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KBS-3H Summary Report

Design of Buffer and Filling Components

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Abstract

The KBS-3H design is a variant of the KBS-3 method and an alternative to the KBS-3V design. KBS-3H includes several bentonite parts defined as the buffer and the filling components. The bentonite buffer is defined as the bentonite inside the perforated Supercontainer and the distance blocks separating the Supercontainers. The filling components correspond to a number of bentonite parts that are planned to fill the parts of the tunnel that are not used for the plugs and the buffer.

The previous design of the KBS-3H concept was reported in 2008. Significant research and testing and technical development have taken place after that report. Therefore the design basis has been developed further to reflect the present understanding especially with respect to design requirements and evolution of the system after artificial watering. As a result a new design of the buffer and the filling components has been developed. The DAWE design with artificial water filling of the empty space in the drift has been chosen and further developed and is presented in this document.

Filling components

The design of the *filling components* has yielded the following results:

Filling inside the drift and compartment plugs

1.3 m inside to the plug will be filled with bentonite pellets. A transition zone with bentonite blocks intended to take the density gradient caused by the compression of the pellet filling will be placed between the pellets and the first distance block. The length of this transition zone depends on the friction angle between the bentonite and the rock surface. For the slightly pessimistic assumption of the friction angle 5 degrees the length will be 6.3 m, based on analytical calculations.

Filling outside the compartment plug

The design is proposed be identical to the design inside the plug.

Filling blocks at intersecting fractures with high inflow rate

No Supercontaniers will be placed at intersecting fractures with an inflow rate >0.1 l/min. Instead there will be a filling block section with half a distance block on each side of the filling blocks. In order to have a respect distance a defined distance between the fracture intersection and the distance blocks will be included in the filling block section. The length of the filling block section will depend on the inflow rate and on the length of the fracture intersection along the drift rock surface. The respect distance is set to 3–6 m depending on the inflow rate.

Filling component at the drift end

Between the innermost distance block and the drift end there will be a bentonite block with the length 0.5 m that is either placed in contact with the drift end surface or with a small pellet filled slot at the end.

Pilot hole

The two meter long pilot hole with the diameter 152 mm at the end of the drift will be filled with bentonite blocks with the diameter 132 mm.

There are still some uncertainties and lack of understanding of the processes in the bentonite that are under investigation, e.g. possible long term decrease in friction angle and the effect of colloid erosion.

Buffer components

The design of the *buffer components* has yielded the following results:

A detailed design of the three types of blocks (ring-shaped bentonite blocks, solid blocks at both ends of the Supercontainer and distance blocks between Supercontainers) has been produced. The bases for the design of the blocks are presented and verifying analyses of the final buffer density are presented. The analyses show the following:

- The derived density of the three types of buffer blocks and the geometry of the blocks and the drift will give a final buffer density at saturation of about 2 000 kg/m^3, the allowed range of tolerance being 1 950–2 050 kg/m^3. The calculations assume nominal values of the density and dimensions of the blocks, nominal dimensions of the drift, a Supercontainer shell with constant volume (corrosion very slow) and no axial swelling. However, allowable deviations have also been considered.
- When combining the highest acceptable density of the blocks, tripled volume of the corroded Supercontainer shell with the minimum acceptable diameter of the drift (1 850 mm), the calculated final density at saturation will be 2 039 kg/m^3 for the case of a Supercontainer shell made of copper.
- The calculations made for a Supercontainer shell made of titanium, which is the present reference material, indicate a buffer density at saturation of between 1 981 and 2 024 kg/m^3.
- An axial swelling of the buffer with nominal values of the buffer and the drift will lead to a lower buffer density at saturation than 2 000 kg/m^3. A simplified calculation of the buffer density between the canister and the Supercontainer when taking into account an axial swelling of 8 mm yields a final buffer density at saturation of 1 976 kg/m^3 for nominal conditions but as low as 1 959 kg/m^3 at extreme cases of buffer block density and drift diameter.
- None of the calculated cases resulted in a saturated buffer density outside the allowed range 1 950–2 050 kg/m^3.

There are still certain uncertainties left in the design which are not, however, assessed as being critical for the feasibility of the design and will be evaluated e.g. in KBS-3H MPT test and other tests. The impact of chemical erosion (diluted groundwater) is presently studied in other projects and implies uncertainty to be resolved in the future.

Contents

1 Introduction

KBS-3H project is a joint project between Svensk Kärnbränslehantering AB (SKB) in Sweden and Posiva Oy in Finland. The overall objectives of this project phase are 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.

This document provides a description of the buffer and the filling components in a KBS-3H repository. KBS-3H is a variant of the KBS-3 method in which multiple canisters containing spent nuclear fuel are emplaced in parallel, 100–300 m long deposition drifts (see Glossary in Appendix F for KBS-3H specific words), slightly inclined down towards the main tunnel (according to SKB's definition, the corresponding term in Posiva's design is central tunnel). SKB and Posiva are engaged in a research, development & demonstration (RD&D) programme with the overall aim at developing 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 tunnel.

The design of the buffer and the filling components reported in previous KBS-3H design was presented on preliminary level (Autio et al. 2008) and a new design for the buffer and the filling components is presented in this document. The design of the KBS-3H drift and the design basis have been further developed and revised to incorporate current understanding and results from extensive testing and research on several issues including studies and testing the functional uncertainties related to buffer behaviour. Some extensive development work has been presented in Börgesson et al. (2005) and SKB (2012).

Previously there were two KBS-3H repository candidate designs. The present reference design for KBS-3H concept is based on Drainage, Artificial Watering and air Evacuation (DAWE). In the DAWE alternative the drift is divided into compartments. A compartment is kept open during installation of Supercontainers and distance blocks, allowing water to flow along the drift floor until a compartment plug that is able to seal off the high hydraulic water pressure, is installed. The empty voids in the gaps between the buffer and the rock walls will be artificially filled with water by using pipes.

The objective of this report is to describe the design of the buffer and the filling components outside the buffer. This report does not include the full design of the buffer and the filling components. The full design should also include a detailed description of the methods used for controlling the bentonite material and the blocks, at what stages inspections are made and the accuracy of the methods.

2 General description of the KBS-3H alternative

2.1 Design

The KBS-3H design is based on horizontal emplacement of several spent fuel canisters in a drift whereas the KBS-3V design means vertical emplacement of the canisters in individual deposition holes. 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 general KBS-3H repository layout based on SKB's design is outlined in Figures 2-1 and 2-2. The drifts are bored from a niche in the central tunnel as shown in Figure 2-1. According to this design, about 40 disposal containers will be deposited in each drift at maximum.

Units consisting of one canister surrounded by buffer blocks confined by a perforated shell, called Supercontainers, are manufactured elsewhere in the repository. They constitute key components and are moved into the deposition drifts (Figure 2-2). They are separated by cylindrical "Distance blocks" in order to restrict the temperature rise resulting from the heat-generating canisters. The purpose of the distance block is also to seal off each canister position from and to prevent water and bentonite transport along the drift. Their axial length will range roughly from 2 to 6 m. The sealing and plugging in the drift system will occur when the distance block absorbs water, swells and obtains proper swelling pressure.

The spent fuel canister is transported via an access ramp tunnel to a reloading station (Figures 2-3 and 2-4). The buffer and the spent fuel canister are assembled into the Supercontainer in the reloading station. The Supercontainer is then transported to the deposition niche, where the deposition equipment, start tube and transport tube are located. The Supercontainer is then transported into the deposition drift.

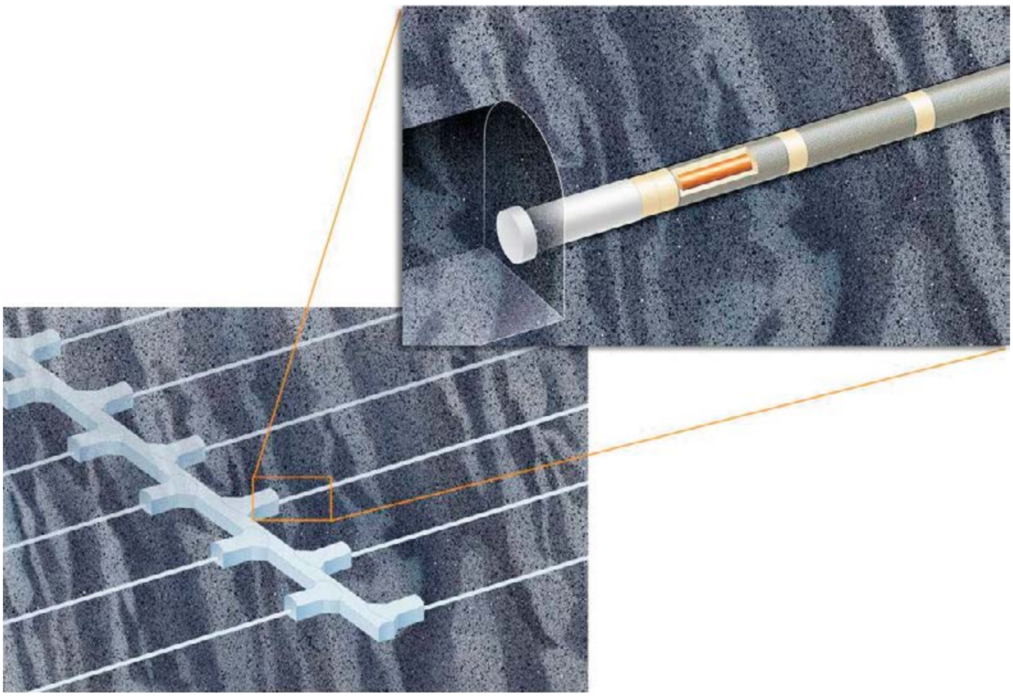


Figure 2-1. *Illustration of a central tunnel with deposition drifts in KBS-3H.*

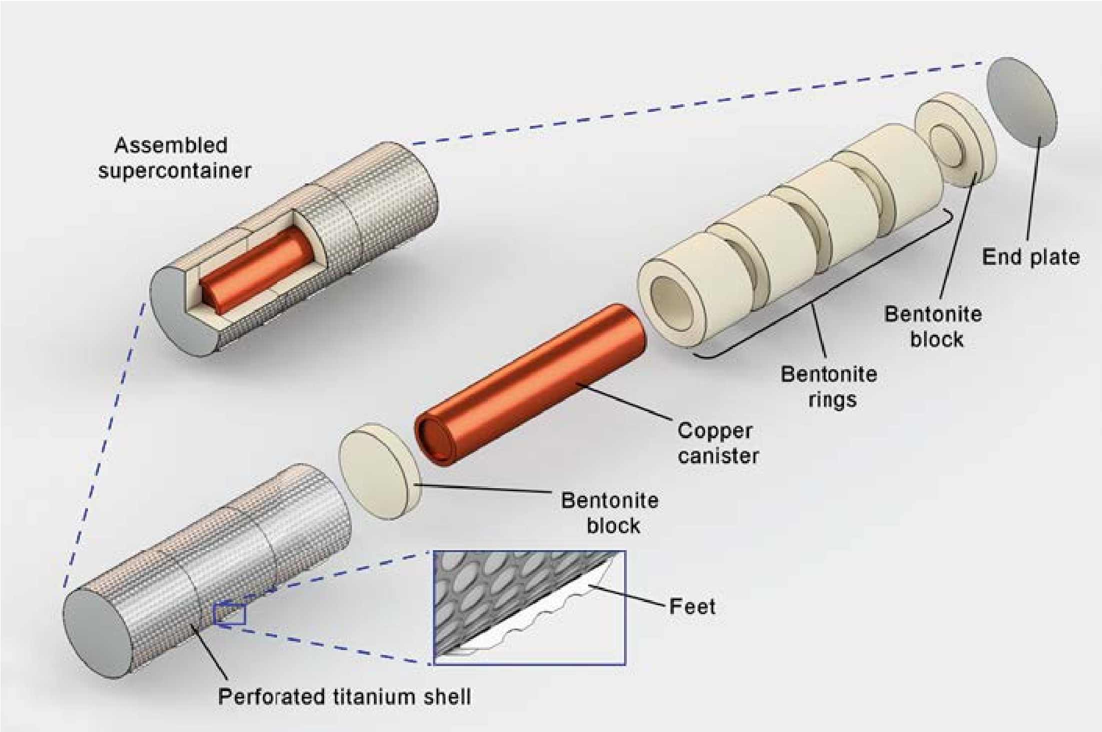


Figure 2-2. *The buffer and canister are embedded in a perforated shell (cylinder) forming a Supercontainer in the KBS-3H design.*

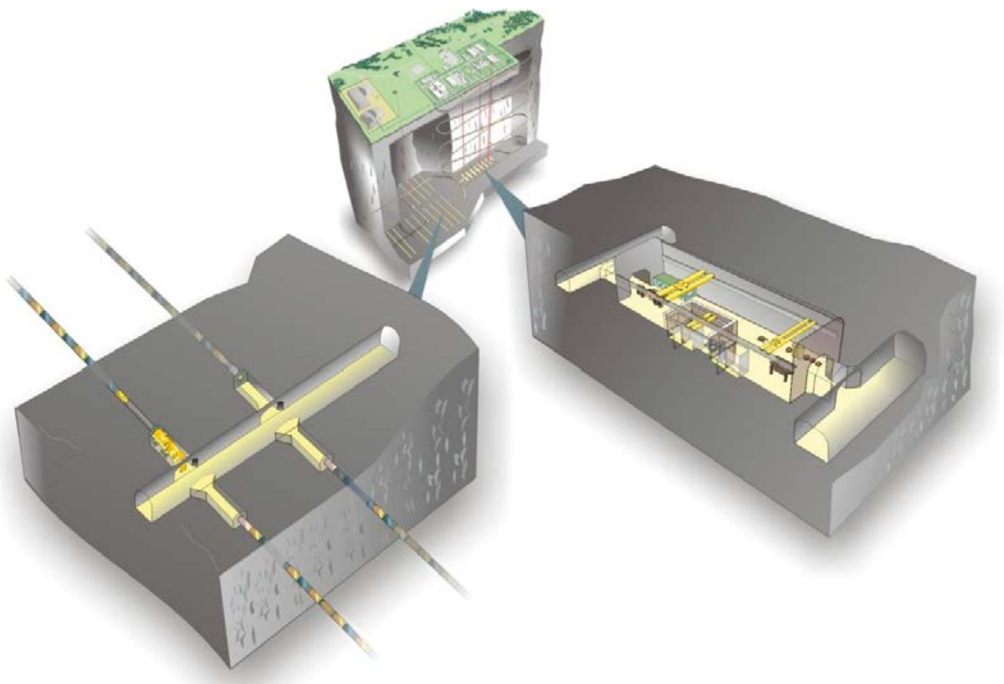


Figure 2-3. *General KBS-3H layout by SKB (top) with the reloading station (right) and deposition area with the main tunnel, the deposition niches and deposition drifts (left).*

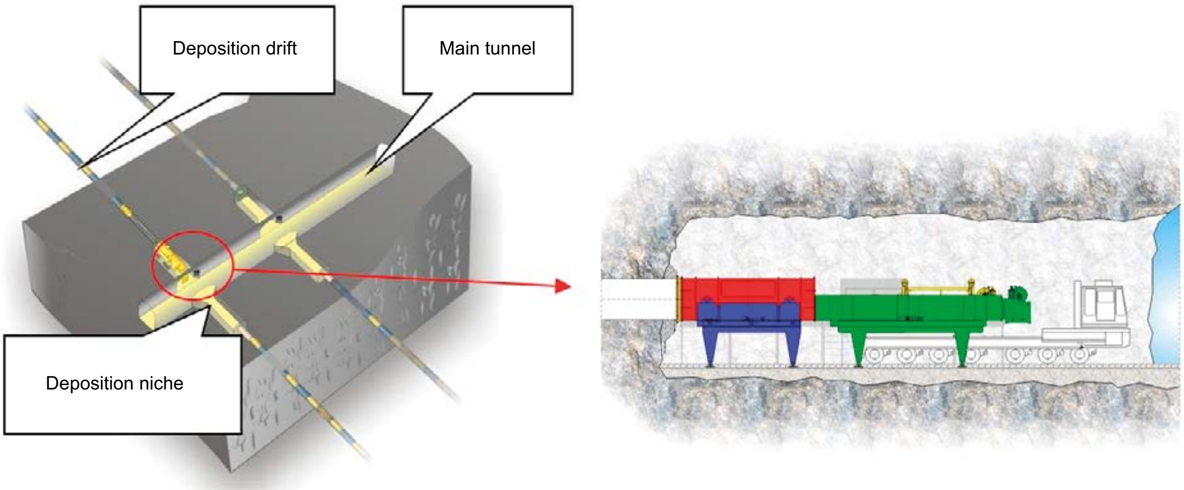


Figure 2-4. Main tunnel, deposition niches, and deposition drifts in the KBS-3H repository design by SKB.

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 the European Pressurized Water Reactor (EPR). The access to the deposition areas and the general design of the deposition areas are different in 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 KBS-3H.

In the KBS-3H design, drifts are divided into compartments by use of compartment plugs and drift plugs in order to facilitate manual watering of the drift and simultaneous air evacuation, ease the operation and reduce possible operational risks.

Beside the Supercontainers and the distance blocks there are a number of filling components needed in the KBS-3H deposition drift. Their role is to fill up space required for safety reasons e.g. at positions with high water inflow rate and required distances to plugs.

The design has five different filling components:

1. Pellet filling and transition blocks adjacent to drift plug.
2. Filling blocks at high inflow positions.
3. Pellet filling and transition blocks adjacent to a compartment plug.
4. Filling component at the drift end.
5. Filling of the pilot hole.

In a compartment the Supercontainers are separated by cylindrical distance blocks in order to manage the heat and to seal off each canister position from the next, and to prevent the transport of water and bentonite along the drift. According to this design, about 30–40 pre-fabricated Supercontainers, depending on the type of spent fuel, will be deposited in each drift. Filling components will be placed in positions, which cannot be used for Supercontainers or distance blocks based on positioning criteria (e.g. long-term safety reasons dictate that the inflow rate into a Supercontainer section including a distance block must be less than 0.1 l/min). Transition blocks together with bentonite pellets, forming a transition zone, are placed adjacent to the plugs. All components excluding the pellet filling sections are centered in the drift so that the gap width between the components and the drift wall is 44.5 mm. The drift components (Supercontainers, distance blocks and filling components) will be deposited using the deposition machine, which is described in more details by Autio et al. (2008).

Use of Mega-packer for groundwater control may reduce inflow leakages into the drifts decreasing bentonite erosion caused by leakages during the operational phase. The drainage of the compartment during deposition is achieved by the inclination of the drift. Water will self- drain along the drift floor out of the drift until the compartment or the drift plug is installed. Spray or drip shields, thin titanium sheets, will be mounted in positions of water inflow where there is a risk of water coming in contact with the bentonite blocks. This is done in order to protect the buffer against mechanical erosion allowing the leakage water to flow freely down the drift walls to the floor.

In this report the bentonite in the KBS-3H tunnels is divided into two different components, the buffer and the filling components. The buffer is defined as the bentonite inside the Supercontainer and the distance blocks. The filling components are defined as all other bentonite materials that are used in the tunnel.

2.2 Preparations in a drift prior to installation of the buffer and filling components

The plugs (compartment plug and drift plug) will be installed in sound rock with no fractures in drift sections that are determined prior to installation of the buffer and filling components. For the installation of the plugs notches have to be excavated in the drift and fastening rings casted in the notches as a preparatory measure before the installation phase. The fastening rings must allow unperturbed emplacement activity in the drift during the installation phase.

The artificial water filling and air evacuation procedure, which are parts of the DAWE (Draining, Artificial Water filling and air Evacuation) design, requires that the long air evacuation pipe is installed in the drift before emplacement of the drift components can be initiated. Installation of the air evacuation pipe is described in more details in Section 2.4.

2.3 Plugging

After the deposition of the drift components is finished, the compartment will be sealed with a plug (compartment plug or drift plug). Mounting of the plug includes installation of the collar on the fastening ring that was already casted in the notch in an earlier phase. In addition, the air evacuation pipe and the wetting pipes will be thread through the collar lead-in tube. Next the cap of the compartment plug (including the pellet filling hole) will be installed on the collar. The section between the compartment plug and the transition block will be filled by bentonite pellets through the pellet filling hole in the cap, see Figure 2-5. The filling hole will be plugged with a blind flange by bolts after filling.

2.4 Wetting and air evacuation

The empty void space in the slot (44.5 mm) between the deposition drift wall and the drift components inside a sealed compartment will be artificially filled with water. This guarantees the initial swelling of the buffer, the development of counter pressure against drift surface and that the canisters are locked in place, which will hinder axial displacement and significant buffer erosion. The volume of the gap for a 150 m long drift compartment is approximately 40 m^3. The water filling is made rapidly and in order to accelerate the swelling of buffer and filling components simultaneously in the compartment. The natural inflow into the drift will eventually slow down as the pressure inside the drift rises after completed filling. This is achieved within hours.

Water filling will be done by pumping fresh water through the plug with short (approximately 2 m) wetting pipes (Figure 2-5). During the water filling air will be compressed and accumulated at the end of the drift compartment due to its slightly upward inclination and this trapped air needs to be evacuated through the air evacuation pipe (maximum length 150 m) to allow complete filling with water. For water filling and air evacuation purpose the collar is equipped with four identical lead-ins with valves, three for the water pipes and one for the air evacuation pipe. The three short water filling pipes extend through the pellet filling section under the transition block, see Figure 2-5.

The air evacuation pipe is led from the end of the drift (or from the compartment plug). Since the air will be left in the ceiling of the drift an extra pipe will be fixed to the bottom block and led up to the roof, as shown in Figure 2-6.

Fresh water is pumped through the three pipes with a flow rate of about 25 l/min per pipe for about 8 hours. When the water starts to come out from the air evacuation pipe all the valves are closed.

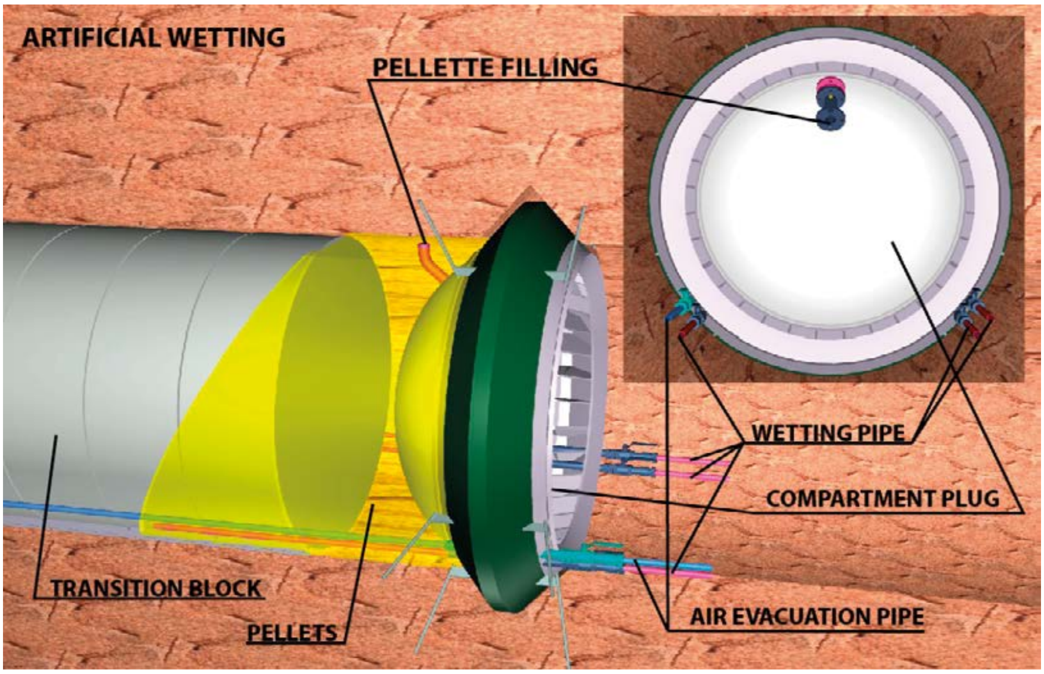


Figure 2-5. *Main components for the water filling system with short pipes through compartment plug (similar design in the drift plug). The three short water filling pipes will lead the water past the pellet filling section underneath the transition block.*

Figure 2-6. *A figure of the bottom filling, the buffer blocks and the air evacuation pipe at the rear end of the drift, as installed in the MPT tests at Äspö. The short pipe in the rear part of the drift that is turned upwards to the roof is needed because the air is accumulated in the upper part of the inclined drift. Three tie-rods (not part of the final design) that keep the 0.5 m thick block slices together are also shown. The feet are also seen under the blocks.*

2.5 Pipe removal and sealing a compartment

After the water filling and air evacuation have taken place the pipes will be removed from the compartment as required due to long-term safety. The pipe removal of the long air evacuation pipe and the short water filling pipes will take place directly after the water filling and air evacuation phases. When removing the long air evacuation pipe the coupling will allow it to be released from the short pipe at the end of the drift (Figure 2-7), which will be left in the drift.

