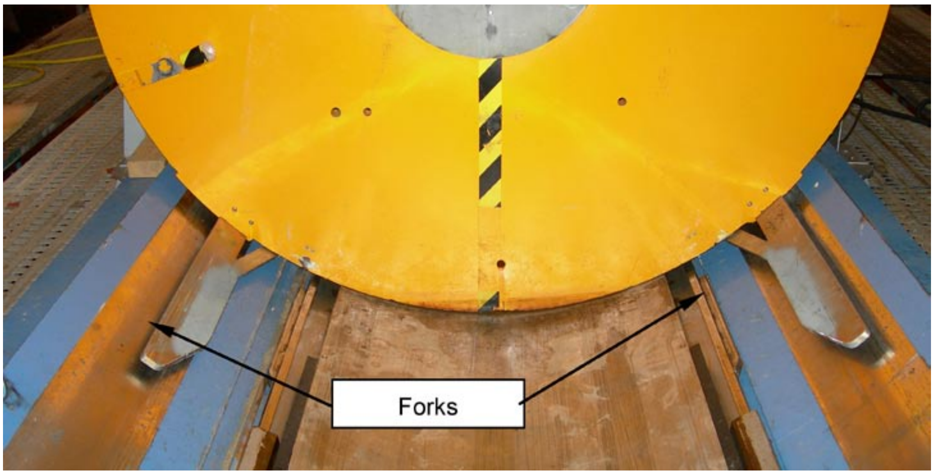


Figure 8-10. *Forks mounted on the radiation shield for centering of the supercontainer.*

The pallet is also equipped with four (4) lift sensors for indication of the lifting height, see Figure 8-11. The sensors are located between the cushions in row 4/5 and 11/12. The lift sensor is a simple toggle-arm fixed to the pallet and by gravity resting against the slide plate. The sensor has five fixed indication levels. The pallett is normally lifted 20–25 mm, which results in a lift of the supercontainer of approximately 10 mm (space measured between the feet on the bottom part and the rock surface).

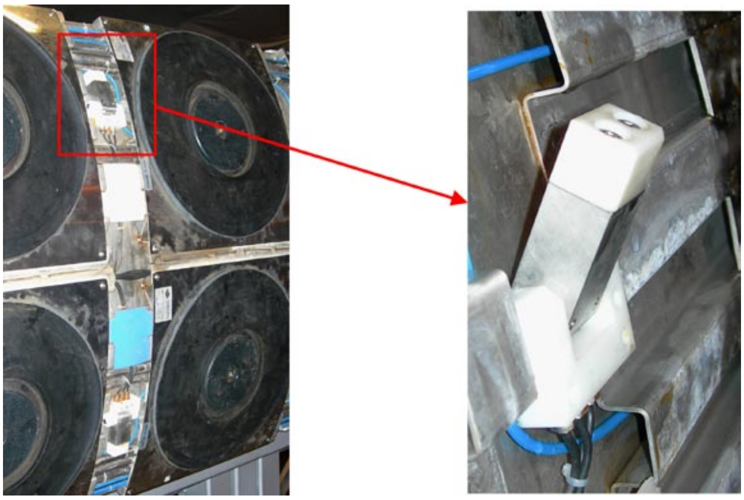


Figure 8-11. Lift sensors of the water cushion pallett.

The water cushions are fed with water from a pump, which takes the water from a tank located at the middle of the deposition machine. The water pumped out from the cushions is pumped back to the tank via a recovery pump located in a sump at the aft of the slide plate.

The pallett is designed to prevent water from coming into contact with the supercontainer. All electric power and communication is done via a cable with integrated optical fibers winded on a motor driven cable reel located in the rear of the deposition machine.

The deposition machine is in case of fire equipped with an automatic fire fighting system consisting of a powder system (9 kg) for machine components and a CO_2 system (2 kg) for electrical cabinets.

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

8.4 Start tube

The transport support gear is equipped with a movable cradle start tube, see Figure 8-5, on which the deposition machine is parked, allowing the start tube for docking to the transport tube.

The transport support for the present test equipment is designed to allow for transportation with SKB's existing transport vehicles.

For demonstration purposes, the start tube is just a half tube, to better observe the deposition machine during the demonstration. When handling real supercontainers with spent fuel canister the start tube will be closed and equipped with gamma gates in the same way as the transport tube.

8.5 Transport tube

The transport tube is designed to allow handling/transportation of the supercontainers in both vertical and horizontal positions. The transport tube is equipped with detachable gamma gates.

The transport support for the present test equipment is designed to allow for transportation with SKB's existing transport vehicles.

The transport tube with gamma gates resting on the transport support is show in Figure 8-12.

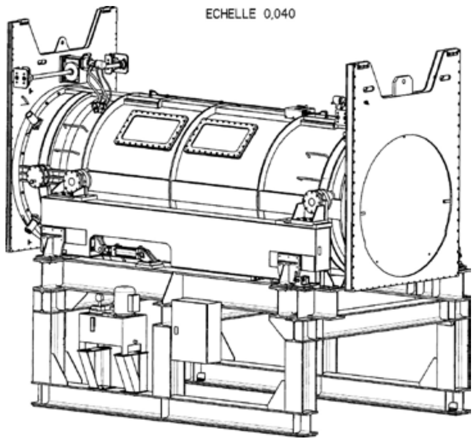


Figure 8-12. *3D-illustration of transport tube with gamma gates resting on the transport support.*

The transport tube is equipped with two inspection windows to allow for view inside the tube, as this equipment will be used for demonstration for the public. The transport support is on the inside equipped with necessary guides supporting and locking the supercontainer during handling/transport from the reloading station to the chamber with the deposition equipment. The supercontainer inside the transport tube, when tilted, is supported by inflatable air bladders.

The transport tube is equipped with six trunions allowing the transport tube to be lifted in the vertical position with the special lifting beam. Tilting of the transport tube is shown in Section 4.4.4 (Figure 4-33).

8.6 Tests performed with the deposition equipment

The KBS-3H deposition equipment has since March 2007 been tested at the Äspö HRL. The main objectives for the tests were:

- Verify in full-scale that the KBS-3H alternative with water cushion technology is technically feasible to emplace supercontainers and distance blocks in a horizontal disposal drift with small tolerances.
- Test the reliability and availability, from a longer time perspective, of the developed deposition machine and ancillary equipment.
- Demonstrate the integrity of the supercontainer and distance blocks during the deposition process.

As mentioned earlier concrete was used as mock-up material for the supercontainer and distance block instead of bentonite buffer. The copper canister used was totally filled with fuel dummies of BWR type surrounded by unreinforced concrete buffer with mechanical properties close to bentonite. The mock-ups had the real payloads and correct physical dimensions.

According to the endurance test programme, the goal was to make one deposition and subsequent recovery per day. The transportation tests performed between April and September in 2007 are shown in Figure 8-13. The cumulative transportation distance in this period was approximately 11–12 km. The test period was only interrupted by the transport tests with distance blocks in June and for the summer vacation period in July. The transportation has been performed in both manual and automatic modes.

The performance requirement for the average deposition speed of 20 mm/s and the transportation speed of the deposition machine 100 mm/s has been verified during the tests.

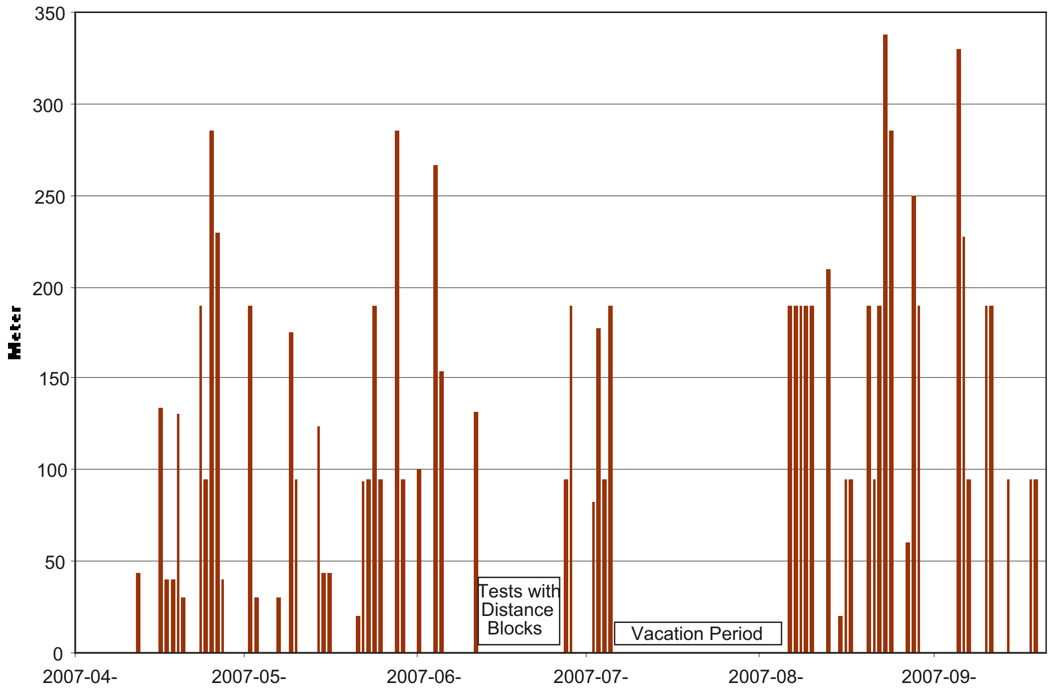


***Figure 8-13.** Diagram showing the total transport distance performed per day.*

Some initial tests with distance blocks have also been done but the performance requirements regarding the deposition speed have, however, not yet been verified. The results from these tests indicate that the fixation of the feet to the blocks must be improved. Figure 8-14 shows a proposal with the feet attached to a "cradle" that distributes the feet loads on a larger surface, however, the design may not fulfil the requirement that, like other system components, it should be compatible with, and support the safety functions of, the canister, the buffer and the host rock (Appendix B.2). It particular, it may be difficult to show that the buffer (or, more specifically, the distance blocks) fulfils its safety function of separating the supercontainers hydraulically one from another, thus preventing the possibility of preferential pathways for flow and advective transport within the drifts through the corrosion products or altered buffer (Appendix B.1).

The integrity of the supercontainer was also tested. The test was carried out with a supercontainer made of a carbon steel shell and with an un-reinforced buffer of concrete. The copper canister used was of the type BWR fully filled with fuel dummies. For this test the supercontainer was transported twice in and out trough the deposition drift, the total transport distance being approximately 360 m.

After the transportation tests the supercontainer was taken into the workshop for examination of potential deformations and/or cracks. The examination consisted of the following:

- Visual examination of the steel shell with regards to deformations.
- Penetrating liquid examination of welds around the feet with regards to cracks.
- Visual examination of concrete blocks with regards to cracks and fall outs.

The examination was performed without any remarks that can jeopardise the integrity of the supercontainer.

The tests performed so far have shown that the deposition equipment tested is operating effectively for the transport and deposition of supercontainers with a weight of 45,000 kg in horizontal drifts excavated in hard rock. Further tests are, however, required to verify the availability and the reliability of the equipment for a longer period of time.

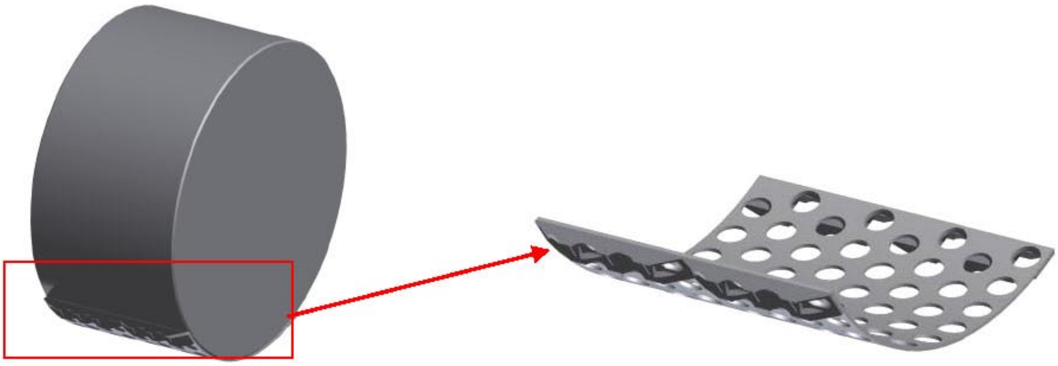


Figure 8-14. *Proposed fixation of feet to the distance block.*

It has also been concluded that the water cushion technique used is sensitive to load variations. This means that the supercontainers must be well balanced for transportation. This requirement implies that all fuel positions in the spent fuel canisters must be filled with fuel elements or fuel dummies to have the canister balanced. Finally, the system/technique is also sensitive to the alignment in the set-up between the transport tube for the supercontainer, the deposition drift and the start tube for the deposition machine. In Figure 8-15 a deposition test is ongoing.

8.7 Operating performance

The deposition machine is designed to meet the following operating performance:

- Average transport speed with supercontainer 20 mm/s.
- Average transportation speed with distance blocks 30 mm/s.
- Transport speed (only deposition machine) 100 mm/s.

The average transportation speed with distance will be reduced if the distance blocks are longer than approximately 2 m. For transportation of distance blocks that are up to 5 m, which is the case for the Olkiluoto site, must the transportation speed be reduced to the same as for the supercontainer (20 mm/s).

The rates above are achieved when running with automatic cycles, the rates are limited if the equipment is operated manually. The minimum requirement is that the equipment should be able to deposit one supercontainer and the required number of distance blocks per one day.

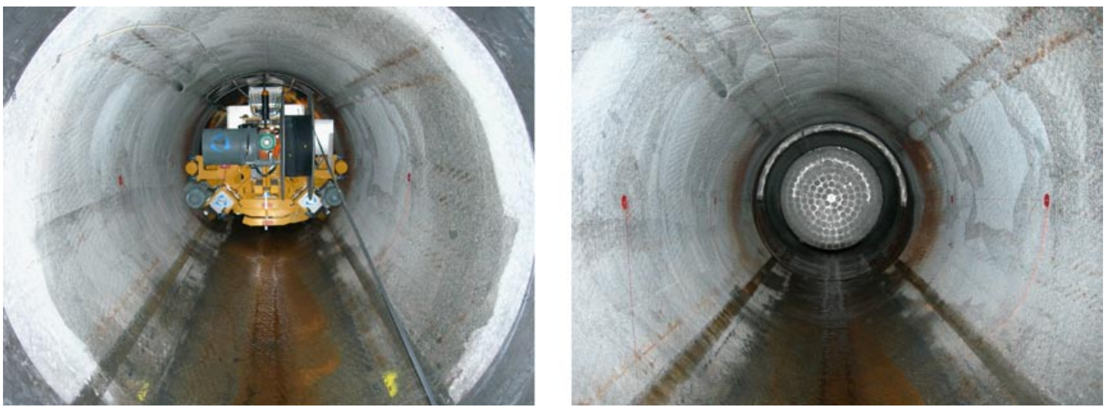


Figure 8-15. *The deposition machine has entered the deposition drift (left). The supercontainer is placed approximately 20 m into the deposition drift (right.)*

It is, however, assumed that the operation of the drift is based on depositing the supercontainers and distance blocks in campaigns. All emplacements in one compartment will be carried out in one campaign in continuous operating shifts.

To calculate the total operational time for deposition of the supercontainers and the distance blocks, the operation sequences have been divided in the following chronological steps including preparatory and supporting works and assumed times. Installatin work for the compartment plug has not been included in this calculation. It is also assumed that all preparational work for the compartment plug has been done before the deposition starts.

The times for installation of distance blocks are based on the DAWE alternative, in case of the STC alternative the installation time must be increased, since the STC design includes the installation sealing rings, possibility to additional compartment plugs. The STC design is merely on schematic level and therefore the operation times are to be calculated later when a more comprehensive design has been made.

The total transport time depends of course on the length of the supercontainer section, which depends on the chosen length of distance blocks and the drift length. In this specific case has data for the Forsmark site been used in the calculations below.

In a 260 m long deposition drift, which is assumed to be the average drift length at the Forsmark site, the expected longest emplacement time for the first distance block is 293 minutes (4.88 hours) and for the first supercontainer is 363 minutes (6.05 hours), including preparation and supporting works.

For the Forsmark site, it is assumed that a total of 28 supercontainers can be deposited in a 260 m long drift divided into two compartments. The time to fill the first compartment with assumed 14 supercontainers will take about 134.3 hours (5.6 days) if the operation is based on three shifts utilizing 24 hours a day operation, and about 80 hours (3.3 days) to fill the second compartment, see Figure 8-16.

The calculation is based on a 7.2 m spacing between the supercontainers and on a drift containing a 35 m long compartment plug containing the unusable part located in the middle of the drift and the drift end plug.

	Work step	Time (min)
1	Positioning and docking of transport tube to the deposition drift	30
2	Positioning and docking of start tube to the transport tube	30
3	Preparation of deposition machine for emplacement of supercontainer	15
4	Transport of supercontainer	25 – 215 [5]
5	Retrieval of deposition machine	5 – 43 [6]
6	Transfer of start tube/deposition machine	15
7	Transfer of transport tube to reloading station	15
8	Positioning and docking of distance blocks to the deposition drift	30
9	Positioning and docking of start tube to the distance blocks	30
10	Preparation of deposition machine for emplacement of distance blocks	15
11	Transport distance blocks	17 – 144 [7]
12	Retrieval of deposition machine	5 – 43 [8]
13	Removal of start tube/deposition machine	15
14	Removal of transport support for distance blocks	15

[5] Depends on transportation distance.
[6] Depends on transportation distance.
[7] Depends on transportation distance.
[8] Depends on transportation distance.

The design time for installing the compartment plug is one day and the estimated time for water filling one compartment in DAWE alternative is 10–14 hours. If it is assumed that the filling components are installed at same efficiency as the distance blocks, the estimated time for operating one compartment in DAWE from start of operation until the compartment has been sealed and filled with water is about 7 days. The operation of the second compartment is estimated to be about 6 days. In case of BD alternative the operational time is longer because of the installation of fixing rings in positions with water leakages. The installation time of fixing ring is 7 hours and this will increase the operating time of one compartment for about one day and operational time for one drift for about 2 days. Therefore the operation of one compartment from start to plugging and sealing is roughly one week.

8.8 Operational safety

A pre-study of a safety analysis has been performed for the KBS-3H operation in form of "what if" analysis with the main intention to look at the possible damage sequences for the copper canister for spent fuel, which can give radiological consequences.

The study has been performed at a stage in the conceptual phase of the project. Therefore, it has not been possible – or relevant to look at too many details.

The study is a comparative study, where deviations towards KBS-3V are studied concerning mainly the reloading station and the repository area. Steps that were considered the same as in KBS-3V are not studied.

The advantages of the KBS-3H alternative compared to KBS-3V from an operational safety point of view are:

- The controlled assembling of the supercontainer (compared to the mounting of bentonite in the deposition holes in KBS-3V).
- No heavy lift with small tolerances in the deposition position (the positioning of the deposition vehicle in KBS-3V must be fairly precise).

The disadvantages compared to KBS-3V that have been identified are:

- Slightly higher risk in the reloading station, most probably tolerable and can be dealt with in the design.
- Higher risk in the final deposition position.

The most important issues from the analysis are listed below.

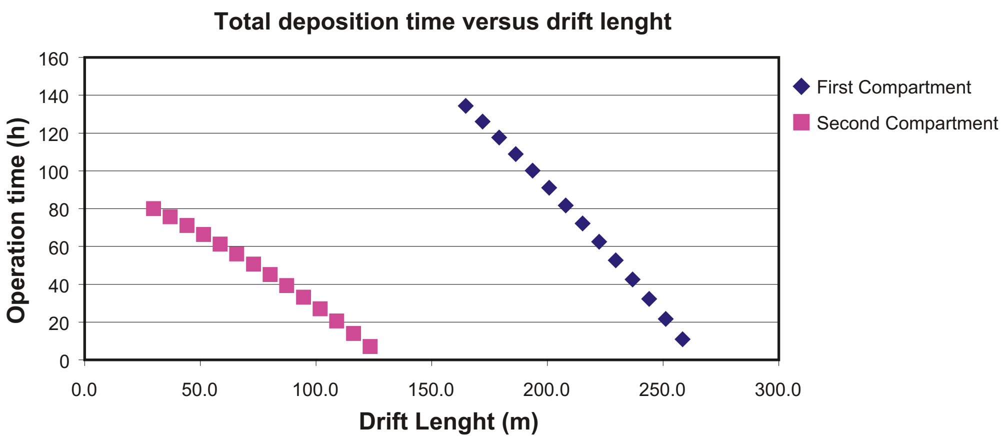


Figure 8-16. Accumulated operational time versus drift length for filling of the first and second compartment with 14 supercontainers and distance blocks, respectively.

Reloading station

- The grab hook; will it be able to open if the position of the traverse crane is incorrect and the canister bounces on the floor (temporarily no load on the grab hook). Identified question.
- The risk of fire is probably higher; longer exposure time, more fire ignition sources and fire load. Some sort of fire protection system should be considered.
- In the design of the open and closure of the handling cell doors it should be considered that these devices are checked regularly and can withstand a single error.

The deposition position

The transport of a vehicle in a narrow drift is a technological challenge. The risks with this are:

- The fire load and ignition sources – high temperatures reached quickly.
- If problems in the lead-in occur, it may be problematic to solve and may require that someone climbs in if the deposition machine cannot be retracted (also via the wire). It shall, however, be mentioned that the dose is not large and there is a radiation protection mounted on the deposition machine.
- The verification of the supercontainer or distance blocks being in correct position. Especially the distance blocks (since it is not possible to verify their position since they shall be tight). This comment is more important for the basic design alternative. The DAWE alternative does not have the same requirements on distance.
- The rubber, screws etc might loosen and be left in the repository and affect the long-term safety. This has not been verified in this analysis – but there also might be some specific type of materials that should be avoided (Any organics or nutrients for microbial growth or potential complex forming with radionculides, or components which might cause copper corrosion, e.g., nitrogen compounds.)
- If the water flow is incorrectly measured or if the compartment plugs, used to separate sections with too high water flow, leaks then several copper canisters may be affected by this failure – compared to a single canister in KBS-3V. The requirements on water measurement etc are hence higher in KBS-3H than in KBS-3V.

Moreover, the availability of the deposition equipment is very hard to predict – though it is fairly obvious that it will not be the same as in KBS-3V (many more parts, more specific solutions etc).

8.9 Dose rates during operation

Estimate of the radiation dose rate for the KBS-3H supercontainer was made at the Technical Research Center of Finland (VTT) in May 2003 (by Mr. Markku Anttila). A real 3D-geometry of VVER 440 canister with 12 bundles of fuel was modeled with MCNP4C computer program /Briesmeister 2000/.

The radiation dose rate at the canister lid surface was about 100 mSv/h. The 35 cm layer of bentonite in the end of the supercontainer decreases the gamma dose rate to 1:200. That means that the dose rate on the end surface of the supercontainer is some 0.5 mSv/h.

If the distance block (bentonite thickness is a few metres) is installed adjacent to the supercontainer, the dose rate through the plug in the drift is negligible. The dose rate through the gap of 50 mm between rock and bentonite distance block is evidently less than the dose rate through the distance block and therefore the dose rates in the KBS-3H deposition drift behind a supercontainer and a distance block are insignificant.

8.10 Uncertainties and proposal for future work

In the performed tests concrete has been used as buffer. One uncertainty is how a bentonite buffer will withstand the handling and transportation.

For future work it is proposed to perform tests with a supercontainer and distance blocks with bentonite buffer. Other issues that remain to be verified are:

- That water is prevented to come in contact with the buffer
- Additional transportation tests with supercontainer are required to verify the reliability and the availability of the equipment
- Additional transportation tests with distance blocks are required to verify that the fixation of the feet is reliable.

9 Groundwater control

9.1 General

Water inflows have significant impact on the feasibility of KBS-3H repository concept, which is sensitive to groundwater inflows. Groundwater inflows into the deposition drift from intersecting water conductive fractures may cause e.g. erosion and transport of buffer. These processes can be prevented to some extent by using special filling components, which, however, reduce the drift utilisation degree significantly and still may not fully resolve the problem. Therefore the objective of groundwater control is to reduce the inflows as much as feasible by using existing sealing principles and materials. In the current project phase grouting was developed as the main option for the groundwater control. Alternative sealing methods like draining or freezing were ruled out due to many uncertainties related to them, for example drill holes outside the drift perimeter and disturbance of the near-field rock due to freezing. The applicability of existing grouting techniques is limited by the preliminary requirement that the holes drilled in a fan outside the drift periphery are not accepted on long-term safety basis as is presented in Appendix B.

According to present understanding the inflow to the drift in a supercontainer position is not allowed to exceed 0.1 l/min before grouting. If the inflow is larger grouting is needed. The amount of inflow after grouting decides if buffer filling blocks or division of the drift into compartments have to be done (see Sections 3.2 and 4.1).

Based on information from investigation holes drilled before excavation the utilisation degree of the drift is evaluated. The evaluation is based on the "predicted inflow"/ transmissivity and the restrictions from the long-term safety analysis.

The fulfilment of the inflow restriction is made based on the investigations and evaluations of the tests performed in the investigation holes ("before grouting"). After this phase grouting is allowed in the drift to achieve acceptable conditions for buffer filling or division of the drift into compartments. Sections that need grouting are not at present allowed for canister deposition.

If a decision is made to excavate a drift a plan is made how and when to perform grouting work in order to minimize the leakage to the drift and optimize the utilisation degree of the drift.

The orientation of KBS-3H deposition drifts can be made on basis of several factors such as rock stress and groundwater inflow. From a grouting point of view it is beneficial to limit the number of grouting occasions and to avoid singular small fractures. It is then more favourable to choose an orientation that gives a few but somewhat more leaking situation than a sparse leakage from several small fractures. The issue is to be evaluated further in later design phases.

9.2 Short description of grouting methods

9.2.1 Introduction

Due to long-term safety requirements no boring of holes adjacent to the drift surface is allowed. This gives that three different methods can be used for grouting of a KBS-3H deposition drift in different phases:

- Pre-grouting in investigations and/or pilot holes inside the drift.
- Pre-grouting in holes inside the drift.
- Post-grouting by using Mega-Packer (see glossary in Appendix A).

The evaluation of sealing effect is made based on these techniques, which are described in following chapters.

9.2.2 Pre-grouting methods

Pre-grouting in investigation and pilot holes

This method is based on using investigation holes (one or several) or the pilot hole to seal water-bearing fractures and is illustrated in Figure 9-1. The investigation boreholes are likely done by directional core drilling to have good control of the borehole orientation. Grouting in pilot holes is similar to investigation holes, however, the equipment has to be adapted to the larger diameter of the pilot, which is typically 10–35 cm.

The effectiveness of grouting by using a pilot hole or only one investigation hole is hampered by the fact that the grout must penetrate a distance of about one meter from the hole which is in the centre of deposition drift into the rock before it actually seal the rock adjacent to drift surface. Therefore the technique is probably only beneficial in sealing larger aperture fractures where reasonable penetration beyond the one metre distance in drift can be expected.

If more than one investigation hole, not centred in the drift, are used the effectiveness of grouting may be improved. In this case the grout must penetrate a shorter distance before it actually seals the rock adjacent to drift surface. The probability of penetrating fractures in water conductive parts also increases with use of several holes.

Pre-grouting in the drift

Pre-grouting can be made in similar way as common pre-grouting. The excavation of the drift has to be stopped during the grouting and the boring equipment has to be removed from the drift, which limits the systematic use of this technique along the whole drift. A major difference is that the boreholes must be kept inside the drift contour. In Figure 9-2 grouting inside the drift is illustrated.

The number of holes that can be drilled inside the contour of the drift increases the possibilities to hit open parts of the fractures and hence fill and seal these compared to one or a few investigation holes in the centre of the drift. The use of this method requires good characterization of the fracture zones to be grouted e.g. by using pilot- or investigation hole data.

The technique to drill and grout boreholes in the drift is not yet developed. The most difficult part is to manage drilling. Most likely will grout holes be made by core drilling since this drilling equipment is smaller than used for percussion drilling. In addition, control of hole orientation is easier with core drilling.

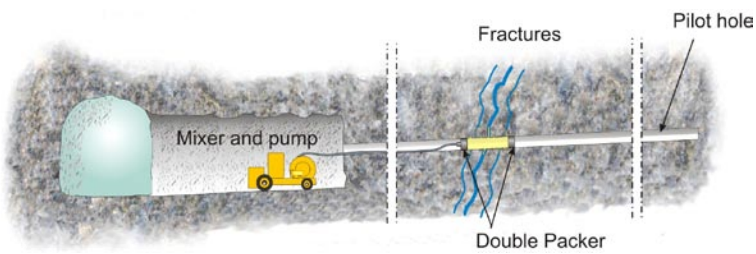


Figure 9-1. *Illustration of pre-grouting of the pilot hole.*

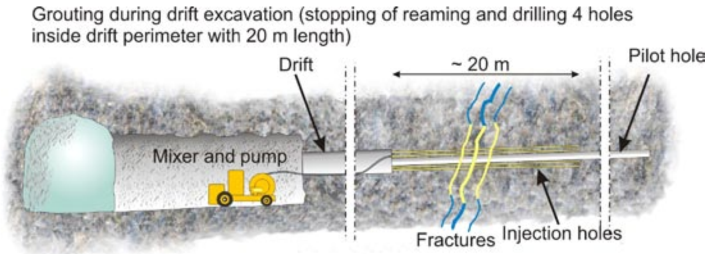


Figure 9-2. *Illustration of pre-grouting in the drift during excavation.*

9.2.3 Post-grouting by using a Mega-Packer technique

Post-grouting in the drift is carried out by using a Mega-Packer. This technique is used as a post-grouting method, i.e. is used for sealing after the drift has been excavated. This technique is tested in KBS-3H in the Demonstration drift at Äspö HRL and a short presentation of the results of the practical tests is given in this chapter.

The working environment in a long drift is demanding and needs special attention using this method.

The Mega-Packer consists of a large tube, with only slightly smaller dimension than the drift, sealed in both ends with expandable packers, see Figures 9-3 and 9-4. The void between the tube and the rock is filled with grout and the pressure is increased with the expected result that the grout penetrates into the conductive fractures and seals them, see Figure 9-5. A test of the Mega-Packer was made in Stripa for sealing vertical pits /Börgesson et al. 1991/.

