Description of KBS-3H Design Variant

Posiva Oy

December 2012
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Posiva has committed itself to submit an application for construction license at the end of 2012 following the decision made by council of state in the year 2003. The application is based on the KHS-3V variant. KBS-3H variant will be included in the application as a topical report, i.e. this report, which is appended to the application.

The KBS-3H design is a variant of the KBS-3 method and an alternative to the KBS-3V design, which is the reference design for both Posiva and SKB. In KBS-3H multiple canisters containing spent fuel are emplaced in parallel, 100-300 m long, slightly upwards inclined deposition drifts at a depth of about 400-450 m in the bedrock whereas the KBS-3V design calls for vertical emplacement of the canisters in individual deposition holes. In both variants the canister spacings (c-c) are the same.

This report presents the current status of the KBS-3H concept together with the DAWE (Drainage, Artificial Watering and air Evacuation) reference design. From the engineering point of view constructing a KBS-3H or a KBS-3V repository will be very similar until the deposition drifts are excavated. The horizontal deposition drifts of KBS-3H eliminate the need to excavate deposition tunnels and hence the need to backfill these tunnels after deposition. There is also a large difference in emplacement work. In the KBS-3H alternative several Supercontainers consisting of both the canister and the buffer need to be emplaced into a deposition drift of up to 300 m in length whereas in the KBS-3V the buffer is lowered into the vertical deposition holes in several steps before and after the canister.

The development of the KBS-3H variant has been carried out both in the joint project between Svensk Kärnbränslehantering AB (SKB) in Sweden and Posiva Oy in Finland but also by Posiva Oy alone in the Plant Design process especially concerning the tasks related to site-specific issues like e.g. layout adaptation at Olkiluoto.

This report is largely based on the results made during the previous phase “KBS-3H Complementary Studies 2008-2010” in the joint project between SKB in Sweden and Posiva in Finland. The current status of the long-term safety studies including the work carried out after the previous project phase is presented in a more detailed level.

Avalainsanat - Keywords
KBS-3H, long-term safety, repository, final disposal, spent nuclear fuel, Olkiluoto, deposition hole, DAWE, Posiva, Supercontainer,
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KBS-3H RATKAISUN KUVAUS

Tiivistelmä – Abstract


KBS-3H ratkaisu muodostaa vaihtoehton KBS-3V:lle, joka on sekä SKB:n että Posivan referenssiratkaisu em. kahdesta KBS-3 menetelmävaihtoehdosta. KBS-3H-vaihtoehdossa kapseilut sijoitetaan 100-300 m pitkiin ja loivasti yläkätisiin loppusijoitusreikiin. Loppusijoitusyvyys on 400-450 m. KBS-3V ratkaisussa puolestaan kapseilit sijoitetaan yksittäisiin pystyreikin, jotka porataan loppusijoitustunnelin lattiatason alapuolelle. Molemmissa vaihtoehdoissa kapseilusijointityö keskipisteistä laskettuna ovat samat.

Tässä raportissa esitetään KBS-3H ratkaisun nykytilanne ja referenssisuunnitelma valittu DAWE (Drainage, Artificial Watering and air Evacuation). Loppusijoituslaitoksen rakentamisen kannalta KBS-3H ja KBS-3V ratkaisut ovat hyvin samankaltaisia keskenään lukuun ottamatta loppusijoitustunneleita (3V) ja loppusijoitusreikiä (3H), joissa ilmenevät suurimmat eroavuudet. 3H-ratkaisussa loppusijoitustunnelia ei tarvita lainkaan, mikä heijastuu tarvittavassa täyttömateriaalin tilavuudessa. Ratkaisuvaihtoehdoihin liittyvät kapseilen loppusijoitustekniikat poikkeavat myös suuresti toisistaan. Vaakaratkaisussa kapseilut pakataan asennuspakkauksiin, jotka koostuvat itse kapseilusta ja sen ympärille asennettavasta puskuribentoniitirkrooksesta sekä rei’itetystä titaanivalmisteseista suojasylinteristä. Pystyratkaisussa osa puskuribentonitiittistä lasketaan pystyreikään ennen kapseilin asentamista, ja osa sen jälkeen.