The winch/pulling system for removing the air evacuation pipe is set up at the deposition niche and the procedure will depend on the location of the plug (compartment plug or drift plug). For the compartment plug located approximately at the middle point of the drift, the pipe can be pulled out as one piece to the first half of the drift and then split to 6 m long pieces. For the drift plug the pipe will be pulled out as long sections as allowed by the space (niche and central tunnel) available, probably as 24–30 m long parts. After the pipe has been completely removed, the ball valve of the lead-in tube is closed, and before the deposition operation continues the ball valve is replaced by a plug.

3 Bases for the new drift design

Comprehensive investigations and development work have been made in order to choose design alternative, further develop the DAWE alternative, resolve critical issues and design some parts of the concept in detail. Significant new information of bedrock properties, engineering design and buffer processes have been gathered since the last design was presented in Autio et al. (2008).

- The DAWE alternative was selected as KBS-3H reference design.
- The DAWE reference design alternative is based on water filling through the compartment or drift plug. Erosion caused by water filling was identified as one important issue and has been studied in the recent project phase. The study concluded that the erosion was not detrimental when using fresh water to fill the voids.
- It has been concluded that filling blocks can be placed in drift sections with higher inflows which would eliminate the need for the previously used dual compartment plug sections.
- The drift end plug made of reinforced concrete has been replaced by a compartment plug made sturdier to take full hydrostatic (5 MPa) and buffer swelling pressure (10 MPa) totalling 15 MPa.
- There is more information available of the groundwater inflows (Hartley et al. 2009) from the selected sites (Olkiluoto and Forsmark) than was available in the previous phase (Autio et al. 2008). The data indicates that the inflows are smaller and more sparsely located than in estimates presented in that report.
- The Mega-Packer post-grouting technique using colloidal silica has proven to be efficient and can be used to reduce the inflows during the installation and the transient phase when buffer swells and fills the open gaps in the deposition drift (Eriksson and Lindström 2008).
- The understanding of the impact of inflows on buffer behaviour has been improved (SKB 2012, Sandén et al. 2008a, b). The present understanding from functional point of view clearly indicates that the inflow has less detrimental effect on buffer and filling components than earlier estimates. Therefore the water inflow limits could be increased from an engineering point of view without affecting the behaviour of the buffer negatively during the time period from emplacement to water filling.

The most important conclusion drawn from the new information is that the water inflow rate into the deposition drifts is lower than earlier expected. There are proven techniques to control the lower inflow rates and the buffer reference design is not as sensitive to inflows as assumed in earlier design alternative (Autio et al. 2008). The conclusion is that the present KBS-3H design is far more robust with respect to water inflow than earlier assumed. Therefore the drift design has been updated to correspond to the new information, which will improve the technical and economic feasibility of the KBS-3H design in several ways.

Possible detrimental chemical erosion of buffer caused by glacial melt waters, which is an issue common with KBS-3V, has not been taken into account when updating the design. This remains an unresolved feature and there is not enough scientific information available presently to assess the effect reliably. This issue is of high priority for SKB and Posiva and the KBS-3H design should be re-evaluated when there is adequate basis that can be incorporated into the design work.

The new information has been incorporated in the design as presented below:

- The dual compartment plug alternative is not needed because the expected inflows do not expose detrimental effect on the buffer during the operation and transient periods and can be replaced by filling blocks.
- Mega-packer post- grouting can be used to reduce inflows to an acceptable level during installation if necessary. The reference design alternative is robust to inflows and therefore it is likely that sealing might not be needed unless the inflows are of order of several litres per minute, which is estimated to be the case in only a few drifts. After water filling the plug will prevent water flow and possible erosion so the grout only needs to function until completed water filling.

- Water filling can be carried out with short pipes through the compartment plug and the drift plug. This has been proven to yield acceptable erosion if fresh water is used (SKB 2012). No long filling pipes are needed. Only one long air evacuation pipe, which is removed after water filling, is required during installation.
- The drift end plug of concrete has been replaced by a compartment plug that is made sturdier and named “Drift plug”.
- Possible detrimental chemical erosion of buffer caused by glacial melt waters is presently studied comprehensively. It is possible that engineered solution need to be developed in future in order to reduce the effect of chemical erosion.

4 Detailed design of filling components

4.1 General

Significant bentonite research, testing and technical development has taken place since the previous KBS-3H design was presented. This increased understanding, especially with respect to design requirements and evolution of the system after water filling, has been taken into account when designing new filling components. This design work has also lead to a revision of the KBS-3H drift design, which incorporates current understanding and results from the extensive testing and research on several issues. The revised design basis and design is presented in this section. There are still some uncertainties left in the design. These are, however, not being assessed as critical for the feasibility of the design and are presented in Chapter 6.

The design includes 5 different filling components (see Figure 4-1); below:

1. Pellet filling and transition blocks inside the compartment and drift plug.
2. Filling blocks at high inflow positions.
3. Pellet filling and transition blocks outside to the compartment plug.
4. Filling component at the drift end.
5. Filling of the pilot hole.

The drift section between the drift plug and the deposition niche is assumed to be filled with filling blocks similar to distance blocks. That will be later revised if needed when the backfilling design of the deposition niche is available.

4.2 Requirements on the drift dimensions and quality

The nominal drift diameter is 1 850 mm. The maximum allowed increase in drift diameter is 5 mm, which yields an acceptable drift diameter 1 850 mm < D < 1 855 mm. The other requirements on the drift are mainly caused by the buffer and described in Section 5.1.2.

4.3 Requirements on the filling components

All engineered system components, including not only the canister and the buffer, but also the auxiliary components must be designed to be mutually compatible. Although all components will inevitably undergo physical and chemical changes over time, none may evolve in such a way as to significantly undermine either the long-term safety functions or the design functions of the other components.

The requirements on the filling components are given in the following sections.

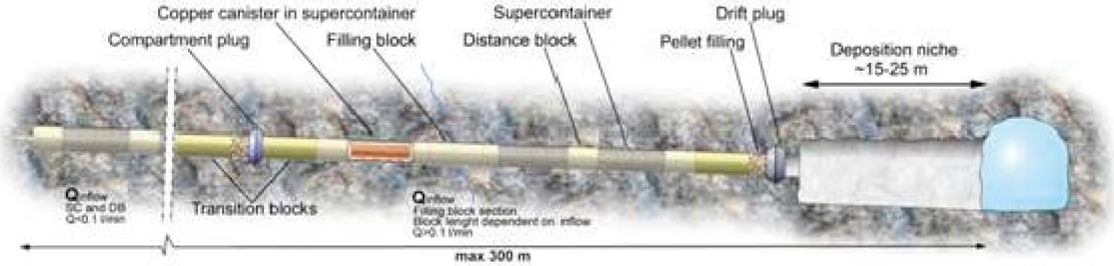


Figure 4-1. *Filling components in a KBS-3H drift.*

4.3.1 Filling blocks

Filling blocks are used in drift sections where relatively high initial (i.e. before sealing by e.g. Mega Packer) groundwater inflows render them unsuitable for Supercontainer and distance block emplacement. The function of the filling blocks shall from a safety perspective be as follows:

(i) to fill the void spaces in the drift and to confine the buffer as it takes up water, such that the filling blocks keep the neighbouring distance blocks unaffected.

(ii) to protect the canisters and buffer from the effects of transient water flows that may occur during the operational period of the drift and the following period leading to saturation (e.g. piping and erosion)

(iii) to isolate the canisters and buffer from larger and more transmissive geological features that may detrimentally affect the canisters and buffer in the longer term and cause preferential pathways for radionuclide transport in the event of canister failure

The following requirements are imposed to support this function.

- The filling blocks shall have a sufficiently low compressibility.

By their low compressibility, the filling blocks should prevent the expansion of the adjoining buffer or distance blocks during their saturation and, also in the longer term, keep the buffer in place so that the density requirements on the buffer are met.

- The filling blocks shall have a sufficient but not excessive swelling capacity.

By their swelling capacity, the filling blocks should ensure that macroscopic void spaces in the drift are filled, and should contribute to the mechanical stability of the deposition drifts and near-field rock. The maximum swelling pressure should not, however, be so high that it would lead to excessive compression of the buffer that could compromise the capacity of the buffer to protect the canisters in the event of rock shear.

- The filling blocks shall have a sufficiently low permeability and lateral extent in order to
  - avoid short circuit between the fracture and the buffer,
  - minimise the effect of colloid erosion so that it does not jeopardize the buffer function.

By their low permeability, the filling blocks should ensure that water that flows through them does not lead to significant erosion of the adjoining distance blocks. Significant erosion here means sufficient erosion to compromise the capacity of the distance blocks to fulfil performance targets related to density. By their low permeability and lateral extent, they shall also prevent the formation of preferential radionuclide transport paths by isolating more transmissive host rock fractures.

The quantitative criteria for the filling blocks with respect to the hydraulic conductivity and swelling pressure have not been evaluated, but likely the criteria for the hydraulic conductivity should be the same as for the buffer. The swelling pressure should also ideally be the same as for the buffer. The maximum allowed deviation needs to be estimated in the future assessment.

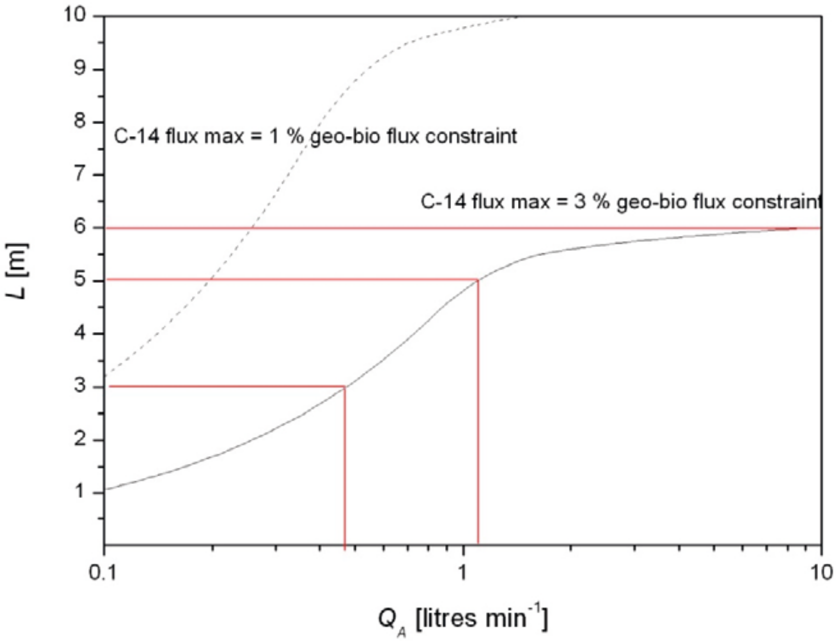
The length of the filling block must be such that it provides adequate respect distance between the high inflow fractures and the canisters. The higher the initial inflow, the larger respect distances that are expected to be needed, on the basis that high initial inflows are indicative of high long-term flow rates and low geosphere transport resistances. Scoping calculations have been used to suggest tentative criteria for minimum respect distances as a function of given initial inflow. The scoping calculations consider the maximum rate of release of C-14 emanating from a failed canister to the fracture following its diffusion through the buffer and filling component. Safety assessments in Sweden and Finland have shown that I-129, Cl-36 and C-14 generally dominate the release or dose maximum following canister failure, with C-14 often dominating in cases of early canister lifetime and a degraded effectiveness of the repository barriers. C-14 was thus selected as an appropriate example radionuclide for the scoping calculations.

It is assumed − in accordance with the current design − that the filling blocks are composed of compacted bentonite and have the same properties as the distance blocks. Tentative criteria are set on the basis that the maximum C-14 release rate should be such that a flux constraint of 0.3 GBq per year across the geosphere/biosphere interface is satisfied by a significant margin (Figure 4-2). The flux constraint is taken from Finnish regulations, and is chosen in preference to a dose or risk constraint for simplicity, since it avoids the need to address biosphere and dose pathway issues.

The choice of compacted bentonite also satisfies the following additional requirements:

1. The composition of the filling blocks must ensure that the chemical environment (e.g. nature and concentrations of solutes) does not have an unfavourable effect on the performance of the main barriers the canister and the buffer.
2. The filling blocks must not promote microbial activity that might otherwise lead to unfavourable chemical conditions in the adjacent buffer and at the canister surface.
3. The filling blocks must prevent the build-up of excessive gas pressure in adjoining drift sections to avoid damage to the main barriers. The drift sections adjoining those occupied by filling blocks may be tight, causing gas pressure to build up most likely at the buffer/rock interface. This gas should be able to escape along the buffer/rock interface and then either through the filling blocks, or along the filling-block/rock interface, to transmissive fractures intersecting the drift sections occupied by the filling blocks.
4. By their erosion resistance and suitable chemical composition, the filling blocks should minimize the formation and loss of colloids at the filling-block/rock interface that could otherwise detrimentally affect the barrier function of the bedrock with respect to radionuclide transport.

Requirements 1 and 2 are fulfilled if the filling blocks have equal properties as the buffer blocks and rings since those requirements are fulfilled for the buffer in KBS-3V as proven in SR-Site. Requirements 3 and 4 might need additional investigations in order to prove the fulfilment.



Initial inflow range [litres min^{-1}]	Respect distance [m]
0.1–0.5	3 m
0.5–1	5 m
> 1	6 m

Figure 4-2. *Proposed minimum respect distance (L) between the high inflow fractures and the canisters as a function of initial inflow from a fracture intersecting the deposition drift (Smith et al. 2007). Note that the upper limit for inflows after grouting is roughly 10 l/min. If inflows are equal or higher than that, the bentonite blocks can get wet during transportation using the deposition machine. High inflow sections will be grouted to lower the inflow rate before the installation phase.*

4.3.2 Filling material adjacent the compartment plugs and drift plugs

Compartment plugs

In the reference KBS-3H design, compartment plugs are used to divide the drift in compartments of suitable length (maximum length 150 m) that can be water filled artificially. The function of the filling components adjacent to the compartment plugs from a long-term safety perspective is identical to that of the filling blocks, namely

(i) to fill the void spaces in the drift and to confine the buffer as it takes up water, such that the filling blocks keep the neighbouring distance blocks unaffected,

(ii) to protect the canisters and buffer from the effects of transient water flows that may occur during the operational period of the drift and the following period leading to saturation (e.g. piping and erosion),

(iii) to isolate the canisters and buffer from larger and more transmissive geological features that may detrimentally affect the canisters and buffer in the longer term and cause preferential pathways for radionuclide transport in the event of canister failure.

The filling material adjacent to the compartment plug on the sealed side shall not have excessive swelling pressure until the drift has been sealed by the drift plug.

The filling material shall not have a swelling pressure that is so high that it gives rise to significant axial movement outwards of the compartment plugs that may increase or decrease the density of the adjoining buffer outside the density criteria.

Additional requirements related to prevention of filling material loss and to the need for mutual compatibility of the components with each other and with the bedrock are the following:

- The compartment plugs and the adjacent filling material shall not give rise to chemical or mineralogical changes in the adjoining buffer, which compromise the performance of the buffer or that of the canisters.
- The compartment plugs and the adjacent filling material shall not undergo volumetric changes which might compromise the performance of the nearby buffer.
- The compartment plugs shall not allow the build-up of excessive gas pressure in adjoining drift sections to avoid damage to the main barriers.

Drift plugs

The function of the filling component on the inside of the drift plug is identical to that of the filling components on the inside of the compartment plug.

The purpose of the drift plugs, similar to the KBS-3V deposition tunnel plugs, is to avoid significant water flow out of the drift, which could give rise to piping and erosion in the buffer, either through the plug itself, or through the adjacent rock. The plugs shall also keep the buffer in place prior to the backfilling of the adjacent central tunnel/deposition niche.

4.4 Additional basis for filling component design

4.4.1 Material selection and design

Na-bentonite of similar type as used for the buffer has been selected to be used for the filling components. The material selection was based on engineering judgement and the following arguments:

- It is assumed that the material used for the buffer fulfils the specified requirements and therefore has a potential to fulfil the requirements for filling components as well.
- The recent research on erosion issues has shown that Wyoming type Na-bentonite material (commonly referred also as MX-80 type bentonite) used as bentonite buffer in the KBS-3H design, can tolerate the erosion during water filling of the drift when the water flows in the gap between drift surface and buffer and when fresh water is used (SKB 2012). These tests also show

that the natural water inflow into the drift during emplacement is acceptable if the water inflow is less than 10 L/min. After water filling the inflow becomes smaller since it is limited by the water absorption capacity of the buffer and filling components.

- The material is well known when compared to other materials or mixtures of materials with adequate swelling capacity and has been proven to be stable for long periods of time.
- The use of the same material for filling components as buffer reduces or eliminates the risk for detrimental or uncertain physical and chemical reactions between filling components and the buffer or other materials in the drift.
- There are some uncertainties related to the behaviour of bentonite material such as post glacial erosion or effect of internal piping over long periods of time. These issues will be addressed in future research. It is likely that use of other materials may introduce new similar uncertainties in chemical and physical short- and long-term processes, which have not been addressed and might therefore initiate new research with impact on several present RD&D activities.

The choice of material for the filling components is based on the design of the distance blocks. The blocks can be composed of cylindrical block slices with a fixed size or the thickness can be adjusted to specific requirements based on operational aspects.

The design of the filling components was based on the following arguments:

- The filling components can be installed using the same type of equipment (in principle) as for emplacing Supercontainers and/or distance blocks, which has been proven technically feasible and efficient.
- The use of pellets is proven technique both regarding installation and function.
- The filling blocks shall be identical to the distance blocks so that both installation and final properties at their interfaces will be the same.

4.4.2 Control of groundwater inflow

The upper limit for inflows is set by installation requirements. During installation i.e. after grouting, the inflow must be lower than roughly 10 l/min. The 10 l/min limit is mainly based on the functionality of present deposition machine, however, there is also risk that the buffer and filling blocks can get wet during transportation with the deposition machine. Since the drift is artificially filled with water in a time period which is less than one day, the effect of natural water inflow during water filling is very small.

The only restriction for the groundwater flow out of the deposition drift during the operational period of the drift is that it must not be so high that it affects the installation of engineered components.

If needed, water inflow into the drifts during the operational period may be reduced by groundwater controlling. It is also important to ensure that there are no significant connective flow paths between the deposition drifts and those parts of the repository that remain open for a long period, since these could lead to high flow rates and mechanical erosion of bentonite components.

4.4.3 Prevention of mechanical displacement and limitation of piping and erosion

The operation of the drift needs to be such that there will be no significant water pressure built up locally in the deposition drifts during emplacement that could cause movement of components or have other adverse effects.

After the artificial water filling, high hydraulic pressure gradients and gradients in buffer swelling pressure may develop along the drifts, which could potentially lead to displacement of the distance blocks and Supercontainers. The distance blocks and filling blocks, together with the compartment and drift plugs, have the important design function of keeping the engineered components in the drift in place, and not allowing any significant loss or redistribution of buffer mass by swelling, compression, piping or erosion. 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 an additional compartment plug or the drift plug is installed.

4.4.4 Artificial water filling

The design presumes that a favourable initial state of the saturation phase is obtained by using the DAWE technique both for the filling components and the buffer components. After artificial water filling the water inflow rate into the drift may be reduced significantly (if it is rather high) because the water pressure in the drift becomes similar to the surrounding bedrock. As a result there is only minor pressure gradients between the drift and surrounding rock mass. The water filling will accelerate the swelling of bentonite. The water filling and buffer swelling will be similar in the whole drift, which is beneficial for preventing piping and erosion. As a result all void spaces in the drift compartment are filled approximately at the same time, thus ensuring that the bentonite will swell and seal the compartment uniformly until this water is consumed by the bentonite. After that the further wetting is dependent on the water supplied by the rock.

4.4.5 Engineering bases

Compartment and drift plugs

The distance 1.3 m between the crown of the compartment plug cap and the adjoining transition block is needed during installation in order to be able to install the cap properly. This assumption, which is used in the calculations below, may be changed to be the distance from the collar of the plug, which would result in a smaller open volume between the plug and adjoining transient block than what has been assumed in this study.

The open volume between the transition block and the plug is filled with pellets, which have lower density than blocks. A change in volume of the open space would thus lead to a slightly different design than derived in the calculations below.

Pilot hole

The length and the diameter of the pilot hole stump at the drift bottom end is approximately 2 000 mm and 152 mm, respectively. The pilot hole is needed in order to steer the cutter head of the drift boring machine.

Drift bottom end

Part of the air evacuation pipe will remain permanently at the drift bottom (Figure 2-6) and at the compartment end. It has been assumed that the shape (curvature) of the drift face would be similar to that from the Äspö demonstration tunnel and the drift end block shall have the shape corresponding to the drift face. Alternatively a remaining open uneven slot will be filled with bentonite pellets. Figure 4-3 shows a picture from the drift end face taken in one of the KBS-3H drifts in Äspö HRL.

Distance block section

The design of the distance block section, which is used to design the transition zone, is described in Chapter 5. There are, however, several alternative lengths of distance block sections based on the type of canister because canister spacing, which defines the length of distance block, depends on the type of spent fuel, lay-out design and bedrock properties. The length of the distance block section is included in the respect distance to inflowing fractures as presented in Section 4.5.3 and therefore the longer the distance block, the shorter the length of filling block section., The length of 2.875 m was selected as the reference length of the distance block section when designing the filling components because it is closest to the average length the distance block section for the Finnish and Swedish conditions.

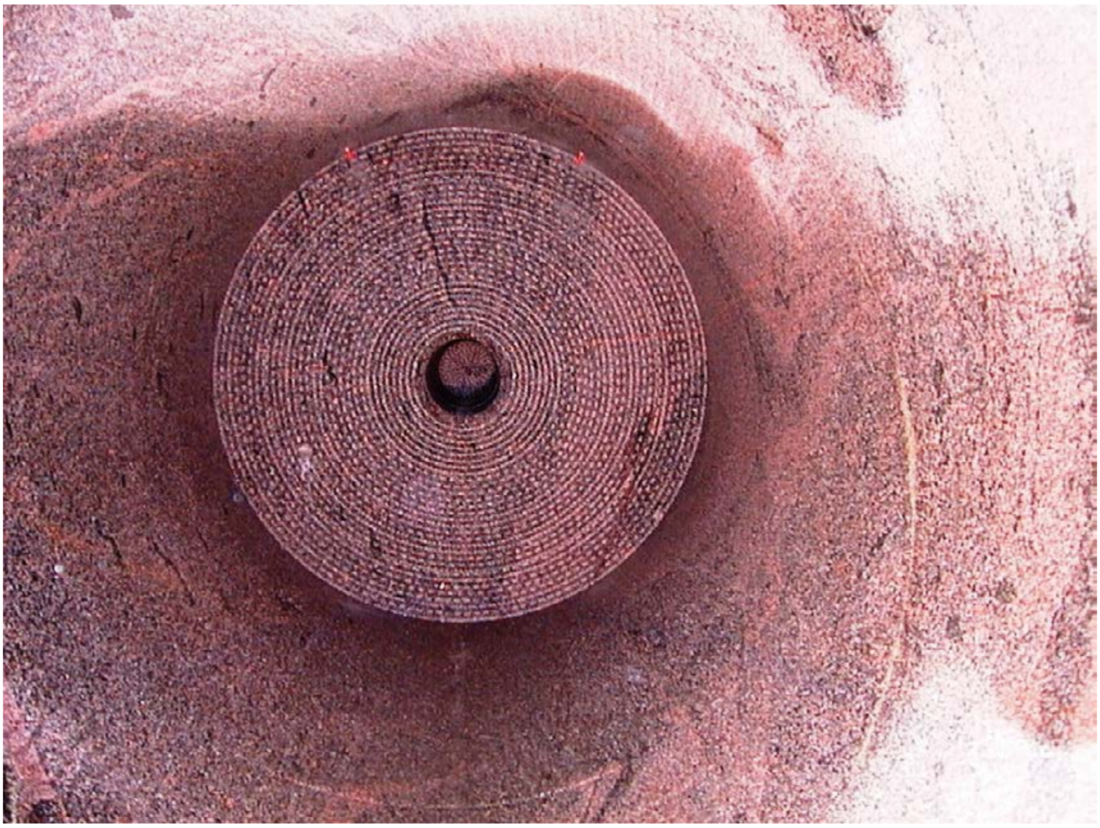


Figure 4-3. *Picture of the drift face at Äspö HRL.*

4.4.6 Operation schedule

The time for the installation of a compartment will be in the order of two weeks when the titanium alloy drift plug is used. It will enable the installation of a drift plug in the pre-excavated notch in one day.