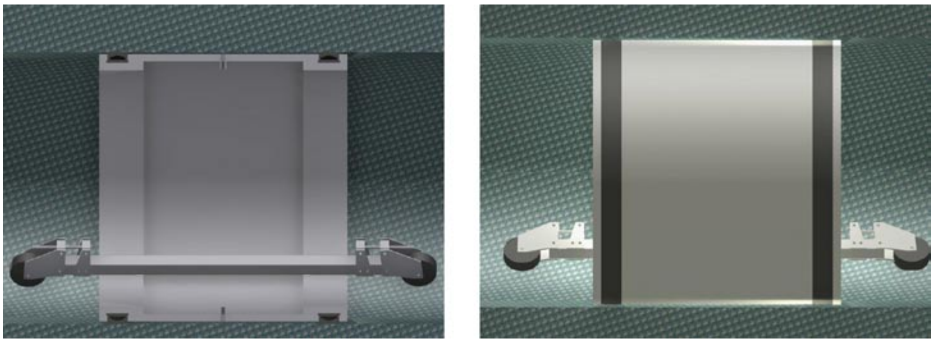


Figure 9-3. *The Mega-Packer grouting device, side view and cross section parallel to the drift.*

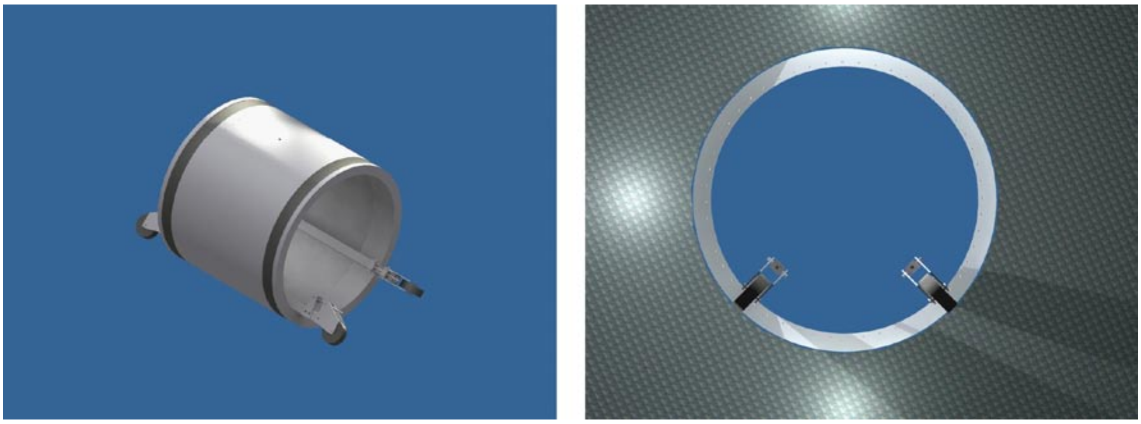


Figure 9-4. *The Mega-Packer grouting device, 3D view and cross section perpendicular to the drift.*

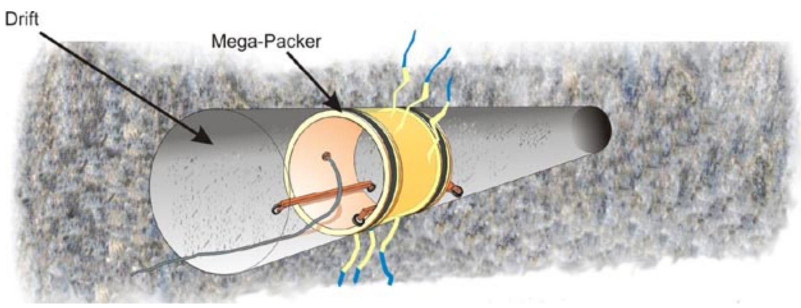


Figure 9-5. *Illustration of post-grouting with Mega-Packer.*

9.3 Hydrogeological conditions

The hydrogeological situation is relevant for the study of groundwater control, both for analysing the probability of inflow and as well for determining suitable grouting methods. For this study, Olkiluoto as the reference site, the occurrence, frequency and orientation of water-bearing fractures at –300 to –700 m is of interest. Flow logs are basic input with a detection limit 10–9 m^2/s. The data mainly originates from /Hellä et al. 2006/ and /Lanyon and Marshall 2006/.

Based on measured data presented by /Hellä et al. 2006/ shown in Table 9-1 it is noticed that a low fracture frequency is expected. Fractures giving an inflow larger than 4 l/min are found in average every 250 m according to /Hellä et al. 2006/. Based on the material presented in the reports it is here found that the distribution of transmissivity can be fairly well represented by Power-law distribution and that a Poisson can represent the fracture frequency.

Based on the results of the transmissivity measurement estimates of distribution functions describing the transmissivity and frequency of fractures can be made as follows:

- 20% of all measured 100 m interval lack transmissive fractures.
- 90% of all measured 5 m interval have transmissivity less than 0.1 l/m (equivalent to allowed inflow in a canister position).
- 85% of all measured 10 m interval have transmissivity less than 0.1 l/m (equivalent to allowed inflow in a canister position).

The data includes uncertainties, which have been discussed by /Hellä et al. 2006/ and /Lanyon and Marshall 2006/, e.g.:

- Biased data due to the subvertical orientation of the boreholes with respect to horizontal orientation of deposition drifts.
- Isotropy in hydraulic properties, and evidence of strong heterogeneity.
- Size of (extension of) transmissive features is generally unknown.
- Channeling and skin-effects are not taken into consideration.

Table 9-1. Transmissivity distribution of fractures in the Olkiluoto bedrock after Hellä et al. (2006). The presented figures present the detailed statistics of how the transmissivity and fracture frequency is found to vary inside and outside local zones.

Transmissivity T (m^2/s) /distance to the zone (m)	Number of fractures				
	Within local zones d = 0 m	Margin of the local zone 0 m < d < 35 m	Outside local zones d > 35 m	Sum	Fractures/m
T > 10^{-7} m^2/s	11	5	0	16	0.004
10^{-8} m^2/s < T < 10^{-7} m^2/s	17	12	7	36	0.01
T < 10^{-8} m^2/s	29	45	49	123	0.03
Sum	57	62	56	175	0.04
Sample length (appr.)	180	1,520	2,350	4,050	
Fractures/m	0.32	0.04	0.02	0.04	

9.4 Calculations

9.4.1 Method of approach

This study aims at discussing a groundwater control program, estimate amount of material. Certain calculations are used to give insight to the control program and the amount of material needed. These are made with approaches as presented under I and II below:

I The groundwater control study is made based on calculations on the grouting results achieved with the different methods. The feasibility of different grouting methods are evaluated by comparing the calculated results using the sealing effect, see Equation 9-1.

Sealing effect (θ) expressed in percent is calculated as:

$$\theta = \frac{Q_1 - Q_2}{Q_1} \cdot 100 \qquad (9\text{-}1)$$

where Q_1 indicates the calculated inflow before grouting and Q_2 the calculated inflow after grouting.

The calculations are made with a finite difference code developed and presented in /Eriksson 2002/. In this, grouting is simulated using a fracture model with varying aperture field. The fracture aperture is assumed to vary with a standard deviation in aperture in relation to the mean aperture, i.e. a coefficient of varying in aperture. The calculations are made probabilistic but are evaluated based on the average calculated value as base for the groundwater study.

Considering fractures of different hydraulic aperture a certain theoretical inflow can occur. This inflow can be calculated based on the transmissivity (T) value:

$$Q = \frac{2\pi \cdot T \cdot H}{\ln(2H/r_t) + \xi} \qquad (9\text{-}2)$$

where H is the groundwater head, r_t the radius of the tunnel and ξ the skin value /Rhén et al. 1997/. Using this equation it is noticeable what inflow fractures in different transmissivity interval is given.

The procedure is then:

- For all methods, calculate the expected sealing effect in each fracture.
- Based on the sealing effect, calculate expected inflow after grouting in different geological situations.
- Estimate the value of the grouting method in a groundwater control sense.

II Calculations concerning amount of grouting material are made based on a semi-continuum fracture model and a statistical description of the hydrogeological situation (see Section 9.4.3). In the calculations the fracture planes are modelled as plan-parallel discs with an aperture based on their transmissivity value (T) according to Equation 9-3, were b denotes the hydraulic aperture and μ_w the viscosity of water.

$$T = \frac{b^3 \cdot \rho g}{12 \cdot \mu_w}. \qquad (9\text{-}3)$$

The grout spread model is based on the description in /Gustafson and Stille 2005/, modified to a numerical model as presented in /Eriksson 2005/. The calculations are made based on Silica Sol as grouting material.

The volume is calculated based on the distribution of transmissivity and on the assumption that discs represent the fractures that are completely filled with grout to a maximum of 15 m. It is also assumed that the depth of grout spread is directly correlated to the size of the aperture. The result is that larger fractures consume the major part of the grout. It is assumed that an appropriate grouting technique is used, so that not more than necessary grout volumes are used.

9.4.2 Grouting material

Silica Sol is the grouting material assumed to be used. This is due to the expected transmissivity distribution. Only a portion of the fractures is estimated to have a hydraulic aperture larger than around 50 µm. Even if the physical aperture can be expected to be larger the possibilities to seal these fractures using cementitious grouts is limited and not fully understood.

It is assumed in the evaluation that the material behaves as a suspension, i.e. have a minimum (b_{min}) and a critical ($b_{critical}$) aperture /Eriksson 2002/. These parameters are used to model a suspension passing a constriction. Silica Sol could be expected to behave like water in the respect of penetrability, i.e. can penetrate any opening. The assumed behaviour and values are in this respect considered to be conservative. The properties used in the calculations are specified below:

- Yield value 0.1 Pa.
- Viscosity [Pas] 0.005 Pas.
- b_{min} 10 µm.
- $b_{critical}$ 20 µm.
- Density 1,200 kg/m^3.
- Bleed 0%.

9.4.3 Hydrogeological situation – Scenarios for evaluation

The hydrogeological situation used in the calculations for the groundwater control study is made fixed to limit the amount of calculations. Four scenarios are presented and described below:

- Scenarios for estimation of sealing effect
  - Scenario 1 represents a situation with a singular fracture of small aperture (20 µm). This scenario is considered the most frequent one to occur.
  - Scenario 2 represents a situation with a singular fracture of small aperture (50 µm).
  - Scenario 3 represents a situation with several fractures where one has larger and the rest have smaller aperture.
- Scenario for estimation of grout take
  - Scenario 4 describes the conductive fractures statistically and is used for estimation amount of Silica Sol needed, based on data presented in /Hellä et al. 2006/.

Scenario 1:

In this scenario one singular fracture with a small hydraulic aperture of 20 µm is assumed. This would theoretically correspond to an inflow of 0.1 l/min using Equation 9-2 with no skin.

The fracture is modelled with a coefficient of variation in aperture of 20% which is less variation than used in the channel model in the DFN study by /Lanyon and Marshall 2006/. However, the variation in aperture can vary largely and the value as such should not interfere with the discussion and relative comparison between different grouting methods. This is briefly discussed in a sensitivity analyse in Section 9.4.8.

Scenario 2:

In this scenario a singular fracture with a small hydraulic aperture of 50 μm is assumed. This corresponds to a situation with a considerable inflow, theoretically according to Equation 9-2 and with no skin factor, of 2 l/min. These fractures are also modelled with 20% coefficient of variation in aperture.

Scenario 3:

In Scenario 3, four fractures are modelled with hydraulic apertures of 10, 20, 30 and 90 μm, respectively. This corresponds to a situation with a considerable inflow, theoretically according to Equation 9-2 and with no skin factor, of 11 l/min. These fractures are also modelled with 20% coefficient of variation in aperture.

Scenario 4:

For the estimation of amount of material needed, a stochastic approach is used and the hydrogeological scenarios are modelled based on statistics. The transmissivity distribution and fracture frequency distribution is described in /Hellä et al. 2006/. The transmissivity distribution is presented with an average value of –8.8 in Log (T) and with a standard deviation in log (T) of 0.8. The corresponding data for fracture distance is 19.67 m (average value) and 32.47 m (standard deviation). A simulation was made based on these statistics, using a log-normal distribution of the transmissivity distribution and a Poisson for the fracture distance distribution. A number of 300 m long drifts were simulated giving a distribution of possible fracture arrangements for the deposition drifts. Based on this an estimation of grout take was made. The premises for this is that no grout should spread further away than 15 m and that 1 m penetration should be obtained in fractures with an aperture of 50 μm. Even smaller fractures could contain grout but the main amount of grout is to be found in the larger fractures.

9.4.4 Grouting technique

The used grouting technique is a highly influencing factor of the grouting result; see /Eriksson 2002/ for a more detailed description. In the calculations the following presumptions of the technique were used:

- Grouting through the investigation hole is based on one grouting hole.
- Grouting in a fan inside the drift contour is based on using 8 grouting holes.
- The stop criteria used is described with a flow criterion and a maximum grouting time. The grouting is stopped after the maximum grouting time of 20 minutes due to the curing of the grout. In scenarios where a flow less than 0.1 l/min is obtained the grouting is stopped even if the time 20 min is not reached.
- The pressures used are 1 MPa over the hydraulic pressure in pre-grouting and when post-grouting with the Mega-Packer.

9.4.5 Requirements for grouting

The requirements on the groundwater inflow into the sections for positioning the canister (supercontainer) and the filling blocks are very precise. The limits of inflow in relation to grouting are expressed as:

- An inflow before grouting of more than 0.1 l/min excludes that position for canister deposition.
- An inflow after grouting of less than 1 l/min facilitates closing that section with back-fill material.
- An inflow after grouting of more than 1 l/min necessitates isolation of the section by a compartment plug.

Based on this, the requirements for the grouting is to limit the inflow in any position to less than 1 l/min. There is no actual incitement to limit the inflow to less than this since no canister at present can be placed due to long-term safety.

Required sealing effect in the different scenarios then become:

- In scenario 1 no grouting is necessary since the inflow is less than 1 l/min.
- In scenario 2 a sealing effect of around 50% is required.
- In scenario 3 a sealing effect of around 90% is required.

9.4.6 Calculated results for the groundwater control study

Pre-grouting

The calculated result concerning median sealing effect is based on 10 simulations in each fracture. The following results were obtained:

Method 1: Grouting with a single borehole.
  Scenario 1: No sealing effect.
  Scenario 2: 64%.
  Scenario 3: 61%.

Method 2: Grouting with 8 boreholes inside the drift.
  Scenario 1: 1% sealing effect.
  Scenario 2: 94%.
  Scenario 3: 99.5%.

Post-grouting

Method 3: Grouting with Mega-Packer. The following results were obtained:
  Scenario 1: 68% sealing effect.
  Scenario 2: 100%.
  Scenario 3: 99.7%.

The calculated results give indications that the requirements on grouting as in Section 9.4.5 can be achieved, but with different methods depending on scenario. In Table 9-2 a summary of the results in relation to the requirements is given.

9.4.7 Calculated results on amount of material

Based on simulation of 1,000 drifts the result grout take is according to Figure 9-6. In the figure the calculated volume of grout material is presented for a full drift. The calculations are made probabilistic and using Monte-Carlo technique. Based on this the most likely scenarios of fractures combinations based on the statistics is simulated.

Table 9-2. Applicability of methods in relation to the requirements as indicated by the calculations.

Method	Scenario 1	Scenario 2	Scenario 3
1	No sealing required	Ok	Not ok
2	No sealing required	Ok	Ok
3	No sealing required	Ok	Ok

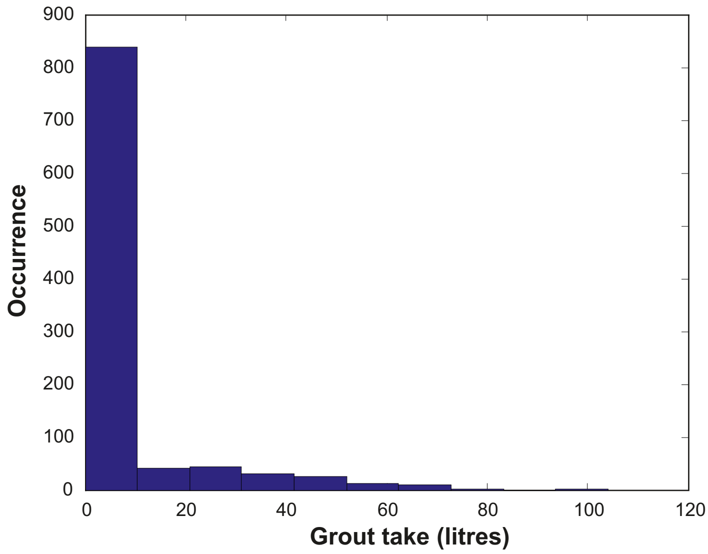


Figure 9-6. *Simulated result of grout takes for 1,000 KBS-3H drifts 300 m long.*

9.4.8 Analysis of results

In Figure 9-7 the simulated number of conductive fractures in a 5-m interval is shown. It is seen that in a majority of the cases (> 750 simulation) no conductive fractures are met. In some cases 1, 2 and 3 conductive fractures are found. Based on this, the scenarios presented earlier are relevant.

In Figure 9-8 the aperture of the simulated fractures are shown. It is seen that the largest simulated fractures have an aperture of around 90 µm. Around 75% of the fractures have an aperture smaller than 40 µm.

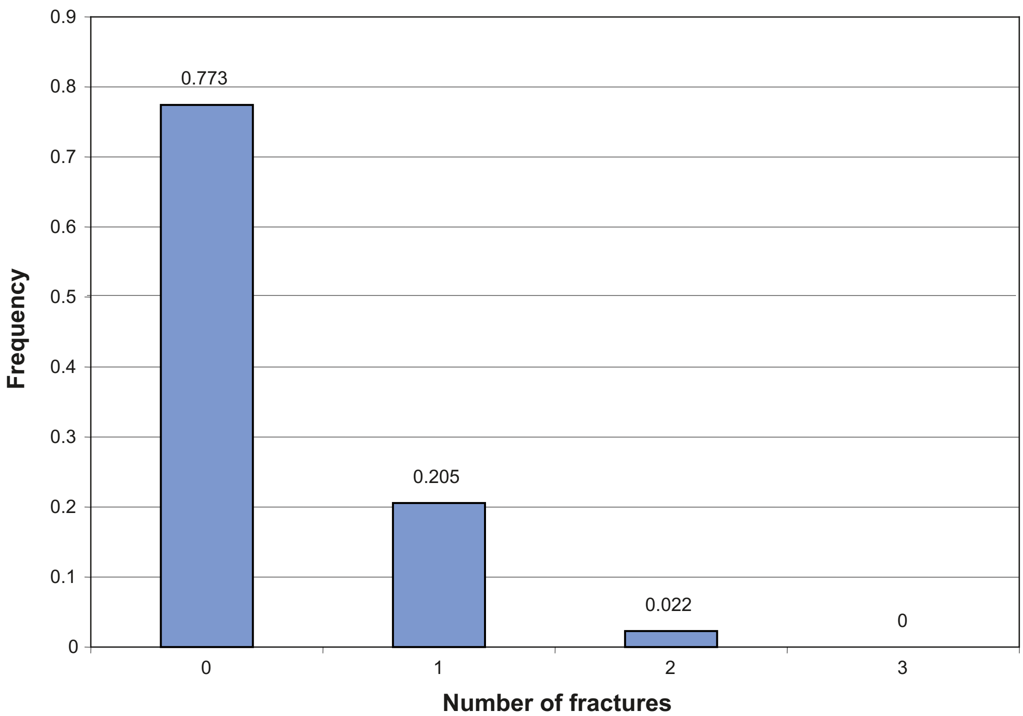


Figure 9-7. *Simulated result of number of fractures in a 5 m intervals.*

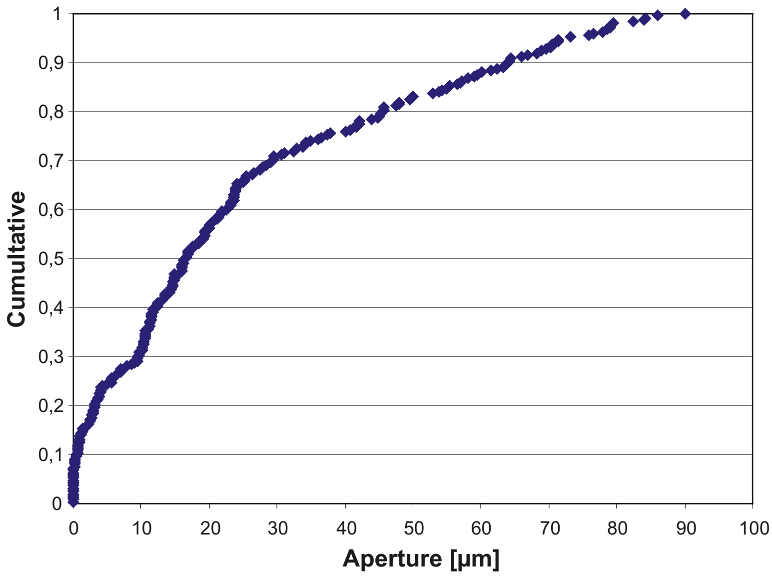


Figure 9-8. *Simulated result of fracture apertures. All simulated fractures are smaller than 90 µm.*

The fractures modelled in the 3 different scenarios where modelled with a variation in aperture of 20%. This value can be an underestimate of the true variation in aperture and it is valuable to see what effect a larger variation in aperture would have on the calculated result with the different methods. The result presented in Section 9.4.6 is therefore compared to results with a 40% variation in aperture in Table 9-3 below. The calculated result indicates a generally higher sealing effect with a larger variation in aperture. Important is that the relative effect using the different methods appear to be equal with a different aperture variation. The largest difference is noticed in Scenario 2 where a complete sealing is calculated in the case of 40% variation. In Scenario 1 and 3 the results are comparable.

The calculated results concerning sealing effect using the Mega-Packer (i.e Method 3) were verified with practical tests at Äspö /Eriksson and Lindström 2008/. At these tests single fractures were accounted with apertures between around 20 µm and up to 120 µm, resembling mainly Scenario 1 and 2. The sealing results varied between 86.8 and 99.8% and are found to verify the theoretical approach of modelling.

9.5 Results of Mega-Packer tests

9.5.1 General

A Mega-Packer was developed and manufactured to enable for grouting from inside the finished drift. The Mega-Packer is in principle a tube (spacer tube) provided with inflatable seals at each end, which will be inserted in the drift, see Figure 9-9. The grouting material will be pumped into the rock area sealed off between the seals and the tube.

Table 9-3. Results of sealing effect of the numerical simulation with 40% and 20% variation in aperture.

Method	40% aperture variation			20% aperture variation		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
1	0	100	54	0	64	61
2	2	100	97.7	1	94	99.5
3	75	100	99.8	81	100	99.7

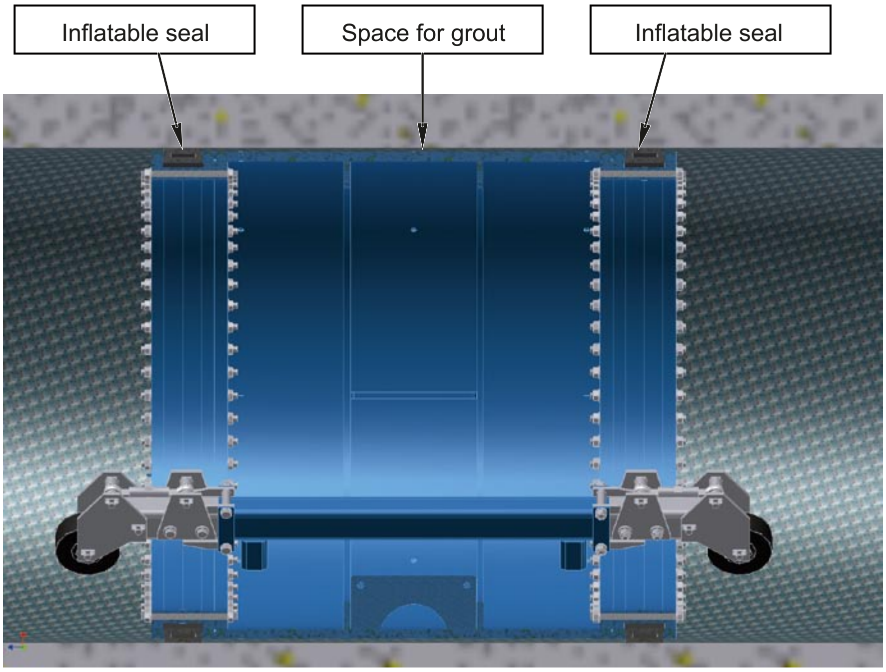


Figure 9-9. *Section view of the Mega-Packer inside the drift.*

The design of the Mega-Packer, i.e. the requirements on material and capacity, was based on calculations solely, since no valid practical experience was known. The Mega-Packer is designed to withstand a grouting pressure of 10 MPa. The grouting length is approximately 1.6 m. The design allows, however, for two spacer tubes to be connected, the grouting length can then be extended to approximately 3.1 m.

The inflatable seals, which are vital for the function of the Mega-Packer, were tested separately before the manufacturing. The tests gave information that with the present configuration should, with regards to the length of life of the seal, the maximum inflating pressure be limited to 5 MPa. The ultimate inflating pressure of the seal is 10 MPa, however, this will reduce the life of the seal significantly.

The practical tests were carried out at Äspö HRL during the autumn 2007 to verify the effectiveness of grouting with Mega-Packer, see Figure 9-10. The test site is the KBS-3H drift at –220 m level. The drift has 5 leaking sections targeted for sealing using the Mega-Packer. These leaking sections have inflow ranging between 0.09 l/min to around 2.2 l/min.

The tests carried out have been hydraulic and grouting tests on all leaking sections. These sections are similar to the two presented scenarios in this chapter named Scenario 1 and 2. The grouting tests have been designed in detail to the specific conditions.

In this section a brief report is given of the two first grouting tests. A complete and separate reporting of the test results is given in /Eriksson and Lindström 2008/.

9.5.2 Obtained sealing effect

The sealing effect is estimated based on the natural inflow before and after grouting. In the first test a sealing effect of around 97% was obtained, from and inflow or 0.45 l/min before grouting to around 0.015 l/min after grouting. In the second test the inflow before grouting was measured to 2.2 l/min. After grouting the inflow was measured to around 0.007 l/min resulting in a sealing effect of around 99.7%.

Figure 9-10. *Mega-Packer in the drift with the personal working inside. Photo by Curt-Robert Lindqvist.*

9.5.3 Amount of used material

The design of the grouting was made to ensure a grouted zone of at least 5 m. In the tests the measurement of used material was very difficult due to several circumstances:

- A complete filling of the Mega-Packer is difficult.
- The logging system was neither accurate nor precise. Tests were made which indicated that the logging system measured larger volumes than actual volumes.
- Only small volumes are grouted in relation to the volumes needed to fill the hoses and the Mega-Packer, around 200 l.

The ambition was to measure the volume of grout entering the rock with a precision of one litre but this could not be obtained.

In the first test the volume grouted was 11 l according to the logging system. This volume is likely larger than the volume actually entering the rock. The actual grouted volume is estimated to around 5 l. In the second test the measured volume to be grouted was 125 l. In this test the remaining amount of grout after the test was measured and based on this it is estimated that around 60 l was actually grouted.

Concerning the amount of used material it is concluded that this question is difficult and that a different approach is needed in future tests to obtain better estimations of the amount of grouting material. The issue is to verify that the predicted and used amount is in the same order.

9.5.4 Lessons learned

The hydraulic tests and grouting tests have resulted in several experiences. In principle the tests showed expected results but some practical issues had been resolved. The main findings are the following:

- The moving of the Mega-Packer was more difficult than expected since it a tendency to twist while moved in the drift. In a relative sense it is, however, found practically feasible to do the grouting with the equipment. Once the transport of the Mega-Packer was functioning the tests were not time consuming and could be performed in a couple of days per position, including transport, hydraulic test, grouting and release of the Mega-Packer and cleaning of the position.
- Filling of the Mega-Packer was initially not perfect and some modification had to be made. In the second grouting a higher degree of filling was obtained which indicates that the problem can be handled (see Figure 9-11).
- Estimation of grouted volume is difficult. This is due to several issues. One is that filling the Mega-Packer is difficult and it is not easy to fully avoid air in the system. This air is compressed when the grouting starts and results in an undetermined volume. A second issue is the measuring system used in combination with the piston pump. In the two performed test the grouted volume in the rock is known only with a margin on several litres, which is not satisfactory. This issue needs to be resolved for the future tests.

The filling of the grouting sections (Position 3 and Position 1) is shown in Figure 9-11. It is seen how the first grouting in Position 3 resulted in an unfilled area at the roof of the drift whilst when grouting in Position 1 the filling was complete.

9.6 Plan for groundwater control

9.6.1 General

The groundwater control program describes a method of investigations and evaluations in order to determine if the position of a drift is suitable from a groundwater control or long-term safety point of view. This includes defining sections with an inflow less than 0.1 l/min before grouting (section where deposition can be made) but also the number of other leakage points, amount of inflow etc. The program also describes how information from the investigations should be interpreted. This is done in order to get indications of the need of grouting and to decide if and what type of grouting (pre- or post-grouting) that is the most suitable in order to fulfil the requirements of inflow to the drift.

The plan for groundwater control includes investigations for characterisation of structures and fractures in the rock, grouting criteria, a description of the grouting work and conclusions and recommendations. This plan includes descriptions of investigations before and during the drift excavation and grouting operation.

Figure 9-11. *Two photos showing the grouted sections after removing the Mega-Packer. Left: Incomplete filling in Position 3. Right: Complete filling in Position 1. Photos by Linda Lindström, Magnus Kronberg.*

The groundwater control program is based on the use of different methods of grouting to limit the inflow and to fulfil the requirements.

The result of the calculations made above is used to discuss a program for groundwater control. The calculated results are, however, highly uncertain and should only be used as guidance and for comparing different methods.

A short description of the groundwater control process is made below:

- Drilling of investigation/pilot holes.
- Investigations and evaluation.
- Decision if the drift is going to be excavated.
- Groundwater control actions:
  - Pre-grouting before excavation.
    - In investigation holes.
    - In pilot hole.
  - Pre-grouting during excavation.
  - Post-grouting using the Mega-Packer.

9.6.2 Investigations and evaluations before drift excavation

Investigation of a planned drift is done by drilling of one or more investigation hole in order to evaluate the position and if it is suitable from the groundwater control or long-term safety point of view. If the position of the drift after evaluation is accepted further evaluation of the results are made. The aim of this evaluation is to decide if the drift is suitable for deposition, if grouting is necessary and what kind of method that are the most suitable.

The investigation holes are characterised concerning number of leaking sections, transmissivity distribution and fracture frequency. The methodologies presented in /Fransson 2001/ can be used to estimate the number of leaking canister positions. Investigations to be done in order to get necessary information are:

- Core drilling, mapping of the core and logging of the hole.
- Pressure build up tests.
- Water loss measurement.

Results from the investigations give information about geological and hydraulic properties of structures/fractures in the drift, such as transmissivity, hydraulic aperture of fractures, fracture fillings, specific capacity etc.

The results from the tests provide input to make a decision if grouting has to be done and in case when and how it should be done to get the best result.

The hydraulic investigations can be done with single- or double packer equipment. A double-packer equipment gives a better opportunity to make characterisation of specific leakage points and hereby be able to choose the most appropriate grouting method. The following descriptions are made:

- Description of the tests.
- Description of the evaluations.
- Description of the results.

9.6.3 Decision on drift excavation

Based on the information from the investigation holes a decision can be made to excavate the drift or not. The decision is based the utilisation degree of the drift, i.e. on how many positions that are expected to be used.

Criteria for minimum number of canister positions for excavation and where leaking sections can be accepted should be set up. For instance, if leaking sections are found deep in the drift, it is possible that the drift is not excavated to full length. If the leaking sections are found early in the drift, they do not affect the deposition deeper in the drift.

9.6.4 Groundwater control actions

If the drift is accepted for excavation it must be determined how to grout the leaking sections. The basic principle is to grout the leakage as early as possible. However, it must be expected that some leakages do not appear before the drift is excavated. Three different situations for grouting are briefly described below.

- If a situation with one or a few fractures with a hydraulic aperture larger than around 50 µm (more than around 1–2 l/min) is recorded in the investigation/pilot holes, grouting is meaningful already before starting excavation. Smaller leakages giving less than 1 l/min are not groutable from a single hole. The basic advantage is that the excavation does not need to be stopped. The grouting is made in the investigation/pilot holes using a double-packer system. A specific design must be developed. Expected effect is > 60%.
- If a situation where the hole contains several fractures with small aperture, pre-grouting from inside the drift is meaningful. At a specified distance before the leakage area the excavation is stopped and the reaming equipment is removed from the drift. Investigation holes are drilled inside the contour of the drift in order to get more detailed information of the possible leakages. These holes are then used for grouting. If the investigation shows that more grouting holes are required more holes are drilled inside the drift perimeter and used for grouting. Expected effect is > 99%.
- After the drift excavation the Mega-Packer is used for post-grouting of leaking areas where this is required. Expected sealing effect is 60–100%. This method is used primarily if unknown leakages arise after excavation, which hampers the function of the drift. No theoretical limitations in the effectiveness in the method can be noticed. After excavation of the drift the inflows to the drift is recorded regarding the type, position and amount of inflow. Based on this information and the allowed amount of inflow to the drift in separate sections a plan is made where to use the Mega-Packer.

Based on the above, any scenario can be expected to be fully sealed. However, there must be noticed that the accumulated sealing effect is difficult to model and the given values of sealing effect is based on each method of its own.

9.7 Predicted and measured result

9.7.1 Expected and measured grouting effect

The results of the study indicate that a high sealing effect is expected in most cases. It is, however, difficult to fully model the complex flow in fractured rock. The theoretical study presented is based on modelling the fractures with a variation in aperture. This variation may, however, be underestimated and the fractures may have contact areas. This would have the effect that it is difficult to hit leaking parts in the fracture with boreholes, instead the Mega-Packer equipment is useful. The level of coefficient of variation in aperture studied in this report is commonly found described in geological and hydrogeological literature but also other estimates are found.

Expected sealing effect

The calculations have shown a high expected sealing effect in all scenarios and using all methods expect in scenario with a singular small fracture where the use of Mega-Packer is necessary to obtain a considered sealing. Using grouting through boreholes the expected sealing effect varies with the number of grouting holes.