Vaakaratkaisun kehitystyötä on tehty useiden vuosien aikana ruotsalaisen Svensk Kärnbränslehanteringin AB (SKB) ja Posiva Oy:n välisessä yhteisprojektissa, mutta myös itse Posivan toimesta osana laitossuunnittelua etenkin paikkasidonnaisten kysymysten osalta, esim. loppusijoitustilojen asemointi Olkiluodossa.

Tämä raportti perustuu suurelta osin yhteisprojektin edellisen vaiheen “KBS-3H Complementary Studies 2008-2010” tuloksiin ja loppuraporttiin. Pitkäaikaisturvallisuuden osalta raporttiin on sisällytetty ajantasaisen kuvaus KBS-3H ratkaisun nykytilanteesta.
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FOREWORD

This topical report, which describes the current status of the KBS-3H design has been produced by different authors, who have contributed to the text, according to the following list:

- Chapter 1 "Introduction": Reijo Riekkola (Saanio & Riekkola Oy)
- Chapter 2 “Development of the KBS-3H alternative and main differences to the KBS-3V design”: Antti Öhberg (Saanio & Riekkola Oy) based on /SKB 2012/
- Chapter 3 “Design Basis”: Jarkko Kyllönen (Fortum)
- Chapter 4 “Overview of the KBS-3H DAWE design”: Antti Öhberg (Saanio & Riekkola Oy) based on /SKB 2012/
- Chapter 5 “Assessment of long-term safety”: Margit Snellman (Saanio & Riekkola Oy) and Paul Wersin
- Chapter 6 “KBS-3H layout adaptation to Olkiluoto site”: Antti Öhberg (Saanio & Riekkola Oy) based on /Kirkkomäki & Rönnqvist 2011/
- Chapter 7 “Ongoing studies to solve important issues for the long-term performance of a KBS-3H drift”: Margit Snellman (Saanio & Riekkola Oy), and Antti Öhberg (Saanio & Riekkola Oy)
- Chapter 8 “Ongoing demonstration work”: Antti Öhberg (Saanio & Riekkola Oy)
- Chapter 9 “KBS-3H specific system descriptions”: Antti Öhberg (Saanio & Riekkola Oy) based on /Kirkkomäki & Rönnqvist 2011/
- Chapter 10 “Description of the facility at repository level”: Antti Öhberg (Saanio & Riekkola Oy) based on /Saanio et al. 2012/ and /Kirkkomäki & Rönnqvist 2011/
- Chapter 11 “Description of operation including occupational and operational aspects”: Antti Öhberg (Saanio & Riekkola Oy) based on internal documents compiled by Ursula Resgren and Elisabet Höge from Scandpower AB
- Chapter 12 “Summary”: Antti Öhberg (Saanio & Riekkola Oy)
1 INTRODUCTION

KBS-3H is a variant of the KBS-3 method and an alternative to the KBS-3V reference design. KBS-3H is based on horizontal emplacement of several canisters in long drifts whereas KBS-3V calls for vertical emplacement of the canister in individual depositions holes within a deposition tunnel, see Fig. 1-1. Horizontal emplacement has been studied in parallel with the development of the KBS-3V reference design since the late 90’s /SKB 2012/. This chapter gives a description of the previous KBS-3H related projects and describes the main reasons for developing an alternative KBS-3 method.

Figure 1-1. Schematic drawing of the KBS-3V reference design (to the left) and KBS-3H (to the right) /SKB 2012/.

Development of systems for disposal of long-lived radioactive waste from nuclear power plants was initiated in Sweden in the mid-seventies. The work resulted in the KBS-3 method which was approved by the Swedish government in 1984. Since then the KBS-3 method has constituted the reference method in the Swedish programme, and later also in the Finnish Programme.
SKB and Posiva have also developed and evaluated several other alternatives to ensure that KBS-3 is the most suitable method. Alternatives that were studied and rejected for further study were the WP-Cave method, Very Deep Boreholes (2-4 km below the ground surface) and the deposition of relatively large canisters in 3-5 km long horizontal drifts, Very Long Holes (VLH). A comprehensive evaluation of different repository alternatives was carried out in PASS-project over the period 1990 to 1992, /SKB, 1993/. The conclusion of the evaluation indicated that KBS-3V and an alternative design based on 200 m long horizontal deposition drift, called Medium Long Hole (MLH, later KBS-3H) concept were considered more feasible than other alternatives.