4.4.7 Groundwater inflow estimate updates

A summary of calculations made of ground water inflow distribution in a generic KBS-3H repository was presented in the Design description 2007 (Autio et al. 2008). The studies on groundwater flow and expected inflows have since then continued. Three representative different groundwater cases for Olkiluoto site, the normal most likely case and two extreme cases (wet and dry), are presented here based on the results of DFN modelling for Olkiluoto, see Hartley et al. (2009, 2010). These are all possible in the repository and the objective is merely to qualitatively illustrate the use of filling components in these different cases. The evaluation was based on the following principles:

- The DFN modelling results covered KBS-3V deposition tunnels in 9-metre sections. Here we assume that similar inflow distributions apply for a KBS-3H deposition drift with 33 such theoretical sections.
- Three cases (median, dry, wet) were selected from the graph in Figure 4-4, with total inflow rate to an entire tunnel differing by 2 orders of magnitude, however the appropriateness of the wet case in this study is not evident and should be addressed separately if needed.
- Expected inflows into a unit length of 9 m (composed of a distance block and a Supercontainer) were calculated according to the graph in Figure 4-5. The unit lengths were studied because an inflow which exceeds the limit will result in rejection of the unit length to be used for Supercontainer emplacement.
- Inflow to each section is assumed to be due to one dominating fracture.

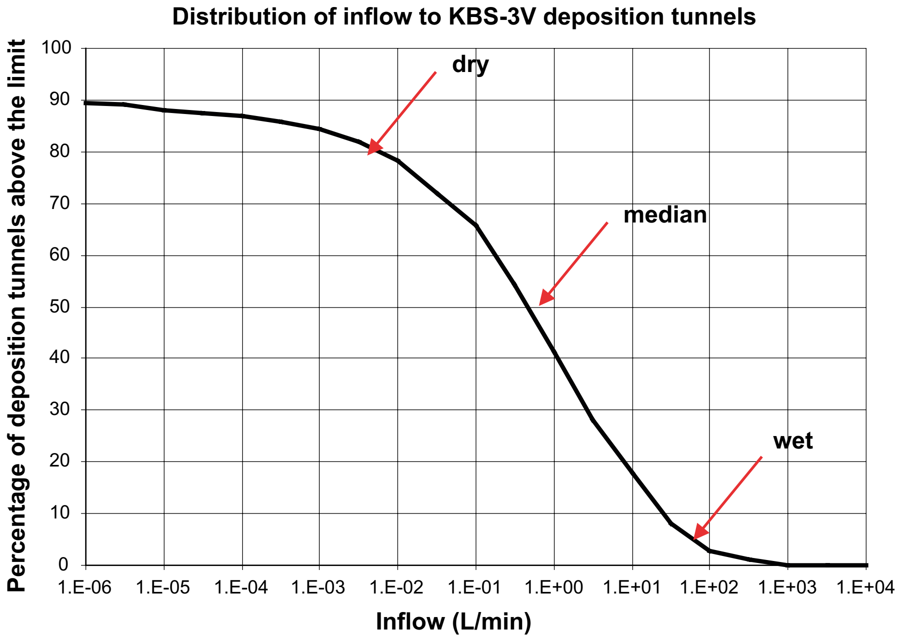


Figure 4-4. *Cumulative distribution of total water inflow rate in KBS-3V deposition drifts (here assumed to be valid also for KBS-3H). The three selected cases of total inflows are shown: the dry, median and wet cases (based on data from Hartley et al. 2009, 2010).*

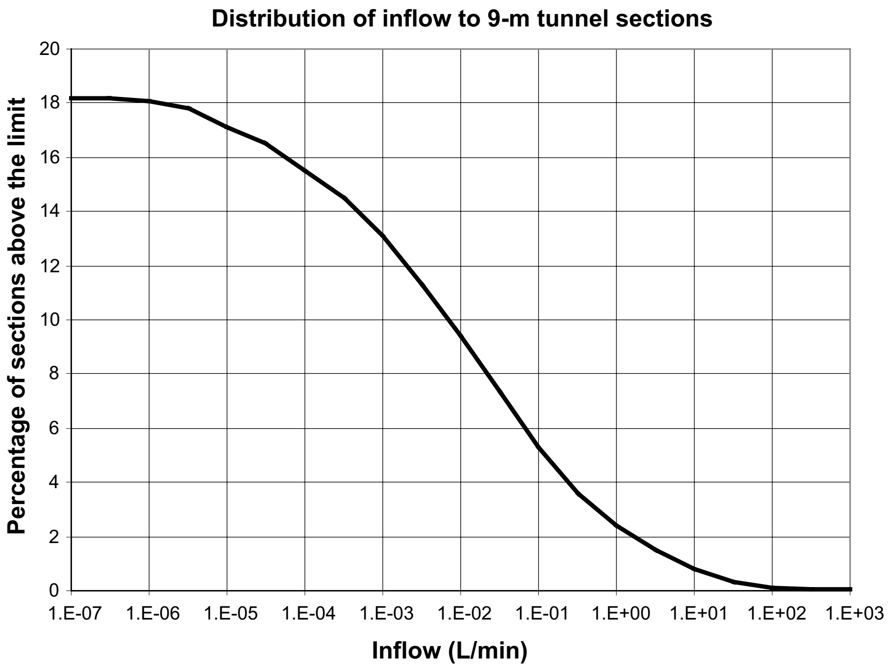


Figure 4-5. *Cumulative distribution of inflow rate into 9 m unit length drift sections (composed of a Supercontainer and distance block) in KBS-3V deposition drifts (here assumed to be valid also for KBS-3H). Based on data from Hartley et al. (2009, 2010).*

Case 1: Median inflow rate in a KBS-3H drift

The results for case 1 with a medium inflow rate indicate the following inflows and inflow positions (see Figure 4-6):

- Total inflow into a 300-metre drift: 0.5 l/min.
- 6 sections out of 33 have inflow:
  - One section with 0.3–1 l/min.
  - One section with 0.01–0.1 l/min.
  - Two sections with 0.001–0.01 l/min.
  - Two sections with < 0.001 l/min.
- One fracture with inflow > 0.1 l/min.
- No fracture with inflow > 0.5 l/min.

Case 2 (wet): High inflow rate in a KBS-3H drift

The results for the wet case 2 indicate the following inflows and inflow positions (see Figure 4-7):

- Total inflow into a 300-metre drift: 50 l/min.
  - About 5 % of all drifts are above this limit.
- 10 sections out of 33 have inflow:
  - One section with 30–100 l/min.
  - One section with 10–30 l/min.
  - One section with 1–10 l/min.
  - One section with 0.1–1 l/min.
  - Two sections with 0.01–0.1 l/min.
  - Two sections with 0.001–0.01 l/min.
  - Two section with < 0.001 l/min.
- Four fractures with inflow > 0.1 l/min.
- Four fractures with inflow > 0.5 l/min.
- Three fractures with inflow > 1 l/min.

Case 3 (dry): Low inflow rate in a KBS-3H drift

The results for the dry case 3 indicate the following inflows and inflow positions (see Figure 4-8):

- Total inflow into a 300-metre drift: 0.005 l/min.
  - About 20 % of drifts are below this limit.
- 2 sections out of 33 have inflow:
  - One section with 0.003–0.01 l/min.
  - One section with 0.001–0.003 l/min.
- No fracture with inflow > 0.1 l/min.

The inflow rates in Figure 4-4, which have been used for the three example cases are taken from Hartley et al. (2010). The earlier calculated inflow rates by Lanyon and Marshall (2006) are compared to the results by Hartley et al. (2010) in Figure 4-9. The comparison shows that the present estimate used in the examples yields lower inflow rates (see the blue curve in Figure 4-9):

The fracture directions have effect on the intersection lengths between the drift and the fractures and therefore affect the length of the filling components.

Figure 4-6. Case KBS-3H Median inflow drift of length 300 m. Inflows and inflow positions are shown.

Figure 4-7. Case KBS-3H Wet inflow drift of length 300 m. Inflows and inflow positions are shown.

Figure 4-8. Case KBS-3H Dry inflow drift of length 300 m. Inflows and inflow positions are shown.

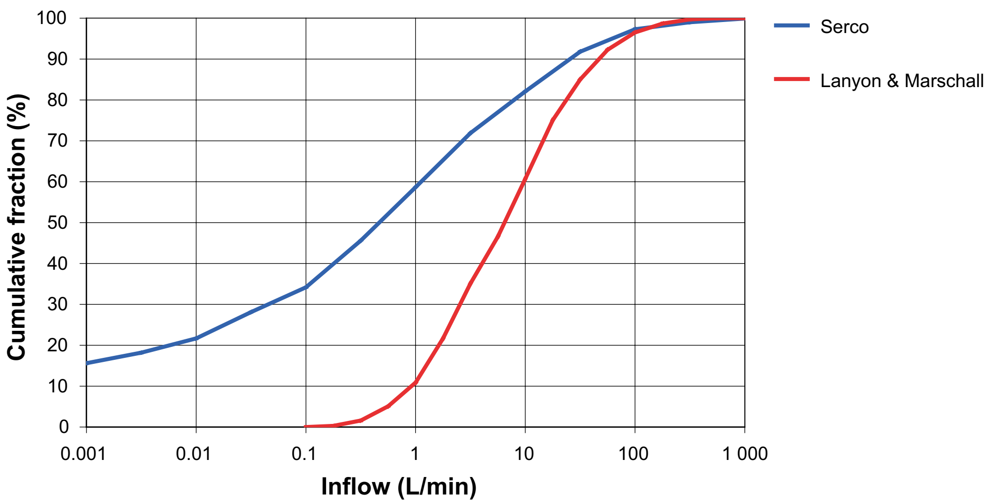


Figure 4-9. Comparison of cumulative distribution of inflow into a deposition drift made earlier by Lanyon and Marshall (2006) in red and the present results based on Hartley et al. (2010) in blue.

4.5 Detailed design of the filling components

4.5.1 General

As presented earlier the updated KBS-3H drift design includes 6 filling components, which are illustrated in Figure 4-10. The design inside the compartment and drift plug (a) are basically the same and 5 different components have been designed.

a) Pellet filling and transition blocks inside the compartment and drift plug.

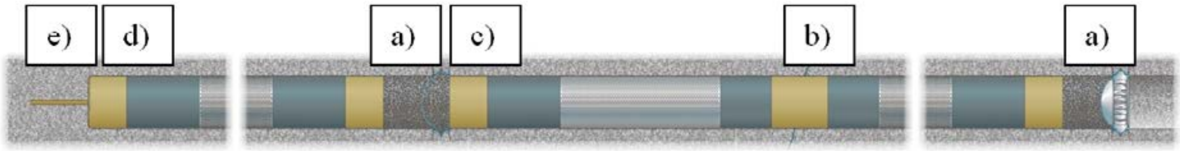
b) Filling blocks at high inflow positions.

c) Pellet filling and transition blocks outside to the compartment plug.

d) Filling component at the drift end.

e) Filling of the pilot hole.

A general requirement for all filling components is that they shall not affect the buffer components so that they deviate from the requirements on the buffer presented in section 5.1.



a) Pellet filling and transition blocks inside the compartment and drift plug
b) Filling blocks at high inflow positions
c) Pellet filling and transition blocks outside to the compartment plug
d) Filling component at the drift end
e) Filling of the pilot hole

Figure 4-10. *KBS-3H Drift design with different filling components.*

The design of the filling components adjacent to pellet fillings is based on the internal friction of the filling material and therefore permanent density gradients will remain in the filling components. This assumption is commonly used in evaluation of buffer performance and is presently being studied in homogenization research in order to provide more evidence as to its validity.

4.5.2 Material used in filling components

The same material that is used in the buffer has been adopted in the filling components. The reference buffer material is bentonite clay with the material composition specified in Table 4-1. Examples of commercial bentonites with this material composition are MX-80 and Ibeco RWC (Deponit CA-N), which were analysed in SR-Can. The same material is used in the compacted blocks in the Supercontainers and in the distance blocks as well as in the pellets.

Table 4-1. Reference buffer material used also in filling components (SKB 2012).

Design parameter	Nominal design [wt-%]	Accepted variation [wt-%]
Montmorillonite content	80–85	75–90
Sulphide content	limited	< 0.5
Total sulphur content (including the sulphide)	limited	< 1
Organic carbon	limited	< 1

4.5.3 Filling blocks in positions of inflows

In the current KBS-3H design, filling blocks will be placed in drift positions intersected by fractures giving initial inflows to the drift above 0.1 l/min (Figure 4-11). Such drift sections are currently excluded as locations for Supercontainers or distance blocks.

The following modifications of the previous schematic design have been made:

- There is half a distance block section on both sides of the filling block section.
- The length of the filling block section depends on the inclination of the fracture, the length of the distance block section and the inflow rate. This is based on the principle that the length of the filling block section sets the transport length (and resistance) from the canister embedded in the Supercontainer to the transmissive feature. Note that the design is consequently based on inflows before any possible sealing operations.
- It is assumed that the filling block section is composed of 50 cm thick bentonite block slices based on the present production technique (uniaxial compression). This, however, can be adjusted and optimised if considered suitable.

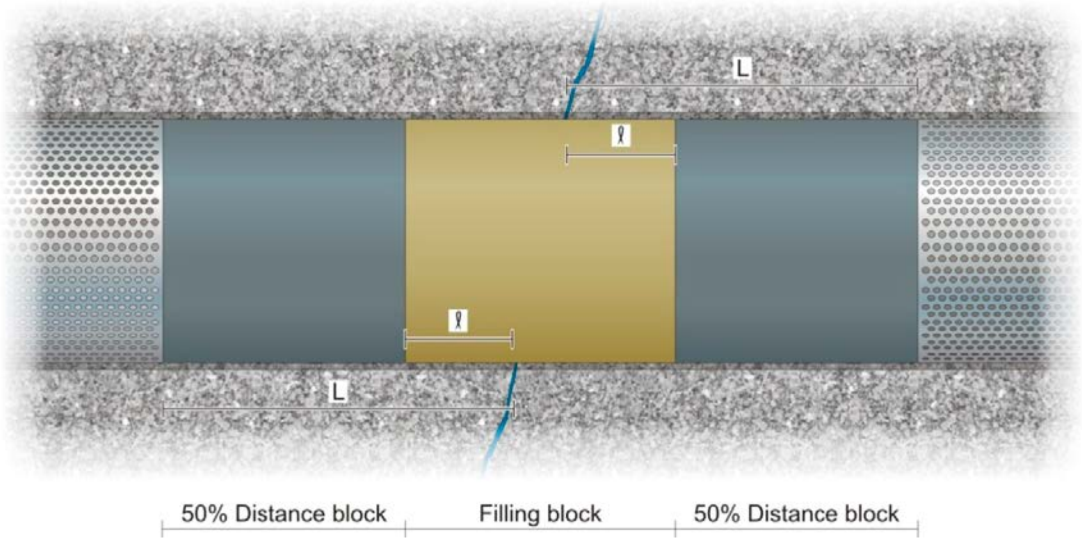


Figure 4-11. KBS-3H drift, showing the position of a filling block section between a split distance block section and two Supercontainers. Note that the inclination of fracture has effect on the length of filling block.

Dimensioning

The length of the filling block section has been established as a function of the initial inflow from the fracture by using the principles presented above. Scoping calculations have given tentative estimates for the respect distance needed to water-conductive fractures with specific inflows ranging from 0.1-0.5 l/min, 0.5-1 l/min and >1 l/min, with upper limit of 10 l/min. These tentative criteria are set on the basis that the release rate of C-14 emanating from a failed canister to the fracture should be such that the Finnish regulatory geo-bio flux constraints are satisfied by a significant margin. Based on these tentative estimates it has been suggested that filling blocks can be placed in sections with higher inflows which would eliminate the need for the previously used double (dual) compartment plug sections. The calculations are presented in Appendix A, B and C and the results are shown in Table 4-2 below. Note that uppermost limit for inflows in the drift based on operation of the deposition equipment is 10 l/min, which is mainly based on the functionality of the present deposition machine. However, there is also risk that the buffer and filling blocks can get wet during transportation with the deposition machine.

Table 4-2. Respect distances (L in Figure 4-11) with respect to inflow rates.

Initial inflow range [litres min^{-1}]	Respect distance [m]
0.1–0.5	3 m
0.5–1	5 m
> 1	6 m

Design

It should be noted that the respect distances in Table 4-2 include half a distance block section on each side as shown in Figure 4-11. The design of the filling block sections that correspond to the selected length of the distance block section and above shown respect distances are presented in Figures 4-13 to 4-15.

The design of the filling blocks is the same as the design of the distance blocks. The reference design of the blocks is presented in Table 4-3. The densities are given as dry densities.

Table 4-3. Reference properties of the transition blocks.

Design parameter	Nominal design	Accepted variation
Dry density (kg/m^3)	1712	±20
Water content (%)	21	±1
Dimensions (mm)	Height: 500 Outer diameter: 1765	±1

The respect distance is measured from the closest point where the fracture plane intersects the drift wall to the Supercontainer, see Fig. 4-13. This applies to both sides of the filling block section. The lengths of the filling block sections have their minimum values in each inflow range category, when the fracture plane runs perpendicularly to the drift with the inclination of 90 degrees. If this is not the case it might be due to:

- The fracture plane does not strike perpendicularly to the drift and it has an inclination 90 degrees or less.
- The fracture plane strikes perpendicularly to the drift but it has an inclination less than 90 degrees.

In these cases the length of the filling block section is increased based on the inclination of the fracture, i.e. the angle α between the drift axis and the fracture plane. α is defined as the inclination between the axis of the drift and the fracture plane seen from the minor axis in the ellipse formed by the fracture intersection contour in the drift wall.

Other parameters which affect the length of a filling block are the length of the distance block section and the inflow rate into the Supercontainer section. As 50 % of length of the distance block section is included in the respect distance this will conclude that the increase in the length of the distance block will shorten the length of the filling block with the same amount. A diagram has been developed to determine the required length of filling block section, see Fig. 4-12. The different cases are illustrated in Figures 4-13 to 4-15.

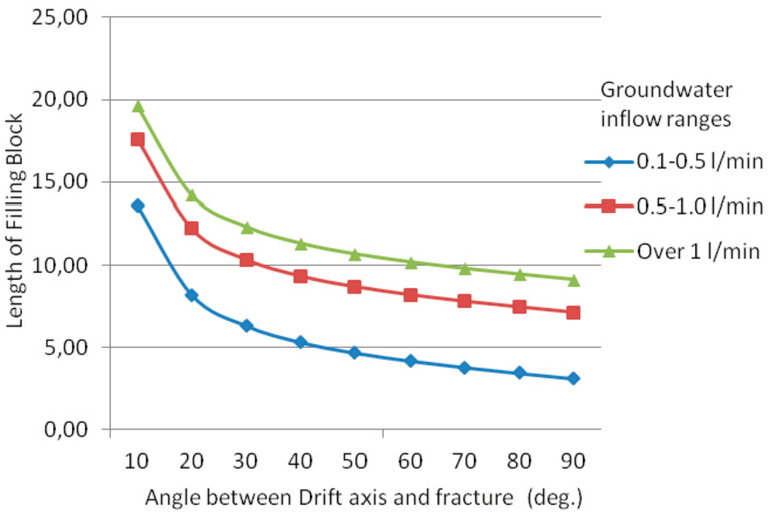


Figure 4-12. *Diagram presenting the dimensioning of the filling block section as a function of the angle (see Figure 4-13) between drift axis and the fracture plane in three different inflow range categories, with specific respect distances. The length of the distance block section that has been used in this case is 2.874 m.*

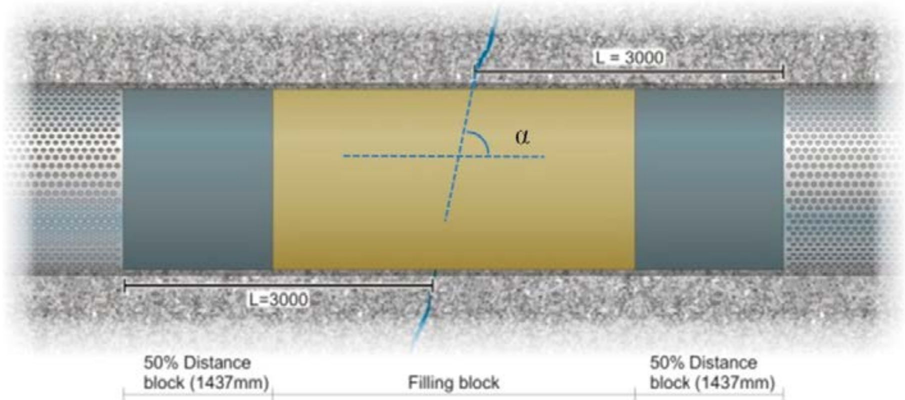


Figure 4-13. Filling block section for positions where the inflow is 0.1–0.5 l/min.

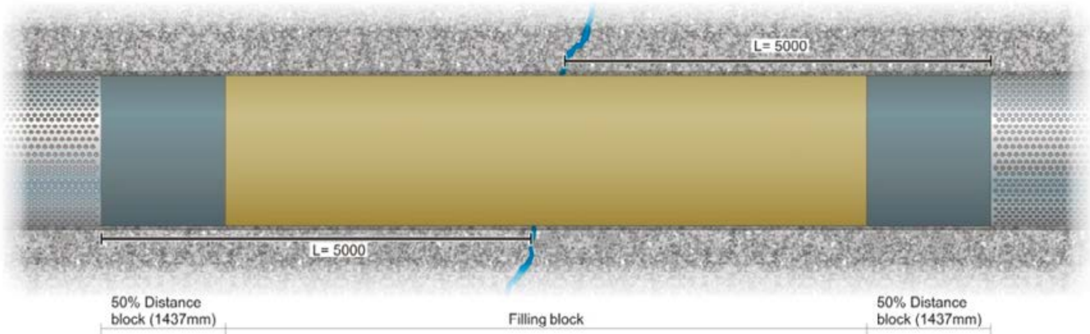


Figure 4-14. Filling block section for positions where the inflow is 0.5–1.0 l/min.

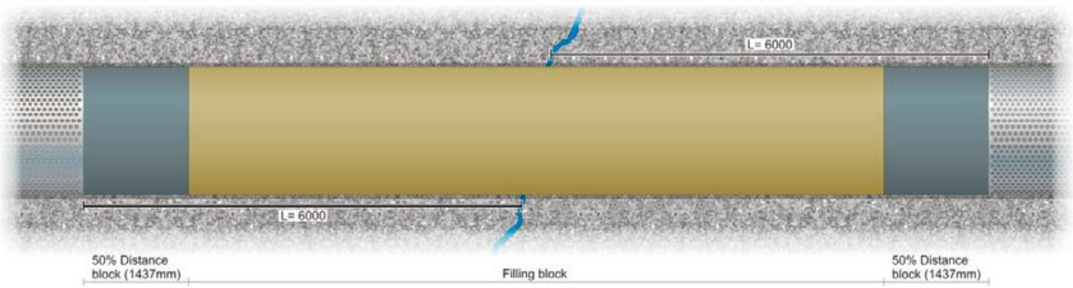


Figure 4-15. Filling block section for positions where the inflow is larger than 1.0 l/min.