Using the Mega-Packer equipment the expected sealing effect is more than 70%. This means that if grouting in boreholes is not successful the Mega-Packer equipment can still seal the fractures. The expected sealing effect is found lower in the small aperture and single fracture and larger in the other cases.

Measured sealing effect

There are few measured cases to verify the calculated results. However, reports of borehole grouting with both cement and Silica Sol show high sealing effects in complicated grouting situations if the design and execution is advanced /Emmelin et al. 2004, Funehag 2007/.

Concerning the Mega-Packer the two practical tests showed very good results with sealing effects of 97% and 99.7%. This verifies the function of the equipment for sealing horizontal drifts with high requirements on low inflows.

Conclusion regarding sealing effect

The conclusion so far is that there is sufficient technique to seal inflow in horizontal drifts that fulfil requirements. However, several questions, both practical and theoretical, need to be resolved before a complete understanding is achieved.

9.7.2 Estimated and measured use of materials

Since the fractures in general have small aperture and the number of leaking fractures is small based on the expected hydrogeological investigation, the amount of grout material necessary to use is small.

Expected use of material

The expected use of material is small. In this case the largest simulated volume based on Olkiluoto data is around 100 litres. In the majority of the cases (85%) less than 20 litres of grout was simulated. Considering that fractures are not planar discs and rarely show a fully 2D grout spread pattern 100 litres should be regarded as a conservative value. However, the porosity in the rock mass is often found to be larger than the hydraulic porosity and reason to increase the value may therefore be considered. According to the results from /Zimmerman et al. 1991/ and /Barton and Quadros 1997/, for instance, values of porosity can be several times higher than the hydraulic aperture state. Based on this reasoning a rough estimate of 500 litres may be used.

Measured use of material

In the experiments at Äspö presented in /Emmelin et al. 2004/ one objective was to minimise the amount of material used when grouting in a deep facility. The results of that test showed that less grout than commonly used can be sufficient. This experiment showed that if investigations and design are well applied a considered sealing effect can be obtained using small amounts of grout. The work also showed that the prediction of grout take is difficult and the models used are not very accurate.

In the Mega-Packer tests in the horizontal drift at Äspö the amount of material used were not minimised but still small, around 5 l and 40 l in the two grouting rounds. If directly compared this is in range of expected. However, in the detailed design of the tests a smaller amount of material was anticipated than actually used.

Conclusions regarding use of grouting material

The conclusions regarding use of grouting material are on one hand that it not been shown that there are accurate methods to predict the necessary amount of grouting material to be used, but on the other hand the practical experience shows that relatively small amounts are necessary. Further development of theoretical methods and practical logging are considered valuable.

9.8 Uncertainties and proposal for future work

Uncertainties

Groundwater control is presented in this chapter as a process during the preparation work of deposition drift in the KBS-3H alternative. This means that it is of vital importance to have prepared a working procedure to handle groundwater control questions. The uncertainties involved in the analyses are several and concerns for instance the description of the fracture statistics and the models used. However, for the groundwater control the main uncertainties are expected to be the practical work in having a sound prognosis made on the basis of the information gained in the investigation holes. It is not known how well it may be detected how many leaking sections to expect.

There are also issues concerning the grouting that needs answering. This concerns for instance to verify the durability of Silica Sol during the open period of the drifts.

Proposal for future work

The verification of the ability of the Mega-Packer is important to continue. In connection to this, study how the inflow changes during grouting different positions in the tunnel is important for the understanding of how the groundwater control program should be detailed. The ability of the Mega-Packer at full repository depth, i.e. 500 m, must as well be verified.

Research projects on the material properties, for instance the durability of Silica Sol, are ongoing and need to be summarised and concluded in respect of the situation for KBS-3H.

Other issues are related to the practical work. Grouting in pilot hole and fan grouting in the drift requires special equipment, which is not yet present.

10 Engineered and other residual materials

10.1 The KBS-3H repository

The quantities of engineered and other residual materials in a KBS-3H repository have been evaluated in /Hagros 2007a/. Only the BD and DAWE design alternatives were considered, because the design state of STC was too preliminary and immature to be included in the study. This chapter summarizes the main findings of the evaluation.

Regarding the layout of the repository, the results of the latest KBS-3H layout adaptation work at Olkiluoto /Johansson et al. 2007/ are used. Accordingly, the repository is assumed to be constructed in one layer at the depth of 400–420 m in the central part of the Olkiluoto Island. The main difference to a KBS-3V repository is that instead of deposition drifts and vertical deposition holes, there are horizontal deposition drifts. Based on the layout by /Johansson et al. 2007/, the dimensions of the deposition drifts are assumed to be the following:

- Number of canisters to be emplaced is 2,840.
- Diameter of deposition drift is 1,850 mm.
- Length of deposition drift is 100–300 m.
- The total number of deposition drifts is 171.
- Total length of drifts used in calculations is 46,432 m.
- Cross-sectional area is some 2.69 m^2, except for the deposition niche, which is a horseshoe-shaped tunnel with the following properties: width 8.5 m, height 6.65 m and cross-sectional area of 50 m^2 (these values are only preliminary). The length of the deposition niche used in the residual material estimate is 15 m but according to the current estimates it will be about 22 m long.
- Accordingly, the total volume of the deposition drifts is estimated to be 246,166 m^3. This is 61% smaller than the total volume of KBS-3V deposition tunnels and holes. On the other hand, the KBS-3H will require a larger area than the KBS-3V design alternative.

The dimensions of the central tunnels are also clearly different in KBS-3H and KBS-3V due to the larger total central tunnel length in KBS-3H. Based on the layout by /Johansson et al. 2007/, the dimensions of the KBS-3H central tunnels are assumed to be the following:

- The total length of central tunnels (at –420 m level, excluding ONKALO) is 8,399 m. This is 23% larger than the total length of central tunnels in KBS-3V.
- The total volume of the central tunnels is, accordingly, 309,644 m^3. The concurrent central tunnel concept /Malmlund et al. 2004/ is used, so the given lengths and volumes include both tubes of the double central tunnel as well as the connecting tunnels between them.

The dimensions of all other parts of the KBS-3H repository are the same as in KBS-3V /Hagros 2007b/. Accordingly, the total volume of the ONKALO is 362,039 m^3. The dimensions of the individual parts of ONKALO have not been updated and they are based on /Hjerpe 2004/.

The total volume of the repository (incl. ONKALO) is 1,016,290 m^3 and the total volume of the actual repository is, therefore, 654,251 m^3. The actual repository includes the deposition drifts, the central tunnels at the –420 m level and a total of 98,441 m^3 of other openings.

All volumes presented here are theoretical volumes, whereas the actual excavated volumes are probably slightly larger due to over break. The theoretical volumes will be used, because the difference is minor with respect to other uncertainties involved in the work, and because the data on the excavations carried out so far are also based on theoretical volumes. However, since the excavated volume is very significant for the estimation of the quantities of the tunnel backfill materials, the volumes (except for those of the deposition drifts) will be multiplied by 1.1 when the backfill materials are considered.

When the quantities of the residual materials have been calculated, three different reference deposition drifts have been assumed for the three different canister types (OL1–2, OL3 and LO1–2), based on the new KBS-3H layout /Johansson et al. 2007/. Each reference drift is assumed to be 300 m long and include one compartment plug, which takes up 30 m of the drift length. The number of canisters in one drift varies because different canister types have different thermal canister spacing, and these affect the actual canister spacing. The number of canisters per drift used in the calculations is 18. The rock mass properties are assumed to be similar in all three reference drifts. The details of the three reference drifts are given in Table 10-1. When estimating the total quantities of the materials in the drift end plugs, the real number of deposition drifts (171 in total) has been assumed.

10.1.1 Quantities per origin of materials

The estimated quantities of residual materials that remain in the repository (incl. ONKALO) after closure are presented in Figure 10-1 and Table 10-2 for the BD design alternative and Table 10-3 for the DAWE alternative. Because the STC design is still at a preliminary stage, no quantities of residual materials are estimated for this third design. In addition to the remaining quantities, the tables also show the estimated total quantities of materials introduced into the repository, presented separately for their most relevant chemical components. Similarly to the approach used by /Hagros 2007b/, the following components of the materials are not considered here:

- water (H_2O),
- oxygen (O_2),
- nitrogen gas (N_2),
- carbon dioxide (CO_2),
- carbon monoxide (CO),
- rock minerals,
- some other substances which are considered to be of minor relevance for the long-term safety of the repository or which could not be calculated due to a lack of data.

As water is not taken into account, all values presented in the following tables refer to the quantities of the dry materials.

The design alternatives listed in the tables are the following:

Rock support alternatives are the following: shotcrete with ordinary cement (A) and low-pH cement (B). The grouting alternatives are: ordinary cement (1), low-pH cement (2), and colloidal silica (3). The backfill alternatives are: a mixture of crushed rock and MX-80-type bentonite (a) or Friedland clay (b).

For example, design alternative "A1a" means that the selected support alternative is A (shotcrete with ordinary cement), the grouting alternative is 1 (100% ordinary cement) and the backfill alternative is "a" (bentonite/crushed rock mixture).

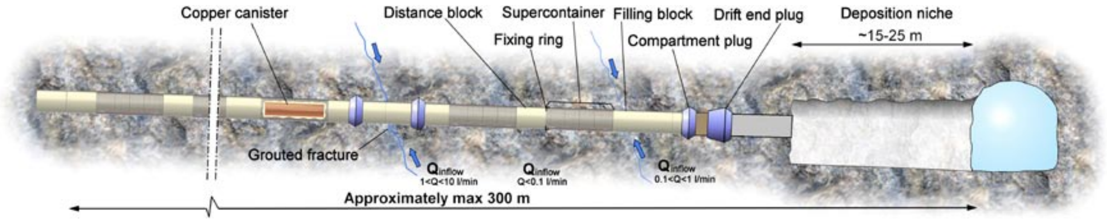


Figure 10-1. Key components containing engineered and residual materials in BD alternative and estimated quantities of cement. Note that in case of DAWE alternative, fixing rings are not needed. The length of the deposition niche is currently about 22 m but 15 m was the length at the time the residual material quantities were estimated.

Table 10-1. Compositions of reference deposition drifts (with average properties) for the three different canister types (based on /Johansson et al. 2007/).

Parameter/Canister type	OL1–2	OL3	LO1–2
Total length of drift	300 m	300 m	300 m
Unusable section in the beginning of the drift	25 m	25 m	25 m
Thermal canister spacing	11.0 m	10.6 m	9.1 m
Number of canisters in drift	17.5	18.2	21.2
Actual canister spacing [9]	15.7 m	15.1 m	13.0 m
Number / Total length of compartment plugs	1 / 30 m	1 / 30 m	1 / 30 m
Total length of blank zones	52 m	52 m	52 m

[9] The actual canister spacing is larger than the thermal canister spacing due to sections with unsuitable rock mass conditions. These sections are assumed to make up 25% of the rock mass at Olkiluoto outside major fracture zones and they will have compartments plugs or blank zones (see Johansson et al. 2007). The percentage is higher in the KBS-3H than in the KBS-3V alternative to take account of the space requirements of the KBS-3H components (compartment plugs and blank zones) that will be used even when the unusable sections are rather narrow.

Table 10-2. Estimated total quantities of residual materials in a KBS-3H repository (BD design alternative), listed by origin (Table 2 in /Hagros 2007a/). The table continues on the next pages.

Origin of the residual materials	Chemical components considered	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
1 Steel cylinders in supercontainers incl. feet	Steel	3,000,000	0	3,000,00
2 Compartment plugs	Steel	640,000	0	640,000
	Cement	92,000	0	92,000
	Silica (SiO_2)	6,100	0	6,100
	Organic materials	40,000	0	40,000
	Chloride	0.1	0	0.1
	Pyrite	14,000	0	14,000
	Gypsum	140,000	0	140,000
	Carbonates (calcite + siderite)	100,000	0	100,000
3 Drift end plugs				
3.1 LHHP plug alternative	Cement	180,000	0	180,000
	Silica (SiO_2)	400,000	0	400,000
	Organic materials	14,000	0	14,000
	Steel	510,000	0	510,000
	Chloride	0.07	0	0.07
3.2 Rock cylinder alternative	Cement	380,000	0	380,000
	Silica (SiO_2)	20,000	0	20,000
	Organic materials	140	0	140
	Steel	360,000	0	360,000
	Chloride	0.4	0	0.4
4 Spray and drip shields	Steel	500	0	500
5 Fixing rings	Steel	410,000	0	410,000
	Cement	16,000	0	16,000
	Silica (SiO_2)	1,000	0	1,000
	Organic materials	6	0	6
	Chloride	0.02	0	0.02

Origin of the residual materials	Chemical components considered	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
6 Impurities in bentonite buffer	Organic carbon	89,000	0	89,000
	Pyrite	31,000	0	31,000
	Gypsum	310,000	0	310,000
	Carbonates (calcite + siderite)	220,000	0	220,000
7 Impurities in distance blocks	Organic carbon	120,000	0	120,000
	Pyrite	42,000	0	42,000
	Gypsum	420,000	0	420,000
	Carbonates (calcite + siderite)	300,000	0	300,000
8 Impurities in blank zones (bentonite blocks)	Organic carbon	67,000	0	67,000
	Pyrite	23,000	0	23,000
	Gypsum	230,000	0	230,000
	Carbonates (calcite + siderite)	170,000	0	170,000
9 Impurities in backfill material				
9a Backfill alternative a (bentonite/crushed rock)	Organic carbon	1,200 000	0	1,200 000
	Pyrite	410,000	0	410,000
	Gypsum	4,100,000	0	4,100,000
	Carbonates (calcite + siderite)	2,900,000	0	2,900,000
9b Backfill alternative b (Friedland clay)	Organic carbon	10,000,000	0	10,000,000
	Pyrite	11,000,000	0	11,000,000
	Gypsum	14,000,000	0	14,000,000
	Carbonates (calcite + siderite)	100,000	0	100,000
10 Explosives	Nitrogen oxides (NO_x)[1]	1,600	99	16
11 Blasting caps and cords	Aluminium	1,700	90	170
	Plastic	1,800	90	180
12 Support bolts	Steel	220,000	0	220,000
	Zinc	4,200	0	4,200
	Cement	86,000	0	86,000
13 Anchor bolts	Steel	50,000	40	30,000
	Cement	6,300	0	6,300
14 Shotcrete				
14A Shotcrete alternative A	Cement	6,900,000	95	350,000
	Aluminium	21,000	95	1,000
	Organic materials	49,000	95	2,400
	Silica (SiO_2)	280,000	95	14,000
	Iron (Fe(III))	4,900	95	200
	Chloride	300	95	17
14B Shotcrete alternative B	Cement	5,100,000	95	260,000
	Aluminium	15,000	95	800
	Organic materials	36,000	95	1,800
	Silica (SiO_2)	2,200,000	95	110,000
	Iron (Fe(III))	3,600	95	180
	Chloride	300	95	13

[1] this is valid for the gas phase, but if soluble nitrogen compouns are formed their removal efficiency is likely much lower.

Origin of the residual materials	Chemical components considered	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
15 Grouting materials				
15.1 Grouting alternative 1	Cement	780,000	20	620,000
	Organic materials	7,800	20	6,200
	Silica (SiO_2)	78,000	20	62,000
	Chloride	800	20	600
	Nitrate	1,000	20	800
15.2 Grouting alternative 2	Cement	590,000	20	480,000
	Organic materials	10,000	20	8,200
	Silica (SiO_2)	130,000	20	110,000
	Chloride	600	20	500
	Nitrate	900	20	700
15.3 Grouting alternative 3	Cement	420,000	20	340,000
	Organic materials	5,000	20	4,000
	Silica (SiO_2)	230,000	20	190,000
	Chloride	5,700	20	4,600
	Nitrate	800	20	600
16 Floors	Cement	5,200,000	98	100,000
	Steel	710,000	99	7,100
17 Miscellaneous constructions	Cement	4,500,000	98	89,000
	Steel	1,000,000	98	20,000
	Aluminium	100,000	98	2,000
	Zinc	6,800	98	140
18 Drainage pipes	Steel	5,800	95	300
	Polyethylene (PE)	3,500	95	180
	Polystyrene (EPS)	1,400	95	70
19 Wear to tyres	Rubber	160,000	90	16,000
20 Exhaust fumes from diesel engines	Nitrogen oxide	1,400,000	99	14,000
	Soot and ash	82,000	93	5,800
21 Diesel oil	Hydrocarbons	210,000	95	11,000
22 Battery acid	Sulphuric acid	3,200	90	300
23 Hydraulic and lubricating oils	Hydrocarbons	47,000	90	4,700
24 Degreasing agents and detergents	Hydrocarbons + other organic materials	70,000	95	3,600
25 Hard metals and metal fragments	Steel	520,000	98	10,000
	Tungsten and cobalt	2,800	99	30
26 Paints	Hydrocarbons	5,500	0	5,500
27 Urine	Carbamide	1,100,000	95	55,000
28 Miscellaneous human waste	Organic materials	700,000	98	14,000
29 Impurities in ventilation air	Organic materials	10,000,000	99	100,000

Table 10-3. Estimated total quantities of residual materials in a KBS-3H repository (DAWE design alternative), listed by origin (Table 3 in /Hagros 2007a/). The table continues on the next pages.

Origin of the residual materials	Chemical components considered	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
1 Steel cylinders in supercontainers	Steel	3,000,000	0	3,000,000
2 Compartment plugs	Steel	640,000	0	640,000
	Cement	92,000	0	92,000
	SiO2	6,100	0	6,100
	Organic materials	40,000.0	0	40,000.0
	Chloride	0	0	0
	Pyrite	14,000	0	14,000
	Gypsum	140,000	0	140,000
	Carbonates (calcite + siderite)	100,000.00	0	100,000.00
3 Drift end plugs				
3.1 LHHP plug alternative	Cement	180,000	0	180,000
	SiO_2	400,000	0	400,000
	Organic materials	14,000	0	14,000
	Steel	510,000.00	0	510,000.00
	Chloride	0.07	0	0.07
3.2 Rock cylinder alternative	Cement	380,000	0	380,000
	SiO_2	20,000	0	20,000
	Organic materials	140	0	140
	Steel	360,000.0	0	360,000.0
	Chloride	0.40	0	0.40
4 Spray and drip shields	Steel	500	0	500
5 Drainage wetting and air evacuation systems (only pipe props are considered)	Steel	500	0	500
6 Impurities in bentonite buffer	Organic carbon	89,000	0	89,000
	Pyrite	31,000	0	31,000
	Gypsum	310,000	0	310,000
	Carbonates (calcite + siderite)	220,000.00	0	220,000.00
7 Impurities and feet of distance blocks	Organic carbon	120,000	0	120,000
	Pyrite	40,000	0	40,000
	Gypsum	400,000	0	400,000
	Carbonates (calcite + siderite)	290,000	0	290,000
	Steel	39,000.00	0	39,000.00
8 Impurities in blank zones (bentonite blocks)	Organic carbon	67,000	0	67,000
	Pyrite	23,000	0	23,000
	Gypsum	230,000	0	230,000
	Carbonates (calcite + siderite)	170,000.00	0	170,000
9 Impurities in backfill material				
9a Backfill alternative a (bentonite/crushed rock)	Organic carbon	1,200,000	0	1,200,000
	Pyrite	410,000.00	0	410,000.00
	Gypsum	4,100,000.00	0	4,100,000.00
	Carbonates (calcite + siderite)	2,900,000.00	0	2,900,000.00

Origin of the residual materials	Chemical components considered	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
9b Backfill alternative b (Friedland clay)	Organic carbon	10,000,000.0	0	10,000,000.0
	Pyrite	11,000,000	0	11,000,000
	Gypsum	14,000,000	0	14,000,000
	Carbonates (calcite + siderite)	100,000	0	100,000
10 Explosives	Nitrogen oxides (NO_x)[1]	1,600	99	16
11 Blasting caps and cords	Aluminium	1,700.00	90	170.00
	Plastic	1,800.00	90	180.00
12 Support bolts	Steel	220,000	0	220,000
	Zinc	4,200	0	4,200
	Cement	86,000.0	0	86,000.0
13 Anchor bolts	Steel	50,000	40	30,000
	Cement	6,300.00	0	6,300.00
14 Shotcrete				
14A Shotcrete alternative A	Cement	6,900,000	95	350,000
	Aluminium	21,000	95	1,000
	Organic materials	49,000	95	2,400
	Silica (SiO_2)	280,000	95	14,000
	Iron (Fe(III))	4,900	95	200
	Chloride	300.00	95	17.00
14B Shotcrete alternative B	Cement	5,100,000	95	260,000
	Aluminium	15,000	95	800
	Organic materials	36,000	95	1,800
	Silica (SiO_2)	2,200,000	95	110,000
	Iron (Fe(III))	3,600	95	180
	Chloride	300.00	95	13.00
15 Grouting materials				
15.1 Grouting alternative 1	Cement	780,000	20	620,000
	Organic materials	7,800	20	6,200
	Silica (SiO_2)	78,000	20	62,000
	Chloride	800	20	600
	Nitrate	1,000.00	20	800.00
15.2 Grouting alternative 2	Cement	590,000	20	480,000
	Organic materials	10,000	20	8,200
	Silica (SiO_2)	130,000	20	110,000
	Chloride	600	20	500
	Nitrate	900.00	20	700.00
15.3 Grouting alternative 3	Cement	420,000	20	340,000
	Organic materials	5,000	20	4,000
	Silica (SiO_2)	230,000	20	190,000
	Chloride	5,700	20	4,600
	Nitrate	800.00	20	600

[1] this is valid for the gas phase, but if soluble nitrogen compouns are formed their removal efficiency is likely much lower.

Origin of the residual materials	Chemical components considered	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
16 Floors	Cement	5,200,000.00	98	100,000.00
	Steel	710,000.00	99	7,100.00
17 Miscellaneous constructions	Cement	4,500,000	98	89,000
	Steel	1,000,000.00	98	20,000.00
	Aluminium	100,000.00	98	2,000.00
	Zinc	6,800.00	98	140.00
18 Drainage pipes	Steel	5,800.0	95	300.0
	Polyethylene (PE)	3,500	95	180
	Polystyrene (EPS)	1,400	95	70
19 Wear to tyres	Rubber	160,000	90	16,000
20 Exhaust fumes from diesel engines	Nitrogen oxide	1,400,000.00	99	14,000.00
	Soot and ash	82,000.00	93	5,800.00
21 Diesel oil	Hydrocarbons	210,000	95	11,000
22 Battery acid	Sulphuric acid	3,200	90	300
23 Hydraulic and lubricating oils	Hydrocarbons	47,000	90	4,700
24 Degreasing agents and detergents	Hydrocarbons + other organic materials	70,000.00	95	3,600.00
25 Hard metals and metal fragments	Steel	520,000	98	10,000
	Tungsten and cobalt	2,800.00	99	30.00
26 Paints	Hydrocarbons	5,500.00	0	5,500.00
27 Urine	Carbamide	1,100,000.00	95	55,000.00
28 Miscellaneous human waste	Organic materials	700,000.00	98	14,000.00
29 Impurities in ventilation air	Organic materials	10,000 000.00	99	100,000

10.1.2 Total quantities in the BD design alternative

Total quantities of chemical components are presented in Table 10-4 and in Tables E-1 to E-6 (see Appendix E) for the BD design alternative over different combinations of tunnel support, grouting, backfill and drift end plug alternatives. Low-pH grouting materials and support materials are the recommended materials for the deposition drift. For comparison, also combinations of other materials have been presented.

- Table E-1 in Appendix E features design alternative A1a[10] with an LHHP plug. Ordinary cement is assumed for use in both shotcreting (support alternative A) and grouting (grouting alternative 1). The backfill plan is based on bentonite/crushed rock mixture (backfill alternative a).
- In Table E-2 (see Appendix E), other alternatives are the same as in Table E-1 (see Appendix E), but the drift end plug is of the rock cylinder type.
- In Table E-3 (see Appendix E), other alternatives are the same as in Table E-1 (see Appendix E), but the backfill strategy is based on Friedland clay (backfill alternative b).
- In Table E-4 (see Appendix E) low-pH cement is assumed for use in both shotcreting and grouting (shotcreting alternative B and grouting alternative 2). The backfill plan is based on a bentonite/crushed rock mixture (backfill alternative a) and the drift end plug is of the rock cylinder type.

[10] Design alternative "A1a" signifies that the selected support alternative is A (shotcrete with ordinary cement), the grouting alternative is 1 (100% ordinary cement) and the backfill alternative is a (mixture of crushed rock and bentonite). The groutings and shotcretings assumed in these alternatives for the ONKALO are explained in /Hagros 2007b/.

- Table E-5 in Appendix E is similar to Table E-4 in Appendix E, except that grouting is based on the use of silica grouts (grouting alternative 3).
- In Table 10-4, low-pH cement is assumed for use in both shotcreting and grouting (shotcreting alternative B and grouting alternative 2). The backfill plan is based on a bentonite/crushed rock mixture (backfill alternative a) and the drift end plug is a LHHP plug.
- In Table E-6 (see Appendix E) low-pH cement is assumed for use in both shotcreting and grouting (shotcreting alternative B and grouting alternative 3). The backfill plan is based on a bentonite/crushed rock mixture (backfill alternative a) and the drift end plug is a LHHP plug.

In these tables the results are categorised according to their chemical nature. Note that, depending on the availability of data, some components have been considered in more detail than others and the categories are, therefore, not necessarily mutually exclusive. For example, the iron (Fe(III)) estimates only take shotcrete into account as a source (some shotcrete additives contain Fe_2O_3) but, clearly, other materials and categorised components contain iron as well. Most notably, iron is a major constituent of steel (metallic iron) but it can also be found as Fe(II) in pyrite and siderite, which occur as impurities in bentonite. Iron is also a constituent of cement, but the chemical constituents of cement were not individually quantified in the tables either.

By using Table 10-2 it is possible to calculate the total material quantities for any combination of alternatives. Only five combinations are presented here for the BD alternative, but the total number of possible combinations is 24.

Table 10-4. Estimated total quantities of chemical components from residual materials in a KBS-3H repository (including ONKALO), based on design alternatives BD and B2a (= support alternative B, grouting alternative 2, backfill alternative a) with a LHHP plug. (Table 9 in /Hagros 2007a/.)

Chemical components	Origin (reference to Table 10-2)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	2, 6, 7, 8, 9a	5,200 000	0	5,200 000
Steel	1, 2, 3.1, 4, 5, 12, 13, 16, 17, 18, 25	6,900,000	32	4,550,000
Carbonates (calcite + siderite)	2, 6, 7, 8, 9a	3,700,000	0	3,700,000
Organic materials (incl. organic carbon and hydrocarbons)	2, 3.1, 5, 6, 7, 8, 9a, 14B, 15.2, 21, 23, 24, 26, 28, 29	13,000,000	87	1,614,000
Cement	2, 3.1, 5, 12, 13, 14B, 15.2, 16, 17	16,000,000	91	1,300,000
Pyrite	2, 6, 7, 8, 9a	520,000	0	520,000
Silica (SiO_2)	2, 3.1, 5, 14B, 15.2	2,400,000	90	630,000
Carbamide	27	1,100,000	95	55,000
Rubber	19	160,000	90	16,000
Nitrogen oxides (NO_x)	10, 20	1,400,000	99	14,000
Soot and ash	20	82,000	93	5,800
Zinc	12, 17	11,000	61	4,300
Aluminium	11, 14B, 17	120,000	97	3,000
Nitrate	15.2	900	20	700
Chloride	2, 3.1, 5, 14B, 15.2	900	43	500
Sulphuric acid	22	3,200	90	300
Iron (Fe(III))	14A	3,600	95	180
Plastic	11	1,800	90	180
Polyethylene (PE)	18	4,000	95	180
Polystyrene (EPS)	18	1,400	95	70
Tungsten and cobalt	25	2,800	99	30

10.1.3 Total quantities in the DAWE design alternative

The total quantities of chemical components are presented in Table 10-5, Tables E-7 and E-8 (see Appendix E) for the DAWE design alternative for two combinations of tunnel support, grouting, backfill and drift end plug alternatives. Low-pH grouting materials and support materials are the recommended materials for the deposition drift. For comparison, also combinations of other materials have been presented.

- Table E-7 is similar to Table E-1 in Appendix E except that DAWE is assumed instead of BD. The design alternative is A1a (ordinary cement in shotcreting and grouting and a bentonite/crushed rock backfill) and an LHHP plug is assumed to be used.
- In Table E-8 (see Appendix E), low-pH cement is assumed to be used in both shotcreting and grouting (shotcreting alternative B and grouting alternative 2). The backfill plan is based on bentonite/crushed rock mixture (backfill alternative a) and the drift end plug is of the rock cylinder type. It is otherwise similar to Table E-4 in Appendix E except that DAWE is assumed instead of BD.
- In Table 10-5, low-pH cement is assumed to be used in both shotcreting and grouting (shotcreting alternative B and grouting alternative 2). The backfill plan is based on bentonite/crushed rock mixture (backfill alternative a) and an LHHP plug is assumed to be used. It is otherwise similar to Table 10-4 in Section 10.1.2 except that DAWE is assumed instead of BD.

By using Table 10-3, it is possible to calculate the total material quantities for any combination of alternatives. Only three combinations are presented here for the DAWE alternative, but the total number of possible combinations is 24.

Table 10-5. Estimated total quantities of chemical components from residual materials in a KBS-3H repository (including ONKALO), based on design alternatives DAWE and B2a (= support alternative B, grouting alternative 2, backfill alternative a) with a LHHP plug. (Table 13 in /Hagros 2007a/.)

Chemical components	Origin (reference to Table 10-3)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	2, 6, 7, 8, 9a	5,200,000	0	5,200,000
Steel	1, 2, 3.1, 4, 5, 7, 12, 13, 16, 17, 18, 25	6,500,000	34	4,150,000
Carbonates (calcite + siderite)	2, 6, 7, 8, 9a	3,700,000	0	3,700,000
Organic materials (incl. organic carbon and hydrocarbons)	2, 3.1, 6, 7, 8, 9a, 14B, 15.2, 21, 23, 24, 26, 28, 29	13,000,000	87	1,614,000
Cement	2, 3.1, 12, 13, 14B, 15.2, 16, 17	16,000,000	91	1,300,000
Pyrite	2, 6, 7, 8, 9a	520,000	0	520,000
Silica (SiO_2)	2, 3.1, 14B, 15.2	2,400,000	90	630,000
Carbamide	27	1,100,000	95	55,000
Rubber	19	160,000	90	16,000
Nitrogen oxides (NO_x)	10, 20	1,400,000	99	14,000
Soot and ash	20	82,000	93	5,800
Zinc	12, 17	11,000	61	4,300
Aluminium	11, 14A, 17	120,000	97	3,000
Nitrate	15.2	900	20	700
Chloride	2, 3.1, 14B, 15.2	900	43	500
Sulphuric acid	22	3,200	90	300
Iron (Fe(III))	14B	3,600	95	180
Plastic	11	1,800	90	180
Polyethylene (PE)	18	3,500	95	180
Polystyrene (EPS)	18	1,400	95	70
Tungsten and cobalt	25	2,800	99	30

10.2 Results for the canister near field

10.2.1 Results for the BD design alternative

Estimates for quantities of residual materials in a single deposition drift of BD type are presented in Table 10-6 and Table E-9 (see Appendix E). The analysed deposition drift in Table 10-7 is based on design alternative B2a, i.e., it incorporates low-pH cement for both shotcreting and grouting purposes and a bentonite/crushed rock mixture as a backfill alternative. A rock cylinder type drift end plug is assumed as well. The analysed deposition drift in Table 10-6 is otherwise similar to Table E-9 in Appendix E except that the end plug is a LHHP plug.

Table 10-7 presents similar estimates for one deposition location, i.e. an 11 m-section of the identical drift.

The deposition drift of interest in Table 10-6 and Table E-9 (see Appendix E) is 300 m long and intended for OL1–2 canisters. The quantities of materials per excavated cubic metre (or per metre of tunnel) are considered to be average values for all deposition drifts. It was assumed here that the drift contains 18 canisters, i.e. 18 supercontainers and 18 distance blocks, as well as one compartment plug and blank zones (filled with bentonite) totaling 47 m in length. The deposition niche is also included.

The 11 m long deposition location considered in Table 10-7 includes one supercontainer (with an OL1/OL2 canister) and one distance block. Materials related to the drift end plug, the compartment plug and the blank zones are not taken into account.

Although design alternative B2a includes shotcrete alternative B, any associated materials have no effect on the results shown in Table 10-6 and Table E-9 (see Appendix E), as shotcrete will not be used in the small-diameter sections of the deposition drifts. Similarly, the backfill alternative has no effect on the displayed results either.