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

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

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

One important conclusion that had been drawn in earlier work was that the canister and the buffer should be emplaced as an integrated waste package and not as separate components. Various emplacement techniques were studied and the conclusion reached was that a waste package – “Supercontainer” – should be developed.

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

During the early development of the Basic Design in 2004 it was concluded that there were several problems related to the presented KBS-3H design. Several of these problems related to the behaviour of KBS-3H design and scope of future research and development work were addressed in the seminar in Stockholm 9th February 2005. The designs were reviewed and assessed to contain significant uncertainties and problems. The most significant functional uncertainties and problems were related to uneven saturation, piping and rupturing of buffer mainly caused by heterogeneous groundwater inflow environment. Therefore the design basis was developed further and two candidate designs were developed in the spring 2005: 1) Basic Design (BD) was
developed more robust and tolerable to inflows. Parallel to that, a novel 2) DAWE design with drainage, air evacuation and Watering and was developed to function robustly at various inflow situations.

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

Figure 1-2. The design selection process for geological disposal from 1990 – 1998 studied in the PASS and JADE projects. Green text indicates design alternatives that remain after the successive evaluations. The final part of the figure introduces the KBS-3H project phases /SKB 2012/.
Posiva has committed itself to submit an application for construction license at the end of 2012 following the decision made by the council of state in the year 2003. According to the regulation in Finland Posiva shall include PSAR into the construction license application where safety shall be justified by a safety case for the KBS-3V alternative i.e. the reference design. In the application KBS-3H will be described as an alternative for KBS-3V and this topical report “Description of KBS-3H design variant” will be appended to the application.

This report will describe the KBS-3H reference design DAWE (Drainage, Artificial Watering and air Evacuation) at the end of the project phase “KBS-3H Complementary Studies 2008-2010”. However, the current status with the long-term safety issues is presented in this report (Chapter 5) in a more detailed level compared to other chapters, which are largely based on the report /SKB 2012/ presenting the design with more details.

The ongoing and planned work in the KBS-3H project is presented in /Posiva 2012a/.
2 DEVELOPMENT OF THE KBS-3H ALTERNATIVE AND MAIN DIFFERENCES TO THE KBS-3V DESIGN

The KBS-3 method, based on multiple barriers, is the proposed spent fuel disposal method both in Sweden and Finland. KBS-3H and KBS-3V are the two design alternatives of the KBS-3 spent fuel disposal method.

KBS-3H is a variant of the KBS-3 method and an alternative to KBS-3V, see Fig. 2-1. In the KBS-3H, in contrast to KBS-3V, each canister, with a surrounding layer of bentonite clay, is placed in a perforated titanium cylinder prior to disposal underground; the entire assembly is called the Supercontainer. Several Supercontainers are positioned along up to 300 m long deposition drifts, which are sealed following canister emplacement using titanium drift plugs. Bentonite distance blocks separate the Supercontainers, one from another, along the drift. The bentonite inside the Supercontainers and the bentonite distance blocks are jointly termed the buffer. Filling blocks are placed at positions where Supercontainer or distance blocks cannot be positioned because inflow is higher than positioning criteria. Titanium compartment plugs can also be used to seal off drift sections in which high initial groundwater inflow renders them unsuitable for Supercontainer, distance block or filling block emplacement, thus creating two or more compartments along the drift in which these elements can be emplaced.

![Figure 2-1. Principles of the KBS-3V (upper left) and KBS-3H (upper right) repository designs and a more detailed illustration of the KBS-3H design (lower) and the Supercontainer (upper right). In this figure the deposition niche is located according to](image-url)
SKB’s design whereas in Posiva’s design the deposition niche is located between the two parallel central tunnels, see Fig. 9-1 /SKB 2012/.

2.1 Development phases

Posiva and SKB have since 2001 conducted a joint research, demonstration and development (RD&D) programme with the overall aim of establishing whether KBS-3H represents a feasible alternative to KBS-3V.