4.5.4 Filling components adjacent to the compartment drift plugs

The design of the filling components inside the drift plug and the compartment plug are identical. In addition the design of the filling components outside the compartment plug is based on same calculation principles. The pellet filling has a rather low density and will be compressed by the neighbouring highly compacted bentonite blocks. This yields a swelling and reduction in density of these blocks. Since the distance block section in contact with the Supercontainer needs to be unaffected with retained density a transition zone between the pellets and the distance blocks must be included. The length of the transition zone needs to be dimensioned so that the density of the distance blocks is unaffected.

The filling adjacent to a drift plug or the sealed side of a compartment plug is illustrated in Figure 4-16. The key requirements and factors specific to the drift plug and the compartment plug affecting the design of the filling components are similar with the exception that the compartment plug is exposed to hydrostatic pressure only and not exposed to significant swelling pressure from the bentonite as the drift plug. This difference was not assessed as having impact on the design of these filling components. The requirements and prerequisites can be summarized as:

- The drift plug must withstand 5.0 MPa hydrostatic pressure plus the swelling pressure of the bentonite inside the drift (<10 MPa), see Chapter 3. The loading from the bentonite filling should be as even as possible to reduce force heterogeneity on the plug.
- The compartment plug must withstand only hydrostatic pressure and only a swelling pressure of few tens of kPa since the function is only required until the drift plug has been installed.
- Both plugs shall be water tight with the largest allowed water leakage past the plug specified as 0.1 l/min (tentative requirement) at a water pressure of 5 MPa. The compartment plug was tested in full-scale at ÄSPÖ HRL. The leakage during the test was initially at approximately 0.05 l/min and after a couple of days it was reduced to 0.002 l/min. Therefore it is likely that the leakage rate past the plug will be significantly lower than the requirement.
- The filling components shall not affect the fulfilment of the requirements of the neighbouring distance block section. Especially the density of adjacent distance block must not be affected.
- The function of the drift plug is needed for a long time, whereas function of compartment plug is needed for a relatively short time (order of weeks until the drift plug is in place).
- It has been found feasible to use pellets to fill empty volumes adjacent to plugs in order to enhance sealing of possible leakages through microfractures and increase the density of the filling.
- In order to be able to build the plug an empty space of 1.3 m is needed inside the plug for emplacing the cap of the plug. The same distance is used on the other side of the plug (see Figure 4-17). The length used in the design is measured from the crown of the cap. However, this may be changed so that it is to be measured from the collar but the following design is based on that the distance is measured from the cap. The plug includes lead throughs that allow for artificial water filling of the unfilled space inside the plug and there is a small lid in the plug for filling of bentonite pellets behind the plug (see Section 2.4).
- It is beneficial if the swelling pressure of the filling components exerted to the compartment plug after full saturation from the both sides of the compartment plug would be roughly equal in order to avoid displacements of the plug.

The design is based on the following principles:

- The empty volume on the sealed side of the plug is filled with pellets resulting in lower density than that of the distance blocks.
- A section of highly compacted blocks called transition blocks is placed between the pellet filling sections and the adjacent distance blocks. As filling components absorb water and swell, there will be a transition zone from the drift plug to distance block with a density gradient. The transition block section can be composed of several smaller blocks in similar way as distance blocks.
- The pellets outside the compartment plug are installed via a hole in the transition block if needed. The hole is filled afterwards with a compacted bentonite cylinder to plug and seal it.

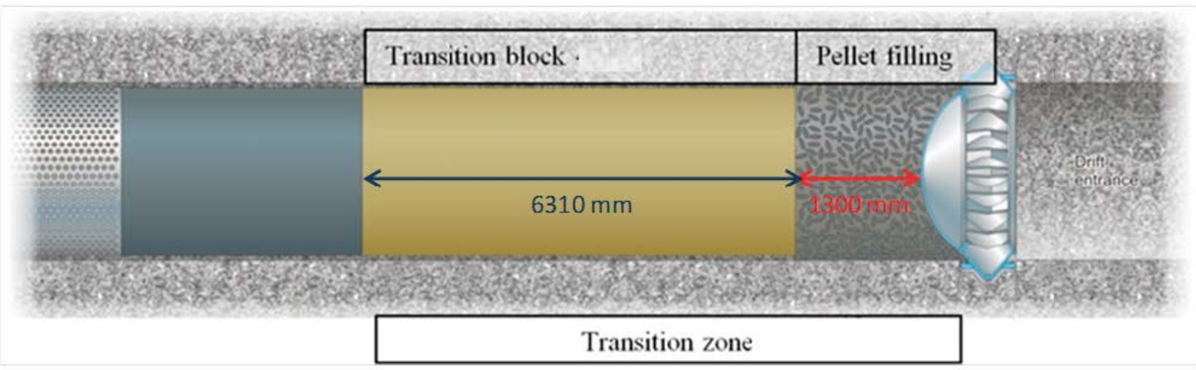


Figure 4-16. *Design of filling components inside the drift plug (the same design applies for the compartment plug). The length refer to the calculation where the friction angle 5° is used.*

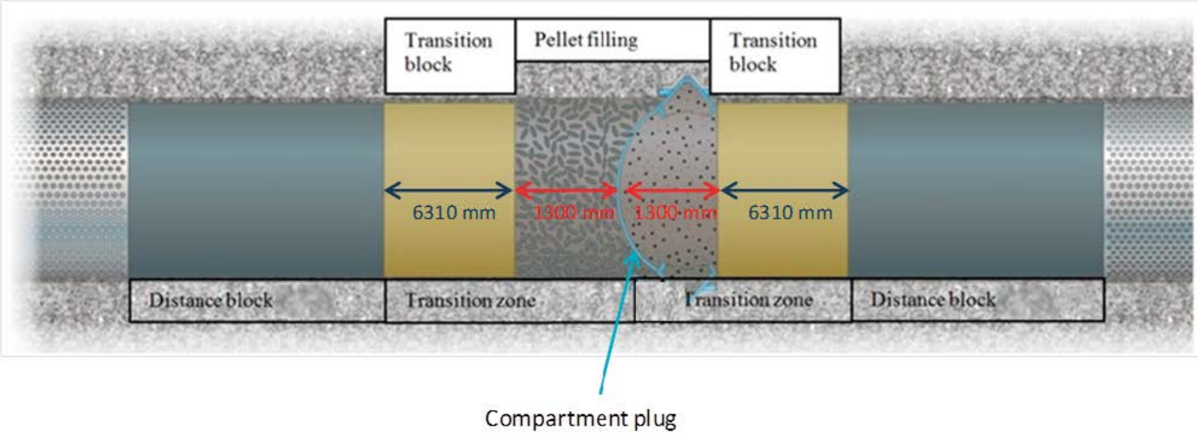


***Figure 4-17.** Design of filling components on both sides of the compartment plug. The length refer to the calculation where the friction angle 5° is used.*

Dimensioning

The design of the transition zone is based on the requirement that the distance block adjacent to the filling section is unaffected by the swelling of the transition blocks and corresponding compression of the pellet filling. Since the pellet filling has much lower density than the transition blocks there will evidently be a transition of density between the distance block and plug where the density gradually changes. The required length of the transition zone is determined by the density gradient caused by the swelling of the transition blocks into the pellet filling. Due to mainly friction between the bentonite and the rock surface the density reduction of the transient blocks will be spatially limited and can be estimated in a simplified way with equations that are derived from force equilibrium in axial direction.

The compartment and drift plug lead-throughs are not included in the analysis since they assessed as being negligible to the design. Only the filling between the plug and the distance block has been considered. The length of the pellet filling is 1.3 m counted from the crown of the cap of the plug. The length of the transition zone has been dimensioned so that the density of the contact surface between the transition block and the distance block are the same assuming that no axial swelling of the distance block takes place. The dimensions of the transition zone and the expected swelling pressure on the plug are requested.

The dimensions of the transition zone can be calculated either numerically using the Finite Element Method or analytically in a simplified way. The analytical solution has been used at this stage, and the results are shown in Table 4-4. The derivation of the analytical solution is presented in Appendix D (Åkesson et al. 2010b). The calculations leading to the results in Table 4-4 are presented in Appendix E.

The required length of the transition zone and the resulting swelling pressure on the plug are very dependent on the friction angle as seen in Table 4-4. A lower the friction angle yields a longer transition zone. The value ϕ=5° is based on Åkesson et al. (2010a) and assumes that the friction angle between bentonite and a smooth plane surface of rock is about 50 % lower than internal friction in bentonite (Börgesson et al. 1995).

A laboratory test simulating the transition zone in the scale 1:10 has been done. The results are reported in Kristensson el al. (2016), which also includes analytical modelling of the test with different friction angles. The results confirm that the modelling technique is feasible and that the friction angle is ϕ=5–10°.

Design

The material properties used for the calculations are as follows:

- Dry density of the pellet filling ρ_{dp}=1 000 kg/m^3.
- Dry density of the transition blocks ρ_{db}=1 712 kg/m^3.
- Dry density of the transition block section before axial swelling (over drift diameter 1.85 m) ρ_{dt}=1 558 kg/m^3.
- Swelling pressure between the transition block and the distance block p_s=5.931 MPa (see Appendix E).

The design of the highly compacted bentonite blocks used as transition blocks is similar to the design of the filling blocks presented above in Tables 4-1 and 4-3.

Table 4-4. Results of the calculations.

Friction angle ϕ	Total length of transition zone L_T	Length of transition block L	Swelling pressure on the plug
5°	7.61 m	6.31 m	1413 kPa
10°	5.67 m	4.37 m	771 kPa
20°	3.74 m	2.44 m	315 kPa
30°	2.98 m	1.68 m	146 kPa

A slightly pessimistic assumption of a friction angle of 5° thus yields a length of the transition block zone of L=6.31 m.

4.5.5 Filling at drift bottom

It is proposed to emplace a filling component in the KBS-3H deposition drift end between the drift face and the adjacent distance block. The motivation for placing a filling component is based on concentrated rock stresses around the corners of the drift end. Therefore the rock adjacent to the drift face might be more vulnerable to smaller scale disturbances and opening of fracturing. If there are small deviations in the drift lengths these can also be compensated by adjustments made by using filling components. The filling component consists of a filling block and pellet filling in the empty space that may be left behind the filling block. The filling component between the drift face and the adjacent distance block could be integrated into the distance block design so that it could be installed in ”one package”. The empty volume behind transition block will be filled with bentonite pellets through a hole in the transition block. The design has not been implemented in detailed level and the following questions should be resolved: a) diameter of filling hole, b) length of the filling hole (through whole transition block or a shorter section).

Dimensioning

The same type of compacted bentonite blocks are used for the filling next to the drift face as for previously presented distance blocks and filling blocks.

Design

The design is presented in Figure 4-18 and the dimensions in Table 4-5. The shape of the bottom of the filling component will if possible be modified to conform to the rock surface so the amount of pellets filled is expected to be small. Only one 0.5 m long filling component with the same properties as a distance block is expected to be placed at the drift bottom.

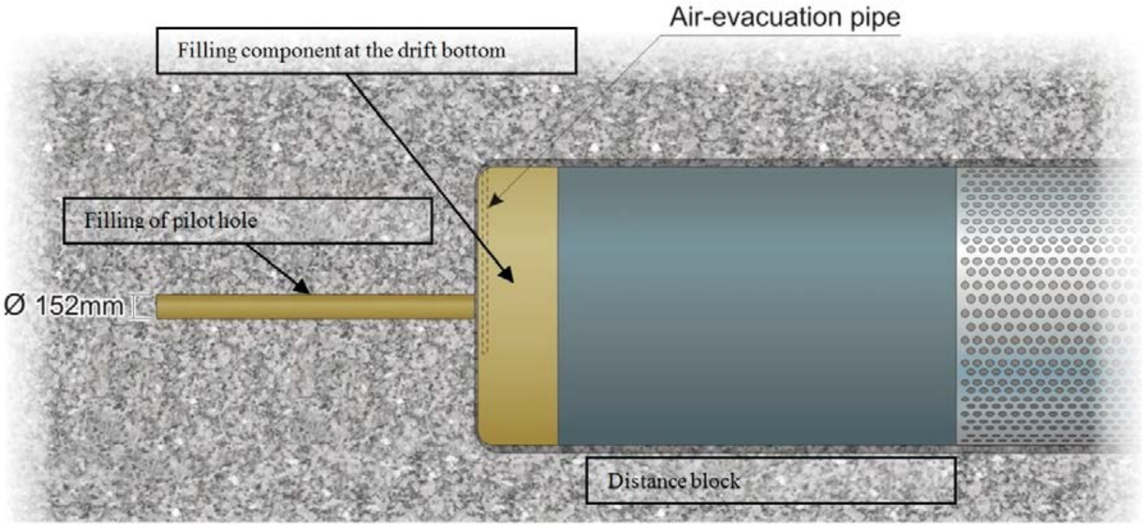


Figure 4-18. Air evacuation pipe and filling component at the drift bottom as implemented in the MPT test (see Figure 2-2 for the details).

Table 4-5. Dimensions and properties of the filling block at the drift bottom.

Length	0.50 m
Diameter of blocks	1.765 m
Initial dry density of blocks	1712 kg/m^3

4.5.6 Filling of pilot hole

The pilot hole will be filled in order to avoid possible open cavities that may reduce the density of the buffer and the other filling components. Another objective is to seal the pilot hole to prevent possible water flow between drift system and host rock.

The pilot hole will be filled with cylindrical highly compacted bentonite blocks with a length of 0.05–0.1 m. The length will be optimized later based on compaction technique etc. The compacted bentonite is of the same type as the filling blocks. The diameter of the pilot hole will be 152 mm and the diameter of the blocks is preliminarily set to 132 mm but may be increased when the actual length and quality of the hole is known. The objective is to reach the same final saturated density as the filling blocks. The design was shown in Figure 4-18 and the dimensions are shown in Table 4-6.

Table 4-6. Dimensions and properties of pilot hole filling component.

Pilot hole length	2.0 m
Hole diameter	0.152 m
Diameter of the blocks	0.132 m
Initial dry density of the blocks	1712 kg/m^3

4.6 Comments

Three cases were defined in representing hydraulic environment at Olkiluoto: a) wet drift, b) normal (median) drift and c) dry drift, see Figures 4-6 to 4-8 for definition of the cases. The design of these different cases is shown in Figures 4-19 to 4-21 to illustrate the use of filling blocks (note that no other filling components except filling blocks are included) assuming nearly perpendicular intersection with leaking fractures and the importance of these to drift utilization efficiency. Note that in the normal case there is only one filling block in a position of 0.4 l/min inflowing fracture in the 300 m long drift and the total length of filling blocks is roughly 3 m in a 300 m long drift. In the wet drift case there are four filling block sections in positions where inflows are 0.8, 2, 12 and 35 l/min and the total length of filling blocks is roughly 34 m. In a dry drift there are no filling blocks. The cumulative inflow distribution curve indicates that the dry drift case is more probable than wet drift case. The likelihood for dry drifts (dryer than the dry case) is about 10 % and for drifts wetter than the "wet case" is roughly 5 %. About 85 % of drifts are between the wet and dry cases.

It should be noted and emphasized that these cases were based on estimates and not made for quantitative purposes but merely for qualitative purposes to illustrate the applicability of the design and the overall feasibility. The results affect the efficiency of the disposal and therefore the relevance of these different cases should be assessed when more accurate bedrock information is available.

The new design of filling components based on the changes in the drift design presented here

- simplifies the design,
- makes the system more straightforward, since all the filling components behave in a similar manner as the buffer,
- improves the utilization degree by allowing adaptation of filling blocks to different inflows,
- reduces the number of required distance blocks,
- eliminates the need for an additional compartment plug.

In addition the change from previous drift end plug design to a single drift plug simplifies the design further and improves the drift utilization degree additionally.

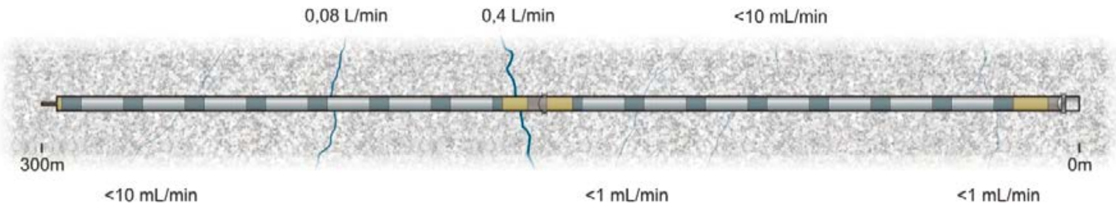


Figure 4-19. *Schematic drawing of the KBS-3H drift design in the normal case.*

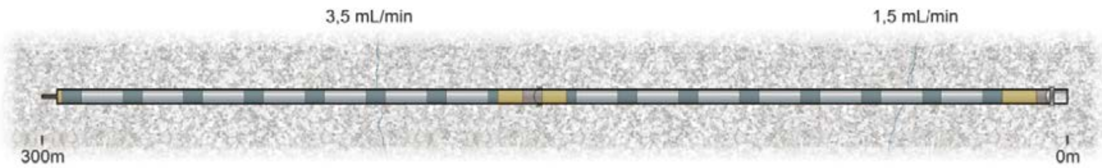


Figure 4-20. *Schematic drawing of the KBS-3H drift design in the dry case.*

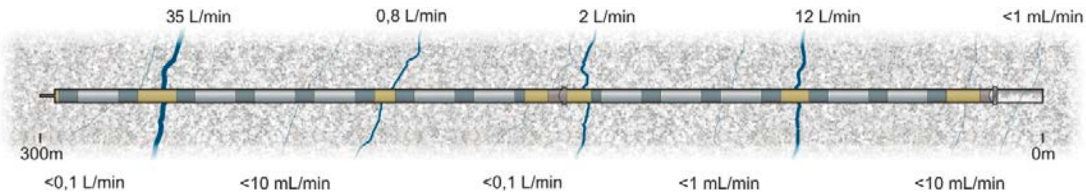


Figure 4-21. *Schematic drawing of the KBS-3H drift design in the wet case.*

5 Detailed design of the buffer

5.1 Design basis

5.1.1 Key design requirements

The following requirements on the design of the buffer must be fulfilled:

- The montmorillonite content of the dry buffer material shall be 75–90 %.
- The content of organic carbon of the buffer material shall be less than 1 wt-% (weight percent).
- The sulphide content of the buffer material shall not exceed 0.5 wt-% of the total mass.
- The total sulphur content of the buffer material (including the sulphide) shall not exceed 1 wt-%.
- The density of the buffer shall be between $1\,950 < \rho_m < 2\,050$ kg/m^3 after saturation.
- The thickness of the buffer around the canister in any direction shall not be less than 350 mm after saturation.
- The buffer shall be possible to manufacture and install with high reliability.

5.1.2 Drift dimensions and quality

The nominal drift diameter is 1 850 mm with an allowed increase of 5 mm.

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

- The maximum allowed deviation from the theoretical centre line of the drift at the end of the deposition drift (300 meters) is 2 meters in total horizontal deviation.
- The maximum allowed waviness from the centre line is ± 10 mm vertically and ± 20 mm horizontally over the length of the Supercontainer (6 m).
- The maximum allowed roughness is 5 mm over a length of 1 meter.
- The deposition drift must have an inclination angle of 2° ± 1° upwards towards the end of drift. The larger inclination is favorable for muck flushing.

5.1.3 Supercontainer

The Supercontainer including the perforated steel shell has an outer diameter of 1 765 mm and an inner diameter of 1 749 mm. An alternative to this design is to use copper for the shell. In the case of using copper the maximum outer diameter of the Supercontainer is 1 769 mm, with an inner diameter of 1 749 mm. A third alternative to this design is to use titanium for the shell. In the case of using titanium the maximum outer diameter of the Supercontainer is 1 761 mm and inner diam. 1 749 mm, see Table 5-1 and Table 5-2. After evaluation of these three options the titanium design alternative has been selected for the reference design of the Supercontainer. The reference geometry of the SKB and Posiva canister is shown in Table 5-3.

Table 5-1. Reference design of the Supercontainer - dimensions and manufacturing tolerances.

	Outer diameter [mm]	Inner diameter [mm]	Length [mm]	Tickness [mm]
SKB PWR	1 761 $^{+0}/_{-2}$	1 749	5 395 $^{+6}/_{-6}$	6
SKB BWR	1 761 $^{+0}/_{-2}$	1 749	5 395 $^{+6}/_{-6}$	6
Posiva BWR	1 761 $^{+0}/_{-2}$	1 749	5 387 $^{+6}/_{-6}$	6
Posiva VVER	1 761 $^{+0}/_{-2}$	1 749	4 187 $^{+6}/_{-6}$	6
Posiva EPR	1 761 $^{+0}/_{-2}$	1 749	5 859 $^{+6}/_{-6}$	6

Table 5-2. Reference design of the Supercontainer – holes and degree of perforation.

	Hole diameter [mm]	No. of holes tangentially	No. of holes lengthwise	Perforation degree [%]
SKB PWR	100	49	48	62
SKB BWR	100	49	48	62
Posiva BWR	100	49	47	61
Posiva VVER	100	49	37	61
Posiva EPR	100	49	52	62

Table 5-3. Dimensions and manufacturing tolerances for canisters.

	Outer diameter (B) [mm]	Total length (A) [mm]
SKB PWR	$1\,050\ ^{+1.2}/_{-1.2}$	$4\,835\ ^{+3.25}/_{-2.75}$
SKB BWR	$1\,050\ ^{+1.2}/_{-1.2}$	$4\,835\ ^{+3.25}/_{-2.75}$
Posiva BWR	$1\,050\ ^{+1.2}/_{-1.2}$	$4\,752\ ^{+3.25}/_{-2.75}$
Posiva VVER	$1\,050\ ^{+1.2}/_{-1.2}$	$3\,552\ ^{+3.25}/_{-2.75}$
Posiva EPR	$1\,050\ ^{+1.2}/_{-1.2}$	$5\,223\ ^{+3}/_{-3}$

5.1.4 Bentonite

The reference buffer material is bentonite clay with the material composition specified in Table 5-4. Examples of commercial bentonites with this material composition are MX-80 and Ibeco RWC (Deponit CA-N), which were analysed in SR-Can.

Table 5-4. Reference buffer material.

Design parameter	Nominal design [wt-%]	Accepted variation [wt-%]
Montmorillonite content	80–85	75–90
Sulphide content	limited	< 0.5
Total sulphur content (including the sulphide)	limited	< 1
Organic carbon	limited	< 1

5.1.5 Hydraulic characteristics

The maximum allowed inflow in a Supercontainer section including the Supercontainer and the distance block (total length about 10 m) from the surrounding rock is specified to 0.1 L/min. The volume between the buffer and the wall of the drift, about 36 m^3 for a 150 m long drift, will be filled with water within 8 hours through pipes according to the DAWE design. Ordinary tap water (fresh water) will be used and the maximum total water flow rate through the pipes will be about 75 l/min.

5.2 Design of buffer components

5.2.1 Buffer blocks inside the Supercontainer

The reference design of the installed buffer inside the Supercontainer is shown in Table 5-5. The buffer consists of four ring-shaped blocks and two solid blocks. The reference designs of the blocks are presented in Table 5-5, Table 5-6 and Figure 5-1.