Table 10-6. Estimated total quantities of residual materials in one 300 m long deposition drift, based on design alternatives BD and B2a (= support alternative B, grouting alternative 2, backfill alternative a) with a LHHP plug. (Table 15 in /Hagros 2007a/.)

Chemical components	Origin (reference to Table 10-2)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	2, 6, 7, 8, 9a	10,000	0	10,000
Steel	1, 2, 3.1, 4, 5, 12, 13, 16, 17, 18, 25	31,000	9	28,860
Carbonates (calcite + siderite)	2, 6, 7, 8, 9a	7,500	0	7,500
Organic materials (incl. organic carbon and hydrocarbons)	2, 3.1, 5, 6, 7, 8, 9a, 14B, 15.2, 21, 23, 24, 26, 28, 29	5,000	40	3,080
Cement	2, 3.1, 5, 12, 13, 14B, 15.2, 16, 17	15,000	74	2,680
Pyrite	2, 6, 7, 8, 9a	1,000	0	1,000
Silica (SiO_2)	2, 3.2, 5, 14B, 15.2	5,500	88	2,880
Carbamide	27	200	95	10
Rubber	19	6	90	0.6
Nitrogen oxides (NO_x)	10, 20	30	99	0.3
Soot and ash	20	2	93	0.1
Zinc	12, 17	5	0	5
Aluminium	11, 14B, 17	20	95	1
Chloride	2, 3.1, 5, 14B, 15.2	0.8	49	0.4
Sulphuric acid	22	0.1	90	0.01
Iron (Fe(III))	14A	5	95	0.2
Plastic	11	1	90	0.1
Polyethylene (PE)	18	3	95	0.1
Polystyrene (EPS)	18	1	95	0.05
Tungsten and cobalt	25	4	99	0.04

Table 10-7. Estimated total quantities of residual materials in one deposition location (an 11 m section of a deposition drift), based on design alternative BD and grouting alternative 2. (Table 16 in /Hagros 2007a/.)

Chemical components	Origin (reference to Table 10-2)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	6, 7	300	0	300
Steel	1	1,100	0	1,100
Carbonates (calcite + siderite)	6, 7	200	0	200
Organic materials (incl. organic carbon and hydrocarbons)	6, 7, 15.2, 26, 28, 29	100	31	80
Cement	15.2	0.7	20	0.6
Pyrite	6, 7	30	0	30
Silica (SiO_2)	15.2	11	20	9
Carbamide	27	3	95	0.1
Chloride	15.2	0.02	20	0.01

10.2.2 Results for the DAWE design alternative

Tables 10-8, 10-9 and Table E-10 in Appendix E present results similar to those in Tables 10-6, 10-7 and Table E-9 (see Appendix E) with the exception that the DAWE design alternative is considered instead of the BD alternative. The discussion regarding the deposition drift and drift section found in the previous Section 10.2.1 is relevant here as well.

Table 10-8. Estimated total quantities of residual materials in one 300 m long deposition drift, based on design alternatives DAWE and B2a (= support alternative B, grouting alternative 2, backfill alternative a) with a LHHP plug. (Table 18 in /Hagros 2007a/.)

Chemical components	Origin (reference to Table 10-3)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	2, 6, 7, 8, 9a	10,000	0	10,000
Steel	1, 2, 3.1, 4, 5, 7, 12, 13, 16, 17, 18, 25	28,000	9	26,860
Carbonates (calcite + siderite)	2, 6, 7, 8, 9a	7,400	0	7,400
Organic materials (incl. organic carbon and hydrocarbons)	2, 3.1, 6, 7, 8, 9a, 14B, 15.2, 21, 23, 24, 26, 28, 29	5,000	40	3,080
Cement	2, 3.2, 12, 13, 14B, 15.2, 16, 17	14,000.	74	2,580.0
Pyrite	2, 6, 7, 8, 9a	1,000	0	1,000
Silica (SiO_2)	2, 3.2, 14B, 15.2	5,500	88	2,880
Carbamide	27	200	95	10.0
Rubber	19	6.0	90	0.60
Nitrogen oxides (NOx)	10, 20	30.0	99	0.30
Soot and ash	20	2.0	93	0.10
Zinc	12, 17	5.0	0	5.00
Aluminium	11, 14B, 17	20.0	95	1.00
Chloride	2, 3.2, 14B, 15.2	0.8	49	0.40
Sulphuric acid	22	0.1	90	0.01
Iron (Fe(III))	14A	5.0	95	0.20
Plastic	11	1.0	90	0.10
Polyethylene (PE)	18	3.0	95	0.10
Polystyrene (EPS)	18	1.0	95	0.05
Tungsten and cobalt	25	4.0	99	0.04

Table 10-9. Estimated total quantities of residual materials in one deposition location (an 11 m section of a deposition drift), based on design alternative DAWE and grouting alternative 2. (Table 19 in /Hagros 2007a/.)

Chemical components	Origin (reference to Table 10-3)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	6, 7	300	0	300
Steel	1, 7	1,100	0	1,100
Carbonates (calcite + siderite)	6, 7	190	0	190
Organic materials (incl. organic carbon and hydrocarbons)	6, 7, 15.2, 26, 28, 29	110	32	80
Cement	15.2	0.7	20	0.6
Pyrite	6, 7	30	0	30
Silica (SiO_2)	15.2	11	20	9
Carbamide	27	3	95	0.1
Chloride	15.2	0.02	20	0.01

10.3 Differences between BD and DAWE

Because the no quantities of residual materials are estimated for the STC design, only the residual materials for BD and DAWE are compared. The quantities of residual materials differ for the BD and DAWE design as see when comparing, e.g., Tables E-1 and E-7 in Appendix E. Such differences are related to the materials in distance blocks, fixing rings or the DAWE pipe system, as all other components are assumed to be identical for both design alternatives.

A comparison between the rounded-off values shown in Tables E-1 and E-7 (see Appendix E) indicates that the main difference between the BD and DAWE design alternatives is related to the quantity of steel, the remaining quantity of which is slightly smaller in DAWE than in BD, the difference being less than 10%. This difference is mainly ascribed to the lack of fixing rings in the DAWE alternative. As the DAWE drainage, wetting and air evacuation systems can be essentially removed, they will have negligible effect on the remaining quantity of steel in the repository. The effect of the steel feet in the DAWE distance blocks is also minor and the smaller size of the DAWE distance blocks has a negligible effect on the total quantities of the bentonite impurities as well.

10.4 Comparison with a KBS-3V repository

The KBS-3H repository assumed in this work includes the following components and materials that are not present in a KBS-3V repository:

- steel cylinders in the supercontainers,
- compartment plugs,
- spray and drip shields,
- fixing rings (BD only),
- drainage, wetting and air evacuation systems (DAWE only),
- distance blocks,
- bentonite blocks in blank zones.

The KBS-3V repository assumed by /Hagros 2007b/ includes the following components and materials that are not present in a KBS-3H repository:

- concrete bottom plates in the deposition holes,
- steel mesh in the deposition drifts.

In addition, the composition of the drift end plugs (KBS-3H) and concrete plugs (KBS-3V) are different in the two alternatives. Also, the quantity of bentonite in the KBS-3H supercontainers is 37% smaller than the quantity of the bentonite buffer in KBS-3V. Furthermore, the quantities of several other materials in the deposition drifts are smaller in KBS-3H due to the fact that the small-diameter parts of the deposition drifts are not excavated by drill and blast, they do not have any rock support or conventional installations, they probably require less grouting due to smaller cross-sectional area and they do not have any tunnel backfill material.

Table 10-10 shows a comparison between the remaining quantities of all residual materials considered in this work and in the KBS-3V report by /Hagros 2007b/. The table assumes the B2a design alternative (shotcreting and grouting mainly with low-pH cement, bentonite/crushed rock mixture as tunnel backfill) in both alternatives and the BD design alternative with a rock plug with respect to the KBS-3H specific options. Most of the total material quantities are nearly the same (±5%) or smaller in KBS-3H, the difference being typically –20%, at most –100% (with respect to copper, which is present in the KBS-3V concrete plugs). The following materials have, however, more than 5% larger remaining quantity in KBS-3H than in KBS-3V:

Table 10-10. Estimated remaining quantities of chemical components, included in the residual materials, in a KBS-3H and KBS-3V repository (based on /Hagros 2007b/). The design alternative is B2a (= support alternative B, grouting alternative 2, backfill alternative a) in both alternatives. The KBS-3H repository is based on the design alternative BD with a rock cylinder plug. (Table 20 in /Hagros 2007a/.)

Chemical components	Remaining quantity in KBS-3H [kg]	Remaining quantity in KBS-3V [kg]	Relative difference (KBS-3H compared with KBS-3V)
Gypsum	5,200,000	6,500,000	–19%
Steel	4,700,000	1,500,000	+210%
Carbonates (calcite + siderite)	3,700,000	4,600,000	–19%
Organic materials (incl. organic carbon and hydrocarbons)	1,600,000	2,000,000	–19%
Cement	1,500,000	5,800,00	–74%
Pyrite	520,000	650,000	–19%
Silica (SiO_2)	250,000	270,000	–7%
Carbamide	55,000	55,000	0%
Rubber	16,000	15,000	+6%
Nitrogen oxides (NOx)	14,000	13,000	+7%
Soot and ash	5,800	5,400	+7%
Zinc	4,300	140,000	–97%
Aluminium	3,000	2,800	+4%
Nitrate	700	700	+2%
Chloride	500	500	0%
Sulphuric acid	300	300	+6%
Iron (Fe(III))	180	140	+33%
Plastic	180	300	–31%
Polyethylene (PE)	180	140	+23%
Polystyrene (EPS)	70	60	+23%
Tungsten and cobalt	30	40	–25%
Copper	0	12,000	–100%

- steel: some 210% larger quantity in KBS-3H than in KBS-3V, mainly due to the steel cylinders in supercontainers but also due to compartment plugs and fixing rings
- iron (Fe(III)): some 30% larger quantity in KBS-3H, due to higher consumption of shotcrete as the total central tunnel length is larger in KBS-3H and also the deposition niches are assumed to have shotcrete
- polyethylene and polystyrene: some 20% larger quantity in KBS-3H, due to the higher consumption of drainage pipes related to shotcrete
- nitrogen oxides, rubber and soot and ash: slightly larger quantity in KBS-3H, due to larger total length of central tunnels causing more traffic with diesel vehicles.

In all, it can be concluded that the KBS-3H alternative is a better to KBS-3V alternative if the total quantities of the remaining materials need to be minimised. The total quantity of all materials listed in Table 10-10 is some 20% smaller in KBS-3H than in KBS-3V. The smaller quantities in KBS-3H are mainly due to the fact that the deposition drifts are much smaller than the KBS-3V deposition tunnels and they are not constructed and furnished in the same way as the KBS-3V deposition tunnels. In particular, the lack of KBS-3V type concrete plugs causes a major reduction in the total quantity of cement in a KBS-3H repository. The KBS-3H drift end plugs contain a significantly smaller quantity of cement than the KBS-3V concrete plugs. This applies to both the rock cylinder plug and the LHHP plug. If cement is not taken into account, the total quantity of materials listed in Table 10-10 is nearly the same for both alternatives.

10.5 Uncertainties and proposal for future work

A significant uncertainty as to the total quantities is caused by the unknown composition of some materials and the possible changes of design, as the KBS-3H design is being further developed at the time of the analysis by developing the new STC design. The exact composition of any material is not yet completely defined (e.g. the bolt types and grouting recipes may change in the future, and steel may be partly replaced by titanium, nickel or copper), but the largest uncertainties are associated with the following materials:

- There appears to be a great uncertainty regarding the composition of MX-80-type bentonites, which is probably due to the fact that the bentonite is not completely homogeneous.
- The crushed rock used in the tunnel backfill material is not assumed to include any significant impurities (residual materials), but this is probably far from the truth. It was not possible to consider such impurities in this work, because it is not known, whether the crushed rock to be used as tunnel backfill is originated from the construction of the repository or from some other source and because factors such as the average time of storage (which affects the accumulation of organic and air-borne impurities) and the cleaning process were also unknown.
- The various KBS-3H specific components such as drift end plugs and distance blocks are still being designed and their composition may be different from that presented in this report. The results concerning especially the BD alternative may include significant uncertainties and should be regarded merely as indicative.
- The STC alternative will replace the BD in the future development of the KBS-3H alternative. After the design of this alternative has reached the current level with BD and DAWE, the residual materials related to it should be evaluated.
- The equipment used to construct, investigate and operate the deposition drifts such as the drift boring machine will emit materials such as grease from the cutter bearings which have not been addressed in this report and need to be evaluated in future.
- Perform a similar study on a Swedish site.

11 Retrievability and delayed reverse operation

This is a description of the different barriers and components that have to be removed and defines different scenarios that can be expected during retrieval of the supercontainers.

Proposals of different feasible techniques necessary for the removal of these barriers and the retrieval of the spent fuel canisters are also presented.

11.1 Definitions

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 supercontainer after the buffer has absorbed water and starts to swell or after plugging and sealing of the drift.

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

- The waste disposal process itself must be reversible in the event a serious error or accident takes place during emplacement.
- Supercontainer recovery could be necessary as a result of supercontainer fault occurring during or after emplacement.
- Container recovery could be necessary if the repository does not function correctly.
- Retrievability is required by the licensing requirements.
- Future generations might have an interest in retrieving emplaced material to meet resource needs.

11.2 Scenarios

The following main scenarios have been identified for supercontainer recovery:

- The bentonite buffer has not absorbed water.
- The bentonite buffer has absorbed water.

In the scenario where the bentonite buffer has not absorbed water, supercontainer recovery can be carried out using the same equipment as that used for the disposal of the supercontainer, i.e., reverse operation.

Reverse operation of the deposition equipment was successfully demonstrated at Äspö HRL during the test period of the deposition equipment. Reverse operation will remain a viable option for quite a long period of time, since the supercontainer and the distance blocks are designed to keep the drift drained during the emplacement phase of supercontainers. This applies only to the DAWE alternative.

Once the entire drift or individual drift compartments have been sealed, it can be assumed that it will no longer be possible to perform supercontainer recovery by reverse operation.

In cases where the bentonite buffer has absorbed water, reverse operation may not function properly and other means will be required for supercontainer recovery, i.e., retrieval.

11.3 Techniques for retrieval

The basic principle considered for the retrieval is to free the canister from the supercontainer. Due to the swelling pressure, the canister may be held quite firmly requiring the application of considerable force to free it. Such handling may result in unacceptable damage to the canister. Therefore, it was concluded that the bentonite surrounding the canister must be removed before the canister can be retracted. The weight for retraction will also be reduced to the weight of the canister itself by this process.

Due to the different barriers (components/material) that will be introduced into the deposition drifts, a number of different techniques will be required for their removal and ultimate retrieval of the canisters.

The different techniques proposed for removal of these barriers include:

- Removal of concrete.
- Removal of bentonite.
- Removal of filling materials.
- Removal of steel components (compartment plugs).
- Cutting the supercontainer end plate.
- Removal of bentonite inside the supercontainer.
- Retrieval of the canister.
- Removal of steel shell (supercontainer).
- Cleaning of the drift.

The removal of the various barriers will take place through a combination of different techniques. It is proposed that the concrete and steel components can 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 can be used; however, tests must be performed to verify that the method will not damage the copper canister.

It has been concluded that it is plausible that the supercontainer and other components can be removed after installation. Figures 11-1 to 11-4 illustrate the sequence for the retrieval of the spent fuel canister.

11.4 Uncertainties and proposal for future work

The most significant uncertainties are the time frame for when it is possible to perform the reverse operation and the efficency of proposed techniques for retrieval.

For future work it is proposed to perform laboratory tests to verify the efficency of the hydro-demolition method and that the method does not damage the copper canister when it is freed.

The techniques for the removal of supercontainer and other components after installation must be developed further and therefore additional research and development is required.

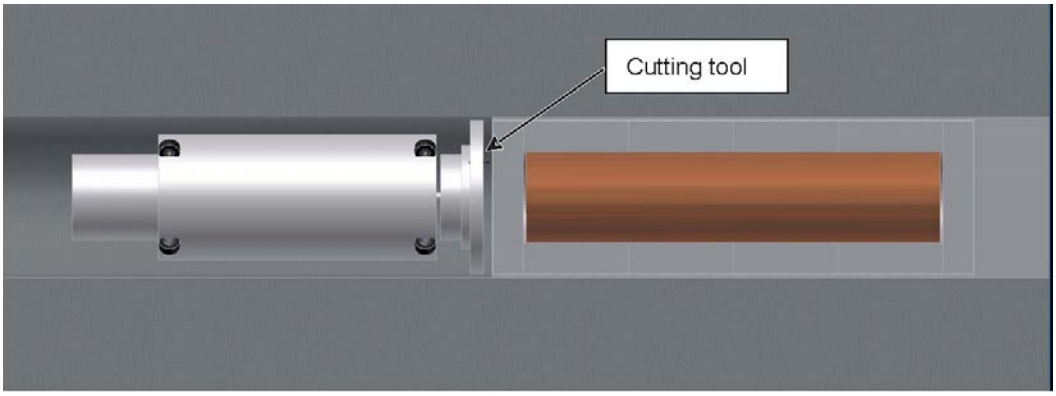


Figure 11-1. *Equipment for removal/cutting of the supercontainer end plate. Proposed technique for such cutting is water jetting.*

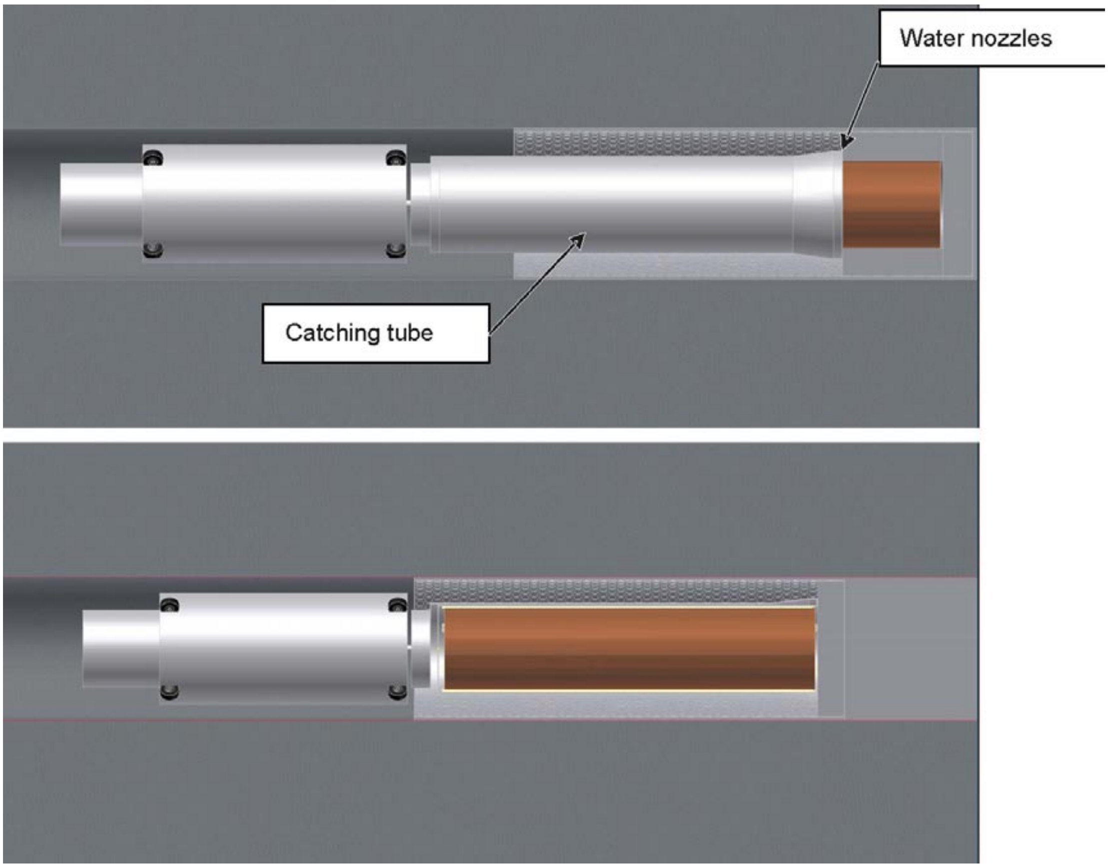


Figure 11-2. *Equipment for "catching" of the spent fuel canister. Surrounding bentonite is removed by means of hydrodynamic/chemical/hydro-demolition methods.*

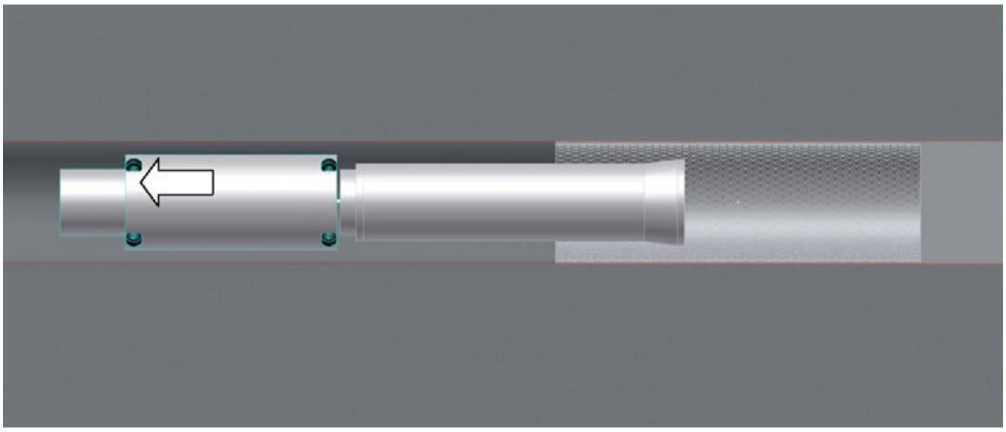


***Figure 11-3.** After removal of the bentonite the canister is transported back to the niche and transferred to a transport cask to allow transportation to other storage area.*

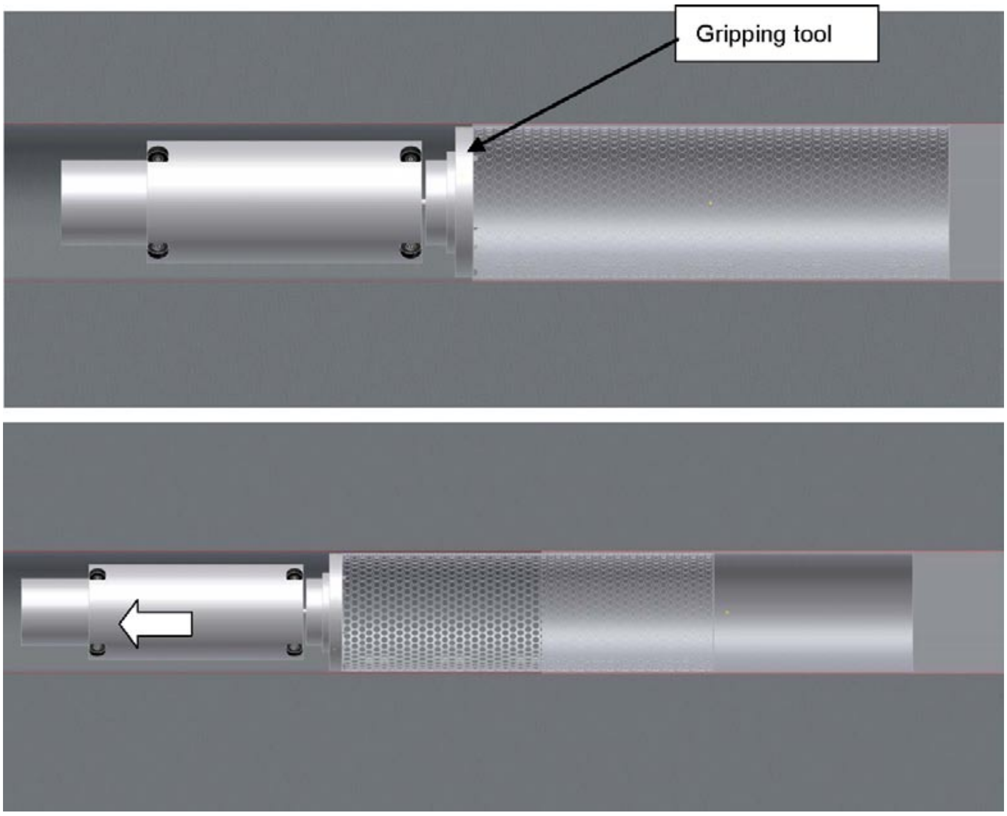


***Figure 11-4.** Catching device for removal of the steel shell.*

12 Layout adaptation at Olkiluoto site

The scope of work associated with developing this KBS-3H design description includes the preliminary adaptation of the conceptual design to the Olkiluoto site in Finland. This process has been ongoing as the KBS-3H design has evolved. The first major work on KBS-3H layout adaptation to the Olkiluoto site was carried out in 2002 /Johansson et al. 2002/. An update of the KBS-3H layout adaptation was made in early 2006 (see /Johansson et al. 2007/) and a new layout based on the present Olkiluoto bedrock model (cf. Figure 12-1) has been made recently by /Johansson et al. 2007/. The new layout is shown in Figure 12-2 and the main results of the work are summarised here. After the 2006 layout was established, some significant changes with regard to the input data occured, which justified the new layout design. The main differences with respect to the last layout work in early 2006 are the following:

- the consideration of the new Olkiluoto site model /Paulamäki et al. 2006, Ahokas and Vaittinen 2007/,
- the principle of not using imaginary (unreal) fracture zones,
- the revised respect distances to major fracture zones,
- results from a DFN modelling study /Lanyon and Marschall 2006/,
- an update of the canister spacings (different spacings for different canister types),
- respect distances to site investigation boreholes.

The new layout is based mainly on the aforementioned new models for Olkiluoto, respect distances, other design premises, distribution of water inflow, and design specifications.

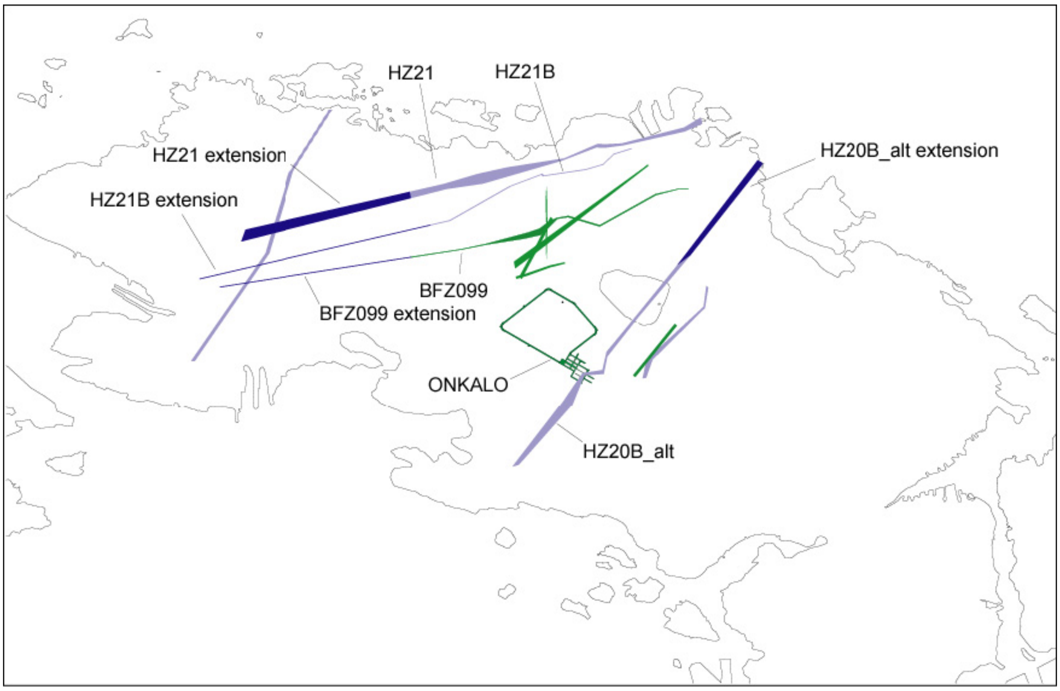


Figure 12-1. *The layout-determining fracture zones at the level –420 m at Olkiluoto showing the extensions of certain fracture zones /Kirkkomäki 2006/ which were considered in this work. HZ indicates major hydraulically conductive fracture zones. Features shown in green are not considered to be layout-determining, as they are allowed to intersect the deposition drifts, although they will require a respect distance to canister positions.*

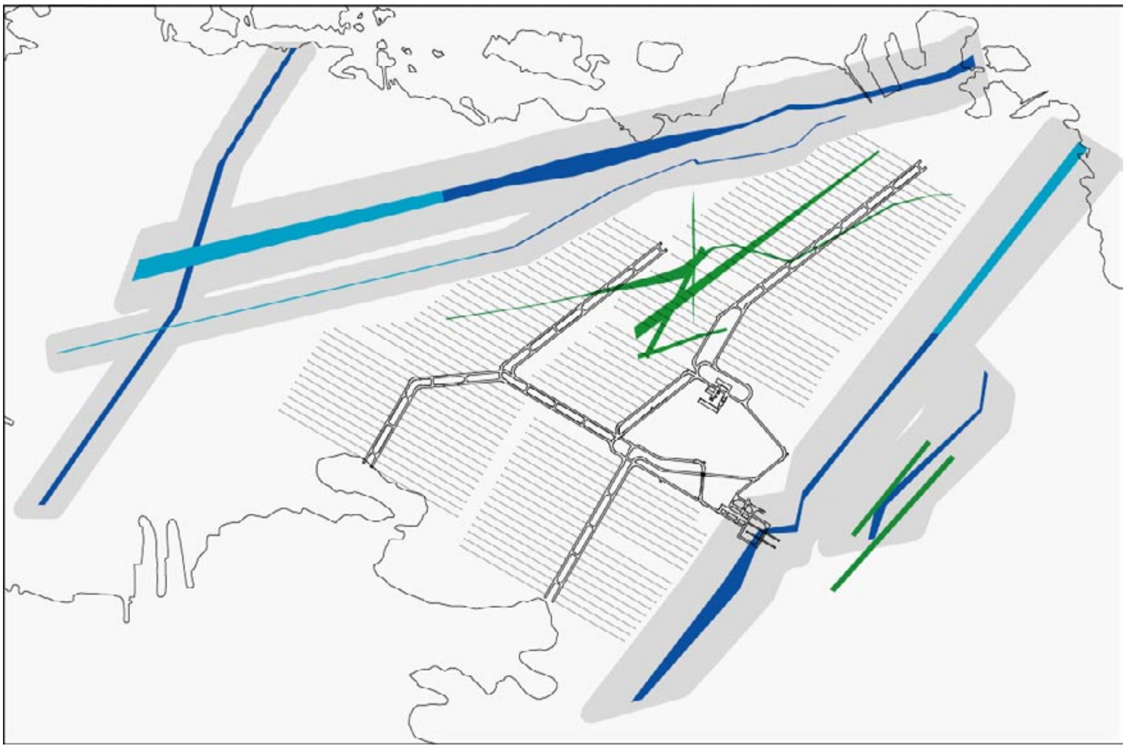


Figure 12-2. The KBS-3H layout of /Johansson et al. 2007/ with canister drift orientation of 120°, level –420 m at Olkiluoto. Grey areas indicate the respect distances to the layout-determining fracture zones (shown in blue). Features shown in green (minor fracture zones) are allowed to intersect the deposition drifts.

The total amount of spent fuel assumed in this work is based on an estimate of the quantities produced by the five nuclear reactors in operation or under construction in Finland. The number of canisters and other technical input data used in this work are presented in Table 12-1. Canister lengths, canister spacing and other details related to Posiva's three canister types are given below in Table 12-1. Otherwise the design bases used in this work are the same as those assumed in 2002 /Johansson et al. 2002/ and in the previous design in early 2006.

The input data shown in Tables 12-1 and 12-2 were used to adapt the KBS-3H layout to the Olkiluoto site at the 420 m depth level. The resulting layout, which is comparable to the KBS-3V layout /Kirkkomäki 2006/, is shown in Figure 12-2. There are 171 deposition drifts, the average deposition drift length is 272 m and the total deposition drift length is some 46,400 m. Additionally, there are 3,779 canister locations, which corresponds to the required number of canisters (2,840, see below).