The stepwise approach with completed and planned steps within this process is as follows:

- 2002: Feasibility study of the concept
- 2003: Basic design
- 2004-2007: Project phase demonstration
  - 2004-2005: Technical development
  - 2006-2007: Demonstration, testing and safety assessment
  - 2007: Evaluation and reporting
- 2008-2010 Complementary studies phase
- 2011-2016 KBS-3H System Design

The development of candidate designs - the Basic Design, STC (Semi Tight Compartment) and DAVE (Drainage, Artificial Watering and air Evacuation) started in 2005 and at a later stage during the project phase “Complementary studies 2008-2010” DAVE was selected as the reference design. The stepwise development, testing and demonstration of the design have been presented in /Autio, 2007/, /Autio et al. 2007/, /Anttila et al. 2008/ and /SKB 2012/.

The summary of long-term safety related studies for KBS-3H concept is presented in this report in Chapter 5 “Assessment of long-term safety”. This chapter includes updated information and current status of the safety studies.

2.2 KBS-3H specific issues

Generally, there are more similarities than differences between the KBS-3V and KBS-3H variants. Same regulatory requirements concern both KBS-3V and KBS-3H repositories and the decision in principle allows both variants. Both variants are based on the KBS-3 method and multi-barrier systems relying on the mechanically and chemically stable bedrock, containment of the fuel in a long-lived canister, and a buffer surrounding the canister that provides hydraulic, mechanical and chemical conditions favouring canister longevity. The conditions in the bedrock and buffer are such that the migration of any nuclides released from the canister if it becomes damaged is expected to be slow. The rate of release of radionuclides will also be limited by the stability of the spent fuel matrix and the low solubility of many radio-elements under the chemical conditions expected in the interior of a damaged canister.

Construction and operation of the repository would, however, be different for the two variants. From an engineering point of view, one major difference is the absence of
large deposition tunnels in the case of KBS-3H and therefore the elimination of a need to backfill these tunnels. There are also major differences with respect to the emplacement work.

For a long-term safety point of view, a difference analysis performed on the KBS-3V and KBS-3H variants /Gribi et al. 2007/ has shown that most of the differences between KBS-3H and KBS-3V relate to internal processes involving KBS-3H-specific components, such as the Supercontainer and other structural components, and the impact of variations in hydraulic conditions along the KBS-3H deposition drifts and their immediate environment. The initial void spaces around the Supercontainers and distance blocks will become filled with bentonite as the drift saturates and the bentonite swells, but the rate at which this occurs may vary considerably along the drift due to the heterogeneity of the rock and the variability of water inflow. As long as water-filled voids exist, there is the potential for large hydraulic pressure differences along the drifts that could, for example, lead to a redistribution of buffer mass by piping and erosion. The management of heterogeneous inflow along the drift and still maintaining the required functions of the buffer is a key consideration in design development for KBS-3H.

2.3 The main differences between 3V and 3H alternatives

2.3.1 General

Examples of potential positive effects of KBS-3H are:

- a more industrialised process during construction and disposal (full-face boring, Supercontainers, distance blocks and plugs)
- prefabricated disposal container (Supercontainer), which enables an easier quality assurance of the canister and adjacent buffer material
- reduced disturbance on the rock mass during construction and operation (no blasting of deposition tunnels)
- less environmental impact during construction (less excavated rock volumes and hence less filling material)
- reduced cost for construction (including reinforcement)
- reduced cost for backfilling

2.3.2 Operational issues

The layout adaptations at Olkiluoto for both vertical and horizontal variants are very similar. The differences are mostly due to the longest allowed drift length in 3H being 300 m whereas the vertical variant allows 350 m long deposition tunnels. Another factor is that the horizontal variant requires 700 mm more height to the central tunnels due to transfer equipment. The deposition drifts and the central tunnels that are connecting the drifts can be adapted in numerous ways. Which alternative must be applied and secondly how large is the total impact on the required excavation volumes due these differences between 3V and 3H is dependent on the final decision for the direction of the deposition tunnels (3V) / deposition drifts (3H). The layout adaptation work /Kirkkomäki & Rönnqvist 2011/ was based on the E-W direction which resulted in total
of 31.6 km in drift length and in total of 9.2 km in central tunnel length. The number of deposition drifts was 122.