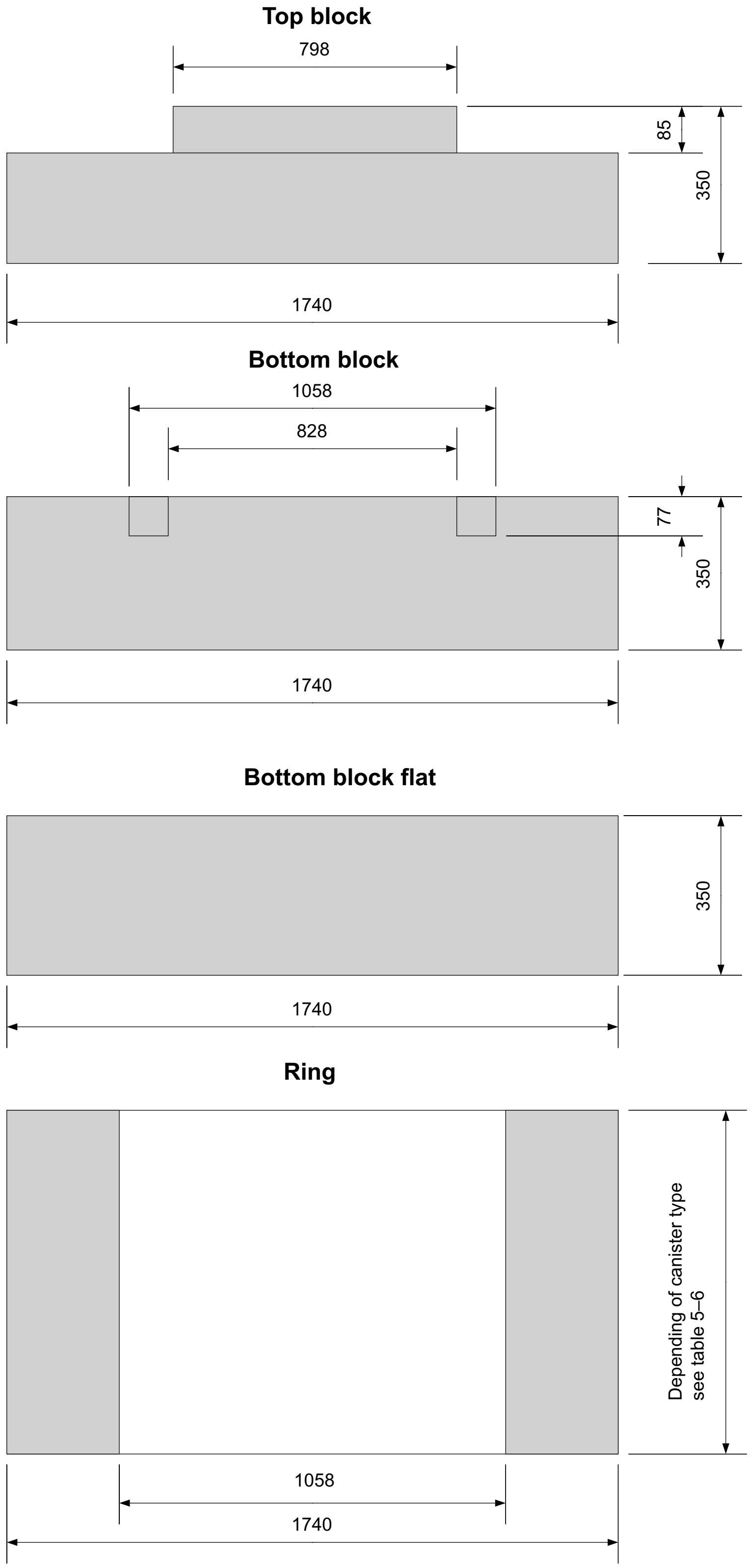


Figure 5-1. Schematic drawing of the bentonite buffer. The "bottom block" is for SKB's canisters with welded bottom lid and the "bottom block flat" is for Posiva's canisters with integral (flat) bottom.

The densities are given as dry densities and are described with a nominal value together with an accepted variation. The water contents of the material are given as an accepted interval and an accepted variation (SKB 2010) for the chosen water content.

Table 5-5. Reference buffer blocks inside the Supercontainer.

Design parameter	Nominal design	Accepted variation
Solid bocks inside the Supercontainer		
Dry density	1753 kg/m^3	±20
Water content	17 %	±1 %
Ring shaped blocks inside the Supercontainer		
Dry density	1885 kg/m^3	±20
Water content	11 %*)	±1 %

*) This is the water content of the bentonite at the delivery. The water content is expected to vary between 10 % and 12 % depending on the weather conditions.

Table 5-6. Reference design, dimension and manufacturing tolerances for the bentonite buffer.

	Outer diameter [mm]	Inner diameter [mm]	Length [mm]
Top Block	1740 $^{+1}/_{-2}$	798 $^{+0}/_{-2}$	350 $^{+1}/_{-1}$
Bottom block, bottom with recess	1740 $^{+1}/_{-2}$	828 $^{+0}/_{-2}$	350 $^{+1}/_{-1}$
Bottom Block, flat bottom	1740 $^{+1}/_{-2}$	–	350 $^{+1}/_{-1}$
Ring, SKB PWR/BWR	1740 $^{+1}/_{-2}$	1058 $^{+1}/_{-2}$	1211 $^{+1}/_{-1}$
Ring, Posiva BWR	1740 $^{+1}/_{-2}$	1058 $^{+1}/_{-2}$	1190 $^{+1}/_{-1}$
Ring, Posiva VVER	1740 $^{+1}/_{-2}$	1058 $^{+1}/_{-2}$	890 $^{+1}/_{-1}$
Ring, Posiva EPR	1740 $^{+1}/_{-2}$	1058 $^{+1}/_{-2}$	1308 $^{+1}/_{-1}$

5.2.2 Distance blocks

The distance blocks are placed between the installed Supercontainers in a drift. The total length of each section of the distance blocks varies from 3 to 6 m. The reference design of the blocks is presented in Table 5-7 and Figure 5-2. The densities are given as dry densities.

Table 5-7. Reference buffer block outside the Supercontainer (distance blocks).

Design parameter	Nominal design	Accepted variation
Dry density (kg/m^3)	1712	±20
Water content (%)	21	±1
Dimensions (mm)	Length: 500[1)] Outer diameter: 1765	±1

1) With existing press. Longer blocks are desirable and may if possible be made in future.

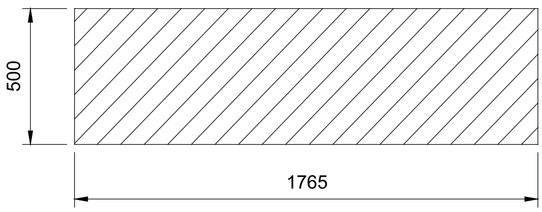


Figure 5-2. Schematic drawing of the solid blocks placed outside the Supercontainers (distance blocks).

5.2.3 Uncertainties

In the production of the buffer blocks there might be a variation in density and dimensions, which in the end are affecting the final density of the buffer. The accepted variations of these parameters are presented in the right most columns of Tables 5-5 and 5-7. Other uncertainties that are affecting the final density of the buffer are the variation in diameter of the drift and the volume of the corroded Supercontainer shell. The effects of these uncertainties are analysed in Section 5.2.4.

Other factors that are affecting the final properties (e.g. swelling pressure and hydraulic conductivity) of the buffer are the type of bentonite and the variation of montmorillonite content (Karnland 2010). These factors are not analysed in this report.

5.2.4 Verifying analysis of the final buffer density

The nominal values of the parameters yield a final buffer density of about 2 000 kg/m^3 after saturation. The following parameters have been varied in order to evaluate the sensitivity of the final buffer density:

1. Three buffer sections have been studied separately. The ring shaped blocks are placed around the canister in the Supercontainer (called Section I of the buffer) while cylindrical blocks are placed at the end sections of the Supercontainer (Section II of the buffer). Distance blocks are positioned outside each Supercontainer (Section III of the buffer) separating the installed Supercontainers.
2. The diameter of the drift (1 850–1 855 mm).
3. The dry density of the blocks (about ±20 kg/m^3 from the nominal values (SKB 2010)).
4. The type of Supercontainer shell (steel/copper/titanium).
5. The volume of the corroded Supercontainer shell after corrosion (constant/tripled for the container made of steel, copper and titanium).

The calculations are made with the assumption that there is no axial swelling of the buffer.

In Table 5-8, Figure 5-3 and Figure 5-4 the results of the calculations made for a steel shell are summarized. The green marked numbers in Table 5-8 are nominal data for the installed system. The figures show that the risk of getting a lower buffer density than 1 950 kg/m^3 at saturation is not high since extreme values are required of the diameter of the drift or the dry density of the blocks.

The highest density occurs when assuming a small drift diameter (1 850 mm), a high initial dry density of the buffer blocks (1 905 kg/m^3 in section I) and that the volume of the Supercontainer has tripled due to corrosion. For all these alternative materials the final volume will be approximately tripled, but the difference is in the time frame when this will happen. For titanium the corrosion will take much longer time than for the other materials. For this case Table 5-8 shows that the final saturated density of the buffer will be 2 032 kg/m^3.

Corresponding calculations for a Supercontainer shell made of copper are summarized in Table 5-9 and plotted in Figure 5-5 and Figure 5-6.

Corresponding calculations for a Supercontainer shell made of titanium (outer diameter 4 mm smaller than with steel shell) are summarized in Table 5-10 and plotted in Figure 5-7 and Figure 5-8.

The calculations made for the distance blocks are shown in Figure 5-9 and summarized in Table 5-8. The final density at saturation of the distance block section is plotted as function of the diameter of the drift at three different initial dry densities of the blocks (reference dry density 1 712 kg/m^3 and reference dry density ±20 kg/m^3 respectively).

Table 5-8. Data extracted from the analyses of the buffer density. The calculations are made for a Supercontainer shell made of steel. Nominal values are marked green.

Diameter drift [m]	Dry density block [kg/m³]	Section	Buffer density at saturation [kg/m³]	Note
1.850	1 885	Section I	2 002	Figure 5-3a
1.850	1 905*)	Section I	2 032	Figure 5-3a***)
1.855	1 865**)	Section I	1 983	Figure 5-3b
1.850	1 753	Section II	1 999	Figure 5-4a
1.850	1 773*)	Section II	2 023	Figure 5-4a***)
1.855	1 733**)	Section II	1 982	Figure 5-4b
1.850	1 712	Section III	1 998	Figure 5-9
1.850	1 732*)	Section III	2 009	Figure 5-9
1.855	1 692**)	Section III	1 981	Figure 5-9

*) The dry density of the buffer blocks is assumed to be 20 kg/m³ higher than the nominal value.

**) The dry density of the buffer blocks is assumed to be 20 kg/m³ smaller than the nominal value.

***) The volume of the Supercontainer is assumed to be tripled when corroded.

Table 5-9. Data extracted from the analyses of the buffer density. The calculations are made for a Supercontainer shell made of copper. Nominal values are marked green.

Diameter drift [m]	Dry density block [kg/m³]	Section	Buffer density at saturation [kg/m³]	Note
1.850	1 885	Section I	2 004	Figure 5-5a
1.850	1 905*)	Section I	2 039	Figure 5-5a***)
1.855	1 865**)	Section I	1 986	Figure 5-5b
1.850	1 753	Section II	2 001	Figure 5-6a
1.850	1 773*)	Section II	2 028	Figure 5-6b***)
1.855	1 733**)	Section II	1 984	Figure 5-6b

*) The dry density of the buffer blocks is assumed to be 20 kg/m³ higher than the nominal value.

**) The dry density of the buffer blocks is assumed to be 20 kg/m³ smaller than the nominal value.

***) The volume of the Supercontainer is assumed to be tripled when corroded.

Table 5-10. Data extracted from the analyses of the buffer density. The calculations are made for a Supercontainer shell made of titanium. Nominal values are marked green.

Diameter drift [m]	Dry density block [kg/m³]	Section	Buffer density at saturation [kg/m³]	Note
1.850	1 885	Section I	2 000	Figure 5-7a
1.850	1 905*)	Section I	2 024	Figure 5-7a***)
1.855	1 865**)	Section I	1 981	Figure 5-7b
1.850	1 753	Section II	1 998	Figure 5-8a
1.850	1 773*)	Section II	2 019	Figure 5-8a***)
1.855	1 733**)	Section II	1 981	Figure 5-8b

*) The dry density of the buffer blocks is assumed to be 20 kg/m³ higher than the nominal value.

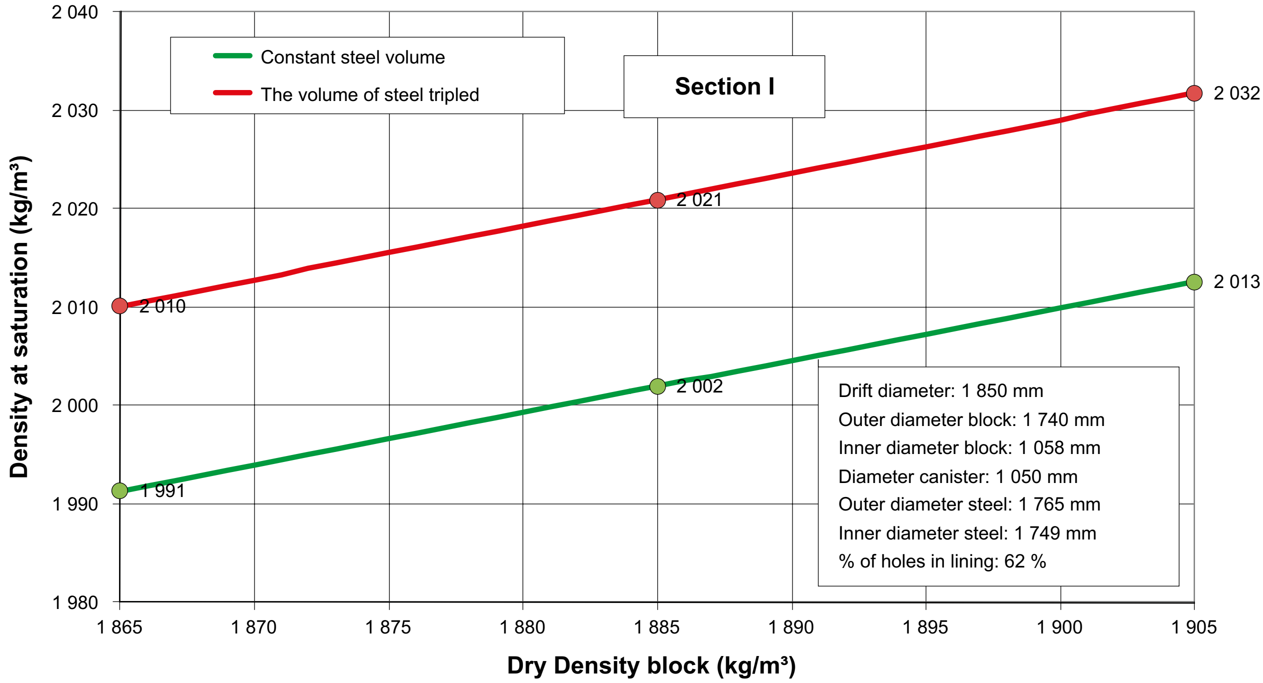
**) The dry density of the buffer blocks is assumed to be 20 kg/m³ smaller than the nominal value.

***) The volume of the Supercontainer is assumed to be tripled when corroded.

5.2.5 The effect of axial swelling on the final buffer density

The calculations made in Section 5.2.4 assume that no swelling in axial direction occurs. The dimensions of the canisters (Table 5-3), Supercontainer shell (Table 5-1) and blocks (Table 5-6) imply that there is a gap between the canister lid and the solid blocks which will result in axial swelling of the buffer during the saturation phase. According to the geometry of the reference design of KBS-3H the total gap between the canister and the solid blocks is 8 mm. Since this gap will vanish during the saturation phase, an average density of the buffer in the section between the canister lid and the Supercontainer lid can be calculated, using a dry density of the solid blocks of 1 753 kg/m³. For constant volume of a titanium Supercontainer and the nominal diameter of the drift (1 850 mm) the average density of the buffer in section II will decrease compared to the value 1 998 kg/m³ shown in Figure 5-8. The volume will increase with 2.3 % (swelling from 350 mm to 358 mm), which yields a decrease in average density at saturation calculated at these conditions to 1 976 kg/m³. This density is above the lowest acceptable density at saturation of 1 950 kg/m³.

However, if the extreme values of the block dry density (1 733 kg/m³) and the extreme values of the tunnel diameter (1 855 mm) are used the average density at saturation will be 1 959 kg/m³, which is rather low but still within the acceptable limits.



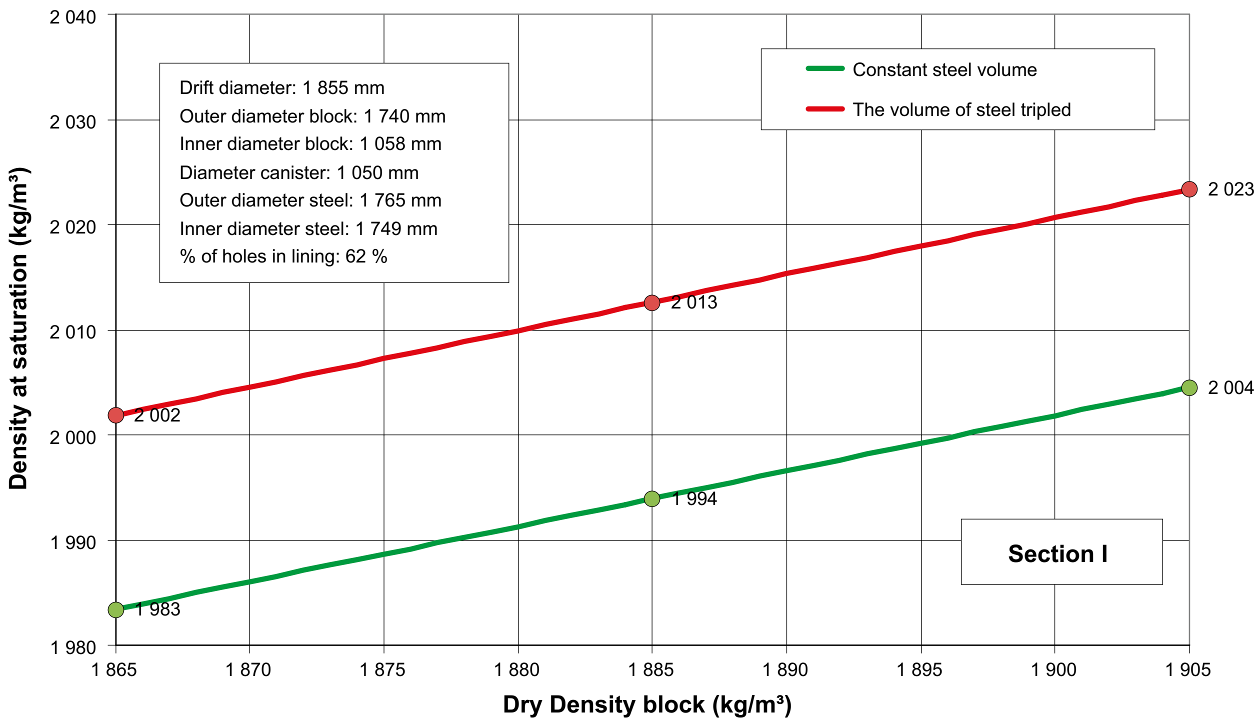
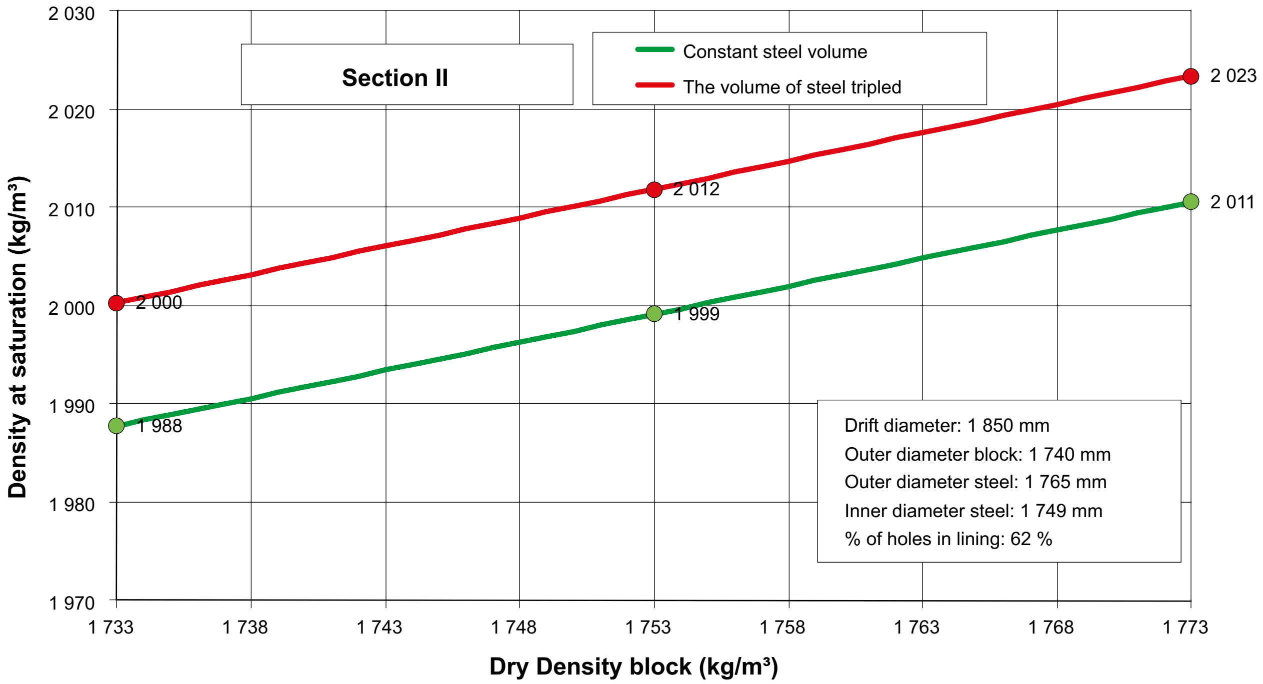


Figure 5-3. *The buffer density around the canister (Section I) for a Supercontainer of steel as a function of the dry density of the blocks for a drift diameter of 1 850 mm (upper) and for a drift diameter of 1 855 mm (lower).*