Table 12-1. Details on Posiva's three canister types and their positioning in a KBS-3H repository.

Parameter/Canister	BWR 1,700 W	VVER 1,370 W	EPR 1,830 W
Canister length [m]	4.8	3.6	5.25
Canister spacing (centre to centre distance) [m] [11]	11.0 [12]	9.1 [13]	10.6 [14]
Supercontainer length [m]	5.53	4.33	5.98
Distance block length [m]	5.475	4.775	4.625
Distance block length with 5 mm gaps [m]	5.465	4.765	4.615

[11] Based on /Ikonen 2003/.
[12] Based on /Ikonen 2003/.
[13] Based on /Ikonen 2003/.
[14] Based on /Ikonen 2005/.

Table 12-2. Technical input data for the KBS-3H layout adaptation at Olkiluoto.

Parameter	Value/criterion
Number of canisters	2,840.
Repository concept	KBS-3H, one layer, no side tunnels – other parts than length of central tunnels, deposition drifts and related niches are similar to present KBS-3V design.
Fracture zone model	Layout model /Ahokas and Vaittinen 2007/ with minor modifications; no imaginary (unreal) fracture zones.
Depth level	420 m (400–420 m). [15]
Spacing between deposition drifts	25 m.
Length of deposition drift	100–300 m.
Orientation of deposition drift	120 ± 10° (parallel to main principal stress) [16]
Filling block length (blank zone)	10 m.
Compartment plug unit length	30 m.
Other space requirements	First canister 25 m from the central tunnel.

[15] For drainage purposes, the deposition drifts are not exactly horizontal; deepest point is 420 m and uppermost point 400 m. The level 420 m is used in the report.
[16] As assumed in the report by /Malmlund and Johansson 2002/ and supported by Posiva (2005).

Approximately 17% of the available bedrock resource in the deposition area is estimated to be unusable due to hydraulic properties and an additional 1% is unusable due to minor (dry) fracture zones. In addition, some 2% is estimated to be unusable due to potentially long (dry) fractures. There may also be other reasons that prevent the use of particular drift sections for disposal (for example, weathered and altered sections), but, as most of such sections are assumed to be located mainly in or near the intersections of fracture zones or drift sections where $T > 2.65 \cdot 10^{-9}$ m^2/s, their effect on the drift utilisation is rather small. However, the percentages related to minor fracture zones and potentially long fractures (1% and 2%, respectively) should be increased, because the actual effect of such sections on the required drift lengths is likely to be greater than 1 and 2 percent. This greater effect arises because the supercontainer will often have to be moved by several metres to avoid an unusable section, no matter how narrow the section. Therefore, it was assumed in the KBS-3H layout adaptation that a total of 25% of the host rock is unusable for disposal within the actual bedrock resource at Olkiluoto. This assumption requires an increase in the total drift length of 25/(100–25) ≈ 33% in the drift sections where supercontainers can be emplaced. In the layout adaptation, this can be taken into account by increasing the number of canister locations by 33%, i.e. from 2,840 to some 3,780.

The previous layout model from 2006 is presented in Figure 12-3 for comparison and the corresponding bedrock model was presented in Chapter 3 in Figure 3-5. The differences between the old and the new layouts are quite limited.

According to the latest layout, the repository can be built in one layer at a depth of 420 m at the Olkiluoto site. However, the KBS-3H layout utilises most of the area between the HZ20 and HZ21 major fracture zones. The KBS-3V layout, on the other hand, allows some area to be left unused /Kirkkomäki 2006/. Accordingly, the KBS-3H alternative requires a larger area than the KBS-3V alternative (e.g. calculating from the deposition tunnel/drift lengths 46.5 km vs. 41.1 km, KBS-3H would need ca. 10–15% more area). This requirement is mainly due to the occupation of long sections of the drift by compartment plugs (30 m) and bentonite blocks in the blank zones (10 m), which reduces the usability of the host rock and results in a larger total length of KBS-3H deposition drifts as opposed to the total length of the KBS-3V deposition tunnels. In the KBS-3V alternative, positioning of the deposition holes is very flexible, and narrow zones with moderate transmissivity usually have only a minor effect on the locations of the canisters.

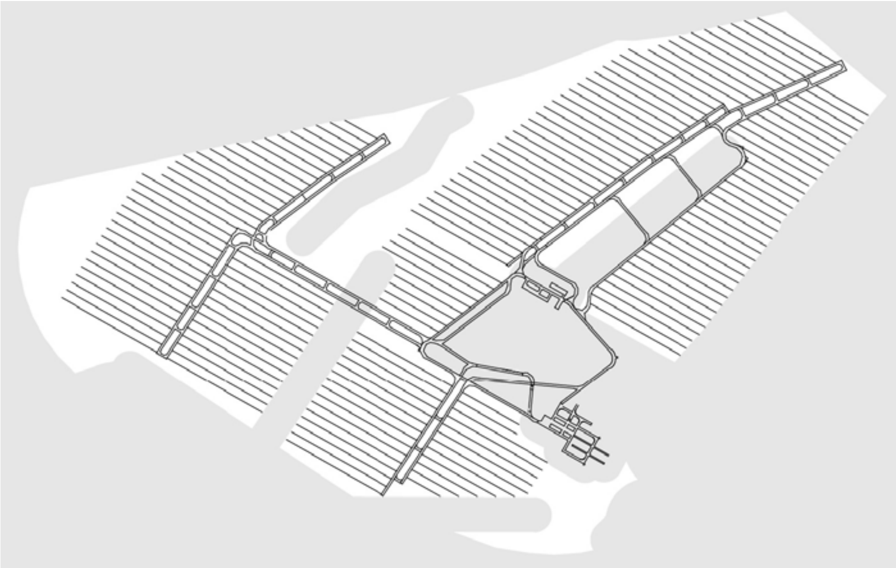


Figure 12-3. *Previous KBS-3H layout adaptation to the Olkiluoto site, depth level 400 m. White areas indicate the usable bedrock resource.*

Uncertainties and proposal for future work

The layout adaptation involves a number of uncertainties relating to, e.g., to the host rock criteria and the details of design. In addition, the layout is significantly affected by the assumed geological model of layout-determining structures which then affects the used respect distances. The layout adaptation can be updated in the future, when necessary, based on the latest bedrock model with presumably more accurate knowledge about the rock stress conditions affecting the orientation of the drifts. In addition, the development of the KBS-3H design and the updated amount of canisters to be disposed are central basic information for any new layout adaptation. Also a layout adaptation of a Swedish site should be performed.

13 Environmental assessment of the KBS-3H alternative

The environmental impact of the KBS-3H alternative has been assessed and compared to that of the KBS-3V alternative with regard to the following aspects:

- Land utilisation.
- Noise.
- Airborne emissions.
- Surface water emissions.
- Effect on groundwater.
- Resource consumption, including excavated rock, bentonite, concrete, steel & iron, explosives, injection, energy, equipment and waste.

The environmental impact of these aspects was quantified (whenever possible) and the two disposal alternatives were evaluated against one another. The results are summarised in Table 13-1.

The major differences between the KBS-3H and KBS-3V alternatives relate primarily to the handling of rock spoil and bentonite/clay. These differences have an environmental impact in the form of airborne emissions and resource consumption. There is, in many cases, a lack of data on which to base the comparison, and a more extensive environmental assessment would require further investigations and more in-depth planning of the KBS-3H method. If the KBS-3V alternative is chosen initially and later changed to KBS-3H when the facility is already operating, the environmental benefits will be less pronounced, if any at all, because the repository (underground facilities, surface buildings, machinery, organisation, etc.) will have been constructed according to the KBS-3V alternative and only limited benefits can be achieved with KBS-3H after construction.

Table 13-1. Summary of environmental aspects and difference in impact between the KBS-3H and KBS-3V alternatives (+ indicates on a positive difference on the environmental impact).

Environmental aspects	Environmental impact	KBS-3H	KBS-3V
Land usage	Little difference	+	
Noise	Little difference	+	
Airborne emissions	Substantial difference	+	
Surface waterborne emissions	Moderate difference	+	
Effect on groundwater	Cannot be assessed		
Resource consumption			
Rock	Substantial difference	+	
Bentonite	Substantial difference	+	
Concrete	Substantial difference	+	
Steel & iron	Little difference		+
Explosives	Little difference	+	
Injection	No difference		
Energy	Cannot be assessed		
Equipment	Cannot be assessed		
Waste	No difference		

14 Conclusions

14.1 Technical feasibility and uncertainties

14.1.1 General

The two main KBS-3H design alternatives (DB and DAWE) have been developed since 2005. Additionally, a new third design alternative (STC) has been introduced. There are uncertainties related to technical feasibility still to be resolved for all of these alternatives, but the nature and level of these uncertainties is different for each.

All the design alternatives are based on dividing the deposition drift into compartments of suitable quality for waste disposal. Based on the available site data the division into compartments seems feasible and the number of compartments is reasonable with respect to drift utilisation (see Section 3.5). It also reasonable to assume that compartment plugs can isolate the leaking fractures efficiently because they are clustered in a zone with limited width. This assumption is based on a site-specific feature, which may change as new information is obtained from the sites or new inflow criteria for compartment plugs are determined. Furthermore, all the design alternatives are based on the assumption that deposition drifts can be excavated according to the quality requirements. Such highly developed excavation would require accurate steering of pilot boring and has not yet been fully accomplished.

14.1.2 BD alternative

The BD alternative has been assessed as not being robust and to contain severe uncertainties because the distance blocks were not found to function according to requirements when exposed to full hydrostatic pressure as described in Section 5.6 and 5.8. The distance block in the BD alternative is the most important design component, and it was associated with significant uncertainties regarding buffer behaviour exist, as described by /Autio et al. 2007/. The most important buffer related uncertainties in the BD design were piping through distance blocks and hydraulic pressure on distance block end surfaces. The later issue was studied both theoretically and by laboratory testing and resulted in the above-mentioned conclusion.

The conclusion was also supported by drawbacks related to lengthened operational times and nonconformity with the drift quality requirements. Since the gap size between the distance blocks and supercontainer in the BD is only a few millimetres, the hydraulic force will open this gap and initiate a progressive process leading to the entire block surface being subjected to full water pressure and pushed through the fixing rings. Although the assessment of this process was based largely on FEM modelling, a set of laboratory results also supported the conclusion. The only way to resolve the problem would be to construct heavy supporting structures, similar to compartment plugs, next to distance blocks in positions with water leakages. However, such a resolution would have significant impact on other factors by increasing the operational time, lowering the drift utilisation degree, increasing cost factors, and increasing the amount of residual materials in the repository.

In principle it could be possible to use the BD alternative in very dry deposition drifts, but, considering the other drawbacks, there is not justification at the present time for doing so.

The conclusion is that the BD alternative will be put on hold and the other two alternatives DAWE and STC will be developed further.

14.1.3 DAWE alternative

The DAWE alternative has been assessed as feasible although there are several issues needing further development. Some of the uncertainties are related to the early evolution of the buffer and related processes. The most important issue is seen to be the development of the buffer swelling pressure after artificial watering and its effect on rock spalling. After wetting, water will migrate to drier parts of buffer and already saturated buffer sections may desiccate as a result. There are indications that the gap between the drift wall and buffer will remain closed and some swelling pressure may be sustained. However, the magnitude of swelling pressure is uncertain as well as the pressure needed to prevent spalling. Other early evolution related uncertainties are the swelling of buffer after artificial wetting and redistribution of water in a heterogeneous inflow environment. These processes may induce pressure gradients, giving rise to internal water flows from wet to dry drift sections.

The compartment plug is a critical component in the DAWE design. It is not present in the KBS-3V alternative and has been developed to meet the needs of the KBS-3H alternative. Therefore these plugs need to be tested to prove the viability of their design and to determine the necessity for any further development. The wetting technique, which is also closely related to pipe removal, should be developed further to optimise the number of pipes, wetting times, and to ensure that the internal wetting flows do not cause erosion of the buffer. The pipe removal has been designed for a maximum compartment length of 150 m (including compartment plug). It would be beneficial if one drift could be operated as one compartment, which would require the development of pipe removal techniques. The filling components in the DAWE alternative are preliminary and should be developed further although no significant problems are envisioned and it seems to be feasible.

14.1.4 STC alternative

The STC design alternative is at a preliminary stage and, as such, the feasibility evaluation is at a much lower level. The design has the potential to be a feasible alternative to DAWE assuming that a more detailed design can be realised and the uncertainties resolved. Although the principle is novel, some of the components are familiar from the BD and DAWE alternatives. The buffer behaviour with regard to processes such as piping and erosion has also been studied as part of the KBS-3H design development.

The most significant uncertainties in the STC design are related to the robustness of function and fulfilment of long-term safety criteria, which depend on the rate of erosion and consequent redistribution of bentonite. The present estimates include significant uncertainties related to erosion rates and expected inflows. The behaviour of the new sealing ring design components and the possibility of encountering detrimentally high hydraulic pressures because of rapidly sealing distance blocks should also be evaluated.

14.1.5 Drift utilisation degree

There are several uncertainties related to the drift layout design and the drift utilisation degree. The maximum and minimum length of deposition drifts has been assumed to be 300 and 100 m, respectively. This assumption has not been fully justified and based on the results from this phase it might be possible to define the range of length more accurately based on both cost and drift utilisation degree.

It has been assumed that the maximum length of a compartment is about 150 m including the compartment plug. However, it could be technically feasible to use one drift as one compartment, which would improve the drift utilisation degree significantly. This concept variation requires further evaluation.

The present drift end plug position is based on avoiding excavation disturbances and it might be possible to move the end plug few metres closer to the drift entrance. This repositioning would require modelling of the rock behaviour in the near field of the drift end plug.

The present estimate for the length of the compartment plug is very rough and it might be possible to reduce the length without compromising functionality. This reduction depends on site-specific factors, such as thickness of leakage zones and design specific factors such as design of filling components.

The inflow criteria for positioning filling components and compartment plugs are approximate only and are based on factors related to erosion of filling components, which have not yet been comprehensively studied. The inflow criteria are based on the conditions anticipated after sealing occurs and so is affected by the groundwater control techniques used.

Groundwater inflows reduce the utilisation degree of KBS-3H deposition drifts (number of canisters that can be emplaced in one drift) by, e.g., increasing the number of compartment plugs and filling components and impairing conditions during operation. A new groundwater control strategy based on using a Mega-Packer device is presented and may improve the utilisation degree significantly. However, it is still under development and there are several uncertainties related to the sealing efficiency to be solved by full-scale testing.

The spacing of deposition drifts in the design has been based on an Olkiluoto specific layout. The spacing can be optimised with respect to the bedrock utilisation degree or cost and the present design is based on optimizing the utilisation degree. It is not entirely clear if the present drift spacing presents the ultimate optimum.

It is noteworthy that, although the STC and DAWE alternatives have been presented as two alternatives, it is likely that they can be used in combination. Further development is needed to define the effect of different inflow parameters on the function of buffer components.

14.2 Critical issues

The presently recognized critical issues related the KBS-3H design are described below. An issue is defined as critical if there is clear uncertainty in fulfilling the design basis. The uncertainty can be purely technical or it can be related to specific processes:

- Division of drifts into compartments (all design alternatives). The uncertainty is conceptual and is site specific.
- Function of compartment plugs (all design alternatives). The uncertainty is related to design and can be improved if necessary.
- Steering of pilot boring (all design alternatives). The uncertainty is related to technical implementation since there are no proven techniques available. However, there is reasonable evidence that it could be implemented in the near future. This uncertainty could also be considered to fall into the design basis category.
- Distance block design in BD as regards the hydraulic pressure on the distance block end surfaces (DB alternative). This uncertainty was specified earlier as a critical issue and was found to ultimately render the BD alternative as not robust and reliable. The uncertainty is related to the buffer behaviour during the early evolution phase and process understanding.
- Pipe removal (DAWE). The uncertainty is related to buffer evolution.
- Buffer swelling pressure related to spalling (DAWE and STC). The uncertainty is related to buffer behaviour during the early evolution phase.
- Buffer evolution related to internal piping (all design alternatives). The uncertainty is related to buffer behaviour during the early evolution phase and process understanding (piping and erosion).
- Supercontainer shell. Selection of a suitable metal (all design alternatives).

14.3 Fulfilling of objectives

The main objectives of the 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 objectives were transferred to relevant subsidiary objectives of the KBS-3H Design subproject, the most important being to develop the present Basic Design (BD) and drainage, watering and air evacuation based (DAWE) KBS-3H candidate designs to proper levels of detail based on Olkiluoto bedrock data. The designs were to be used to evaluate the feasibility of the KBS-3H alternative. Therefore the determination of required level of details was based on the level required for cost estimate and the level required to ensure the function of the design components.

Other technical subsidiary objectives were to:

- 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.
- By means of investigations and trials show that the buffer functional requirements can be fulfilled.
- Seal at least one deposition drift by constructing a plug made of low-pH shotcrete and design alternative drift end plugs
- To develop the KBS-3H candidate designs and layout adaptation based on Olkiluoto bedrock data.
- To study the retrievability of canisters for the KBS-3H alternative.

The fulfilment of objectives was presented in most important preliminary milestones and deliveries, which were specified in the subproject plan. The most important milestones and achievements were:

- Excavation of full-scale deposition drifts at Äspö.
- Design and manufacturing of supercontainers and deposition equipment.
- A plug was made of low-pH shotcrete and tested at Äspö.
- Extensive study on buffer behaviour and fullfilment of functional requirements.
- Production of two design alternatives (BD and DAWE) and required development of design basis.
- Verification of the functioning of the most important design components by reporting of design in 2007.
- Description of the means to handle groundwater inflow including the Mega-Packer device by reporting of design in 2007.
- Planning and evaluating the testing of the Mega-Packer and compartment plug in 2007.
- Field testing of Mega-Packer device at Äspö in late 2007.
- Design of retrieval.
- Olkiluoto specific layout adaptation in early 2007.
- Finalisation of the designs in 2007.

The above-listed objectives of this subproject were with only one exception fulfilled by this report and the work described in it. One item, testing of compartment plug was postponed until the next project phase. The low-pH shotcrete plug test indicated several uncertainties in the design and therefore a cast low-pH conrete plug was specified as the reference design.

The study on buffer behaviour indicated severe uncertainties in the behaviour of BD alternative and promoted the use of DAWE alternative for future development in addition to a new schematic STC design. In addition to the above mentioned subproject objectives, several other activities were undertaken that provide important supporting functions related to the KBS-3H design, the most important being:

- Development of conceptual design for an additional third design alternative (STC).
- Extensive and comprehensive buffer testing program and development of understanding of buffer behaviour.
- Evaluation of engineered residual materials.
- TM modelling of rock behaviour around a deposition drift and effect on spalling.
- Report describing input data for the KBS-3H safety case /Autio et al. 2007/.
- Evaluation of operational safety.
- Evaluation of alternative supercontainer materials.

14.4 Need for future development

There are several design issues which will require future development and work, the most important ones were presented as critical issues in Section 14.2. In general the future work can be divided as follows:

- Detailed design of remaining key design components (e.g. filling components, sealing rings in STC, drift end plug).
- Resolution of critical issues. Most of these issues (see Section 14.2) are significant uncertainties in fulfilment of design requirements to be resolved. These can be uncertainties in design basis, understanding of processes and evolution of design components, and uncertainties in implementation.
- Optimisation of design especially with respect to drift utilisation degree. The design presented in this document is likely be conservative since the starting point has been to present a design that will function even in the most extreme conditions presented in the design basis while making allowance for uncertainties. In cases where the design basis is uncertain, conservative assumptions have been used. Therefore the drift utilisation degree can most likely be improved as discussed in Section 14.1.5.
- Verifying and demonstrating design functions under realistic conditions in combination with other relevant components. The most important components (e.g., buffer in supercontainer, distance blocks, pipe removal) should be tested at large scale (e.g., Big Bertha scale, see Sandén et al. 2008), under laboratory conditions if possible before proceeding to resource intensive in situ testing. In situ testing will ultimately be necessary to demonstrate system function. It should also be remembered that the functioning of many components are coupled to other components and therefore testing should be carried out under relevant conditions (e.g., compartment plug should be tested with filling and adjoining buffer components).

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Appendix A

Glossary

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.
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	(**K**ärn**b**ränsle**s**äkerhet). 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	(**K**ärn**b**ränsle**s**äkerhet **3**-**H**orisontell). Design alternative of the KBS-3 method in which several spent fuel canisters are emplaced horizontally in each deposition drift.
KBS-3V	(**K**ärn**b**ränsle**s**äkerhet **3**-**V**ertikal). 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 they boring of pilot hole.
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.
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.
Äspö HRL	Äspö Hard Rock Laboratory, near Oskarshamn, Sweden.

Appendix B

Long-term safety requirements for KBS-3H system components

B.1 Safety functions in the KBS-3H design alternative

The canister, the buffer (i.e. the bentonite material originally inside the supercontainers, together with the distance blocks) and the host rock are the main KBS-3H system components that together ensure isolation of the spent fuel and containment of radionuclides according to the safety concept shown in Figure B-1. Other system components, including the filling blocks, the compartment and drift end plugs, the steel supercontainers, fixing rings and other structural materials, have not been assigned safety functions. They are, however, designed to be compatible with, and support the safety functions of, the canister, the buffer and the host rock.

The main long-term safety function of the canisters is to ensure a prolonged period of complete containment of the spent fuel as in the KBS-3V alternative. 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.

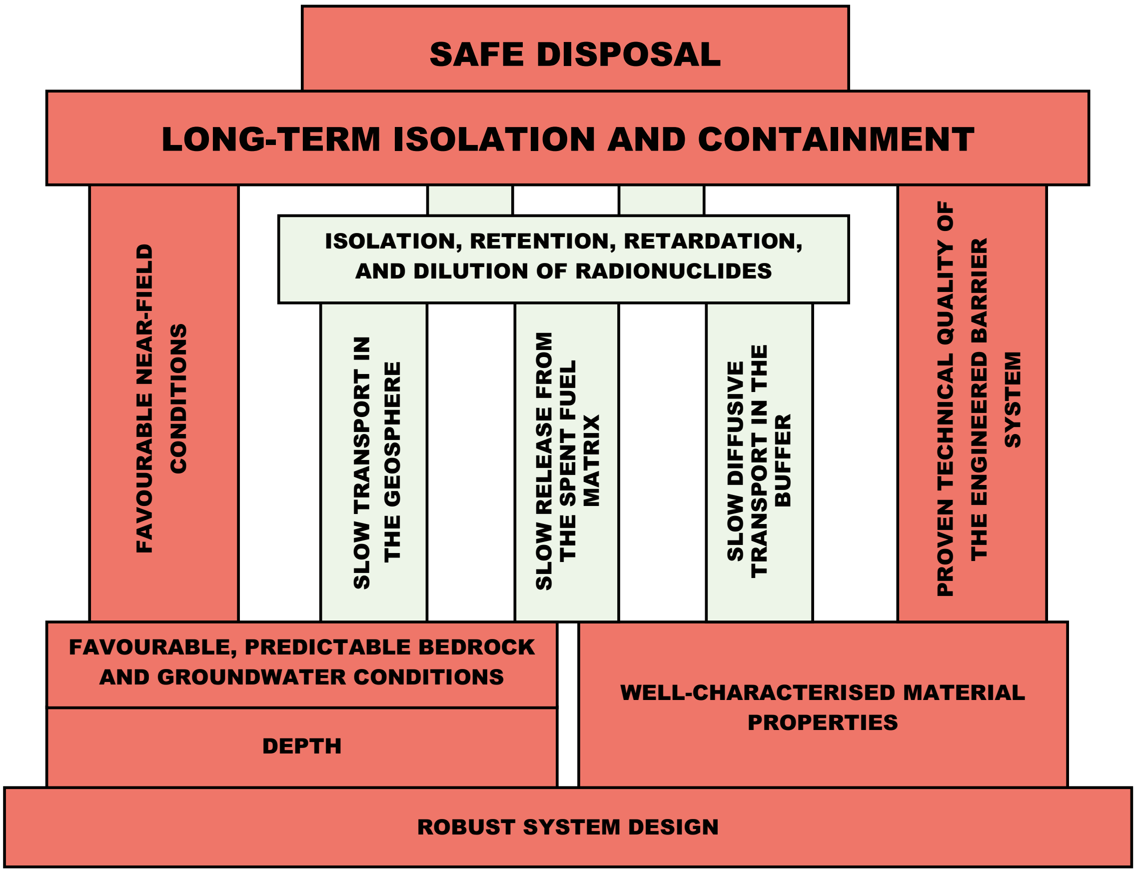

Figure B-1. *Outline of the safety concept for a KBS-3 type repository for spent fuel in crystalline bedrock. Red pillars link characteristics of the disposal system to other characteristics on which they primarily depend. Green boxes and pillars indicate secondary characteristics and dependencies (after / Posiva 2006/).*

Long-term safety functions of the buffer are (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 alternatives. The current KBS-3H design includes the use of steel components external to the canisters that will corrode over time and give rise to potentially porous or fractured corrosion products. These may interact chemically with adjacent bentonite and the slow formation of an altered zone with perturbed mass-transport properties at the bentonite/rock interface at supercontainer locations cannot be excluded. A final safety function of the KBS-3H buffer (or, more specifically, the distance blocks) is, therefore, (c), to separate the supercontainers hydraulically one from another, thus preventing the possibility of preferential pathways for flow and advective transport within the drifts through the corrosion products or altered buffer.

The safety functions of the host rock are again the same as for the KBS-3V alternative. They are (a), to isolate the spent fuel from the biosphere and normal human habitat, (b), to limit and retard inflow to and release of harmful substances[17] from the repository, and (c), to 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.

B.2 Design requirements to support the safety functions

B.2.1 Design requirements related to mutual compatibility of the system components

A requirement common to all engineered system components, including not only the canister and the buffer, but also the filling blocks, the compartment and drift end plugs, the steel supercontainers shells and other structural materials, is that they should be mutually compatible. Although all components will inevitably undergo physical and chemical changes over time (e.g. due to chemical alteration or corrosion, saturation, swelling), none should evolve in such a way as to significantly undermine either the long-term safety functions or the design functions of the others. Thus:

- no component should contain any chemical constituents that lead to significant negative effects on the performance of the others;
- no component should generate gases at rates that could lead to a build-up of potentially damaging gas pressure (taking into account the gas permeability of the other components);
- no component should give rise to mechanical stresses that could lead to significant damage to the canisters or host rock; and
- no component should undergo volume changes (due, e.g. to swelling, compaction, corrosion or alteration) that could lead to significant changes in density of the adjacent buffer.

The degree to which the current reference design meets these requirements is discussed in the KBS-3H Evolution Report /Smith et al. 2007a/, including the significance of interactions of iron and cement[18] with the buffer and (in the case of cement) the host rock, the issue of gas generation and pressurisation, the potential of swelling pressure and gas pressure to damage the rock, and the stability of the canister under isostatic loading.

Scoping calculations of potential buffer density changes during the early phase of evolution are described in the KBS-3H Process and Evolution Reports /Gribi et al. 2007, Smith et al. 2007a/. The range of densities compatible with the buffer fulfilling its safety functions taking into account the evolution of groundwater and buffer porewater salinity (1,890 to 2,050 kg/m^3) is discussed in Appendix B.5.

The following sections describe design requirements over and above the general requirement of mutual compatibility, which are intended to support the safety functions, and indicate how they are met in the current design.

[17] Including the chemically toxic components of spent fuel.

[18] No quantitative limits on the maximum amounts of such materials have been set – rather, in view of potentially adverse effects, amounts are kept as low as reasonably achievable.

B.2.2 Design requirements to support the safety function of the canister

The requirements on the canister are common for KBS-3V and KBS-3H. 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 the 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 system but the safety assessment must address less likely situations as well.

In order to achieve its design lifetime, canisters are required to have:

1. a low probability of occurrence of initial penetrating defects;
2. corrosion resistance; and
3. mechanical strength.

The probability of occurrence of initial penetrating defects is still under investigation. In the current design, corrosion resistance is provided by the copper canister shell, and mechanical strength primarily by the cast iron insert.

The minimum design lifetime also implies a number of design requirements on repository layout (avoidance of fractures that may undergo shear movements that could damage the canisters – see Section 2.2.7 of the KBS-3H Evolution Report, Smith et al. (2007a) and the buffer.

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.

B.2.3 Design requirements to support the safety functions of the buffer

The first safety function of the buffer (a, Section B.1) is to protect the canisters from external processes that could compromise their safety function of the complete containment of the spent fuel. Corresponding design requirements on the buffer are that it should be:

- sufficiently plastic (or ductile) to protect the canister from small rock movements, including shear displacements smaller than 10 cm at canister locations (the issue of potential larger shear movements caused by large earthquakes is discussed in Section 7.4.5 of the KBS-3H Evolution Report, Smith et al. 2007a);
- sufficiently stiff to support the weight of the canisters and maintain their central vertical positions in the drift in the long term;
- dense enough that microbes are metabolically barely active in the buffer and thus do not give rise to unfavourable chemical conditions at the canister surface; and
- sufficiently impermeable, once saturated, that the movement of water is insignificant and diffusion is the dominant transport mechanism for corrosive agents present in the groundwater that may reduce the lifetime of the canisters.

A further safety function of the buffer (b, Section B.1) is to limit and retard the release of any radionuclides from the canisters, should any be damaged. This implies design requirements that the buffer be:

- again impermeable enough, once saturated, that the movement of water is insignificant and diffusion is the dominant radionuclide transport mechanism;

and have:

- a sufficiently fine pore structure such that microbes and colloids are immobile (filtered) and microbe- or colloid-facilitated radionuclide transport will not occur.

It also implies a self-healing capability of the buffer, 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 are rapidly closed.

These safety functions are common to KBS-3V and KBS-3H. In addition, for the KBS-3H design the final safety function of the buffer (c, Section B.1) is to separate the supercontainers hydraulically one from another. This implies the design requirement that the buffer should provide:

- tight interfaces with the host rock within a reasonable time.

Competing requirements on buffer density are balanced in the design process. For example, excessive density would lead to a correspondingly high swelling pressure and to a risk of damage to the rock. It would also offer less protection of the canisters from rock movements. On the other hand, insufficient density would lead to the possibility of colloid-facilitated radionuclide transport. The choice of MX-80-type bentonite as a buffer material with a design target for saturated density of 2,000 kg/m^3 is made with a view to balancing these various requirements.

The filling blocks are not considered part of the buffer and are not assigned any long-term safety functions – i.e. they are not required to contribute directly to the isolation of the spent fuel and containment of radionuclides. On the other hand, in the current design, they have the same properties as the buffer as they are likely, in practice, to contribute to the limitation and retardation of the release of any radionuclides from the canisters, should any canisters be damaged.

During the saturation of the repository, high hydraulic pressure gradients and gradients in buffer swelling pressure may develop along the drifts, which could potentially lead to phenomena such as piping and erosion of the buffer and displacement of the distance blocks and supercontainers. The distance blocks and filling blocks, together with the compartment and drift end plugs, have the important design function of keeping the adjoining buffer in place, and not allowing any significant loss or redistribution of buffer mass by piping and erosion during the operational period and subsequent period of buffer saturation. The fixing rings also have the short-term safety-related design function of preventing displacement of a distance block while the adjoining components are installed. The distance blocks and filling blocks have a low hydraulic conductivity at saturation and will develop swelling pressure against the drift wall, such that friction will resist buffer displacement. Furthermore, each compartment plug is designed to stay in place under the applied loads (i.e. no significant displacement are allowed) until the next compartment is filled and a further compartment plug or drift end plug installed. Likewise, the drift end plug is designed to stay in place under the applied loads (no significant displacement allowed) until the adjoining transport tunnels are backfilled. Issues of piping and erosion and of displacement of the distance blocks and supercontainers are discussed further in the KBS-3H Process and Evolution Reports /Gribi et al. 2007, Smith et al. 2007a/.

The temperature of the buffer is kept below 100ºC to avoid significant chemical alteration of the buffer that could undermine its ability to satisfy the above requirements. This in turn imposes requirements on buffer layout and dimensioning (Section 2.2.7 of the KBS-3H Evolution Report, /Smith et al. 2007a/.