The volume of the central tunnels in the horizontal variant is higher than in the vertical variant and this is due to a more straightforward adaptation in the 3V case in the NE side of the technical rooms at Olkiluoto /Kirkkomäki & Rönnqvist 2011/.

Regarding the open volumes during the operational phase there are no significant differences between the two variants.

The time from the deposition of the first Supercontainer until the drift plug is in operation shall be in the order of two weeks when using the titanium alloy drift plug. The installation of a compartment plug in the pre-excavated notch will be possible to be performed in one day.

Transportation/emplacement of the canister is carried out with different techniques in the two variants. In 3H the canister is packed into a Supercontainer in the reloading station and transported inside the transportation tube with the transportation vehicle to the intermediate storage or straight to the deposition area where the transportation tube will be docked to the deposition drift as described in Section 9.3. The deposition machine will be used for the deposition of the Supercontainer into the drift. The transportation of a canister in 3V from the canister lift to the deposition hole is described in /Saanio & al. 2012/.

Regarding the operational safety issues a study has been carried out, see Section 11.2. In the study the following additional risks, compared to KBS-3V were identified for the process of preparation a drift:

- Too high inflows of groundwater to the drift will give problems with eroding buffer when the Supercontainers and distance blocks are deposited. It is important that the rock characterisation is made properly and that the zones with high water inflows are grouted to ease the installation process.
- It is technically a more complex task to excavate a 300 m long drift, especially meeting the strict geometrical requirements, and to manage the water inflows in it.
- During the preparation of a drift several components are installed; fastening rings for the plugs, an air evacuation pipe and spray and drip shields to block water from coming in contact with the buffer. If these are incorrectly installed and not identified by inspection it can affect the deposition process in a negative way.

Regarding the operational safety issues the following additional risks, compared to KBS-3V were identified for the process of reloading station. The following additional risks, compared to KBS-3V were identified for this part of the process:

- Lowering of the copper canister into the Supercontainer
- Lift of the transportation tube used for Supercontainer transportations
- Longer radiation exposure time. Though, the copper canister is always shielded when it is moved.
Regarding the operational safety issues compared to KBS-3V the following advantages were identified in KBS-3H (see also Section 11.2):

- During deposition the deposition machine lifts the Supercontainer with water cushions and the lifting height is very low. There is no risk for dropping the canister.
- The fire load on the deposition machine is less for KBS-3H. Fire cannot be spread to other material than the deposition machine and cables.

The following disadvantages from a safety/availability point of view were identified in 3H (see also Section 11.2):

- It is not optimal to use the deposition machine for transporting distance blocks in the drift. The stepwise movement of the blocks might cause cracks in the bentonite near the feet attachment. Alternative machines should be considered. A KBS-3H machine inventory will be developed early in the current project phase to clarify these potential needs. The implications in drift operation and costs should also be included in current work.
- The air evacuation pipe can get stuck in the swelling buffer. The air evacuation pipe may act as flow path for water and might erode buffer in zones where it has not swollen yet. However, the air evacuation pipe getting stuck is not considered to be an issue any longer, see Section 9.10.
- Compared to KBS-3V the KBS-3H alternative will probably have lower availability. The canisters are deposited in a sequence in the same drift, hence it will be a more complex task to correct a failure event, e.g. unwanted wetting of the buffer or mechanical failure to the deposition machine and buffer degradation.

Differences in the occupational safety issues are connected primarily to

- The preparation of deposition drifts (3H)/deposition tunnels and deposition holes (3V) including excavation procedures. The excavation techniques used in the two variants are different. Full face boring technique is used in 3H whereas drill and blast technique used in the deposition tunnels and full face technique in the vertical holes in 3V.
- Activities in the reloading station (3H). This is a 3H-specific procedure. In the area of reloading station the work is fully automated and remote, see Section 9.5. The physical involvement of personnel is small. The main activities are performed inside radiation shielded area.
- Installation of the drift components including e.g. Supercontainers into the drift (3H) /installation of the canisters into the vertical holes and back-filling of the deposition tunnels (3V). The risks during deposition work in 3H are mostly connected to the welding of fastening rings during installation of compartment plugs. Well functioning ventilation system and additional physical barriers including monitoring of oxygen concentrations in the breathing air are necessary.
2.3.3 Long-term safety aspects