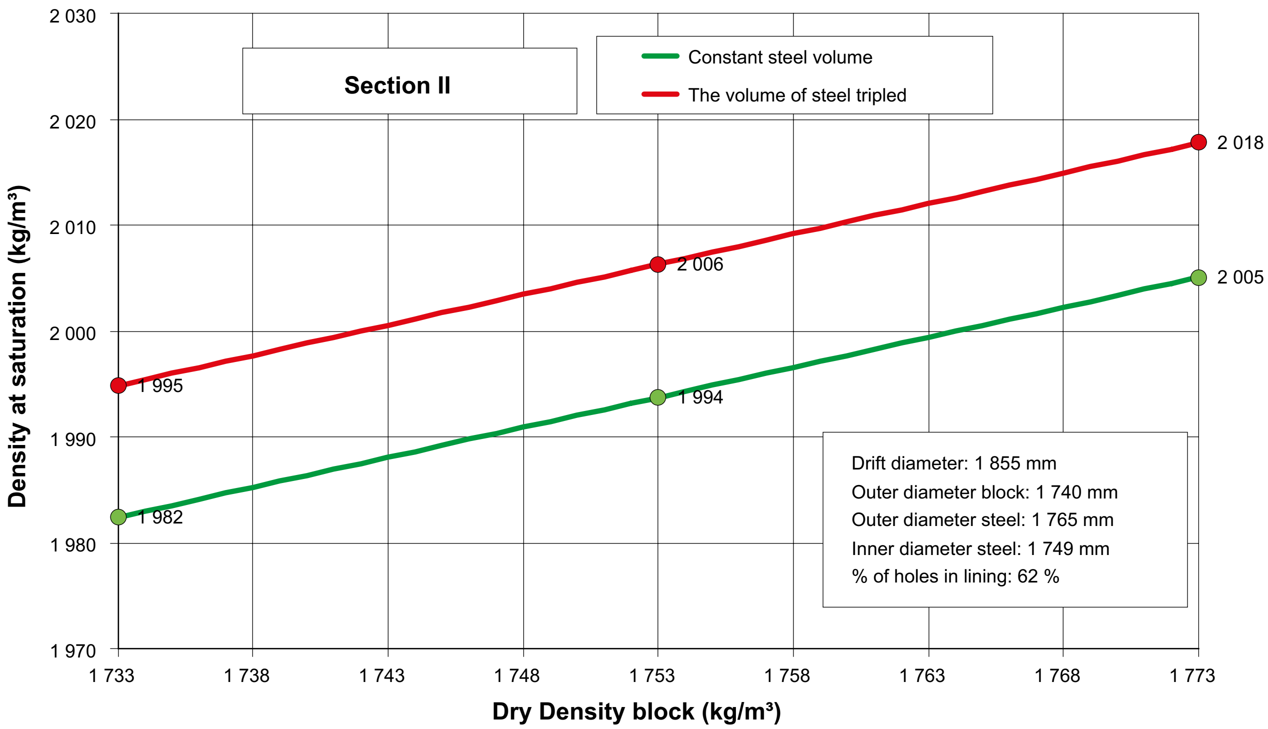
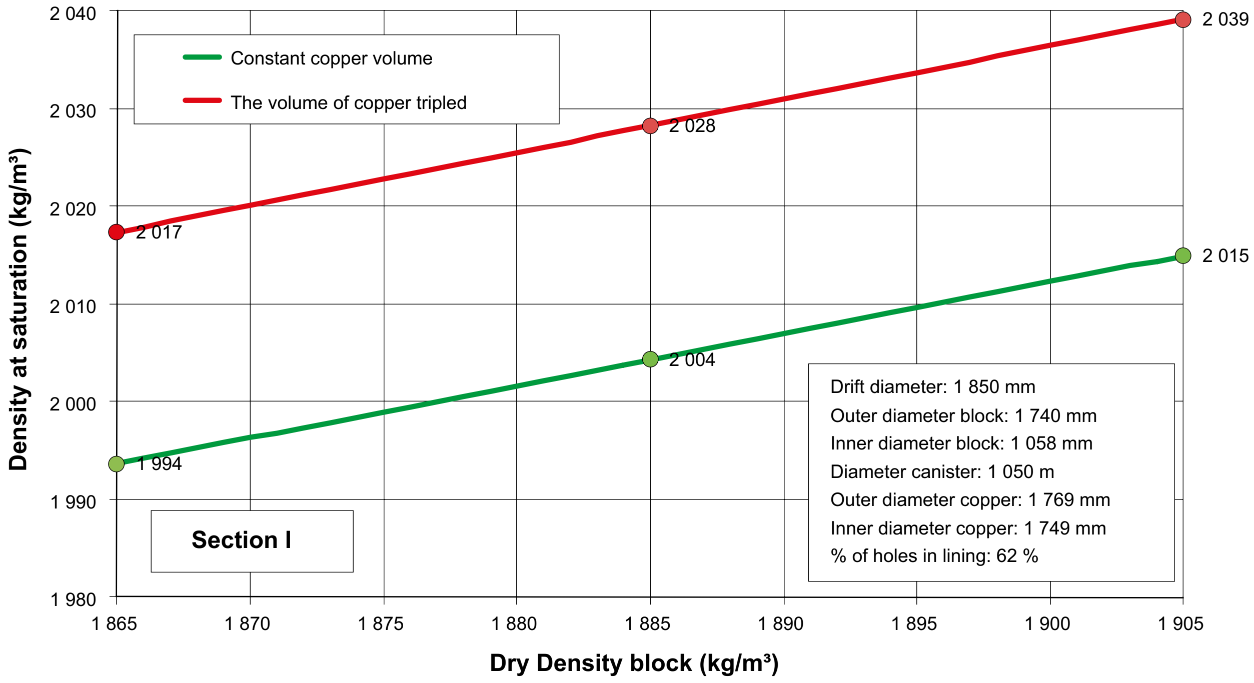


Figure 5-4. *The buffer density between the canister and the Supercontainer (Section II) for a Supercontainer of steel as a function of the dry density of the blocks for a drift diameter of 1 850 mm (upper) and for a drift diameter of 1 855 mm (lower).*



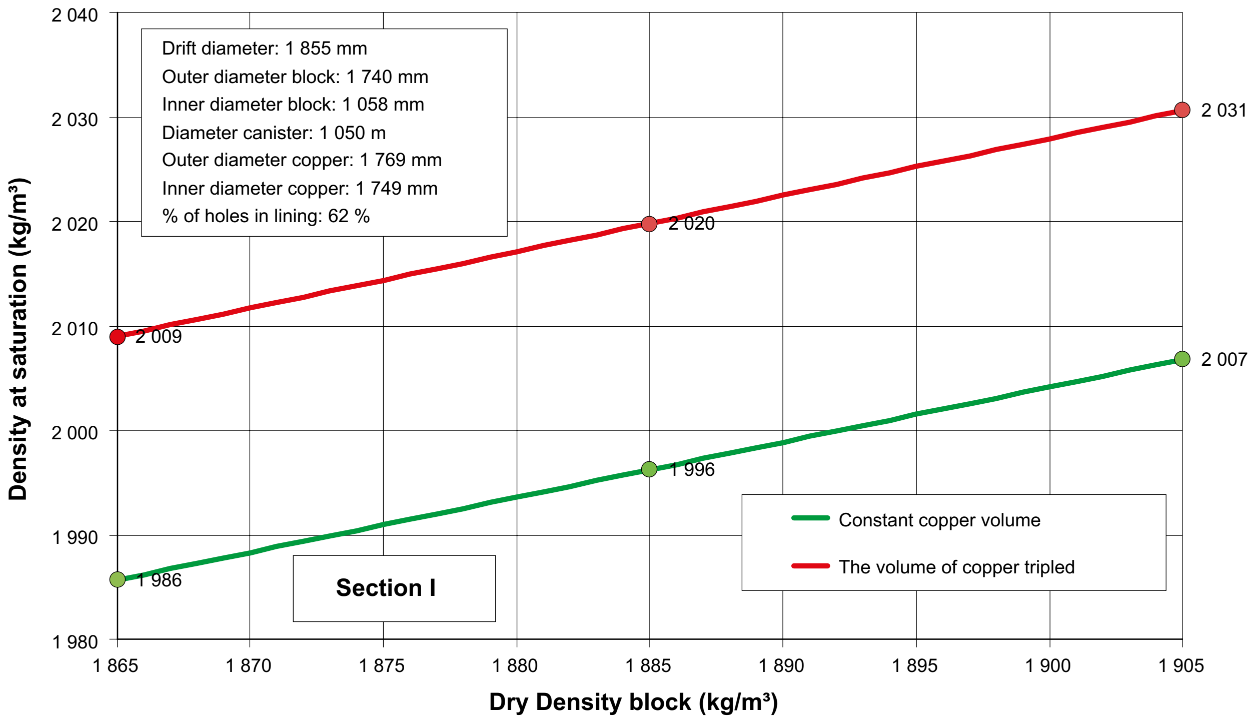
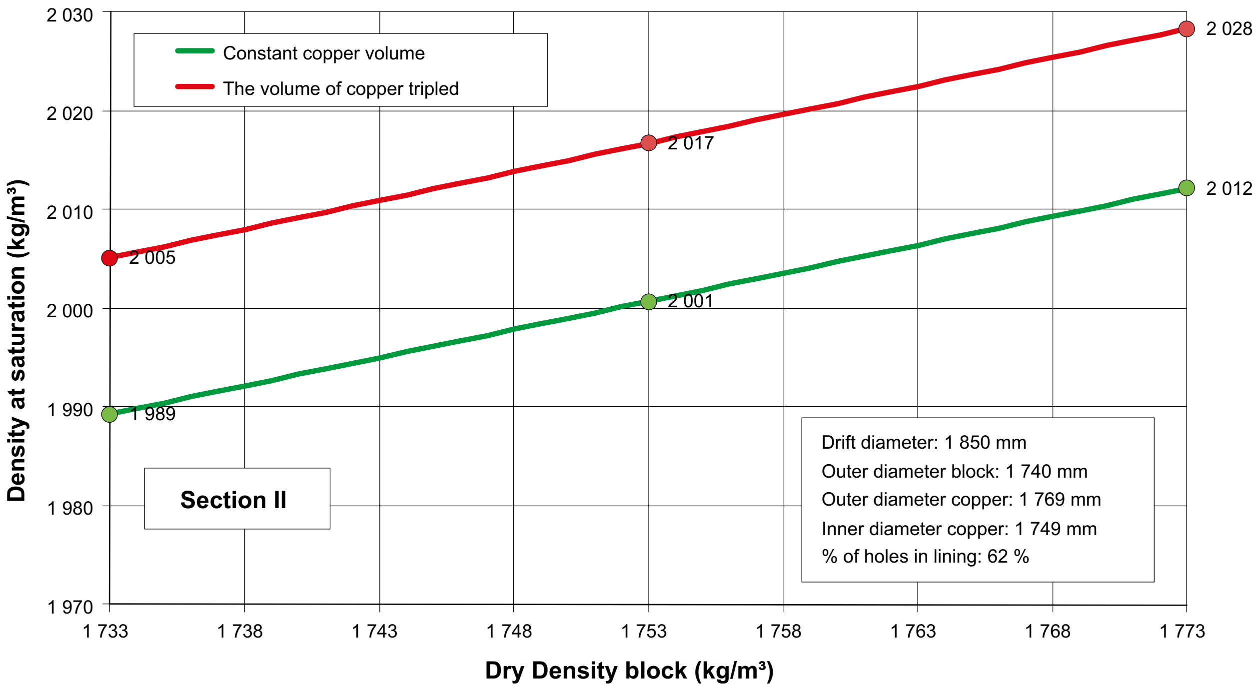


Figure 5-5. *The buffer density around the canister (Section I) for a Supercontainer of copper as a function of the dry density of the blocks for a drift diameter of 1 850 mm (upper) and for a drift diameter of 1 855 mm (lower).*



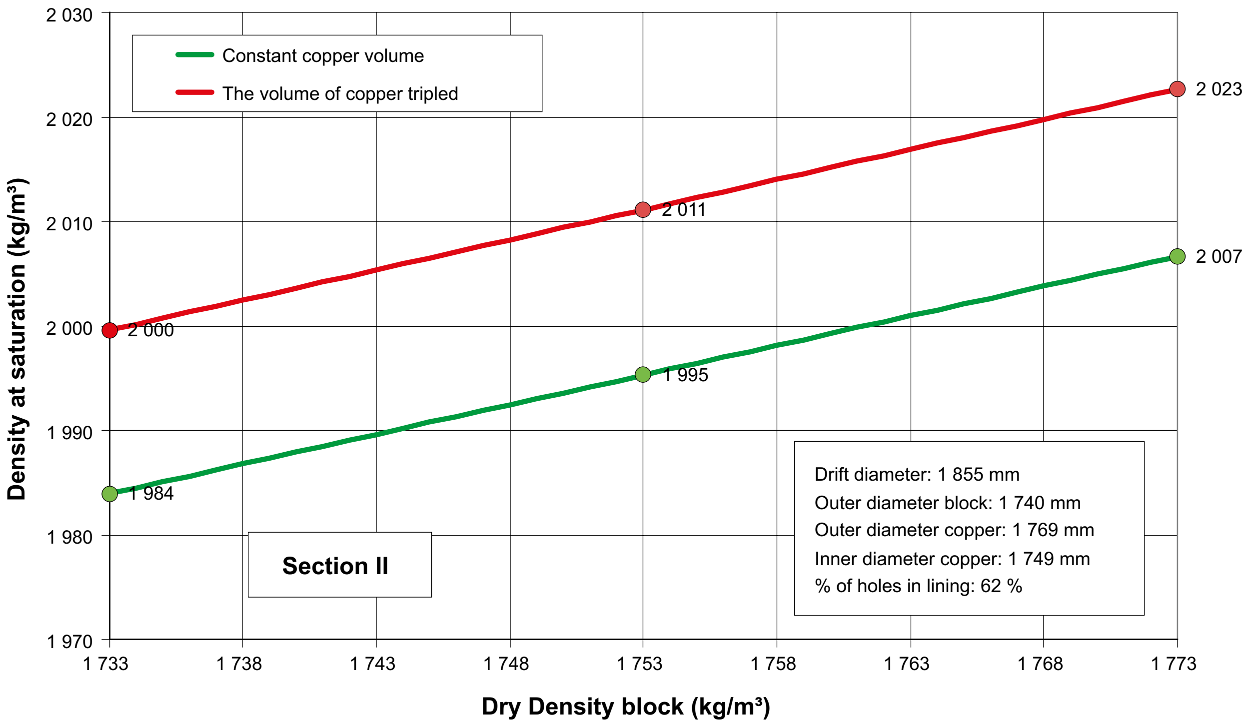


Figure 5-6. *The buffer density between the canister and the Supercontainer (Section II) for a Supercontainer of copper as a function of the dry density of the blocks for a drift diameter of 1 850 mm (upper) and for a drift diameter of 1 855 mm (lower).*

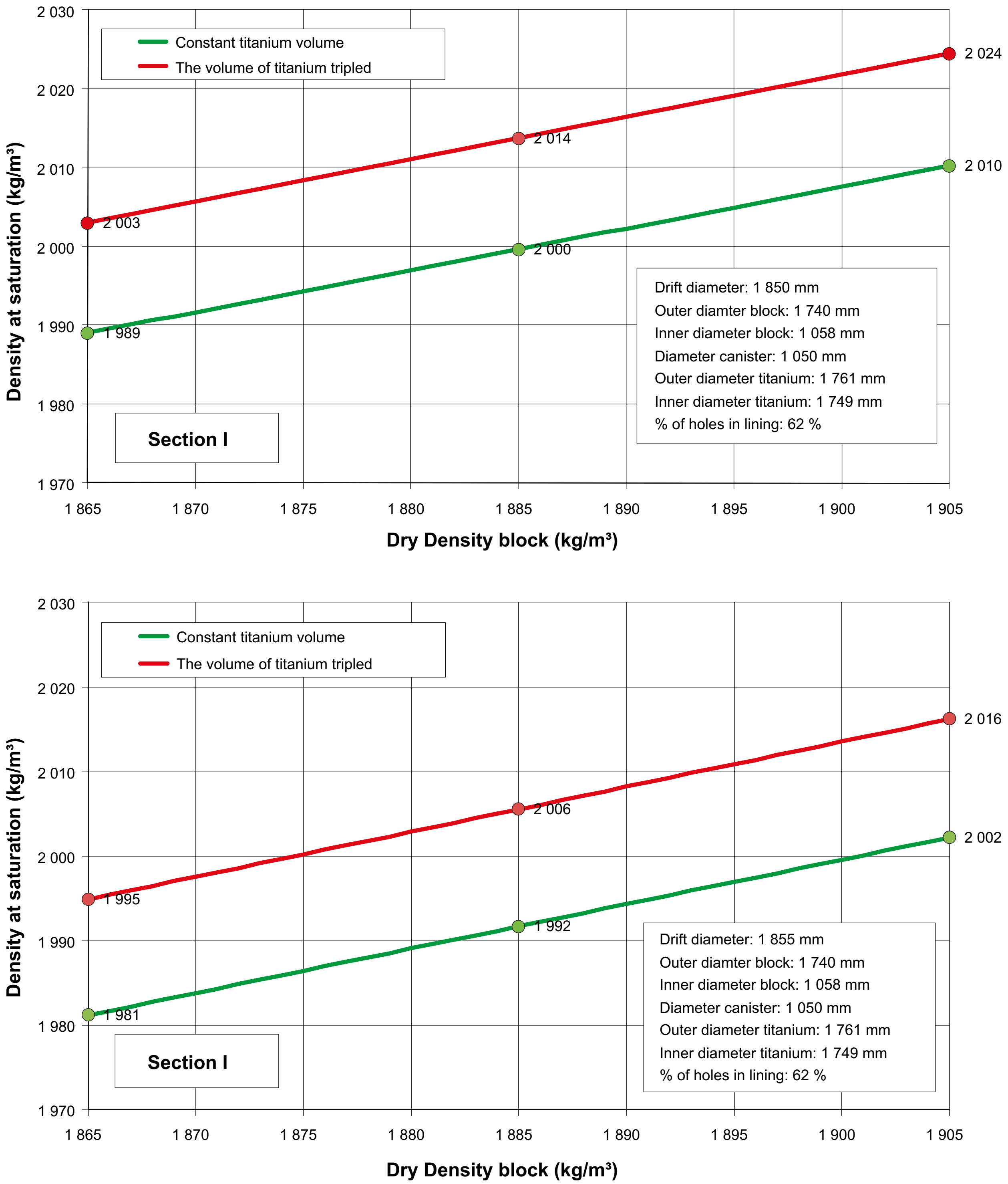
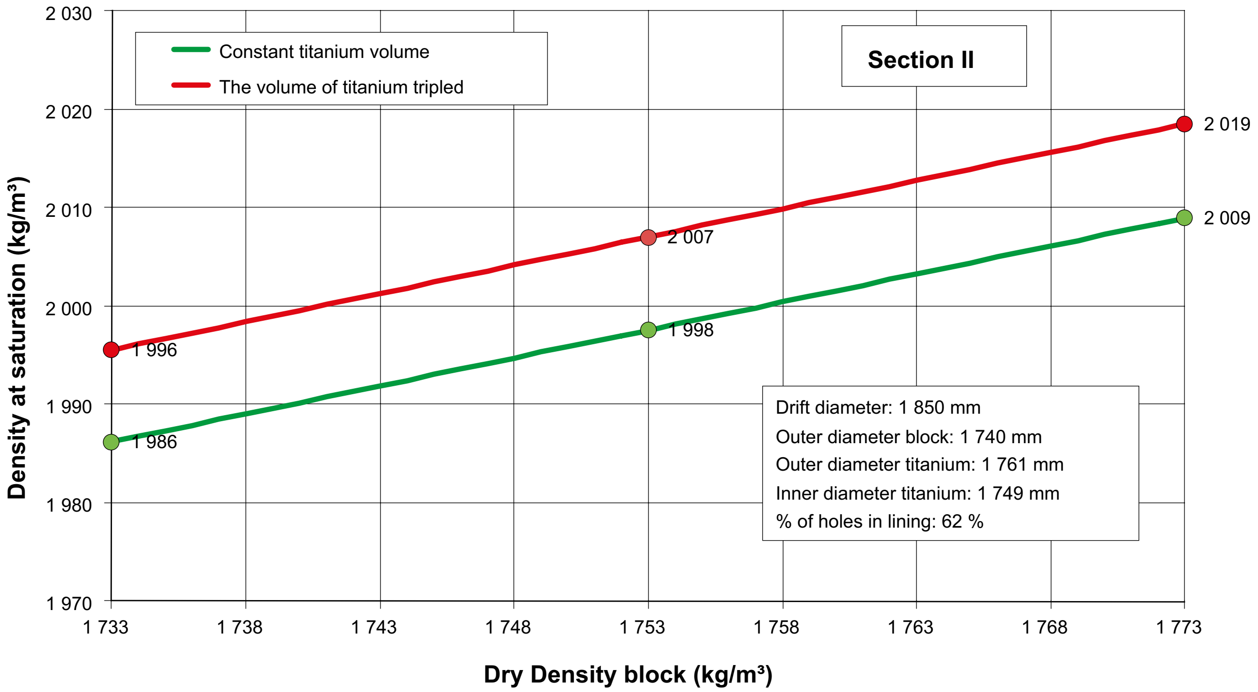


Figure 5-7. *The buffer density around the canister (Section I) for a Supercontainer of titanium as a function of the dry density of the blocks for a drift diameter of 1 850 mm (upper) and for a drift diameter of 1 855 mm (lower).*



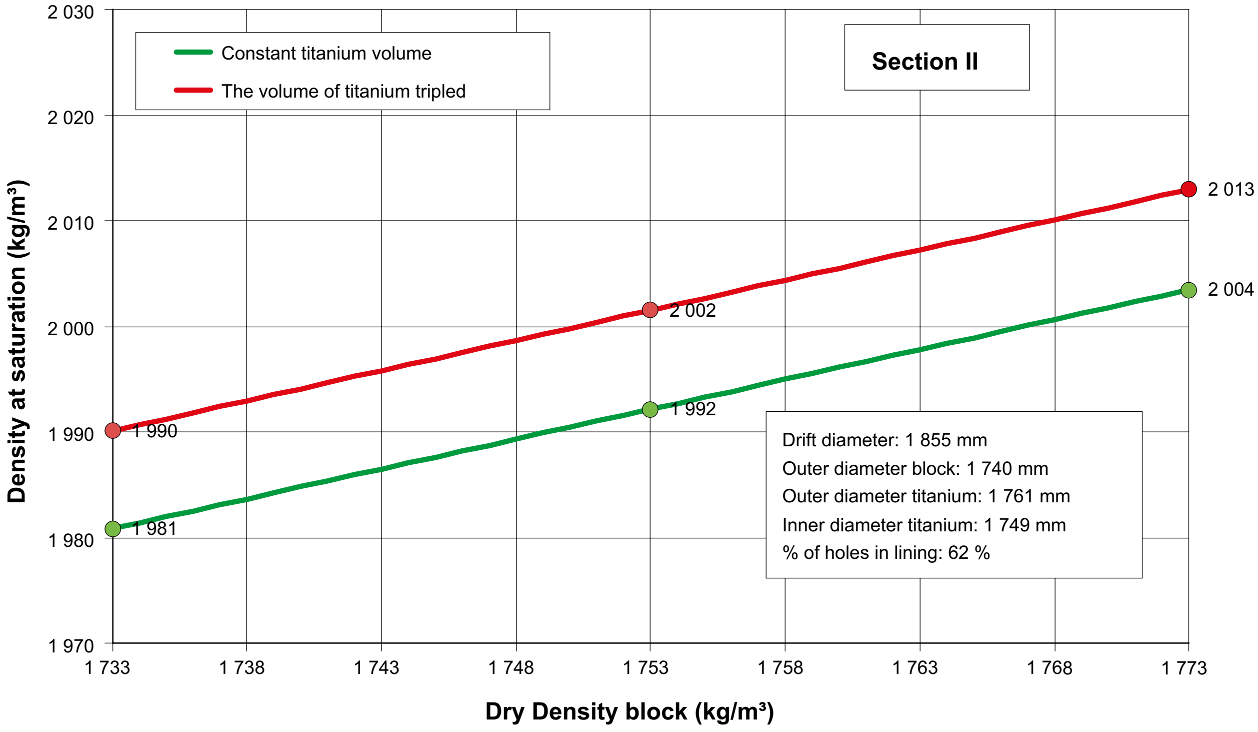


Figure 5-8. *The buffer density between the canister and the Supercontainer (Section II) for a Supercontainer of titanium as a function of the dry density of the blocks for a drift diameter of 1 850 mm (upper) and for a drift diameter of 1 855 mm (lower).*

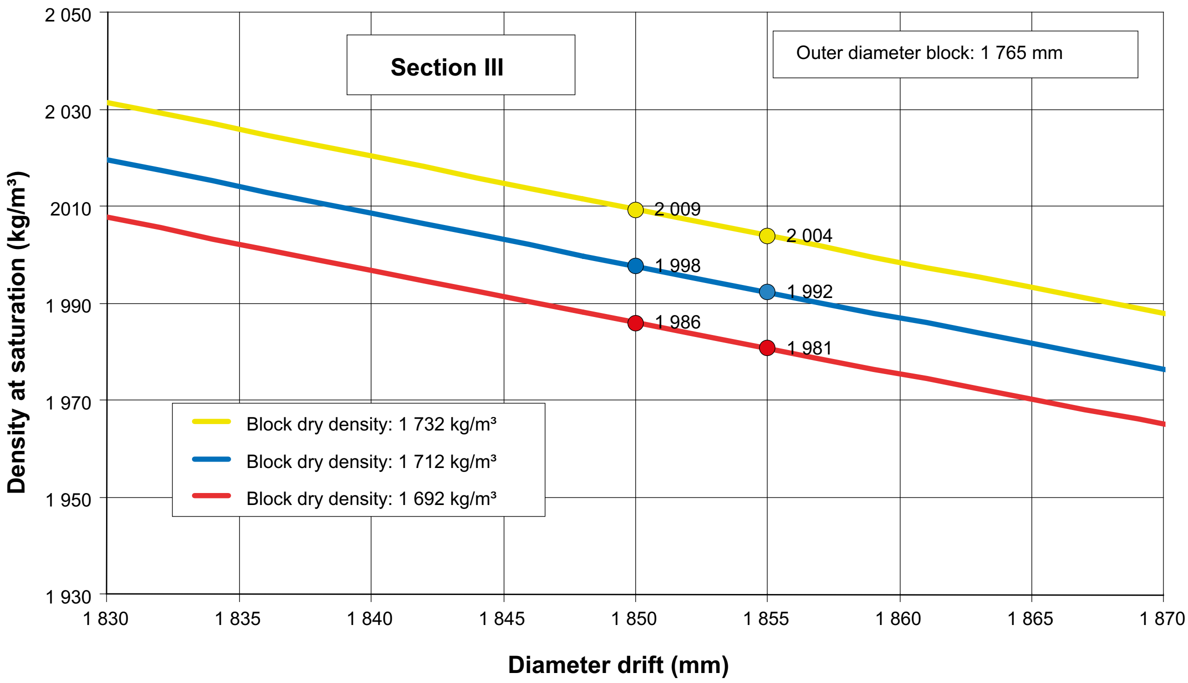


Figure 5-9. *The density of the distance block section (Section III) as a function of the drift diameter and the initial dry density of the blocks.*

6 Conclusions

6.1 General

The previous design of the KBS-3H concept was reported in 2008. Significant research and testing and technical development have taken place after that report. Therefore the design basis has been developed further to reflect the present understanding especially with respect to design requirements and evolution of the system after artificial watering. As a result a new design for the buffer and the filling components (the DAWE design with artificial water filling of the empty space in the drift) has been developed and is presented in this document.