B.2.4 Design requirements to support the safety functions of the host rock

Unlike the engineered component of the repository, the implementer has no control over the undisturbed properties of the host rock, except in as far as by grouting of intersecting transmissive fractures during construction to avoid drawdown of surface waters and upconing of saline groundwaters, and by adaptation of the depth and layout of the repository, for example, to avoid unacceptable features (see, e.g. Section 2.2.7 of the KBS-3H Evolution Report, /Smith et al. 2007a/. It should be noted, however, that grouting also affects the rock mass properties. Futhermore it should be noted, however, that backfilling and sealing of the repository cavities 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 the inadvertent human intrusion to the repository more difficult. Requirements on the host rock related to site selection are similar to those for the KBS-3V design and will not be further discussed here.

B.2.5 Design requirements related to the issue of repository gas

The repository must be designed so as to avoid the build-up of potentially damaging pressures due to repository-generated hydrogen gas § This does not imply that the drifts and access tunnels need to be gas permeable, provided that gas can escape to from the drift by other routes, e.g. via transmissive fractures in the rock. The issue of gas pressurisation in the repository near field is discussed in the KBS-3H Process and Evolution Reports /Gribi et al. 2007, Smith et al. 2007a/.

B.3 Safety function indicators and criteria

B.3.1 Use of safety function indicators in safety assessment

To assess the performance and safety of a KBS-3H or KBS-3V repository, it is necessary to assess the conditions under which the identified safety functions will operate as intended, and the conditions under which they will fail, or operate with reduced effectiveness. Following the methodology adopted in the Swedish SR-Can safety assessment /SKB 2006ab/, KBS-3H safety studies make use of the concept of safety function indicators and associated criteria. One or more safety function indicators are 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. If the safety function indicators fulfil certain criteria, then the safety functions can be assumed to be provided. If, however, plausible situations can be identified where the criteria for one or more safety function indicators are not fulfilled, then the consequences of loss or degraded performance of the corresponding safety function must be evaluated in the safety assessment.

It is important to distinguish design requirements from the criteria on safety function indicators. In general, design requirements refer to 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. Repository design also aims to ensure that the criteria on the safety function indicators are fulfilled over the required time frames, but this is seen as a target, rather than as a design requirement.

Adherence to design requirements is primarily the concern of design studies, whereas safety studies focus more on the fulfilment of safety function indicator criteria, taking into account the associated uncertainties. It is emphasised that, if there are plausible situations where one or more the criteria on safety function indicators are not satisfied, this does not imply that the system as a whole is unsafe. Such situations must, however, be carefully analysed, for example by means of radionuclide release and transport calculations, as described in the Radionuclide Transport Report /Smith et al. 2007b/.

B.3.2 Safety function indicators and criteria for the canisters

Four fundamental modes have been identified by which, in principle, one or more canisters could fail to provide their safety function of complete containment of spent nuclear fuel and associated radionuclides /SKB 2006a/: i) initial, penetrating defects, ii) failure due to corrosion of copper shell, iii) rupture due to rock shear and the transfer of shear stresses from the rock via the buffer to the canister (in particular, in the event of post-glacial earthquake), and iv) collapse due to isostatic loading.

Safety function indicators for the canister are (i), minimum copper thickness – failure occurs if this is zero at any point on the canister surface, due to the presence of an initial defect that penetrates the entire thickness of the shell or due to localised and general corrosion processes leading to the gradual thinning of the shell, (ii), the isostatic pressure on the canister – failure occurs if this exceeds the isostatic pressure for collapse, and (iii), the shear stress on the canister – failure occurs if this exceeds the rupture limit. The canister safety function indicators and associated criteria, as presented in SR-Can /SKB 2006a/, are summarised in Table B-1.

Table B-1. 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.

B.3.3 Safety function indicators and criteria for the buffer

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

1. Loss or redistribution of buffer mass

The loss or redistribution of buffer mass due, for example, to piping and erosion by flowing water could in principle lead to:

- 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 increased 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 buffer hydraulic conductivity, which, if sufficiently high, could lead to 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 affect);
- 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 than 10 cm.

2. Mineral alteration of the buffer

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 affected 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.

3. Freezing of the buffer

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, 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. According to present knowledge based on past glaciations, the permafrost layer is not expected to reach more than 180 metres below ground at Olkiluoto /Hartikainen 2006/ and is thus not considered as a potential cause of major loss of buffer safety functions in the present study. The possibility that conditions at Olkiluoto could in the future differ significantly compared with those during the past glaciations and lead to buffer freezing may, however, require further consideration in future studies.

Consideration of these three possible modes for loss or degradation of the buffer safety functions leads to the safety function indicators and associated criteria that are summarised in Table B-2. Most are taken directly from SR-Can. It should be noted that the criterion given in Table B-2 that there is a negligible impact on the rheological and hydraulic properties of the buffer due to mineral alteration subsumes the SR-Can criterion for a Swedish KBS-3V repository that buffer temperature remains below 100°C. The potential chemical processes

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

Safety function indicator	Criterion	Rationale
Bulk hydraulic conductivity	$< 10^{-12}$ m/s	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 [19]	Prevent canister sinking.
Saturated density	> 1,650 kg/m^3	Prevent colloid-facilitated radionuclide transport (note, however, that higher densities may be required to fulfil the above criteria on swelling pressure – see Section B.5).
	< 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 interaction or related to temperature).	See main text.
Minimum buffer temperature	> –5°C	Avoid freezing.

[19] 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 alternative since, in KBS-3H, the weight of the canister is distributed over a larger horizontal area compared to KBS-3V.

that 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. But neither experimental or natural analogue studies have shown that these processes will actually occur. The effect of buffer cementation due to silica precipitation is, however, an issue for further work. The present criterion takes account of the concern that the buffer of a KBS-3H repository may be more affected by certain chemical interactions, and particularly those between the corrosion products of steel components external to the canisters and bentonite and those between cementitious materials and bentonite, than is the case for a KBS-3V repository.

B.3.4 Safety function indicators and criteria for the host rock

Loss or degradation of the isolation function of the host rock would occur if the Precambrian Shield were to erode away sufficiently to expose the repository at the surface (this situation, which concerns the farthest future, is discussed in Chapter 9 of the KBS-3H Evolution Report; Smith et al. 2007a). Loss or degradation of the protective function of the host rock 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. Finally, there are several rock properties that can favour its performance as a radionuclide transport barrier (for example, absence or low frequency of highly transmissive fractures, low hydraulic gradient, mineralogical and geochemical characteristics giving high retention by sorption). Safety-related aspects of the hydraulic properties of fractures intersecting a drift at canister and buffer emplacement locations are discussed in Appendix B.4. Some safety-relevant properties may vary over time (especially geochemical characteristics), potentially leading to some degradation of the host rock as a transport barrier.

The host rock safety function indicators and associated criteria as presented in SR-Can and are summarised in Table B-3.

Table B-3. Safety function indicators and criteria for the host rock (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
Maximum chloride concentration or minimum pH	$pH^{GW} > 4$ or $[Cl^-]^{GW} < 3$ M	Avoid chloride corrosion of canister
Limited alkalinity	$pH^{GW} < 11$	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

B.4 Hydraulic properties of fractures intersecting a drift at canister and buffer emplacement locations

In determining where along a deposition drift canisters and buffer can be emplaced, a key consideration is the avoidance of significant buffer loss or redistribution by piping and erosion phenomena during saturation. The potential for transient water flows to cause piping and erosion is described in Section 5.5.6 of the KBS-3H Evolution Report /Smith et al. 2007a/. There, it is noted that laboratory and modelling studies indicate that, for the current reference design, piping will not occur provided the inflow rate to a supercontainer drift section comprising a supercontainer plus a distance block during saturation is 0.1 litres per minute or less, and provided there is no significant deformation and displacement of the distance blocks relative to the supercontainers (this is an issue addressed on ongoing design developments).

There are, however, considerations related to the evolution of the repository subsequent to saturation that also have a bearing on the suitability of particular drift sections as emplacement locations. In particular, it is at least desirable that any flow through the intersecting fractures be such that:

- there is no significant long-term erosion of the buffer by flowing water that could affect its barrier function;
- the rate at which species with the potential to corrode the copper shell of the canister can migrate from the rock via the buffer to the canister surface does not lead to an unacceptable rate of loss of copper coverage, and hence early canister failure by corrosion; and
- the rock provides an effective barrier to the transport of released radionuclides in the event of canister failure.

It is also clearly desirable that canister positions are not intersected by fractures capable of undergoing potentially damaging slip as a result of large earthquakes. The buffer is expected to protect the canisters from shear displacements smaller than 0.1 m. The issue of potential larger shear movements caused by large, post-glacial earthquakes is discussed in Section 7.4.5 of the Evolution Report /Smith et al. 2007a/.

The rate of groundwater inflow to the drift during saturation is related to the transmissivity and frequency of fractures intersecting the drift. Hence, it is also related to the long-term flow subsequent to saturation (the relationship is, however, complicated by a number of factors, as discussed below). The purpose of the scoping calculations presented in this appendix is to discuss how design requirements related to the saturation period and, in particular, the requirement that inflow is 0.1 litres per minute or less, compare to desirable properties related to the post-closure evolution and performance of the repository, and especially fracture transmissivity.

The calculations assume that the system is implemented as planned. Perturbing features and processes, such as the presence of initial defects in the canisters, poor emplacement of the buffer and the possibility of processes that could disturb the buffer / rock interface (rock spalling and iron / bentonite interaction, cement-bentonite interaction) are assumed to be of negligible importance or avoided by design. Such features and processes are, however, taken into account in the overall description of system evolution in the Evolution Report.

B.4.1 Hydrodynamic relationships

Inflow and transmissivity

Assuming that saturation in a drift section occurs principally due to radial inflow from the rock (rather than water migration parallel to the drift), a relationship between fracture transmissivity and the rate at which a drift section saturates with water in the early phase of evolution may be obtained from Darcy's law in a radial configuration (Thiem's equation). Assuming that *n* fractures intersect the section:

$$Q = 2\pi \frac{\Delta P}{\rho_w \, g \ln\left(l_h / r_t\right)} \sum_{i=1}^{n} T_i \, , , \qquad \text{(Eq. B-1)}$$

with:

Q inflow from the n intersecting fractures [m^3/s].

T fracture transmissivity [m^2/s].

ΔP magnitude of the maximum hydraulic pressure difference between the drift and the undisturbed rock during saturation (about 4 MPa for a 400 m repository depth).

l_h hydraulic length (from drift to nearest major fracture zone – assumed here to be about 50 m, consistent with the modelling reported in /Lanyon and Marschall 2006/.

r_t drift radius (0.925 m).

According to this equation, a single fracture with a transmissivity 3×10^{-9} m^2/s will deliver an initial inflow of about 0.1 litres per minute, which is currently taken to be the maximum allowable value if the possibility of piping and erosion is to be avoided.

There are, however, other factors that may affect the initial inflow from transmissive fractures such that fractures with transmissivities above 3×10^{-9} m^2/s could potentially give initial inflows of less than 0.1 litres per minute. Firstly, it may be possible to reduce the initial inflow through some larger aperture fractures by injecting grout, such that significant piping and erosion do not occur during the operational period and subsequent buffer saturation, but this grout is likely to become degraded and ineffective in reducing flow in the longer term (in view of current uncertainties in the performance of any grout, an inflow of less than 0.1 litres per minute prior to grouting is used as a criterion for a drift section to be suitable for the emplacement of canisters and buffer in deriving a preliminary repository layout). Furthermore, initial inflows may also be reduced by drawdown of the water table, which will give a reduction in the hydraulic pressure at repository depth, by the impact of other open repository tunnels and drifts, and potentially by mineral precipitation and degassing in the fracture. These are generally transient effects which do not affect flow in the longer term, once the drifts are saturated. Finally, inflow is determined not only by the hydraulic properties of fractures intersecting the drift, but also by those of other connected fractures in the wider fracture network.

The impact of fracture network effects on the initial rate of inflow to a drift at canister and buffer emplacement locations is illustrated by the results of the discrete fracture network (DFN) modelling of /Lanyon and Marschall 2006/. Lanyon and Marschall constructed a series of model variants in which one or more KBS-3H drifts were positioned within a network of deterministically positioned major fracture zones and stochastically generated local fracture zones and discrete water-conducting fractures in the background rock, each with a distribution of transmissivities based on field measurements at Olkiluoto. Based on the above consideration of Thiem's equation, fractures intersecting the drift with transmissivities above about 3×10^{-9} m^2/s were considered unsuitable as canister and buffer emplacement locations, but were rather assumed to be sealed using filling blocks or compartment seals. Flow simulations were carried out to evaluate, among other issues, the time to fill the supercontainer gap volumes (assumed to be 1.38 m^3). From these times, the inflow rates [20] to drift sections containing supercontainers, which are intersected by one or more fractures with transmissivities of 3×10^{-9} m^2/s or less can be evaluated (Table B-4).

In none of the simulations did the inflow rate to the gap around a supercontainer exceed about 0.05 litres per minute, implying a 0.1 litre per minute maximum inflow rate to a drift section containing a supercontainer plus distance block. In most cases, inflow was significantly less than this. This indicates that the initial inflow criterion of 0.1 litres per minute might be satisfied if it were possible to exclude fractures with transmissivities above 3×10^{-9} m^2/s at canister and buffer emplacement locations. It does not, however, necessarily show that avoiding locations

[20] The inflow rate will, in reality, decrease with time as the gap is filled and the pressures of the fluids (water and air) inside the gap increase. The storage model used in the calculations was, however, set up in such as way that this decrease was small (high compressibility while the gap volumes are being filled).

with inflows greater than 0.1 litres per minute will ensure that there are no intersecting fractures with transmissivities greater than 3×10^{-9} m^2/s. In practice, characterisation of fractures intersecting the drift is likely to be based largely on observations made at the drift wall, including inflow. It must further be kept in mind that the impact of repository excavation on the rock matrix pore pressure around the drift, and hence on inflow, was not been considered in the model used to generate Table B-4. Nor have the possibilities of mineral precipitation and degassing reducing initial inflow been considered. All these issues require further investigation. Thus, the possibility that, in reality, some higher transmissivity fractures are present must be acknowledged.

In the following sections and in the majority of radionuclide transport calculations in the safety assessment of a KBS-3H repository at Olkiluoto /Smith et al. 2007b/, the flow around a deposition drift is calculated based on the assumption that the drift section containing the canister under consideration is intersected by a fracture with a transmissivity of 3×10^{-9} m^2/s. This is viewed as a moderately pessimistic assumption, but is not necessarily the "worst case". Intersection of the drift by a higher transmissivity fracture at the location of a failed canister is, however, considered in some variant cases in radionuclide transport calculations.

Transmissivity and aperture

Fracture transmissivity and aperture are clearly related, although the form of the relationship depends on the geometry of the fracture (the presence of constrictions, etc). For the purposes of this appendix, following /Lanyon and Marschall 2006/, it is assumed that the fracture half-aperture b_v [m] is related to transmissivity via the equation:

$$b_v = \frac{\sqrt{T}}{2c}, \qquad \text{(Eq. B-2)}$$

where c is a constant (2 seconds$^{-1/2}$).

Flow around a deposition drift

In the following sections, it is assumed that a fracture (transmissivity 3×10^{-9} m^2/s) intersects the drift at a canister location with the fracture plane perpendicular to the drift and aligned with the regional hydraulic gradient, taken to be 0.01 in current safety studies. In reality, more than one fracture may intersect a drift section, which will tend to increase overall flow, whereas flow will tend to be reduced by the dip of the fractures with respect to the regional gradient. Furthermore, fractures that will intersect the drift at a range of angles and other connected fractures will have a perturbing effect on the flow. These effects are again illustrated in the DFN modelling of Lanyon & Marschall (2006), where DFN models variants with different cut-off transmissivities are used to evaluate the flow into and out of a cylindrical volume of rock around a drift element containing a supercontainer, with its outer surface 0.5 m from the drift wall (1.425 m from the drift centre line). Values obtained by /Lanyon and Marschall/ vary significantly between drift sections, but are never more than 4×10^{-11} m^3/s (Table B-5). A single 3 ×

Table B-4. Inflow rates to the gap around a supercontainer calculated for four single drift models (derived from Table 5-6 in /Lanyon and Marschall 2006/).

Drift	Number of supercontainers	Number intersected by features in model	Inflow rate [litres per minute] Max.	Av.	Min.
W01T01	23	6	0.048	0.015	0.009
W01T12	25	9	0.019	0.006	0.003
W01T22	19	5	0.025	0.011	0.005
W01T23	17	4	0.022	0.017	0.007

Table B-5. Flows across supercontainers calculated from steady state DFN flow models for two model drifts (after Table B-1 in /Lanyon and Marschall 2006/).

Drift	Model transmissivity cut-off [m^2/s]	Supercontainers not intersected	Flow [$\times 10^{-11}$ m^3/s] Max.	Av.
W01T01	10^{-10}	15	4	1.5
W01T01	10^{-11}	1	4	0.6
W01T02	10^{-10}	14	5	0.2

10^{-9} m^2/s fracture aligned with the regional gradient and with the fracture plane perpendicular to the drift axis would give rise to a similar flow of ~ 4×10^{-11} m^3/s into and out of this cylindrical volume (3×10^{-9} $m^2/s \times 0.01 \times 2 \times 0.66$ m)[21]. It is therefore concluded that basing the flow around a deposition drift on a single fracture with the properties described above represents a reasonable assumption in safety assessment.

B.4.2 Buffer erosion

The swelling pressure of the buffer of a KBS-3H repository following saturation may be sufficient to cause bentonite to be extruded into open fractures intersecting the drift. The advancing clay front will be composed of a soft clay gel, which may potentially be eroded by flowing groundwater. There are two broad ways in which this might happen:

- mechanical erosion, in which the viscous force exerted by the flowing water on the particles of the clay gel exceeds the average particle bond strength; and
- chemical erosion, in which the concentration of cations in solution at the gel / water interface falls below the value required to maintain the stability of the gel (e.g. as a result of the penetration of dilute waters to repository depth in association with glaciation).

Either of these mechanisms may in principle cause the gel to break up and disperse in the form of colloids. They are discussed in turn below.

a. Mechanical erosion

The shear stress (traction) exerted by a laminar flow through a fracture on the buffer, τ [Pa], is given by Newton's law of viscosity:

$$\tau = \mu \frac{dv}{dy} \qquad \text{(Eq. B-3)}$$

where v [$m\,s^{-1}$] is the groundwater velocity in the fracture, averaged across its aperture, y [m] is normal distance from the buffer/rock interface and μ [Pa.s] is the viscosity of water (about 10^{-3} Pa.s). The influence of the interface on the water velocity in the fracture extends to a distance of a few fracture apertures from the interface /Liu and Neretnieks 2006/. The velocity gradient perpendicular to the buffer/rock interface is therefore of the order:

[21] The solution of Darcy's Law for flow around an impermeable circular drift shows that the fluid velocity in a fracture along a line passing through the drift centre and normal to the flow direction is $v = V(1+r_t^2/r^2)$ for $r > r_t$, where r is distance from the drift centre, r_t is drift radius and V is the undisturbed water velocity at large distances from the drift. By integrating v with respect to r between $r = r_t$ and $r = r_t + 0.5$ m, it can be shown that, because of distortion of the flow by the drift, the flow passing through the cylindrical volume is equivalent to the flow passing through a fracture of width 2×0.66 m in the undisturbed rock.

$$\frac{dv}{dy} \cong \frac{v}{b_v}. \qquad \text{(Eq. B-4)}$$

Considering a single fracture intersecting the deposition drift, and neglecting the distortion in the streamlines caused by the cylindrical shapes of the buffer, the groundwater velocity in the fracture away from the influence of the interface is given by:

$$v = \frac{T \cdot i_0}{2b_v}. \qquad \text{(Eq. B-5)}$$

where i_0 is hydraulic gradient (0.01).

From Eq. B-3 to B-5:

$$\tau \cong \frac{\mu T i_0}{2b_v^2}. \qquad \text{(Eq. B-6)}$$

If a fracture intersecting the drift at supercontainer and distance block emplacement locations is assumed to have a transmissivity of 3×10^{-9} m^2/s, then, according to Eq. B-2, the fracture half-aperture is in the order of 10^{-5} m. For a hydraulic gradient of 0.01, Eq. B-6 gives a shear stress in the order of 10^{-4} Pa. In practice, the fracture aperture is likely to vary locally around the buffer / rock interface, giving some corresponding variability in the shear stress, which may be higher or lower than the 10^{-4} Pa indicated above. However, while a locally smaller aperture will, according to Eq. B.2-6, give rise to a higher shear stress, this does not take account of the mitigating effect of channelling – i.e. flow will tend to be channelled around any local constrictions, offsetting to some extent the effect of the smaller aperture on shear stress.

The typical Bingham yield stress of the gel front is strongly dependent on the composition of the clay and ionic strength of the water, but a review of experimentally determined values by Liu & Neretnieks (2006) indicates that 1.0 Pa may be taken as a conservative estimate of the minimum shear stress required for mechanical erosion. The expected shear maximum stress is around four orders of magnitude smaller than this once the influence of transient pressure gradients associated with repository saturation has passed, which implies that no mechanical erosion will occur once the repository is saturated, in spite of the uncertainties noted above associated with the variability of aperture, the effects of channelling and the possibility that fractures with transmissivities greater than 3×10^{-9} m^2/s will intersect the drift at canister and buffer emplacement locations. Some limited erosion associated with piping during the saturation phase cannot, however, currently be excluded.

b. Chemical erosion

The next glacial retreat, and hence the next possibility for penetration of glacial meltwater to repository depth, is assumed to be in 70,000 years time, according to the Weichselian-R climate scenario. Penetration of glacial meltwater to repository depth could lead to some chemical erosion of the buffer (see Section 7.4.7 of /Smith et al. 2007a/.

Significant erosion is here defined as that required for advective conditions to occur within the buffer. /Börgesson and Hernelind 2006/ have calculated the buffer swelling pressure for cases where, in the KBS-3V alternative, one, two and three entire bentonite rings surrounding the canister have been omitted, to illustrate the effects of a local loss of large amounts of bentonite.

The conclusion was that a mass loss of 1,200 kg to a fracture intersecting the deposition hole would lead to conditions where advective conditions in the buffer must be considered. Due to the similarity between the deposition hole diameter in KBS-3V (1.75 m) and the deposition drift diameter of in KBS-3H (1.85 m), this conclusion can be taken to apply to both alternatives.

A model of chemical erosion has been developed by SKB for SR-Can. If the model is applied to a KBS-3H repository at Olkiluoto, the results indicate that significant erosion could occur in a single glacial cycle if fractures intersecting the buffer have transmissivities in excess of about 3×10^{-8} m^2/s. The SKB model is, however, tentative (a new model is currently under development by SKB / KTH) and model uncertainties are probably too great to draw any firm conclusions regarding those fractures that should be avoided in emplacing supercontainers and distance blocks.

B.4.3 Canister corrosion

A model for the time required for canister failure by corrosion to occur for a given set of flow conditions around the drift and a given groundwater sulphide concentration is given in Appendices B.8 and B.9 of the Evolution Report /Smith et al. 2007a/. Assuming that no processes occur that lead to detrimental perturbations to the buffer or buffer / rock interface, canister lifetime (t_a [s]) is given by:

$$t_a = \frac{d}{c_{local} j_a}, \qquad \text{(Eq. B-7)}$$

with:

d thickness of the copper canister shell (0.05 m)

c_{local} factor for uneven corrosion of copper [-] (50, note – a lower value of 5 was used in earlier studies in Finland – p 94 of /Vieno et al. 1992/; a higher and more conservative value is, however, consistent with current understanding, as described, for example, in SR-Can, where a factor of about 35 is used)

j_a copper corrosion rate [m/s].

Noting that 2 moles of copper are corroded per mole of sulphide arriving at the canister surface, the maximum rate of uniform copper corrosion is given by:

$$j_a = \frac{2 f_{\max}}{\rho_c} \frac{N_c}{N_s}, \qquad \text{(Eq. B-8)}$$

with:

ρ_c density of copper (8,900 kg/m^3).

N_c molar weight of copper (64 g/mol).

N_s molar weight of sulphide (33 g/mol).

f_{max} rate of arrival of sulphide at the canister surface at the location where this is the highest (directly opposite the fracture/drift line of intersection) [mol/s].

f_{max} is given by:

$$f_{\max} = \frac{\pi D_e C_s}{2(r_t - r_c)} \frac{1}{\log_e\left(\frac{2(r_t - r_c)}{b_v}\right)} \frac{Q_b}{Q_b + Q_f}, , \qquad \text{(Eq. B-9)}$$

with:

D_e effective diffusion coefficient of anions in the saturated buffer (10^{-11} m^2/s; Table A-11 of SKB 2006b).

r_t drift radius (0.925 m).

r_c canister radius (0.525 m).

b_v fracture half aperture (from Eq. B-2).

C_s concentration of sulphide in groundwater approaching the drift [kg/m^3] (see below).

Q_b [m^3/s] and Q_f [m^3/s] are transfer coefficients given by:

$$Q_b = \frac{A_{frac}}{\pi}\sqrt{\frac{2D_w T \cdot i_0}{r_t b_v}}\ , \qquad \text{(Eq. B-10)}$$

and

$$Q_f \approx \frac{\pi D_e A_{frac}}{2b_v \log_e\left(\frac{2(r_t - r_c)}{b_v}\right)}\ . \qquad \text{(Eq. B-11)}$$

D_w [m^2/s] is the diffusion coefficient of ions in free water (2×10^{-9} m^2/s) and A_{frac} [m^2], the area of intersection of the fracture with the drift, is given by:

$$A_{frac} = 4\pi b_v r_t\ , \qquad \text{(Eq. B-12)}$$

In deriving Eq. B-9, it is assumed that the buffer has uniform transport properties from the canister surface to the drift wall. In reality, there are a number of features and processes that could perturb mass transfer in the buffer and at the buffer / rock interface. The impacts of such features and processes are considered in Appendix B.7 of the Evolution Report /Smith et al. 2007a/.

Figure B-2 shows the calculated canister lifetime as a function of the transmissivity of a fracture assumed to intersect the drift adjacent to a canister position, for different values of groundwater sulphide concentration:

- 12 mg/l (the highest currently observed value);
- 42.5 mg/l (the maximum value calculated for future times – see /Pastina and Hellä 2006/.

The results show that the canister lifetime exceeds the minimum design lifetime of 10^5 years by one to two orders of magnitude in the case of a transmissivity of 3×10^{-9} m^2/s. It continues to exceed the minimum, though by a reduced margin, as fracture transmissivity is increased. This is because, even at high transmissivities, the barrier to sulphide transport provided by the buffer severely limits the rate at which sulphide can reach the canister surface. Consideration must, however, be given to the possibility of chemical erosion of the buffer at high transmissivities, as discussed in Section (iii) (this and the impact of other possible perturbations to the buffer and the buffer / rock interface are discussed in Appendix B.7 of Smith et al. 2007a).

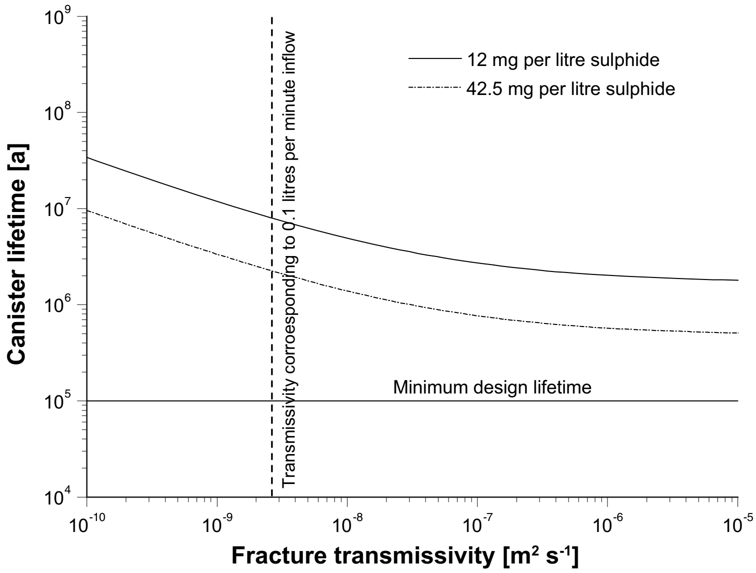

Figure B-2. Canister lifetime as a function of fracture transmissivity for two different groundwater sulphide concentrations.

B.4.4 Geosphere transport barrier

In terms of the hydrogeological properties of the rock, the effectiveness of the geosphere and a transport barrier to radionuclides released in the event of canister failure is a function of the "transport resistance", defined as W / Q, where W [m] is the width of a representative transport path within the fracture network, L [m] is the transport distance along this path and Q [m^3/a] is the flow through the path. Experience from past Posiva safety assessments is that a value of WL / Q of a few thousands or more years per metre provides an effective barrier to the transport of many safety relevant radionuclides (the median value for all sites given in TILA-99 is 5×10^4 years m^{-1} – see Section 11.6 in /Vieno and Nordman 1999/.

The transport resistance of a single fracture may also be expressed in terms of transmissivity:

$$\frac{WL}{Q} = \frac{L}{Ti_0}. \qquad \text{(Eq. B-13)}$$

In a heterogeneous geosphere, the transport resistance is additive along different sections of the overall transport path. It is, however, likely that, where the migrating radionuclides encounter higher-transmissivity features, low transmissivity fractures between the near-field/geosphere interface and some point within the geosphere, perhaps a few tens of metres away, dominate the transport resistance.

Figure B-3 shows transport resistance plotted against transmissivity for transport path lengths of 10 m, 50 m and 100 m, where transmissivity is to be understood as the transmissivity of fractures intersecting the drift near a canister emplacement position, and transport path length is the assumed distance from the drift to the most highly transmissive features along the transport path.

The figure shows that, for a pessimistic transport path length of 10 m to the nearest higher-transmissivity fracture, a transmissivity of about 3×10^{-9} m^2/s provides a transport resistance of the order of 10,000 years per metre, and thus a effective geosphere transport barrier for many safety-relevant radionuclides (this is roughly equivalent to the transmissivity giving rise to a maximum 0.1 litre per minute inflow during saturation).

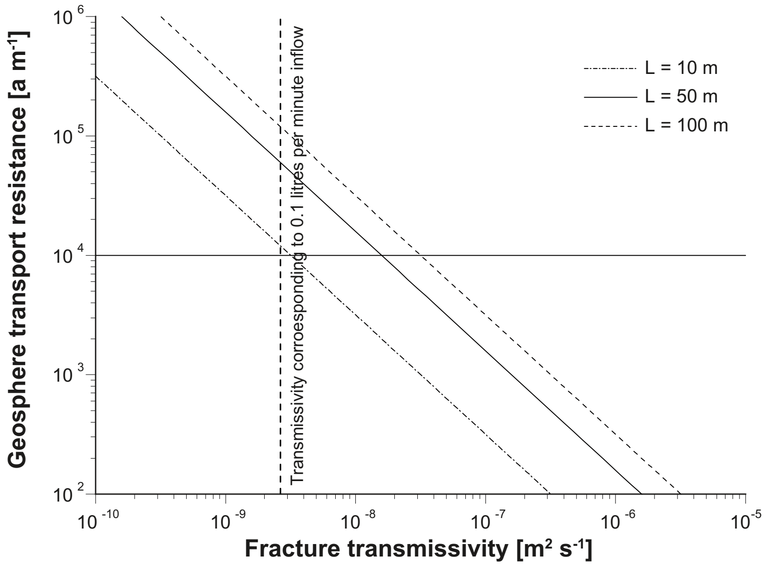

Figure B-3. *Transport resistance plotted against transmissivity for different transport path lengths. The figure indicates the fracture transmissivity which is assumed to give rise to a maximum 0.1 litre per minute inflow during saturation (see, however, the caveats given in Section (ii)).*

/Lanyon and Marschall 2006/ carried out steady state flow modelling using their discrete fracture representation of the Olkiluoto site, and evaluated transport resistances from various supercontainer deposition locations to the outer boundary of their model, 50 m from the modelled deposition drift. Histograms of the results for model drift W01T01, which were obtained using particle tracking, are shown in Figure B-4. The results show that none of the particle tracks gave transport resistances less than about 5×10^4 years m^{-1}, the highest value being obtained for supercontainer location W01T01:CO16. The results for other modelled drifts gave still higher minimum transport resistances (see Figure B-3 parts b–d in /Lanyon and Marschall 2006/. Figure B-5 shows particle tracks from which the lowest transport resistance was calculated (supercontainer location W01T01:CO16, which is circled in red). In this realisation of the DFN model, supercontainer location W01T01:CO16 is separated by a distance block from a 10 m section of filling blocks intersected by a fracture with a relatively high transmissivity of about 10^{-7} m^2/s. Even in this location, although the smallest transport resistance is about 5×10^4 years m^{-1}, the mean is about an order of magnitude higher.