KBS-3H includes more prefabricated industrial components and a reduced amount of human involvement in the deposition process which is preferable and should result in small deviations and high quality. The assembly of the Supercontainer in the reloading station is done in an industrial process in a controlled environment, which is likely to be more consistent than “manual” emplacement of canister, backfill and buffer separately. The mechanical excavation (full face reaming of the pilot holes by push reaming) of deposition drifts will also be more consistent than the “manual” excavation of deposition tunnels, although it should of course be mentioned that the deposition holes of KBS-3V are also made by means of mechanical excavation.

In the horizontal variant using artificial water filling will also ensure a better defined initial state, which is beneficial for evaluating long-term safety aspects.

Two critical issues that could lead to a common mode failure e.g. the case of multiple canister failure, have been identified, which also could possibly be more troublesome for KBS-3H than for KBS-3V; these are chemical erosion and earthquake compression shear.

2.3.4 Excavated volumes in 3H and 3V

The major advantage with KBS-3H is due to the smaller volume of excavated rock, approximately 60 % of the KBS-3V volume. This is, as a consequence of the deposition tunnels being eliminated in the horizontal variant. The excavated volumes of the two variants are presented in Section 6.3.3 in Table 6-2.

The total excavated volume in the 3H variant is about 200 000 m$^3$ smaller than in the 3V variant. The most significant difference is caused by the total volumes between deposition drifts and deposition tunnels. The total volume of the deposition drifts in 3H is below 100 000 m$^3$ whereas the total volume of deposition tunnels including the vertical deposition holes is about 5-folded i.e. close to 500 000 m$^3$ in KBS-3V /Kirkkomäki & Rönnqvist 2011/.

2.3.5 Environmental issues

From the environmental aspects the most important factor that favours the horizontal alternative is the impact during construction i.e. less excavated rock volumes and hence less filling material, which both have also a substantial impact on lowering the costs.
3 DESIGN BASIS

The design basis for the KBS-3H method is largely similar to the design basis for the KBS-3V method which has been reported in /Posiva 2012b/ and /SKB 2009/. The laws, regulatory and stakeholder requirements are independent of the method chosen, as are most of the requirements set for the canister, buffer and host rock. The main differences arise due to the differences in the emplacement method; i.e. use of horizontal deposition drifts instead of vertical deposition holes, and the need to install the canister together with the buffer in a Supercontainer. The buffer in the KBS-3H method is slightly different from the buffer in the 3V-method. The KBS-3H method does not have a separate tunnel backfill component like the KBS-3V method. Instead, the buffer of the KBS-3H deposition drift consists of the buffer surrounding the canisters in the Supercontainers and distance blocks that separate the Supercontainers from each other.

The formulation of the specific target properties and design requirements for KBS-3H is one of the aims of the current KSB-3H project phase. The requirements are planned to be published in 2014 as a Design Basis for KBS-3H report. This section of the report focuses on the aspects of the KBS-3H design that differ from KBS-3V based on the work during the 3H project during 2008-2010.

3.1 Safety concept and safety functions

Safety concept

The safety concept of the KBS-3H method is equal to the safety concept of the KBS-3V method. The safety concept, as depicted in Fig. 3-1, is a conceptual description of how these principles are applied together to achieve safe disposal of spent nuclear fuel in the conditions of the Olkiluoto site. Due to the long-term hazard of the spent nuclear fuel, it has to be isolated from the surface environment over a long period of time. The KBS-3 method provides long-term isolation and containment of spent nuclear fuel by a system of multiple barriers, both engineered and natural, and by ensuring a sufficient depth of disposal (the key safety features of the system in Figure 3-1). All of these barriers have their roles in establishing the required long-term safety of the repository system. These roles constitute the safety functions of the barriers (see Table 3-1). The surface environment is not given any safety functions; instead it is considered as the object of the protection provided by the repository system.