6.2 Filling components

6.2.1 Design

The design of the five *filling components* has yielded the following results:

Filling inside the drift and compartment plugs

1.3 m close to the plug will be filled with bentonite pellets. A transition zone with bentonite blocks intended to take the density gradient caused by the compression of the pellet filling will be placed between the pellets and the first distance block. The length of this transition zone depends on the friction angle between the bentonite and the rock surface. For the slightly pessimistic assumption of the friction angle 5 degrees the length will be 6.3 m.

Filling outside the compartment plug

The design is proposed be identical to the design inside the plug.

Filling blocks at intersecting fractures with high inflow rate

No Supercontaniers will be placed at intersecting fractures with an inflow rate >0.1 l/min. Instead there will be a filling block section with half a distance block section on each side of the filling blocks. In order to have a respect distance, a defined distance between the fracture intersection and the distance blocks will be included in the filling block section. The length of the filling blocks will depend on the inflow rate and on the length of the fracture intersection along the drift rock surface. The respect distance is set to 3–6 me depending on the inflow rate.

Filling component at the drift end

Between the innermost distance block and the drift end there will be a bentonite block with the length 0.5 m that is either placed in contact with the drift end surface or with a small pellet filled slot at the end.

Pilot hole

The two meter long pilot hole with the diameter 152 mm at the end of the drift will be filled with bentonite blocks with the diameter 132 mm.

6.2.2 Uncertainties and important issues

There are some issues including uncertainties in the design of the filling components.

In the layout adaptation of KBS-3H repository horizontal fracture zones will be avoided if possible. In addition long fractures with a strike in the direction of the drift should be avoided. Especially water leaking of nearly horizontal fracture intersections might influence the drift utilization degree significantly.

The dimensioning of filling components adjacent to the drift and compartment plugs are based on mathematical calculations and include uncertainties such as the friction angle between the bentonite and the rock surface (see Section 4.5 and Appendices D and E) and the assumptions that hysteresis has no significant influence on the swelling. In addition the calculations are based on the assumption that high density bentonite filling can maintain density and swelling pressure difference for long periods of time, which is related to the homogenization processes in bentonite.

The possible heterogeneity of pressure loading on drift plugs is not addressed and it is assumed that the plugs can tolerate uneven loading. This assumption is verified in other work outside the scope of this report.

There seems to be potential to reduce the dimensioning pressure on the drift end plug because the transient zone evidently will reduce the pressure. This, however, depends on the results of ongoing homogenization studies where e.g. the effect of internal friction of bentonite filling components in the long term is being studied.

For the compartment plug the development of swelling pressure with respect to time should be evaluated in order to confirm the estimates on dimensioning pressure. At normal deposition advance the swelling pressure on the compartment plug will be very low due to the slow saturation process.

The "one sided compartment plug", which is designed to take pressure only from the sealed side, differs from earlier design (double/dual compartment plugs), which was designed to take pressure from both sides. The validity should be evaluated from a safety point of view.

The possible consequences of post-glacial erosion are not considered in the design work since there is today not adequate design basis for incorporating that into design.

6.2.3 Need for future development

The new design of filling components based on the proposed changes in the design basis simplifies the design and improves the utilization degree and eliminates the need for an additional compartment plug. In addition the change from the previous compartment plug + drift end plug design to a single drift plug simplifies the design further.

There are still some uncertainties in the design and the design basis/premises which are proposed to be resolved in the future development work. In general the future work can be divided to include the following issues:

- The effect of postglacial erosion.
- The ability of compacted bentonite to maintain large density and swelling pressure differences.
- Viability of "the one sided compartment plug" concept from the safety point of view.
- Evaluation of drift utilisation degree based on fracture data (more accurate fracture estimates and criteria for taking into account e.g. possible canister shearing risk).
- Evaluation of the behaviour of the whole drift system (including all components) from emplacement to target state.

6.3 Buffer

6.3.1 Design

The design of the *buffer components* has yielded the following results:

A detailed design of the three types of blocks (ring-shaped bentonite blocks, solid blocks at both ends of the Supercontainer and distance blocks between Supercontainers) has been produced. The calculations used to estimate system design are based on the data of the drift, the Supercontainer and the buffer blocks presented in this report. The following conclusions can be made from these calculations:

- The derived density of the three types of buffer blocks and the geometry of the blocks and the drift will give a final buffer density at saturation of about 2 000 kg/m^3, the allowed range of tolerance being 1 950–2 050 kg/m^3. The calculations assume nominal values of the density and dimensions of the blocks, nominal dimensions of the drift, a Supercontainer shell with constant volume (corrosion very slow) and no axial swelling
- When combining the highest acceptable density of the blocks, tripled volume of the corroded Supercontainer shell with the minimum acceptable diameter of the drift (1 850 mm), the calculated final density at saturation will be 2 039 kg/m^3 for the case of a Supercontainer shell made of copper.
- The calculations made for a Supercontainer shell made of titanium, which is the present reference material, indicate a buffer density at saturation of between 1 981–2 024 kg/m^3.
- An axial swelling of the buffer inside the Supercontainer with nominal values of the buffer and the drift will lead to a lower buffer density at saturation than 2 000 kg/m^3. A simplified calculation of the buffer density between the canister and the Supercontainer when taking into account an axial swelling of 8 mm yields a final buffer density at saturation of 1 976 kg/m^3 for nominal conditions but as low as 1 959 kg/m^3 at extreme cases of buffer block density and drift diameter.
- None of the calculated cases resulted in a saturated buffer density outside the allowed range 1 950–2 050 kg/m^3.

In summary, for all the cases examined for Supercontainer installation in horizontal boreholes (KBS3H – DAWE option), the equilibrated, water-saturated density of the buffer was within the allowable range of 1 950 to 2 050 kg/m^3. This should ensure that this type of installation also meets the thermal, hydraulic and mechanical requirements.

6.3.2 Uncertainties and need for further development

With respect to the water content, research carried out after the finalization of this document has pointed that it would be beneficial to harmonize the water content of the solid blocks (17 %) and ring blocks (11 %), to one, because the relative humidity in the assembly halls cannot be optimized for two different water contents. However, given that all safety assessment work within the KBS-3H System Design project phase is done for 11 and 17 % a redesign has not been done at this stage. Calculations for 14 % has been initiated and 14 % is planned to be tested in future tests but 11 and 17 % remain the KBS-3H reference design. Additional development is needed for this issue.

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Appendix A

Relationship between initial inflow and long-term flow

A high initial inflow from a fracture intersecting an open drift clearly suggests that the long-term flow through this fracture around the drift once the EBS has been emplaced and early, transient processes associated with saturation and heat generation have ceased is also likely to be relatively high. Below, a simplified modelling approach is adopted to quantify this relationship. This approach is based on some assumptions that are not well substantiated. Nevertheless, the approach is deemed sufficient for the purposes of the present tentative calculations. Detailed groundwater flow modelling in which multiple realisations of the fracture network are considered would be needed to obtain a more accurate indication of the relationship between initial inflow and long-term flow.

Consider a fracture intersecting the drift that gives an initial inflow Q_A [m^3 s^{-1}]. Assume that, at some distance L_f [m] from the drift, the fractures is intersected by a larger feature, such that the hydraulic pressure difference between this feature and the drift, together with the transmissivity of the fracture, controls initial inflow. From the solution of Darcy's Law in cylindrical polar coordinates, the transmissivity of the fracture, T[m^2 s^{-1}] is given by:

$$T = \frac{\rho g Q_A}{2\pi P} \ln\left(\frac{L_f + r_t}{r_t}\right); \qquad \text{(A-1)}$$

with:

ρ density of water (1 000 kg m^{-3})

g gravitational acceleration (9.81 m s^{-2})

P hydrostatic pressure at repository depth (4×10^6 Pa)

r_t drift radius (0.925 m).

In the long-term, flow around the drift is assumed be controlled by the fracture transmissivity and by the regional hydraulic gradient, such that the flow per unit width of fracture is given by:

$$Ti = \frac{\rho g Q_A i}{2\pi P} \ln\left(\frac{L_f + r_t}{r_t}\right) \qquad \text{(A-2)}$$

with:

i long-term hydraulic gradient (which may vary due to major climate change, see Appendix C).

Appendix B

Relationship between long-term flow and aperture

The transport aperture of a fracture, $2b$ [m], is related to its hydraulic aperture (and hence its transmissivity and long-term Darcy velocity), but tends to be around an order of magnitude smaller: see Figure B-1. For the present study, the Cubic Law is used to obtain the hydraulic aperture and it is assumed that:

$$2b = f\left(12\frac{T\upsilon}{g}\right)^{1/3}, \quad \text{(B-1)}$$

with

υ kinematic viscosity of water (10^{-6} m^2 s^{-1});

g gravitational acceleration (9.81m s^{-2});

f a variable, dimensionless scaling factor.

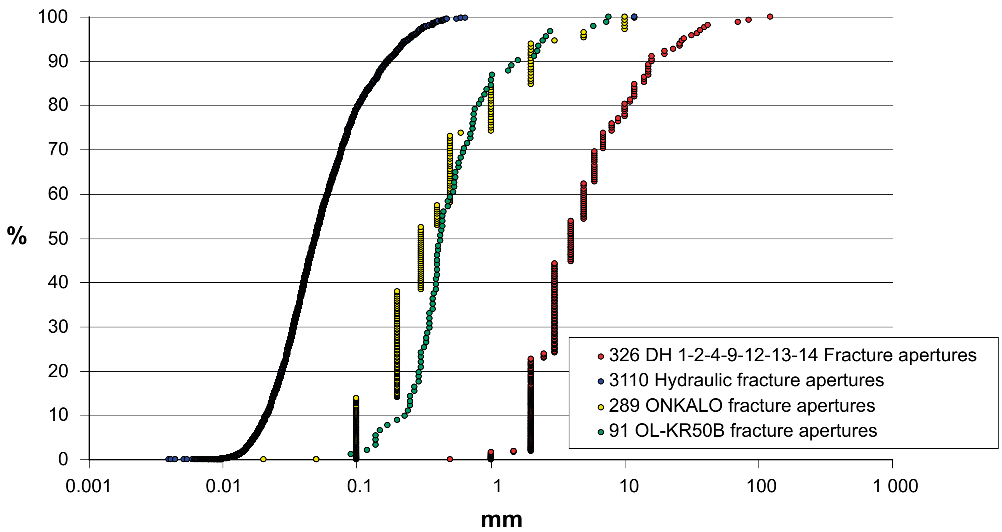

Figure B-1. *Cumulative distributions of hydraulic aperture at Olkiluoto. Blue: hydraulic apertures, others: transport apertures obtained by other techniques.υ*

Appendix C

Diffusion along the drift

The system to be modelled is shown in Figure C-1. Diffusion takes in the drift in both the r-direction (assumed relatively rapid, such that there are no concentration gradients in r) and in the x-direction. Conservatively, only the volume between $r = r_c$ (the canister radius) and $r = r_t$ (the drift radius) is assumed to be accessible by diffusion, i.e. diffusion takes place through a cross-sectional area:

$$A = \pi\left(r_t^2 - r_c^2\right), \qquad \text{(C-1)}$$

The equation governing diffusion along the drift is:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}, \qquad \text{(C-2)}$$

where C [Bq m^{-3}] is C-14 dissolved concentration and D is the pore diffusion coefficient of C-14 in bentonite, which is here taken to be 1.2×10^{-10} m^2 s^{-1} (value for neutral and cationic species in Section 5.2 of the report Smith et al. 2007).

No exact analytical solution is known to the author that would account both for transfer of C-14 from the drift to the fracture, and continuing diffusion along the drift beyond the fracture. Instead, two limiting cases are considered:

Case a: in which C-14 that exits the failed canister diffuses only in the positive x-direction towards the fracture, and is captured by the fracture, such that there is no diffusion along the fracture for $x<0$ or for $x>L$.

Case b, in which C-14 that exits the failed canister diffuses in the positive and negative x-directions, and only a small fraction is captured by the fracture, such that the evolution of C-14 concentration in the drift can be assumed to be unaffected by the fracture.

Case a becomes an increasingly good approximation as the flow rate in the fracture increases. Case b is a good approximation for low flow rates in the fracture. Both are expected to be conservative, in the sense that they will tend to over-estimate C-14 release to the fracture. Thus, the release to the fracture, R [mol a^{-1}] is taken to be:

$$R = Q\begin{cases} C_a\big|_{x=L} = \varepsilon DA\dfrac{\partial C_a}{\partial x}\Big|_{x=L} \\ C_b\big|_{x=L} \end{cases} \quad \text{the smaller} \qquad \text{(C-3)}$$

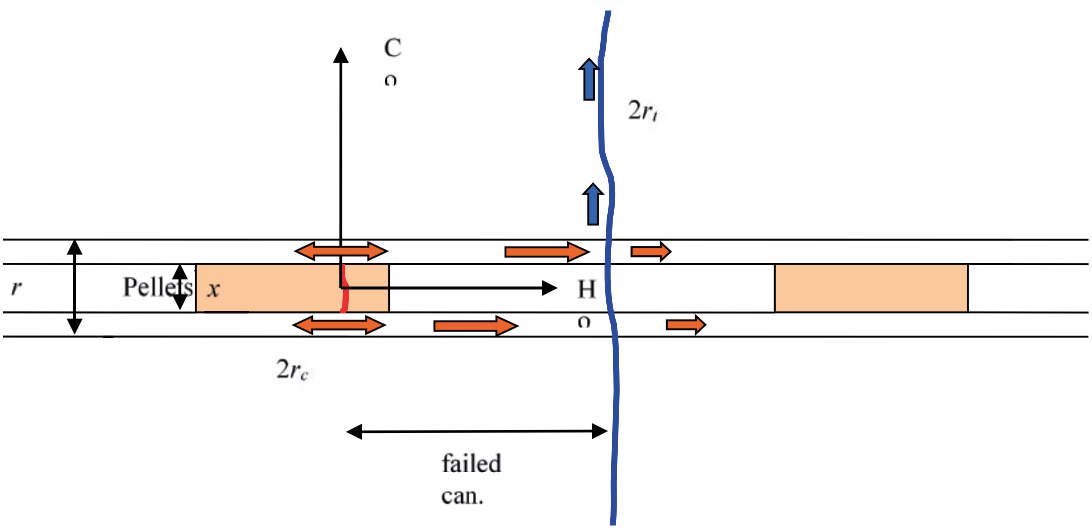

***Figure C-1.** The system to be modelled.*

where C_a and C_b are C-14 concentrations, evaluated for cases a and b, respectively, ε is the effective porosity for C-14, taken to be 0.43 (value for neutral and cationic species in Section 5.2 of Smith et al. 2007) and Q is an effective flowrate through fracture that takes into account the transport resistance of the filling blow/rock interface. It is given by:

$$Q_{eff} = 4\sqrt{2D_w Tir_t b} \tag{C-4}$$

where D_w is the diffusion coefficient of C-14 in water (2×10^{-9} m^2 s^{-1}). $2b$, the transport aperture of the fracture, is obtained using Equation B-1. The product Ti is obtained using Equation A-2.

Case a

In case a, where diffusion takes place only in the positive x-direction, the boundary condition at the failure location on the canister ($x = 0$) is:

$$\varepsilon DA\int_0^t \left.\frac{\partial C_a}{\partial x}\right|_{x=0} dt = \begin{cases} 0 & t=0 \\ M & t>0 \end{cases} \tag{C-5}$$

where M is the mass of C-14 released from the canister to the drift upon canister failure and $t = 0$ is canister failure time.

In order to solve Equation C-2, consider the parameter V, where:

$$V(x,t) = \int_0^t C_a(x,\tau)d\tau\,. \tag{C-6}$$

V is also governed by the diffusion equation:

$$\frac{\partial V}{\partial t} = D\frac{\partial^2 V}{\partial x^2}\,. \tag{C-7}$$

From Eq. C.5, boundary condition at the canister ($x = 0$) is:

$$\varepsilon DA\left.\frac{\partial V}{\partial x}\right|_{x-0} = \begin{cases} 0 & t=0 \\ M & t>0 \end{cases}. \tag{C-8}$$

From Equation C-3, the boundary condition where the drift intersects the fracture ($x = L$) is:

$$\varepsilon DA\left.\frac{\partial V}{\partial x}\right|_{x=L} = VQ \tag{C-9}$$

The solution to this equation can be found in Carslaw and Jaeger (1959, problem iv, p 125):

$$V = \frac{M}{Q}\left\{1 + H\left(1-\frac{x}{L}\right) - \sum_{n=1}^{\infty}\frac{2H\left(\alpha_n^2+H^2\right)\cos\left(\alpha_n x/L\right)}{\alpha_n^2\left(H+H^2+\alpha_n^2\right)}\exp\left(-\alpha_n^2 T\right)\right\}, \tag{C-10}$$

where:

$$T = \frac{Dt}{L^2}\,, \tag{C-11}$$

$$H = \frac{LQ}{\varepsilon DA}\,, \tag{C-12}$$

and α_n are the positive roots of:

$$\alpha\tan\alpha = H\,. \tag{C-13}$$

The flux to the fracture for this case is given by:

$$QC_a\big|_{x=L} = Q\left.\frac{\partial V}{\partial t}\right|_{x=L} = \frac{2HMD}{L^2}\sum_{n=1}^{\infty}\frac{\left(\alpha_n^2+H^2\right)\cos\left(\alpha_n\right)}{\left(H+H^2+\alpha_n^2\right)}\exp\left(-\alpha_n^2 T\right). \tag{C-14}$$

Case b

In case b, where diffusion takes place only in the positive and negative *x*-directions, the boundary condition at the failure location on the canister ($x = 0$) is

$$\varepsilon DA\int_0^t \frac{\partial C_b}{\partial x}\bigg|_{x=0} dt = \begin{cases} 0 & t=0 \\ M/2 & t>0 \end{cases}, \tag{C-15}$$

where, in this case, only $M/2$ diffuses towards the fracture.

The fracture is assumed to have negligible influence on the diffusive transport of most C-14 along the drift. The boundary condition at large distances from the failed canister is:

$$C_b \to 0 \text{ as } x \to \infty. \tag{C-16}$$

In order to solve Equation C-2 for these boundary conditions, we again consider the parameter V, as defined by Equation C-6. From Equation C-15, boundary condition at the canister ($x = 0$) is:

$$\varepsilon DA\frac{\partial V}{\partial x}\bigg|_{x-0} = \begin{cases} 0 & t=0 \\ M/2 & t>0 \end{cases}. \tag{C-17}$$

and, from Eq. C.16:

$$V \to 0 \text{ as } x \to \infty. \tag{C-18}$$

The solution to this equation can be found in Carslaw and Jaeger (1959, problem i, p 75):

$$V = \frac{M}{\varepsilon D\pi r_t^2}\left\{\sqrt{\frac{Dt}{\pi}}\exp\left(-\frac{x^2}{4Dt}\right) - \frac{x}{2}\text{erfc}\frac{\text{x}}{2\sqrt{\text{Dt}}}\right\}, \tag{C-19}$$

The flux to the fracture at $x = L$:

$$QC_b\big|_{x=L} = Q\frac{\partial V}{\partial t}\bigg|_{x=L} = \frac{MDH}{2L^2}\left\{\frac{1}{\sqrt{\pi T}}\exp\left(-\frac{1}{4T}\right)\right\} \tag{C-20}$$

The flux along the drift at $x = L$ is:

$$\varepsilon DA\frac{\partial C_b}{\partial x}\bigg|_{x=L} = \frac{MD}{4TL^2}\left\{\frac{1}{\sqrt{\pi T}}\exp\left(-\frac{1}{4T}\right)\right\} \tag{C-21}$$

Note that, in this case, the flux to the fracture has a maximum when:

$$Q\frac{\partial C_b}{\partial t}\bigg|_{x=L} = 0 \tag{C-22}$$

From Equation C-20, this occurs when:

$$T = \frac{1}{2}. \tag{C-23}$$

At this time, the flux to the fracture at $x = L$ is:

$$QC_b\big|_{x=L} = \frac{MDH}{2L^2}\sqrt{\frac{2}{\pi e}} \tag{C-24}$$

and the flux along the drift is:

$$\varepsilon DA\frac{\partial C}{\partial x}\bigg|_{x=L} = \frac{MD}{2L^2}\sqrt{\frac{2}{\pi e}}. \tag{C-25}$$

Case b is a good approximation if the flux along the drift should be much greater than the flux to the fracture, i.e. if:

$$H >> 1. \tag{C-26}$$

Appendix D

Simplified calculation of axial swelling and homogenisation of bentonite in a cylindrical confinement

The theoretical solution considers the final state after swelling and homogenisation when the bentonite has come to force equilibrium. Figure D-1 shows the relation between an infinitesimal swelling distance z and the change in swelling pressure $d\sigma$. The swelling pressure is assumed to be isotropic.

r = hole radius

σ_0 = swelling pressure at $z = 0$

τ = $\sigma \tan\phi$

ϕ = friction angle (=10°–30° depending on the swelling pressure)

Force equilibrium on the bentonite ring with the thickness dz in axial direction (disregarding gravity and internal friction):

$$-d\sigma \cdot \pi r^2 = \sigma \tan\phi \cdot 2\pi r \cdot dz$$

$$-\frac{d\sigma}{\sigma} = \frac{2\tan\phi}{r} \cdot dz$$

$$-dz = \frac{r}{2\tan\phi} \cdot \frac{d\sigma}{\sigma}$$

Integrating:

$$-\int_0^z dz = \frac{r}{2\tan\phi} \int_{\sigma_0}^{\sigma} \frac{d\sigma}{\sigma}$$

$$-z = \frac{r}{2\tan\phi}\left(\ln\sigma - \ln\sigma_0\right)$$

$$e^{\left(\ln\sigma - \ln\sigma_0\right)} = e^{-\frac{2z\tan\phi}{r}}$$

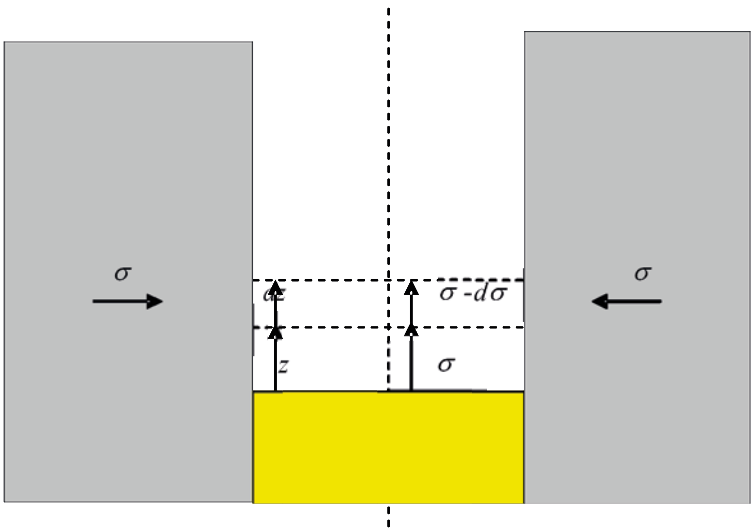

Figure D-1. Integration of the relation between swelling pressure σ and swelling distance z.

$$\sigma = \sigma_0 \cdot e^{\frac{-2z\tan\phi}{r}} \tag{D-1}$$

$$z = \frac{r}{2\tan\phi} \ln\frac{\sigma_0}{\sigma} \tag{D-2}$$

Equations D-1 and D-2 thus yield the relation between the axial swelling distance *z* and the swelling pressure *σ*.