This discussion suggests that an assumption of a transport resistance of 5×10^4 years m^{-1} is conservative for the purposes of geosphere transport modelling, and is assumed in analysing many of the assessment cases in the Radionuclide Transport Report /Smith et al. 2007b/.

B.4.5 Conclusions on the transmissivity criteria

The scoping calculations presented some above illustrate the potential impact of fracture transmissivity on various processes relevant to long-term safety.

Considering the possibility of failure by corrosion, the canister lifetime will remain well in excess of the minimum design lifetime of 100,000 years, irrespective of fracture transmissivity (the impact of perturbations to the buffer on canister lifetime is considered in Appendix B.7 of the Evolution Report, /Smith et al. 2007a/. Mechanical erosion of the buffer is shown to be irrelevant even at high transmissivities. In the case of chemical erosion due to the penetration of dilute glacial meltwater to repository depth, model uncertainties are probably too great to draw any firm conclusions regarding those fractures that should be avoided in emplacing supercontainers and distance blocks. It should, however, be noted that the next possibility for penetration of glacial meltwater to repository depth is in 70,000 years time and, even if advective conditions then become established in parts of the buffer, it will take time for canister failure to occur – thus the minimum design lifetime may still be achieved.

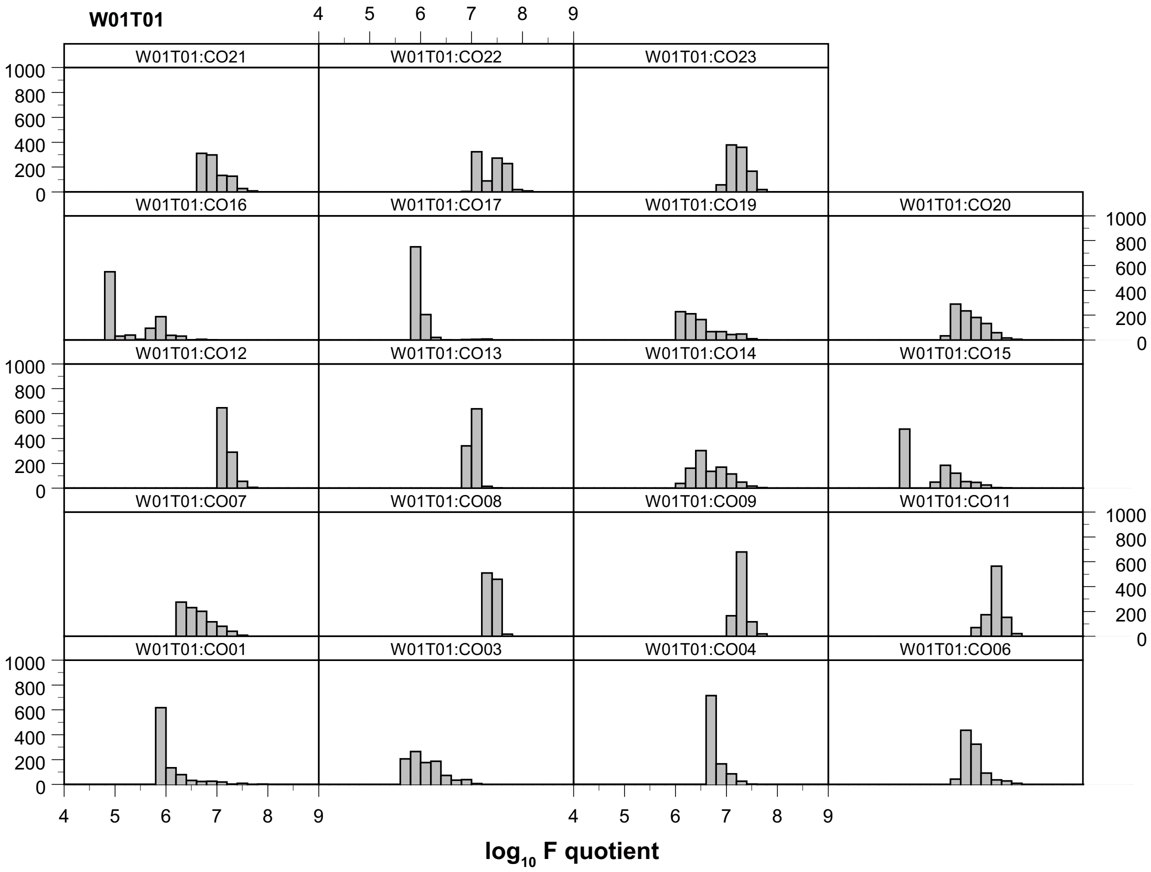

Figure B-4. *Histograms of transport resistances (termed here F quotient) from particles released at different supercontainer locations in a DFN model of the Olkiluoto site (after Figure B-3 of /Lanyon and Marschall 2006/).*

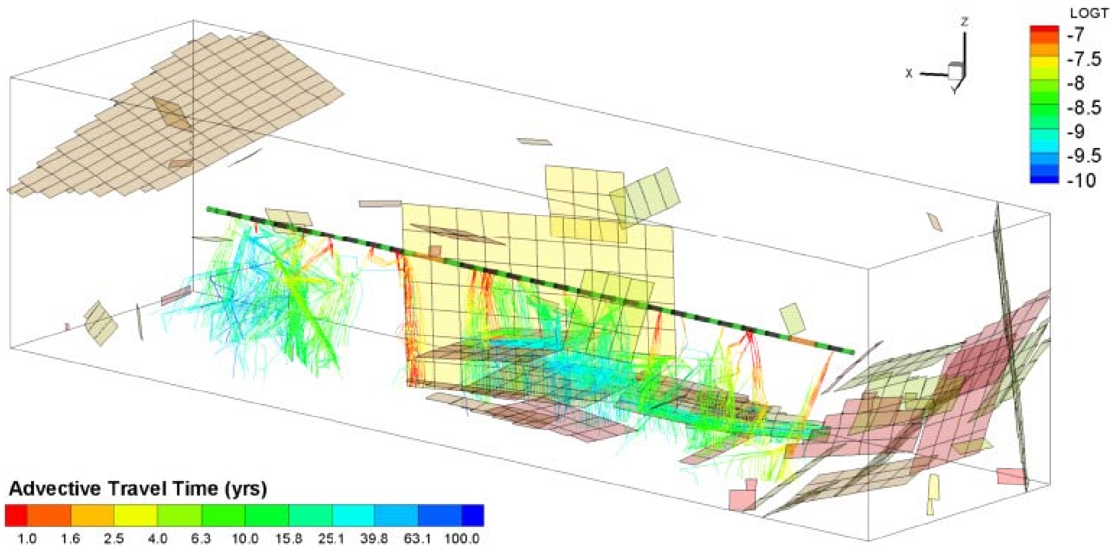

Figure B-5. *Particle tracks from supercontainer drift elements. Supercontainer location W01T01:CO16, which gives the lowest calculated transport resistances, circled in red. Tracks coloured by travel time. Features coloured by log transmissivity, only features with transmissivity greater than 10–8 m²/s are shown (after Figure B-1 of /Lanyon & Marschall 2006).*

In terms of the transport barrier provided by the geosphere, a 10 m long transport path having a transmissivity of about 3×10^{-9} m^2/s provides a transport resistance in the order of 10,000 years per metre, which corresponds to an effective geosphere transport barrier for many safety-relevant radionuclides. This is also roughly the transmissivity giving rise to a maximum 0.1 litre per minute inflow during saturation – i.e. the maximum inflow if the possibility of piping and erosion is to be avoided – see, however, the caveats given in Section (ii).

Overall, it is concluded that a transmissivity limit of about 3×10^{-9} m^2/s for fractures intersecting the drift at canister and buffer emplacement locations desirable from the point of view of long-term safety. This criterion is derived in the first place from considerations of the geosphere transport barrier, being the most restrictive of those described in this appendix. In practice, however, it is unlikely that a transmissivity criterion can be applied directly in selecting locations for canister and buffer emplacement. Characterisation of fractures intersecting the drift is likely to be based largely on observations made at the drift wall, and other quantities including inflow, that can be measured directly, rather than on transmissivities inferred from a model that are therefore subject to greater uncertainty.

There are various mechanisms, such as erosion by transient water flows, whereby some loss or redistribution of buffer mass may occur during the saturation of a KBS-3H repository – Sections 5.4 and 5.5 of the KBS-3H Evolution Report /Smith et al. 2007a/. The magnitude of the resulting changes in density affects whether many of the safety function indicator criteria on the buffer remain satisfied. Buffer density is a safety function indicator. The hydraulic conductivity and swelling pressure of the buffer, which are also safety function indictors, are functions of buffer density. They are also, however, functions of buffer pore water salinity, which will vary over time due to transient changes in the groundwater. This appendix discusses how, in the case of a KBS-3H repository at Olkiluoto, provided the saturated buffer density remains in the range of about 1,890 to 2,050 kg/m^3 (the design density is 2,000 kg/m^3), changes in swelling pressure and hydraulic conductivity caused by salinity variations are expected to be minor, and the criteria on the buffer safety function indicators will continue to be met.

B.5 Range in buffer densities ensuring that relevant safety function indicators are satisfied for a KBS-3H repository at Olkiluoto

The upper bound for saturated buffer density that the buffer can be assumed to perform its safety functions (2,050 kg/m^3) is taken directly from Table B-2 and is based on the requirement on the buffer to protect the canisters in the event of rock shear movements. The lower bound of 1,890 kg/m^3 is derived firstly from the requirement on the buffer to prevent significant microbial activity. The corresponding safety function indicator criterion given in Table B-2 is a swelling pressure of 2 MPa. Studies indicate that bacterial activity will be suppressed, and both culturability and viability will decrease, at swelling pressures exceeding 2 MPa /Stroes-Gascoyne et al. 2006, Masurat 2006/. It is likely that microbes are barely active under these conditions (although this is an issue that is still under investigation). Below about 2 MPa, however, significant microbial activity cannot be excluded. This lower bound for swelling pressure is met for 0.3 M NaCl solution (corresponding roughly to the present-day 10–20 g per litre total dissolved solids – TDS – at Olkiluoto) if the dry density is above about 1,300 kg/m^3 (1,830 kg/m^3 saturated) (see Figure 4-7 of /SKB 2006a/. A conservative estimate of the maximum salinity that could occur at a depth of about 550 m at Olkiluoto at future times is 30–45 g per litre. There is currently about 12 g per litre of TDS at repository depth (420 m below ground), which may rise transiently to around 25 g per litre as a result of the upconing associated with excavations, before decreasing again as a result of continuing post-glacial uplift (Figure 4-1 of /Smith et al. 2007a/. For a 1 M NaCl solution (which corresponds to about 60 g per litre TDS) a 2 MPa swelling pressure is achieved at a dry density of about 1,400 kg/m^3 (1,890 kg/m^3 saturated).

In addition to preventing significant microbial activity, a saturated density of 1,890 kg/m^3 will prevent colloid-facilitated radionuclide transport (Table B-2 of the present appendix – see also Section 2.5.4 of /SKB 2006c/ for further discussion). Furthermore, since the swelling pressure will never be less than 2 MPa, irrespective of salinity variations in the expected range, it will also prevent the possibility of canister sinking and ensure tightness at the drift wall and self sealing capability (Table B-2). Finally, it will ensure diffusion-dominated transport in the buffer, given that hydraulic conductivities of less than 10^{-12} m^2/s are measured in MX-80-type bentonite in saline conditions at dry densities above about 1,200 kg/m^3 (1,760 kg/m^3 saturated) (see Figure 4-8 of /SKB 2006a/). Diffusion dominates over advection as a transport process at these low conductivities.

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Appendix C

List of input parameters

The purpose of this appendix is to list the input data used in this report and in the other KBS-3H long-term safety study reports. Data used in this report are based on the preliminary information available at the time of the writing of the long-term safety reports (2006–2007). Design data are to be considered preliminary as the KBS-3H design work is still in progress. The information for design provided in this table is mostly based on the information given in the main text and other Appendices of this report. A generic report on data, models, codes, and databases that would apply both to the KBS-3V and KBS-3H will be produced at a later time.

C.1 Origin of input data

The data in Table C-1 is based on different origins, as discussed below. The references are in the table next to the data. Design data are to be considered as preliminary as the design work is still in progress.

- Repository depth: the values are from the preliminary design for a KBS-3V repository in Olkiluoto.
- Deposition drift: the drift diameter is from the buffer design studies and design descriptions 2006 and 2007 (the latter for tolerances). Drift length and separation between drifts are from the Layout Adaptation report. The drift dip appeared first in the KBS-3H summary report 2004. The drift orientation is from the Layout adaptation report and the main principal stress is from the Olkiluoto Site Description 2004.
- Canister and insert: dimensions are from the canister design report for all fuel types. The 2006 spent fuel inventories for Posiva's fuel types are from the KBS-3V Evolution Report.
- Supercontainer shell: supercontainer shell material, dimensions and surface areas (including hole edges and feet) are from the DD-2006. Carbon steel composition is from the European Structural Steel Standard EN 10025. Shell diameter and steel thickness as well as perforation hole diameter and degree of perforation are from KBS-3H buffer studies. Alternative values for other fuel types (VVER and EPR) are from the Layout Adaptation report and the Canister Design report.
- Buffer rings and end blocks: Initial water content of the buffer ring is 10% after KBS-3H buffer studies (Buffer study report 2002–2004). Buffer block length and gap to canister are also from the same studies. Other buffer dimensions are from the DD-2006. The saturated porosity of the buffer is from SKB's SR-97 Process report and the swelling pressure is from SR-Can Main report. The reference value of buffer porosity is used in scoping calculation in this report and in the Evolution Report. The alternative value was used in the radionuclide transport calculations, according to SR-Can.
- Distance blocks: all data concerning the Basic Design is from the DD-2006 and references therein. Data concerning the DAWE design is partly from KBS-3H buffer studies.
- Fixing rings: Data is from the DD-2006, the *assumption* on the number of fixing rings in a drift (4–5) is from the Residual Materials report.
- Filling blocks: all data is from the DD-2006. Filling blocks have not yet been designed in detail so the information is very preliminary at this stage.
- Plugs: all data is from the DD-2006. The composition of the low-heat high performance cement is from AECL (Canada) but this type of plug has not been tested yet in the Olkiluoto conditions.
- Spray and drip shields: the description is from the DD-2006, the *assumption* on the inventory is from the Residual Materials report. In these reports, the thickness of these shields is not reported. In the present report, the *assumption* on the thickness (1 mm) was made to calculate the amount of gas generated per shield (see Section 5.5.1).

- Backfill: the *assumptions* on backfill inventories for the deposition niches and the access tunnels are from the Residual Materials report. The backfill material has not yet been selected.
- Cement and colloidal silica: the *assumptions* on cement inventory for the deposition niches and the access tunnels are from the Residual Materials report. Grouting estimates are based on ONKALO grouting experience, scaled to the relevant drift size. Grouting cement composition is *measured* on samples from ongoing cement tests in ONKALO. The composition of colloidal silica used for grouting is measured and comes from the Silica Sol supplier (BASF via EKA Chemicals).
- Bentonite: MX-80-type bentonite composition is from SR-Can Main report.
- Steel: steel corrosion rate for the supercontainer shell and the cast iron insert is from *experimental work* on steel corrosion rates in presence of bentonite. *Expert judgment* has been exercised in selecting the long-term steel corrosion rate based on experimental studies and natural analogues information available in the literature. The rationale for rate selection is described in Section 2.5.1 and Section 5.7.1 of the present report.
- Rock properties:
  - Geochemical properties: TDS (Total dissolved solids) data in present day conditions is from the Olkiluoto Site Description 2006 and is a sum of concentrations of cations and anions *measured* at the repository depth (400–500 m). Hydrochemical data are from the OIVA database. This database is continuously updated along with the new data collected from Olkiluoto, as described in /Pitkänen et al. 2007/. The data table used for this report was from the file called "uusiOIVA_10032006.xls". Future evolution of the TDS is from the KBS-3V Evolution Report and they are the result of *modelling* work and *expert judgment*. pH, redox potential, dissolved metals, dissolved gases are *measured* data. Solubilities of gases were taken from the literature.
  - Geological properties: Fractures are from the geological *model* presented in the Site Description 2006. Fracture density and transmissivity are *calculated/assumed* statistical analyses of vertical borehole data from depths of 300–700 m at Olkiluoto /Hellä et al. 2006/. The hydraulic conductivity range of mica gneiss and gneiss is *estimated (expert judgement)* from a range of rock conditions. Rock porosity, gas effective diffusion constant and gas intrinsic permeability are *measured* on Gneissic tonalite in the Research Tunnel at Olkiluoto. Hydraulic conductivity was *calculated* from the gas permeability values using a scaling factor to convert to diffusivity of heavier molecules in water- saturated samples by 1/35,000 /Autio et al. 1999/. EDZ properties are from *observations and measurements* in the Research Tunnel at Olkiluoto. EDZ properties at repository depth are still highly uncertain at present.
  - Hydraulic properties: leakage rates in a drift without sealing are *estimated* based on statistical analyses of borehole data. The leakage after grouting in a drift is from the KBS-3H DFN model /Lanyon and Marschall 2006/. The maximum inflow *calculated* in all realisations is about 15 L/min with less than 1% of drifts exceeding 10 L/min. The saturation time for the drift is *calculated* from buffer studies. The hydraulic gradient is based on site-scale groundwater flow modeling results /Löfman 1999/.
  - Mechanical properties: stress state is from in situ borehole measurements at relevant depths, as reported in the Olkiluoto Site Description 2006. Rock strength values (including spalling strength) are *estimated* based on laboratory tests on core samples from Olkiluoto and in situ observations from the Äspö Pillar Stability Experiment. Some *expert judgment* was applied in deriving the Olkiluoto in situ rock strength from laboratory results and Äspö observations.
  - Thermal properties: the temperature of the Olkiluoto rock at repository depth has been *measured.*

Table C-1. Input parameter values for the KBS-3H Process Report and in other KBS-3H long-term safety reports.

PARAMETER	Unit	Symbol	Reference value	Alternative values	Reference
REPOSITORY DEPTH					
one-storey	m		400–420		/Saanio et al. 2004/.
two-storeys	m			420 and 500–520	/Saanio et al. 2004/.
DEPOSITION DRIFT					
Diameter	mm	$2\ r_t$	1,850 0/–10mm	1,840	/Börgesson et al. 2005/, /Autio et al. 2007/, tolerances are from this report.
Length	m		300 (272 mean)	100–300	/Johansson et al. 2007/. The total length includes the deposition niche.
separation between drifts	m	d	25	40	/Johansson et al. 2007/.
Drift dip	°		2 +/–1		/Thorsager and Lindgren 2004/.
Drift orientation	°		120 +/–10, parallel to main principal stress		/Johansson et al. 2007/, /Posiva 2005/.
CANISTER					
Reference case					
Posiva, BWR 1,700 W					
outer diameter	mm	$2\ r_c$	1,050 $^{+2,35}/_{-2,35}$		/Raiko 2005/, tolerances are from this report.
Length	mm	l_c	4,800	4,835 $^{+2,85}/_{-2,35}$	/Raiko 2005/, tolerances are from this report.
thickness	m		0.05		Raiko 2005
total number of canisters			1,210		/Pastina and Hellä 2006/.
total amount of spent fuel	tU		2,530		/Pastina and Hellä 2006/.
Cast iron insert					
dimensions of fuel channels	m		4.45×0.16×0.16		/Raiko 2005/.
number of fuel channels per insert	-		12		/Raiko 2005/.
mass of iron and steel	kg		13,400		/Raiko 2005/.
void space	m^3		0.95		/Raiko 2005/.
Alternative cases					
Posiva VVER 1,370 W					
outer diameter	m	$2\ r_c$		1.05	/Raiko 2005/.
length	m	l_c		3.60	/Raiko 2005/.
thickness	m			0.05	
total number of canisters				700	/Pastina and Hellä 2006/.
total amount of spent fuel	tU			1,020	/Pastina and Hellä 2006/.
Posiva EPR 1,830 W					
outer diameter	m	$2\ r_c$		1.05	/Raiko 2005/.
length	m	l_c		5.25	/Raiko 2005/.
thickness	m			0.05	
total number of canisters				930	/Pastina and Hellä 2006/.
total amount of spent fuel	tU			1,980	/Pastina and Hellä 2006/.
Overall Posiva inventory					
Total number of canisters			2,840	3,000	/Pastina and Hellä 2006/. A rounded up value of 3,000 canisters was used in scoping calculations in the Evolution Report /Smith et al. 2007/.
Total amount of spent fuel	tU		5,530		/Pastina & Hellä 2006/.

PARAMETER	Unit	Symbol	Reference value	Alternative values	Reference
COPPER PROPERTIES					
density	kg m^{-3}	ρcu	8,900		/CRC 2007/.
molar weight	g mol^{-1}		64		/CRC 2007/.
SUPERCONTAINER SHELL, SC					
A SC + distance block unit can be placed in the drift in sections with water inflow rate < 0.1L/min					
Container materials and dimensions					
Reference case – Posiva, BWR 1,700 W					
Shell material			carbon steel S235JRG2		/Autio et al. 2007/.
Fraction of total mass of elements	%				/EN 10025/.
C			<0.17		
Si-Mn			<0.14		
P			<0.045		
S			<0.045		
Cr,Ni,Al,Cu			-		
Shell, total mass	kg		1,031, with feet 1,071	890	/Autio et al. 2007/, the alternative value corresponds to an older shell design.
Shell, length	mm	l_{sc}	5,525	5,556 $^{+5}/_{0}$	/Autio et al. 2007/, tolerances are from this report
feet, total mass (10 feet per SC)	kg		40.2		/Autio et al. 2007/.
Shell, outer diameter	mm	$2\ r_{sc}$	1,765 $^{0}/_{-2}$		/Börgesson et al. 2005/.
inner diameter	mm		1,749		/Börgesson et al. 2005/.
steel, thickness	mm		8		/Börgesson et al. 2005/.
Void volume to canister and around a SC before saturation	mm		5		See definition of gaps below under Bentonite blocks in the SC
SC surface area					
External+ internal surface area+ hole edges surface area+ feet	m^2		41.52	41.39 (min)	/Autio et al. 2007/.
External+ internal surface area+ feet	m^2		35.73	35.6 (min)	/Autio et al. 2007/.
shell, diameter of perforation holes	mm		100		/Börgesson et al. 2005/.
shell, degree of perforation	%		62		/Börgesson et al. 2005/.
End plate, no perforation	%		0		/Autio et al. 2007/.
steel thickness	mm		8		/Autio et al. 2007/.
Alternative cases					
Posiva VVER 1,370 W					
Total mass	kg			880	/Autio et al. 2007/.
Length	mm	l_{sc}		4,330	/Raiko 2005/.
Posiva EPR 1,830 W					
Total mass	kg			1,140	/Autio et al. 2007/.
Length	mm	l_{sc}		5,980	/Raiko 2005/.
STEEL PROPERTIES					
Steel corrosion rate for the super-container shell	µm a^{-1}	R	1	2	/Smart et al. 2004/. Section 5.7.1 in /Gribi et al. 2007/.
Steel corrosion rate for the cast iron insert	µm a^{-1}	R	1	10 (only for sensitivity analysis purposes)	/Smart et al. 2004/. Section 2.5.1 in /Gribi et al. 2007/.
Density of iron/steel	kg m^{-3}		7,800		/CRC 2007/.
Molar weight of iron	g mol^{-1}		56		/CRC 2007/.

PARAMETER	Unit	Sym-bol	Reference value	Alternative values	Reference
Bentonite blocks in the SC					
Bentonite, MX-80					
ring blocks					
initial water content	w-%		10		/Börgesson et al. 2005/.
initial dry density	kg m^{-3}		1,885	1,789–1,977	/Autio et al. 2007/.
saturated density after swelling	kg m^{-3}		2,000	1,950–2,050	/Autio et al. 2007/.
end blocks					/Autio et al. 2007/.
initial water content	w-%		10		/Autio et al. 2007/.
initial dry density	kg m^{-3}		1,753	1,667–1,837	/Autio et al. 2007/.
saturated density after swelling	kg m^{-3}		2,000	1,950–2,050	/Autio et al. 2007/.
ring and end blocks					
saturated porosity after swelling	%	ε_b	44	43	/SKB 1999/ and /Autio et al. 2007/.
swelling pressure	MPa		7–8		/SKB 2006/.
Block dimensions					
Gap to canister (radial)	mm		5		/Börgesson et al. 2005/.
gap to supercontainer (radial)	mm		5		/Autio et al. 2007/.
diameter end blocks	mm		1,739	1,740 $^{+1}/_{-2}$	/Autio et al. 2007/, tolerances are from this report.
outer diameter ring blocks	mm		1,739	1,740 $^{+1}/_{-2}$	/Autio et al. 2007/, tolerances are from this report.
inner diameter ring blocks	mm		1,058 $^{+1}/_{-1}$		This report.
length end blocks	mm		700 (2*350) $^{+2}/_{-2}$		/Börgesson et al. 2005/, tolerances are from this report.
length ring blocks	mm		4,810 (4* 1,202.5)	4,844 $^{+4}/_{-4}$ (4*1,211 $^{+1}/_{-1}$)	/Autio et al. 2007/, modified to the reference length (4,844 –> 4,810 mm). The alternative value and tolerances are from this report.
Bentonite, total mass in one SC	kg		16,445		
DISTANCE BLOCKS					
Reference case –Posiva, BWR 1,700 W, 25 m separation between drifts					
Basic Design, BD					
Distance block					
Total length	mm		5,475		/Autio et al. 2007/.
Distance block unit is composed of “tight” and “loose” component					
”Tight” component					
Diameter	mm		1,850	1,840	/Autio et al. 2007/.
Length	mm		1,000		/Autio et al. 2007/.
block slices of thickness of 500 mm					
Bentonite MX-80					
initial water content	w-%		24		
initial dry density	kg m^{-3}		1,559	1,570	Alternative value is from Fig 4.8 in Sr-Can /SKB 2006a/.
saturated density after swelling	kg m^{-3}		2,000		
saturated porosity after swelling	%	ε_b	44		/Autio et al. 2007/.
”Loose” component					
Diameter	mm		1,820		/Autio et al. 2007/.
Length	mm		4,475		/Autio et al. 2007/.
block slices of thickness of 500 mm					

PARAMETER	Unit	Sym-bol	Reference value	Alternative values	Reference
Centred blocks					
Supporting feets, material type and design, not done	-				
Bentonite MX-80					
initial water content	w-%		24	26	/Autio et al. 2007/.
initial dry density	kg m^{-3}		1,610		/Autio et al. 2007/.
saturated density after swelling	kg m^{-3}		2,000		
saturated porosity after swelling	%	ε_b	44		
Total amount of bentonite (dry mass)/distance block	kg		22,940		
DAWE					
Distance blocks					
Diameter	mm			1,765	/Börgesson et al. 2005/.
Length	mm			5,475	/Autio et al. 2007/.
void slot	mm			37.5–42.5	/Börgesson et al. 2005/.
Centred blocks					
Supporting feet, material type	-			steel	
Feet, 4 feet per block	kg			13.9	/Autio et al. 2007/.
Bentonite, MX-80					
initial water content	w-%			21	/Autio et al. 2007/.
Dry density	kg m^{-3}			1,712	/Autio et al. 2007/.
saturated density after swelling	kg m^{-3}			2,000	/Autio et al. 2007/.
Total amount of bentonite (dry mass)/distance block	kg			22,940	
FIXING RINGS, BD					
to prevent movement of distance blocks, in every position where the inflow to SC+DB unit is larger than 0.01 L/min					
material type	-		10 mm thick steel plate		
mass	kg		600		/Autio et al. 2007/.
fixing material, low pH cement					
cement	kg		23		/Autio et al. 2007/.
SiO_2	kg		1.5		
organic material	kg		0.009		
Total number of fixing rings in a drift			4.5	4–5	/Hagros 2007a/.
SUPERCONTAINER +DISTANCE BLOCK UNIT					
BD AND DAWE					
Reference case – Posiva, BWR 1,700 W, 25 m separation between drifts					
Length (pitch, centre to centre distance)	m	p_c	11.0		/Autio et al. 2007/.
Gap between DB and SC (BD)	mm		5	max. 7	/Autio et al. 2007/.
Void volume within and outside a SC and DB unit	m^3		1.5		Appendix B.3 of KBS-3H Evolution report /Smith et al. 2007/. Void space excludes unsaturated buffer pores and spaces
Alternative cases					
Posiva VVER 1,370 W					
Length (pitch, centre to centre distance)	m	p_c		9.1	/Raiko 2005/, /Autio et al. 2007/.

PARAMETER	Unit	Sym-bol	Reference value	Alternative values	Reference
Gap between DB and SC (BD)	mm			5 (max. 7)	
Posiva EPR 1,830 W					
Length (pitch, centre to centre distance)	m	p_c		10.6	/Raiko 2005/, /Autio et al. 2007/.
Gap between DB and SC	mm			5 (max. 7)	
FILLING BLOCKS, BD AND DAWE					
Distance block units (defined above)					
placed in positions were gw inflow before sealing is >0.1 l/min and < 1L/min (after sealing)					/Autio et al. 2007/.
Dimensions and properties as for corresponding distance blocks in BD/DAWE					/Autio et al. 2007/.
Length per position	mm		10,000		/Autio et al. 2007/.
PLUGS, BD AND DAWE					
Steel compartment plugs					
Compartment plugs will be used to isolate a section of the drift with higher inflow than 1L/min					
material type, steel	-		10 mm steel plate, S355J0		
Compartment plug components:					/Autio et al. 2007/.
fastening ring	kg		400		/Autio et al. 2007/.
collar	kg		1,250		/Autio et al. 2007/.
cap	kg		440		/Autio et al. 2007/.
bolts, steel	kg		20		/Autio et al. 2007/.
total mass of one single-sided plug	kg		2,110		One-sided plugs were considered in the residual material inventory /Hagros 2007a/. Double-sided plugs are used in this report.
mass of one double-sided plug	kg		2,550		/Autio et al. 2007/.
fixing material, low-pH cement					
cement	kg		300		/Autio et al. 2007/.
SiO_2	kg		40		
organic material	kg		0.2		
Total mass, steel 2 plugs	kg		5,100		
Total mass, cement 2 plugs	kg		600		
Filling adjacent to steel compartment plug					
Bentonite pellets, MX-80					
Dry bulk density	kg m^{-3}		950		/Autio et al. 2007/.
Bulk density (for individual pellets)	kg m^{-3}		1,830		
Sand filling in compartment plug	m^3		1		
Transition blocks to compensate for the density reduction in the filled open volume					
"Loose" distance block					
Diameter	mm		1,820		/Autio et al. 2007/.
Length	mm		4,475		/Autio et al. 2007/.
slices of thickness of 500 mm					
Centred blocks					
Supporting feet, material type and number of not designed	-				

PARAMETER	Unit	Sym-bol	Reference value	Alternative values	Reference
Filling between steel compartment plugs					Not designed.
Permeable filling material in the leaking fracture intersection					/Autio et al. 2007/.
crushed rock with proper grading					
In other parts compacted bentonite					/Autio et al. 2007/.
Total section length	mm		30,000		
Drift end plug					
Steel-reinforced concrete plug (reference design)					
Length	mm		2,000		/Autio et al. 2007/.
Steel mass	kg		860		
low-pH concrete	m^3		8		LHHPC, /Martino et al. 2002/.
low-pH concrete (mixture: LHHP cement)	kg		19,200		/Martino et al. 2002/.
cement	kg		780		
silica	kg		2,300		
coarse aggregates	kg		8,320		
sand	kg		7,160		
organics (SP)	kg		82		
cooling and grouting pipes	mm		123,000		/Autio et al. 2007/.
Rock plug					/Autio et al. 2007/.
Length	mm			2,000	
Steel mass	kg			200	
low-pH concrete	m^3			1	
low-pH concrete	kg			1,900	/Autio et al. 2007/.
Fixing ring + steel compartment plug included in all drift end plug options					
Compartment plug					
steel mass	kg		2,110		/Autio et al. 2007/, one sided plug with bolts.
Fixing material, low-pH cement					
cement	kg		300		
silica, SiO2	kg		20		
organic material	kg		0.1		
Fixing ring (as defined above)					
Total length of fixing ring + Compart-ment plug	mm		1,000		
SPRAY AND DRIP SHIELDS, BD AND DAWE					
Material type			steel		/Autio et al. 2007/.
Weight of one drip shield	kg		0.600		/Autio et al. 2007/.
Number of drips shields in one drift			5	4-6	/Hagros 2007a/.
Thickness	mm		1		Assumption used for gas generation values (Section 5.5.1 in /Gribi et al. 2007/).
Total amount per drift	kg		3		/Hagros 2007a/.
DRAINAGE, ARTIFICIAL WATERING AND AIR EVACUATION PIPES (DAWE)					These are removed from drift.
Watering pipes					One pipe in each SC section.
Material				steel	
Diameter	mm			17.2	

PARAMETER	Unit	Sym-bol	Reference value	Alternative values	Reference
Air evacuation system					One/two pipes in the drift.
Material				steel	
Diameter	mm			10	
BACKFILL PER DRIFT					
The first 10-15 m of the drift which has a wider diameter will be backfilled	m^3		750(max)		
Backfill crushed rock/bentonite	w %		70/30		/Hagros 2007a/.
Bentonite			MX-80		
Density, dry (average)	kg/m^3		2,150		
85% of the volume					
In addition the first 5 meters of the drift with the diameter 1.85 m will be backfilled with compacted bentonite					
CEMENT IN A DRIFT (excluding the first 15 m emplacement section)					
Basic Design, BD					
Cement in compartment plugs, end plug (**reference LHHP plug**), fixing rings	kg		2,140		/Hagros 2007a/.
Cement in compartment plugs, end plug for the **alternative grouted rock plug**, and fixing rings				2,960	
Composition of low-pH cement (mixture: LHHP see drift end plug)			See drift end plug		/Martino et al. 2002/.
Low-pH cement for grouting	kg			500	
Composition (mixture: P308B)					
cement	kg/m^3			335	/Ahokas et al. 2006/.
SiO_2	w%			52.8	/Ahokas et al. 2006/.
Organic materials	w%			4	/Ahokas et al. 2006/.
Density	kg/m^3			1,354	/Ahokas et al. 2006/.
Total amount of cement in a drift (excl. the first 15 m)	kg		2,140	3,460	/Hagros 2007a/.
Reference material, Silica Sol for grouting					
Silica Sol	l		100–500		
Silica Sol	kg		130–670		
Composition (mixture: MEYCO MP320)					
SiO_2	w%		33.5		/Hagros 2007b/.
Accelerators (NaCl)	w%		1.7		/Hagros 2007b/.
organic materials (biocides)	w%		<0.01		/BASF 2007/.
Density	kg/m^3	ρ	~1,300		/Ahokas et al. 2006/.
CEMENT IN THE DRIFT (the first 15 m emplacement section)					
Support bolts, anchor bolts, shot-crete, grouting – remaining amount					/Hagros 2007a/.
Low-pH shotcrete					
Cement	kg		320	320	
Other cement bearing components	kg		170	170	
Total cement for first 15 m of a drift			490	490	
TOTAL AMOUNT OF CEMENT IN A DRIFT (BD)	kg		2,630	3,950	
DAWE					
Total amount of cement in a drift	kg			3,700	/Hagros 2007a/.

PARAMETER	Unit	Sym-bol	Reference value	Alternative values	Reference
BENTONITE					
Bentonite MX-80			MX-80		/SKB 2006/.
Montmorillonite	w %		87		
Na-			72%		
Ca-			18%		
Mg-			8%		
K-			2%		
pyrite	w %		0.07		
Gypsum	w %		0.7		
calcite+ siderite	w %		0–1		
Quartz	w %		3		
Cristobalite	w %		2		
Mica	w %		4		
Albite	w %		3		
Dolomite	w %		0		
Anorthoclase	w %		0		
organic carbon	w %		0.2		
CEC	meq/ 100g		75		
ROCK PROPERTIES					
Geochemical conditions (at 400–500 m depth)					
Salinity (TDS, Total dissolved solids)					
Present level	g l^{-1}		10–13	10–20	/Andersson et al. 2007/, /Pastina and Hellä 2006/.
Post-emplacement	g l^{-1}		10–25(420 m depth)	25–45 (550m depth)	/Pastina and Hellä 2006/, max. at 100 years after disposal.
pH			7.5–8.2		/Pitkänen et al. 2004/.
Redox potential	mV		–300..–250	≈ –250..–200	/Pitkänen et al. 2004/.
Dissolved Fe(II)	mg l^{-1}		0.11(median)	0.01–0.72	/OIVA data-base/ (file name: "uusiOIVA_10032006. xls") (see text).
Dissolved sulphide	mg l^{-1}		0.25 (median)	12 (max)	Ibid.
Dissolved gases					
H_2	ml l^{-1}		<1	20–25 (< 800 m)	/Pitkänen and Partamies 2007/.
CH_4	ml l^{-1}		< 400	920 (< 800m)	/Pitkänen and Partamies 2007/.
Solubilities of gases at 30 °C (after ≈ 2,000a) at 0.1MPa					/SKB 1999/ p 100.
H_2	mol m^{-3}		0.77		/Himmelblau 1960/.-
	ml l^{-1}		19		/Himmelblau 1960/.
CH_4	mol m^{-3}		1.3		/Himmelblau 1960/.
Geological properties					
Gneiss (migmatitic gneiss): fracture properties					
fracture type	-		fractures	vein-like	/Andersson et al. 2007/.
orientation	-		several sets		
density	m^{-1}	*N*	1to –3	3–10	/Hellä et al. 2006/.
aperture	mm	*a*	calc. from T-distribution		
transmissivity	$m^2 s^{-1}$	*T*	10^{-14}–10^{-7}		
hydraulic conductivity	m s^{-1}		10^{-8}–10^{-15}		Estimated range of rock hydr. cond. in /Börges-son et al. 2005/.

PARAMETER	Unit	Sym-bol	Reference value	Alternative values	Reference
Gneiss: average matrix properties					
porosity	%	ε_m	0.14	0.1–0.2	/Autio et al. 2003/.
hydraulic conductivity	m s^{-1}		10^{-14}	≈<10^{-15}	Estimated range of tightest rock hydr.cond. in /Börgesson et al. 2005/.
gas effective diffusion constant	m^2 s^{-1}		2.63 10^{-10}		/Autio et al. 2003/.
intrinsic gas permeability	m^2		5.16 10^{-21}		/Autio et al. 2003/.
EDZ: properties of crushed zone (0–4 mm)					
thickness (radial extent)	mm		4		/Autio et al. 2003/.
porosity	%		0.64	2–4	/Autio et al. 2003/.
fracture type	-		open cracks		/Montoto et al. 2003/.
mean fracture aperture	µm		2		/Montoto et al. 2003/.
small fractures (< 5.4 µm)	%		90		/Montoto et al. 2003/.
larger fractures (> 5.4 µm)	%		10		/Montoto et al. 2003/.
EDZ: properties of microfractured zone (4–9 mm)					
thickness (radial extent)	mm		5		/Autio et al. 2003/.
porosity	%		0.34		/Autio et al. 2003/.
fracture type	-		open cracks		/Autio et al. 2003/.
mean crack specific surface	µm^{-1}		0.004		/Montoto et al. 2003/.
small fractures (< 2.16 µm)	%		60%		/Montoto et al. 2003/.
EDZ: properties of zone of minor damage (9–23 mm)					
thickness (radial extent)	mm		14		/Autio et al. 2003/.
fracturation	-		similar as in undisturbed rock		/Autio et al. 2003/.
EDZ: average properties (0–23 mm)					
thickness	mm		23		Combined thickness of crushed zone, micro-fractured zone and zone of minor damage.
porosity	%	ε_{EDZ}	0.34		/Autio et al. 2003/.
gas effective diffusion constant	m^2 s^{-1}		3.97 10^{-9}		/Autio et al. 2003/.
intrinsic gas permeability	m^2		2.96 10^{-19}		/Johnson et al. 2005/, Appendix C in /Gribi et al. 2007/.
max hydraulic conductivity	m s^{-1}	K_{EDZ}	3 x 10^{-12}		The maximal hydraulic conductivity of the EDZ was indirectly calculated by taking the average intrinsic gas permeability (see line above) as an upper bound for the transport of water in the EDZ.
Hydraulic properties					
Leakage rates for 300 m drift without sealing	L/min				/Hellä et al. 2006/.
long dry sections			"tight"		
Zones with 1–3 local fractures			>4		One fracture per 250 m.
a few fractures or fracture zones			0.4–4		One fracture per 100 m.
six 5 m long sections (per 300 m)			>0.1		
four to five 10 m long sections (per 300 m)			>0.1		
total leakage into a drift			10		/Hellä et al. 2006/, the likely range of inflow into a drift.

PARAMETER	Unit	Sym-bol	Reference value	Alternative values	Reference
Leakage after grouting for a 300 m drift (successful grouting to a T< 10–8 m^2/s)					
Inflow	l/min		<10 (99%)	<10 (99%)	/Lanyon and Marschall 2006/, max. inflow in all realisations is about 15 l/min with less than 1% of drifts exceeding 10 l/min.
Saturation time for a supercontainer section in the drift	a		10	12,000	Figure 8-14 in /Börgesson et al. 2005/.
Hydraulic gradient (post-closure phase)	%		0.01	0.01 – 1	/Löfman 1999/.
Hydraulic length (from drift to the nearest major fracture zone)	m		50		/Lanyon and Marschall 2006/. Assumed distance to constant head hydrostatic boundary in discrete fracture network modelling.
Mechanical properties at repository depth					
Main horizontal stress	MPa	σ1 or σH	5+0.021z min 10+0.042z max		/Andersson et al. 2007/, 300< z < 800 m
Secondary horizontal stress	MPa	σ2 or σh	0.021z min 5+0.027z max		Ibid.
Vertical stress	MPa	σ3 or σv	0.015z min 0.030z max		Ibid.
Spalling strength	MPa		65		/Hakala et al. 2008/, Table 2.3
Thermal properties					
Ambient temperature	°C	T_0	+10.5 °C (400m)	0	/Ikonen 2003/, gradient 1.5°C/100 m.
Heat output	W				
BWR canister, OL 1–2			1,700		/Raiko 2005/.
PWR canister				1,370	/Raiko 2005/.
EPR Canister				1,830	/Raiko 2005/.
Thermal conductivity (gneiss)	$Wm^{-1} K^{-1}$		2.7		/Posiva 2003/, p 114, for a temperature 22°C.
Heat capacity (gneiss)	$J\ kg^{-1} K^{-1}$		797		/Posiva 2003/, p 114.
Thermal diffusivity (gneiss)	$m^2\ s^{-1}$		$1.23\ 10^{-6}$		/Posiva 2003/, p 114.
Thermal conductivity (bentonite)	$Wm^{-1} K^{-1}$		1.0		/Ikonen 2003/.
Maximum temperature at canister surface (for thermal dimensioning)	°C		90		10° below the design basis max. of 100°, /Ikonen 2003/.

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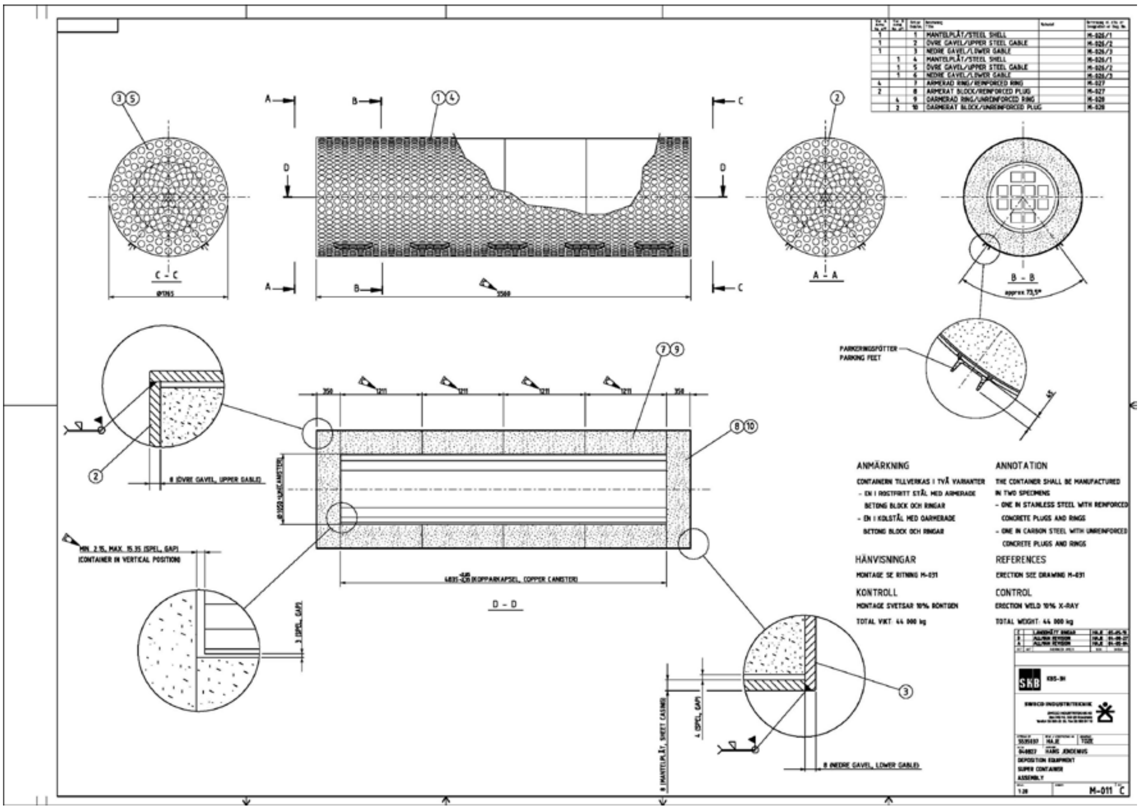
Appendix D

Deposition equipment, Supercontainer assembly. Drawing M-011-C.



Appendix E

Estimated total quantities of chemical components and residual materials – Tables

Table E-1. Estimated total quantities of chemical components, sorted by remaining quantity, from residual materials in a KBS-3H repository (including ONKALO), based on design alternatives BD and A1a (= support alternative A, grouting alternative 1, backfill alternative a) with an LHHP plug (Table 4 in Hagros 2007a).

Chemical components	Origin (reference to Table 10-2 in Section 10.1.1)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	2, 6, 7, 8, 9a	5,200,000	0	5,200,000
Steel	1, 2, 3.1, 4, 5, 12, 13, 16, 17, 18, 25	7,100,000	32	4,800,000
Carbonates (calcite + siderite)	2, 6, 7, 8, 9a	3,700,000	0	3,700,000
Cement	2, 3.1, 5, 12, 13, 14A, 15.1, 16, 17	18,000,000	91	1,500,000
Organic materials (incl. organic carbon and hydrocarbons)	2, 3.1, 5, 6, 7, 8, 9a, 14A, 15.1, 21, 23, 24, 26, 28, 29	13,000,000	87	1,700,000
Pyrite	2, 6, 7, 8, 9a	520,000	0	520,000
Silica (SiO_2)	2, 3.1, 5, 14A, 15.1	760,000	37	480,000
Carbamide	27	1,100,000	95	55,000
Rubber	19	160,000	90	16,000
Nitrogen oxides (NO_x)	10, 20	1,400,000	99	14,000
Soot and ash	20	82,000	93	5,800
Zinc	12, 17	11,000	61	4,300
Aluminium	11, 14A, 17	120,000	97	3,200
Nitrate	15.1	1,000	20	800
Chloride	2, 3.1, 5, 14A, 15.1	1,100	43	600
Sulphuric acid	22	3,200	90	300
Iron (Fe(III))	14A	4,900	95	200
Plastic	11	1,800	90	180
Polyethylene (PE)	18	3,500	95	180
Polystyrene (EPS)	18	1,400	95	70
Tungsten and cobalt	25	2,800	99	30

Table E-2. Estimated total quantities of chemical components from residual materials in a KBS-3H repository (including ONKALO), based on design alternatives BD and A1a (= support alternative A, grouting alternative 1, backfill alternative a) with a rock cylinder plug. (Table 5 in Hagros 2007a).

Chemical components	Origin (reference to Table 10-2 in Section 10.1.1)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	2, 6, 7, 8, 9a	5,200,000	0	5,200,000
Steel	1, 2, 3.2, 4, 5, 12, 13, 16, 17, 18, 25	6,900,000	32	4,700,000
Carbonates (calcite + siderite)	2, 6, 7, 8, 9a	3,700,000	0	3,700,000
Cement	2, 3.2, 5, 12, 13, 14A, 15.1, 16, 17	18,000,000	90	1,700,000
Organic materials (incl. organic carbon and hydrocarbons)	2, 3.2, 5, 6, 7, 8, 9a, 14A, 15.1, 21, 23, 24, 26, 28, 29	13,000,000	87	1,600,000
Pyrite	2, 6, 7, 8, 9a	520,000	0	520,000
Silica (SiO2)	2, 3.2, 5, 14A, 15.1	390,000	72	110,000
Carbamide	27	1,100,000	95	55,000
Rubber	19	160,000	90	16,000
Nitrogen oxides (NOx)	10, 20	1,400,000	99	14,000
Soot and ash	20	82,000	93	5,800
Zinc	12, 17	11,000	61	4,300
Aluminium	11, 14A, 17	120,000	97	3,200
Nitrate	15.1	1,000	20	800
Chloride	2, 3.2, 5, 14A, 15.1	1,100	43	600
Sulphuric acid	22	3,200	90	300
Iron (Fe(III))	14A	4,900	95	200
Plastic	11	1,800	90	180
Polyethylene (PE)	18	3,500	95	180
Polystyrene (EPS)	18	1,400	95	70
Tungsten and cobalt	25	2,800	99	30

Table E-3. Estimated total quantities of chemical components from residual materials in a KBS-3H repository (including ONKALO), based on design alternatives BD and A1b (= support alternative A, grouting alternative 1, backfill alternative b) with an LHHP plug. (Table 6 in Hagros 2007a).

Chemical components	Origin (reference to Table 10-2 in Section 10.1.1)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	2, 6, 7, 8, 9b	15,000,000	0	15,000,000
Steel	1, 2, 3.1, 4, 5, 12, 13, 16, 17, 18, 25	7,100,000	32	4,800,000
Carbonates (calcite + siderite)	2, 6, 7, 8, 9b	880,000	0	880,000
Cement	2, 3.1, 5, 12, 13, 14A, 15.1, 16, 17	18,000,000	91	1,500,000
Organic materials (incl. organic carbon and hydrocarbons)	2, 3.1, 5, 6, 7, 8, 9b, 14A, 15.1, 21, 23, 24, 26, 28, 29	22,000,000	51	11,000,000
Pyrite	2, 6, 7, 8, 9b	11,000,000	0	11,000,000
Silica (SiO2)	2, 3.1, 5, 14A, 15.1	760,000	37	480,000
Carbamide	27	1,100,000	95	55,000
Rubber	19	160,000	90	16,000
Nitrogen oxides (NOx)	10, 20	1,400,000	99	14,000
Soot and ash	20	82,000	93	5,800
Zinc	12, 17	11,000	61	4,300
Aluminium	11, 14A, 17	120,000	97	3,200
Nitrate	15.1	1,000	20	800
Chloride	2, 3.1, 5, 14A, 15.1	1,100	43	600
Sulphuric acid	22	3,200	90	300
Iron (Fe(III))	14A	4,900	95	200
Plastic	11	1,800	90	180
Polyethylene (PE)	18	4,000	95	180
Polystyrene (EPS)	18	1,400	95	70
Tungsten and cobalt	25	2,800	99	30

Table E-4. Estimated total quantities of chemical components from residual materials in a KBS-3H repository (including ONKALO), based on design alternatives BD and B2a (= support alternative B, grouting alternative 2, backfill alternative a) with a rock cylinder plug. (Table 7 in Hagros 2007a).

Chemical components	Origin (reference to Table 10-2 in Section 10.1.1)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	2, 6, 7, 8, 9a	5,200,000	0	5,200,000
Steel	1, 2, 3.2, 4, 5, 12, 13, 16, 17, 18, 25	6,900,000	32	4,700,000
Carbonates (calcite + siderite)	2, 6, 7, 8, 9a	3,700,000	0	3,700,000
Cement	2, 3.2, 5, 12, 13, 14B, 15.2, 16, 17	16,000,000	91	1,500,000
Organic materials (incl. organic carbon and hydrocarbons)	2, 3.2, 5, 6, 7, 8, 9a, 14B, 15.2, 21, 23, 24, 26, 28, 29	13,000,000	87	1,600,000
Pyrite	2, 6, 7, 8, 9a	520,000	0	520,000
Silica (SiO_2)	2, 3.2, 5, 14B, 15.2	2,400,000	90	250,000
Carbamide	27	1,100,000	95	55,000
Rubber	19	160,000	90	16,000
Nitrogen oxides (NO_x)	10, 20	1,400,000	99	14,000
Soot and ash	20	82,000	93	5,800
Zinc	12, 17	11,000	61	4,300
Aluminium	11, 14B, 17	120,000	97	3,000
Nitrate	15.2	900	20	700
Chloride	2, 3.2, 5, 14B, 15.2	900	43	500
Sulphuric acid	22	3,200	90	300
Iron (Fe(III))	14A	3,600	95	180
Plastic	11	1,800	90	180
Polyethylene (PE)	18	4,000	95	180
Polystyrene (EPS)	18	1,400	95	70
Tungsten and cobalt	25	2,800	99	30

Table E-5. Estimated total quantities of chemical components from residual materials in a KBS-3H repository (including ONKALO), based on design alternatives BD and B3a (= support alternative B, grouting alternative 3, backfill alternative a) with a rock cylinder plug. (Table 8 in Hagros 2,007a).

Chemical components	Origin (reference to Table 10-2 in Section 10.1.1)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	2, 6, 7, 8, 9a	5,200,000	0	5,200,000
Steel	1, 2, 3.2, 4, 5, 12, 13, 16, 17, 18, 25	6,900,000	32	4,700,000
Carbonates (calcite + siderite)	2, 6, 7, 8, 9a	3,700,000	0	3,700,000
Cement	2, 3.2, 5, 12, 13, 14B, 15.3, 16, 17	16,000,000	91	1,400,000
Organic materials (incl. organic carbon and hydrocarbons)	2, 3.2, 5, 6, 7, 8, 9a, 14B, 15.3, 21, 23, 24, 26, 28, 29	13,000,000	87	1,600,000
Pyrite	2, 6, 7, 8, 9a	520,000	0	520,000
Silica (SiO_2)	2, 3.2, 5, 14B, 15.3	2,500,000	87	330,000
Carbamide	27	1,100,000	95	55,000
Rubber	19	160,000	90	16,000
Nitrogen oxides (NO_x)	10, 20	1,400,000	99	14,000
Soot and ash	20	82,000	93	5,800
Zinc	12, 17	11,000	61	4,300
Aluminium	11, 14B, 17	120,000	97	3,000
Nitrate	15.3	800	20	600
Chloride	2, 3.2, 5, 14B, 15.3	6,000	23	4,600
Sulphuric acid	22	3,200	90	300
Iron (Fe(III))	14A	3,600	95	180
Plastic	11	1,800	90	180
Polyethylene (PE)	18	4,000	95	180
Polystyrene (EPS)	18	1,400	95	70
Tungsten and cobalt	25	2,800	99	30

Table E-6. Estimated total quantities of chemical components from residual materials in a KBS-3H repository (including ONKALO), based on design alternatives BD and B3a (= support alternative B, grouting alternative 3, backfill alternative a) with a LHHP plug. (Table 10 in Hagros 2007a).

Chemical components	Origin (reference to Table 10-2 in Section 10.1.1)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	2, 6, 7, 8, 9a	5,200,000	0	5,200,000
Steel	1, 2, 3.1, 4, 5, 12, 13, 16, 17, 18, 25	6,900,000	32	4,550,000
Carbonates (calcite + siderite)	2, 6, 7, 8, 9a	3,700,000	0	3,700,000
Organic materials (incl. organic carbon and hydro-carbons)	2, 3.1, 5, 6, 7, 8, 9a, 14B, 15.3, 21, 23, 24, 26, 28, 29	13,000,000	87	1,614,000
Cement	2, 3.1, 5, 12, 13, 14B, 15.3, 16, 17	16,000,000	91	1,200,000
Pyrite	2, 6, 7, 8, 9a	520,000	0	520,000
Silica (SiO_2)	2, 3.1, 5, 14B, 15.3	2,500,000	87	710,000
Carbamide	27	1,100,000	95	55,000
Rubber	19	160,000	90	16,000
Nitrogen oxides (NO_x)	10, 20	1,400,000	99	14,000
Soot and ash	20	82,000	93	5,800
Zinc	12, 17	11,000	61	4,300
Aluminium	11, 14B, 17	120,000	97	3,000
Nitrate	15.3	800	20	600
Chloride	2, 3.1, 5, 14B, 15.3	6,000	23	4,600
Sulphuric acid	22	3,200	90	300
Iron (Fe(III))	14A	3,600	95	180
Plastic	11	1,800	90	180
Polyethylene (PE)	18	4,000	95	180
Polystyrene (EPS)	18	1,400	95	70
Tungsten and cobalt	25	2,800	99	30

Table E-7. Estimated total quantities of chemical components from residual materials in a KBS-3H repository (including ONKALO), based on design alternatives DAWE and A1a (= support alternative A, grouting alternative 1, backfill alternative a) with a LHHP plug. (Table 11 in Hagros 2007a).

Chemical components	Origin (reference to Table 10-3 in Section 10.1.1)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	2, 6, 7, 8, 9a	5,200,000	0	5,200,000
Steel	1, 2, 3.1, 4, 5, 7, 12, 13, 16, 17, 18, 25	6,700,000	33	4,500,000
Carbonates (calcite + siderite)	2, 6, 7, 8, 9a	3,700,000	0	3,700,000
Organic materials (incl. organic carbon and hydrocarbons)	2, 3.1, 6, 7, 8, 9a, 14A, 15.1, 21, 23, 24, 26, 28, 29	13,000,000	87	1,700,000
Cement	2, 3.1, 12, 13, 14A, 15.1, 16, 17	18,000,000	91	1,500,000
Pyrite	2, 6, 7, 8, 9a	520,000	0	520,000
Silica (SiO_2)	2, 3.1, 14A, 15.1	760,000	37	480,000
Carbamide	27	1,100,000	95	55,000
Rubber	19	160,000	90	16,000
Nitrogen oxides (NO_x)	10, 20	1,400 000	99	14,000
Soot and ash	20	82,000	93	5,800
Zinc	12, 17	11,000	61	4,300
Aluminium	11, 14A, 17	120,000	97	3,200
Nitrate	15.1	1,000	20	800
Chloride	2, 3.1, 14A, 15.1	1,100	43	600
Sulphuric acid	22	3,200	90	300
Iron (Fe(III))	14A	4,900	95	200
Plastic	11	1,800	90	180
Polyethylene (PE)	18	3,500	95	180
Polystyrene (EPS)	18	1,400	95	70
Tungsten and cobalt	25	2,800	99	30

Table E-8. Estimated total quantities of chemical components from residual materials in a KBS-3H repository (including ONKALO), based on design alternatives DAWE and B2a (= support alternative B, grouting alternative 2, backfill alternative a) with a rock cylinder plug. (Table 12 in Hagros 2007a).

Chemical components	Origin (reference to Table 10-3 in Section 10.1.1)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	2, 6, 7, 8, 9a	5,200,000	0	5,200,000
Steel	1, 2, 3.2, 4, 5, 7, 12, 13, 16, 17, 18, 25	6,500,000	34	4,300,000
Carbonates (calcite + siderite)	2, 6, 7, 8, 9a	3,700,000	0	3,700,000
Organic materials (incl. organic carbon and hydrocarbons)	2, 3.2, 6, 7, 8, 9a, 14B, 15.2, 21, 23, 24, 26, 28, 29	13,000,000	87	1,600,000
Cement	2, 3.2, 12, 13, 14B, 15.2, 16, 17	16,000,000	91	1,500,000
Pyrite	2, 6, 7, 8, 9a	520,000	0	520,000
Silica (SiO_2)	2, 3.2, 14B, 15.2	2,400,000	90	250,000
Carbamide	27	1,100,000	95	55,000
Rubber	19	160,000	90	16,000
Nitrogen oxides (NO_x)	10, 20	1,400,000	99	14,000
Soot and ash	20	82,000	93	5,800
Zinc	12, 17	11,000	61	4,300
Aluminium	11, 14A, 17	120,000	97	3,000
Nitrate	15.2	900	20	700
Chloride	2, 3.2, 14B, 15.2	900	43	500
Sulphuric acid	22	3,200	90	300
Iron (Fe(III))	14B	3,600	95	180
Plastic	11	1,800	90	180
Polyethylene (PE)	18	3,500	95	180
Polystyrene (EPS)	18	1,400	95	70
Tungsten and cobalt	25	2,800	99	30

Table E-9. Estimated total quantities of residual materials in one 300 m long deposition drift, based on design alternatives BD and B2a (= support alternative B, grouting alternative 2, backfill alternative a) with a rock cylinder plug. (Table 14 in Hagros 2007a).

Chemical components	Origin (reference to Table 10-2 in Section 10.1.1)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	2, 6, 7, 8, 9a	10,000.0	0	10,000.00
Steel	1, 2, 3.2, 4, 5, 12, 13, 16, 17, 18, 25	31,000.0	9	28,000.00
Carbonates (calcite + siderite)	2, 6, 7, 8, 9a	7,500.0	0	7,500.00
Organic materials (incl. organic carbon and hydrocarbons)	2, 3.2, 5, 6, 7, 8, 9a, 14B, 15.2, 21, 23, 24, 26, 28, 29	5,000.0	40	3,000.00
Cement	2, 3.2, 5, 12, 13, 14B, 15.2, 16, 17	15,000.0	74	3,800.00
Pyrite	2, 6, 7, 8, 9a	1,000.0	0	1,000.00
Silica (SiO_2)	2, 3.2, 5, 14B, 15.2	5,500.0	88	700.00
Carbamide	27	200.0	95	10.00
Rubber	19	6.0	90	0.60
Nitrogen oxides (NO_x)	10, 20	30.0	99	0.30
Soot and ash	20	2.0	93	0.10
Zinc	12, 17	5.0	0	5.00
Aluminium	11, 14B, 17	20.0	95	1.00
Chloride	2, 3.2, 5, 14B, 15.2	0.8	49	0.40
Sulphuric acid	22	0.1	90	0.01
Iron (Fe(III))	14A	5.0	95	0.20
Plastic	11	1.0	90	0.10
Polyethylene (PE)	18	3.0	95	0.10
Polystyrene (EPS)	18	1.0	95	0.05
Tungsten and cobalt	25	4.0	99	0.04

Table E-10. Estimated total quantities of residual materials in one 300 m long deposition drift, based on design alternatives DAWE and B2a (= support alternative B, grouting alternative 2, backfill alternative a) with a rock cylinder plug. (Table 17 in Hagros 2007a).

Chemical components	Origin (reference to Table 10-3 in Section 10.1.1)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	2, 6, 7, 8, 9a	10,000.0	0	10,000.00
Steel	1, 2, 3.2, 4, 5, 7, 12, 13, 16, 17, 18, 25	28,000.0	9	26,000.00
Carbonates (calcite + siderite)	2, 6, 7, 8, 9a	7,400.0	0	7,400.00
Organic materials (incl. organic carbon and hydrocarbons)	2, 3.2, 6, 7, 8, 9a, 14B, 15.2., 21, 23, 24, 26, 28, 29	5,000.0	40	3,000.00
Cement	2, 3.2, 12, 13, 14B, 15.2, 16, 17	14,000.0	74	3,700.00
Pyrite	2, 6, 7, 8, 9a	1,000.0	0	1,000.00
Silica (SiO_2)	2, 3.2, 14B, 15.2	5,500.0	88	700.00
Carbamide	27	200.0	95	10.00
Rubber	19	6.0	90	0.60
Nitrogen oxides (NO_x)	10, 20	30.0	99	0.30
Soot and ash	20	2.0	93	0.10
Zinc	12, 17	5.0	0	5.00
Aluminium	11, 14B, 17	20.0	95	1.00
Chloride	2, 3.2, 14B, 15.2	0.8	49	0.40
Sulphuric acid	22	0.1	90	0.01
Iron (Fe(III))	14A	5.0	95	0.20
Plastic	11	1.0	90	0.10
Polyethylene (PE)	18	3.0	95	0.10
Polystyrene (EPS)	18	1.0	95	0.05
Tungsten and cobalt	25	4.0	99	0.04