Appendix E

Dimensioning of the transition zone

Inside the compartment plug

The analytical solution in Appendix D is used to calculate the length of the transition zone.

Prerequisites

The initial conditions and geometries of the system are described in Figure E-1. The bentonite properties have been simplified and assumed to be completely saturated and radially homogenised from start. The plug has been simplified to be without curvature. The average density after radial swelling has been used for the transition blocks.

Geometry

- Radius=0.925 m.
- Distance from the filling block to the plug filled with pellets: 1.3 m.

Initial properties

The average dry density of the transition block section is calculated from the geometries and the initial dry density of the blocks:

- Block diameter: D=1.765 m.
- Tunnel diameter: D=1.85 m.
- Dry density of the blocks: rdb =1 712 kg/m^3.
- Average calculated initial dry density of the transition blocks: rd= rdb·1.7652/1.852 = 1 558 kg/m^3.

The initial conditions are thus:

- Dry density of the pellet filling rdp=1 000 kg/m^3.
- Average dry density of the transition block section rdt=1 558 kg/m^3.
- The swelling pressure of the transition block section ps has been calculated according to Equation E-1.

p_s=5.931 MPa

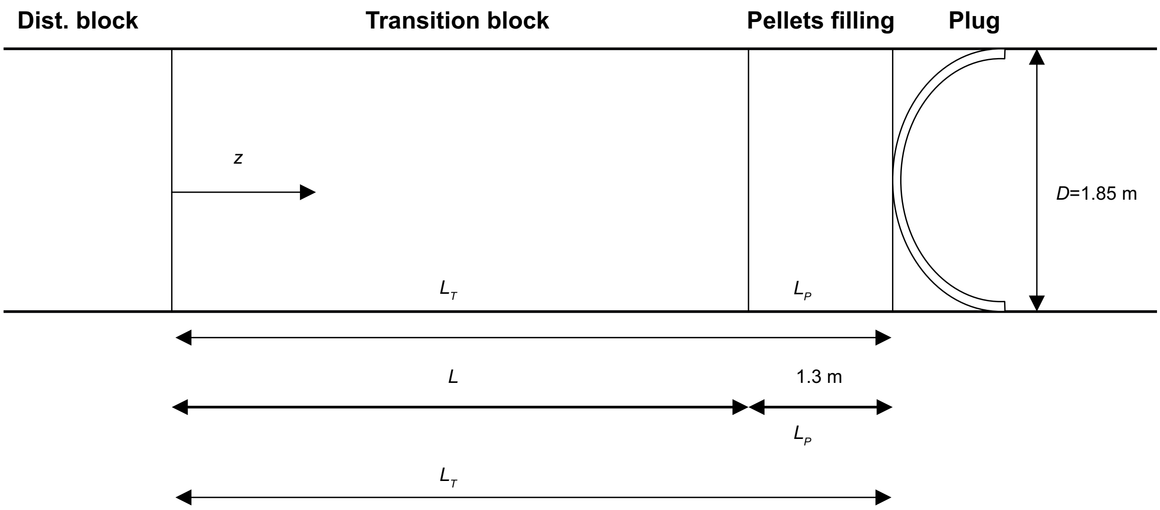

Figure E-1. *Basic geometry used for the calculation.*

The relation between swelling pressure and dry density can for MX-80 be described by Equations E-1 and E-2 (Börgesson et al. 1995).

$$p = p_r \left(\frac{e}{e_r} \right)^{\frac{1}{\beta}} \quad \text{(E-1)}$$

,where

e = void ratio

e_r = reference void ratio (=1.1)

p = swelling pressure (at e)

p_r = reference swelling pressure (at e_r) (=1 000 kPa)

$\beta = -0.19$

$$\rho_d = \frac{\rho_s}{1+e} \quad \text{(E-2)}$$

where

ρ_d = dry density

e = void ratio

ρ_s = density of solids = 2 780 kg/m^3

Dimensioning calculations

The calculations are made in the following way: The large difference in density and resulting swelling pressure of the bentonite in the transition block zone and the bentonite in the pellet filling results in a swelling of the bentonite from the transition block zone and compression of the bentonite in the pellet filling. There will not be a complete homogenisation due to the shear resistance (friction angle) between the bentonite and the rock. Instead there will be a swelling pressure (and thus density) gradient between the plug and the end of the transition zone. The length of the transition block zone will be dimensioned by the position where the density is unchanged.

The dry density distribution can be calculated from the swelling pressure distribution by combining Equations E-1 and E-2 with the following Equations E-3 and E-4 that describe the axial swelling pressure as a function of the axial distance from the unaffected bentonite at equilibrium after completed swelling in a cylindrical confinement (see e.g. Åkesson et al. 2010b).

$$p = p_0 \cdot e^{-\frac{2z \tan\phi}{r}} \quad \text{(E-3)}$$

$$z = -\frac{r}{2\tan\phi} \ln \frac{p}{p_0} \quad \text{(E-4)}$$

where

z = axial distance from the unaffected bentonite

r = radius

p = swelling pressure at z

p_0 = swelling pressure at $z = 0$

ϕ = friction angle (=5°–30° depending on the swelling pressure and the roughness of the rock surface)

The swelling can be modelled according to Equations E-1 to E-3. Combining the expressions in Equations E-1 and E-3 for the swelling pressure yields Equation E-5.

$$p_r \left(\frac{e}{e_r} \right)^{\frac{1}{\beta}} = p_0 \cdot e^{-\frac{2z \tan\phi}{r}} \quad \text{(E-5)}$$

Applying Equation E-2 for the relation between void ratio and dry density and

e_r=1.1 = reference void ratio

p_r =1 000 kPa = reference swelling pressure at e_r=1.1

p_0= 5 931 kPa = swelling pressure at z = 0

yield Equation E-6:

$$1000 \cdot \left(\frac{\left(\frac{\rho_s}{\rho_d} \right) - 1}{1.1} \right)^{\frac{1}{\beta}} = 5931 \cdot e^{-\frac{2z \tan\phi}{r}} \tag{E-6}$$

$$\frac{\frac{\rho_s}{\rho_d} - 1}{1.1} = \left(5.931 \cdot e^{-\frac{2z \tan\phi}{r}} \right)^{\beta} \tag{E-7}$$

$$\frac{\rho_s}{\rho_d} = 1.1 \cdot e^{-\frac{2z \tan\phi}{r}\beta} \cdot 5.931^{\beta} + 1 \tag{E-8}$$

Applying $\beta = -0.19$, $r = 0.925$ m and $\rho_s = 2.78$ t/m^3 yields

$$\frac{2.78}{\rho_d} = 0.784 \cdot e^{\frac{0.38 \cdot z \cdot \tan\phi}{0.925}} + 1 \tag{E-9}$$

$$\rho_d = \frac{2.78}{0.784 \cdot e^{0.41 \cdot z \cdot \tan\phi} + 1} \tag{E-10}$$

Equation E-10 thus yields the dry density distribution along the tunnel axis after force equilibrium. But in order to settle the required length of the transition zone L we need to use the fact that the mass of bentonite lost in the transition zone due to swelling is the same as the mass gained in the 1.3 m long pellet filling part due to the same swelling and subsequent compression of the pellet filling meaning that the total dry mass of bentonite between the plug and the unaffected distance block section is the same before and after swelling.

The dry mass dm_s over an axial length of dz of the tunnel can be formulated with Equation E-11.

$$dm_S = \rho_d \cdot \pi r^2 dz = \frac{2.78}{0.784 \cdot e^{0.41 \cdot z \cdot \tan\phi} + 1} \cdot \pi r^2 dz \tag{E-11}$$

$$dm_S = \frac{2.78 \pi 0.925^2 dz}{0.784 \cdot e^{0.41 \cdot z \cdot \tan\phi} + 1} = \frac{7.47}{0.784 \cdot e^{0.41 \cdot z \cdot \tan\phi} + 1} dz$$

(E-12)

$$dm_S = \frac{9.528}{e^{0.41 \cdot z \cdot \tan\phi} + 1.276} dz$$

In order to calculate the total mass M_{ST} we have to integrate the mass from z=0 to $z = L$+1.3 m = L_T, but at first we change Equation E-12 to Equation E-13:

$$dm_S = \frac{a}{e^{b \cdot z} + c} dz \tag{E-13}$$

Where

a=9.528

b=0.41·tanϕ

c=1.276

Integration according to Equation E-14 yields the total mass M_{ST} according to Equation E-15.

$$M_{ST} = \int_{z=0}^{z=L_T} dm_S = \int_{z=0}^{z=L_T} \frac{a}{e^{b \cdot z} + c} dz \qquad \text{(E-14)}$$

$$M_{ST} = \frac{aL_T}{c} - \frac{a}{bc}\ln(c + e^{bL_T}) + \frac{a}{bc}\ln(c+1) \qquad \text{(E-15)}$$

We thus have a general expression of the distribution of the total dry mass over the length of the transition zone and the pellet filling after swelling.

The initial dry mass of bentonite in the transition zone (over the length L) is calculated according to Equation E-16.

$$M_{S1} = \rho_d \pi r^2 L = 1.558 \cdot \pi \cdot 0.925^2 \cdot L = 4.190L \qquad \text{(E-16)}$$

The initial mass of dry bentonite in the pellet filling (L_P) is according to Equation E-17

$$M_{S2} = \rho_d \pi r^2 L_P = 1.0 \cdot \pi \cdot 0.925^2 \cdot 1.3 = 3.494 \qquad \text{(E-17)}$$

The total dry mass is thus

$$M_{ST}=M_{S1}+M_{S2}=4.190L+3.494=4.190(L_T-1.3)+3.494 \qquad \text{(E-18)}$$

By combining Equations E-15 and E-18 we can calculate L_T for different friction angles. By including the total length in Equation E-3 we can also calculate the swelling pressure on the plug. Table E-1 shows the results.

Table E-1. Results of the calculations.

Friction angle ϕ	Total length of transition zone L_T	Length of transition block L	Swelling pressure on the plug
5°	7.61 m	6.31 m	1413 kPa
10°	5.67 m	4.37 m	771 kPa
20°	3.74 m	2.44 m	315 kPa
30°	2.98 m	1.68 m	146 kPa

The required length of the transition zone and the resulting swelling pressure on the plug are thus very dependent on the friction angle. The friction angle for swelling pressures between 1 and 10 MPa is about ϕ=10° and it increases with decreasing swelling pressure. However, the friction angle between bentonite and a smooth plane surface of rock can be lower (about 50 % according to Börgesson et al. 1995), which perhaps would motivate to use ϕ=5°.

Figure E-2 shows the total length of the transition zone L_T as a function of the applied friction angle. Figure E-3 shows the swelling pressure on the plug as a function of the friction angle. Finally Figure E-4 shows the density distribution along the entire transition zone at different friction angles.

Figure E-5 shows a relation between swelling pressure (expressed as average effective stress) and the friction angle of MX-80 derived by Börgesson et al. (1995).

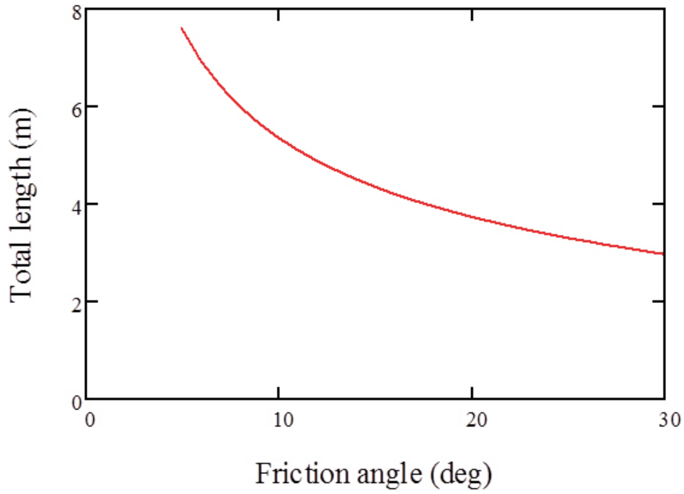

Figure E-2. *Total length of the transition zone L_T as a function of the applied friction angle.*

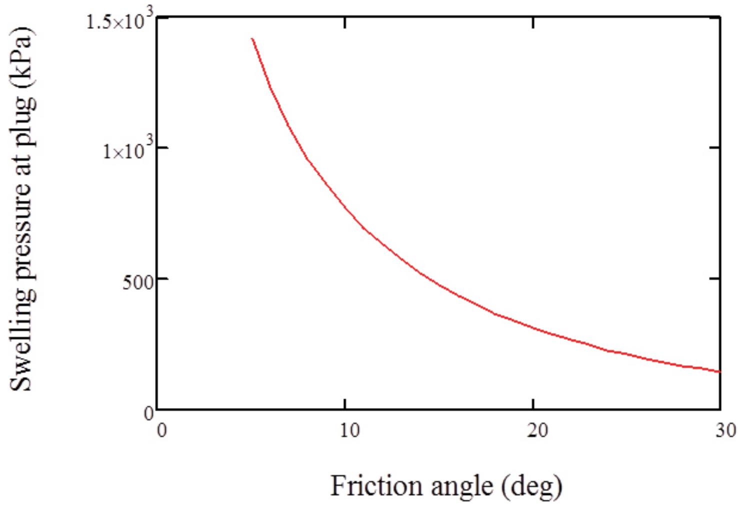

Figure E-3. *Swelling pressure on the plug as a function of the friction angle.*

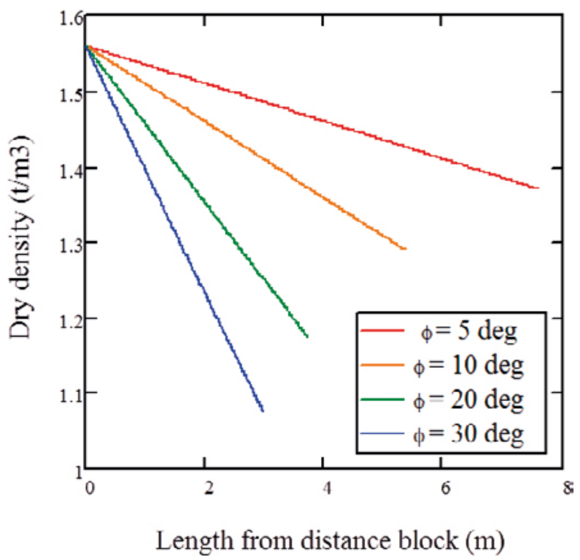

Figure E-4. *Density distribution along the entire transition zone at different friction angles.*

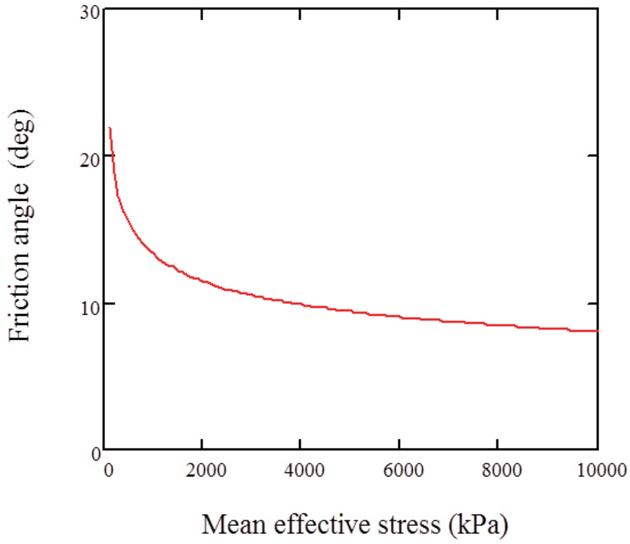

Figure E-5. *Relation between swelling pressure (expressed as average effective stress) and the friction angle of MX-80.*

Outside the compartment plug (drift entrance side)

The geometry is shown in Figure E-6. The transition block inside the plug (on the seal side) is dimensioned with a pellet filling of 1.3 m from the crown of the plug. The required length of the pellet filling outside the plug (drift entrance side) is 1.0 m. However, it is logical to use the same length of the pellet filling outside the plug, since if a shorter pellet filling (1.0 m) would be used the total length will only be 2.3 meter and after plug disintegration and bentonite swelling equilibrium, the efficient length of the two parts will be only 1.15 m. This may jeopardize the dimensioning of the transition block length inside the plug and thus cause a density reduction that reaches into the distance block.

Length of pellet filling: L_p=1.3 m.

The lengthy of the transition block zone L will thus for this case be the same as the length of the transition block zone inside the plug.

Length of transition blocks: see Table E-1.

If ϕ=5° L=6.31 m.

Uncertainties

There are several simplifications and uncertainties related to these calculations. The following simplifications have been made:

1. The geometry of the plug is simplified.
2. No account has been taken to the initial slot between the bentonite blocks and the rock surface and the resulting radial density distribution.
3. No account has been taken to the water saturation phase, which in combination with the slot at the rock surface may affect the stress path during swelling.
4. The analytical calculation includes several simplified assumptions:
   a. No consideration to the hysteresis effects at loading and unloading has been taken.
   b. Potential radial stress gradients caused by the axi-symmetric swelling has not been taken into account.
   c. Potential differences between radial and axial stresses at uniaxial swelling and compression have not been taken into account.

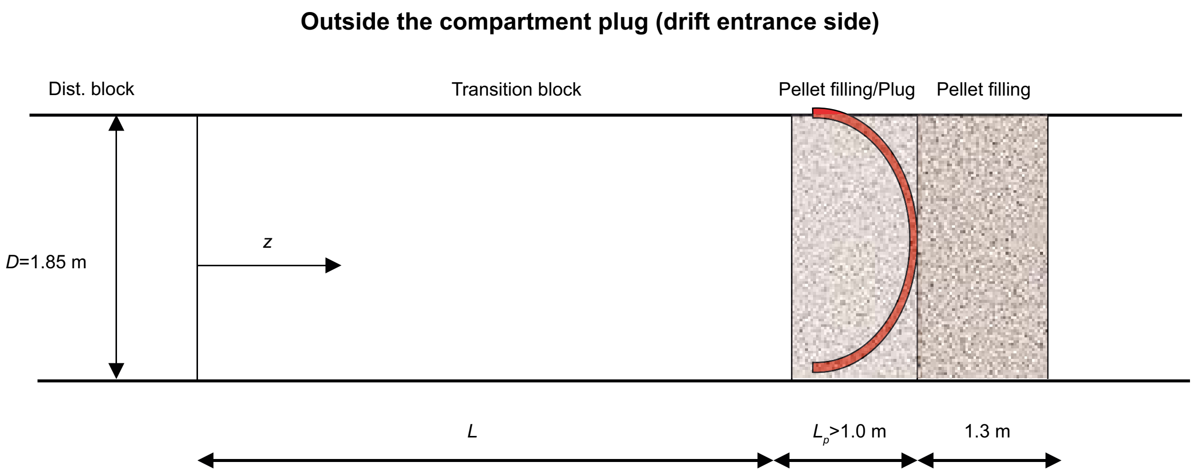

Figure E-6. *Basic geometry used for the dimensioning of the drift entrance side.*

It is difficult to estimate the importance of these simplifications. However, similar analytical calculation techniques have been used in different situations for KBS-3V and comparisons with FEM-calculations have shown reasonable agreement (Åkesson et al. 2010).

Another uncertainty is of course the friction angle between the bentonite and the rock. By using the friction angle ϕ=5° the results should be on the safe side.

Since there is a distance block section between the super container and the transition zone according to the present design, this is judged to yield enough safety margins for the uncertainties caused by the simplified calculation method. If, however, the distance block section is removed it is advisable to do more careful FEM-calculations of this case.

Appendix F

Glossary

Air evacuation	Removing of air from a drift compartment through a 150 m (max.) long pipe during artificial watering.
Artificial watering	Adding water through three short pipes to fill the voids in the compartment with water in order to facilitate accelerated buffer saturation.
Backfilling	Filling the deposition niche, transport/central tunnels and other parts of the repository.
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 two compartments by a compartment plug.
Compartment plug	Plug used to seal off drift sections, thus dividing the drift into compartments.
Cutting tool	Device for removal/cutting of Supercontainer end plate during retrieval.
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 plug	Combined drift end plug and compartment plug. Design is based on heavy duty compartment plug that can take full loading form hydrostatic groundwater pressure and swelling pressure from buffer for long periods of time.
Drip (and spray) shield	Thin titanium 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 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	Ring used to fasten the compartment and drift plugs to the rock.
Filling block	Filling blocks are placed at positions where Supercontainer sections cannot be positioned because inflow is higher than the positioning criteria. Filling block is one type of filling component.
Filling components	All bentonite materials not included in the buffer are filling components. All drift sections that are not suitable for Supercontainer sections (SC and DB) must be filled with a filling component before sealing with a plug. Filling blocks and transition blocks are examples of filling components.
Gamma gate	Sliding radiation protection gates located on the transport tube or at the entrance of the deposition drift.

Gripping tool	Device for removal of canister from the drift during retrieval.
Handling cell	Shielded space for handling of spent fuel canister.
Handling equipment	Equipment for handling of spent fuel canister within the reloading station.
Horizontal push-reaming	Excavation method to ream the pilot hole to full drift size, known also as horizontal blindboring, reverse raiseboring or horizontal box-hole boring.
KBS	(Kärnbränslesäkerhet). The method for implementing the spent fuel disposal concept based on multiple barriers (as required in Sweden and in Finland). KBS-1, KBS-2 and KBS-3 are variations of this method.
KBS-3H	(Kärnbränslesäkerhet 3-Horisontell). Design alternative of the KBS-3 method in which several spent fuel canisters are emplaced horizontally in each deposition drift.
KBS-3V	(Kärnbränslesäkerhet 3-Vertikal). The reference design alternative of the KBS-3 method in which the spent fuel canisters are emplaced in individual vertical deposition holes.
LHHP cement	Low-Heat High-Performance cement, used for spent fuel repository applications, characterized by a low heat of hydration, and a lower release of free hydroxide ions and lower pH than for ordinary cement.
Mega-Packer	Large-scale post-grouting device for grouting of rock.
MPT	Multi Purpose Test in Äspö HRL.
ONKALO	Underground rock characterisation facility in Olkiluoto, Finland.
Parking feet **Pellet filling**	Feet on the Supercontainer The empty chamber behind the plugs that is needed for mantling the cap will be filled with pellets through the filling hole in the cap after the plug has been constructed.
Pilot hole	Rotary drilled hole for guiding horizontal push-reaming excavation.
Piping	Formation of hydraulically conductive channels in the bentonite due too high water flow and hydraulic pressure difference along the drift.
Post-grouting	Grouting method used in deposition drift after excavation.
Pre-grouting	Grouting made through investigation or pilot holes before reaming the drift to full size.
Pre-pilot hole	Core-drilled investigation hole made before drilling the pilot hole. This may be used for guiding the boring of pilot hole.
Reloading station	Station at the repository level where the Supercontainers are assembled.
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.
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 Titanium shell (6 mm thick) that holds together the canister and the bentonite surrounding it.

Transition block **Transition Zone**	A filling component adjacent to the plugs. Located between a plug and the adjacent distance block. Composed of transition block and pellet filling section.
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.

Arkitektkopia AB, Bromma, 2017

SKB is responsible for managing spent nuclear fuel and radioactive waste produced by the Swedish nuclear power plants such that man and the environment are protected in the near and distant future.

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