Most radionuclides in the spent nuclear fuel are embedded in a ceramic matrix (UO$_2$) that itself is resistant to dissolution in the expected repository conditions. The slow release of radionuclides from the spent nuclear fuel matrix is part of Posiva’s safety concept. Moreover, the near-field conditions should contribute to maintaining the low solubility of the matrix.
Figure 3-1. Outline of the safety concept for a KBS-3 type repository for spent nuclear fuel in a crystalline bedrock (adapted from Posiva 2003). Orange pillars and blocks indicate the primary safety features and properties of the disposal system. Green pillars and blocks indicate the secondary safety features that may become important in the event of a radionuclide release from a canister.

Implementation of the KBS-3 method entails the introduction of a number of closure components because of engineering, operational safety or long-term safety needs. Long-term safety needs arise, for example, because implementation involves the construction of a system of underground openings, including the access tunnel and shafts, that would significantly perturb the safety functions of the host rock unless backfilled and sealed at closure of the disposal facility. These closure components with long-term safety functions include:

- backfill of underground openings, including the central tunnels, access tunnel, shafts, and other excavations, and
- drillhole plugs, mechanical plugs, long-term hydraulic plugs at different depths and plugs near the surface.

The preliminary safety functions of the EBS components and host rock are summarised in Table 3-1. In the TURVA-2012 safety case documentation, the spent nuclear fuel, EBS and the host rock are jointly termed the repository system, whereas the term disposal system is used when the repository system and the surface environment are both considered (see Table 3-1).
Safety functions

The safety functions set in the KBS-3V design basis for the host rock and the EBS components that are common to both methods are considered to apply also for the KBS-3H. The drift plugs of the 3H deposition drifts are not structurally similar to those used in the 3V deposition tunnels, but have similar safety functions. The long-term safety of disposal is based on a system of natural and engineered barriers which all have their roles in establishing the required long-term safety of the repository system. These roles constitute the safety functions of the barriers. According to YVL D.5, paragraph 405:

“Engineered barriers and their safety functions may consist of waste matrix, in which radioactive substances are incorporated; hermetic, corrosion resistant and mechanically strong container, in which the waste is enclosed; chemical environment around waste packages, which limits the dissolution and migration of radioactive substances; material around waste canisters (the buffer), which provides containment and yields minor rock movements; other containment structures in the emplacement rooms; backfilling materials and sealing structures, which limit transport of radioactive substances through excavated rooms.”

Posiva's definition of safety functions follows this guidance. However, since an engineered barrier is a barrier that has been designed to provide certain safety function(s) and fulfil certain performance criteria, the spent nuclear fuel matrix is not considered an engineered barrier. In Posiva’s case, the spent nuclear fuel elements are disposed of in the form they are received from the utilities and are not “designed” in any way (e.g. conditioned or reprocessed) before packaging in canisters.

It is acknowledged that most radionuclides in the spent nuclear fuel are embedded in a ceramic matrix (UO₂) that itself is resistant to dissolution in the expected repository conditions. The slow release of radionuclides from the spent nuclear fuel matrix is part of Posiva’s safety concept. Moreover, the near-field conditions should contribute to maintaining the low solubility of the matrix. As these conditions can be constrained by repository design, performance targets and target properties are assigned to the engineered barriers and the host rock. In the safety assessment, the properties of the spent nuclear fuel are taken into account in the release rate of radionuclides from the source term.

The safety functions for each barrier have been presented in Table 3-1. It should be noted that these are preliminary for the KBS-3H and may change later in the development process. The surface environment is not given any safety functions; instead it is considered as the object of the protection provided by the repository system.
Table 3-1. Preliminary safety functions assigned to the barriers (EBS components and host rock) in a KBS-3H repository. Note that the safety functions for the canister, host rock and closure are equal to those of KBS-3V. The 3H buffer has an additional requirement.

<table>
<thead>
<tr>
<th>Barrier</th>
<th>Safety functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canister</td>
<td>• Ensure a prolonged period of containment of the spent nuclear fuel. This safety function rests first and foremost on the mechanical strength of the canister’s cast iron insert and the corrosion resistance of the copper surrounding it.</td>
</tr>
</tbody>
</table>
| Buffer    | • Contribute to mechanical, geochemical and hydrogeological conditions that are predictable and favourable to the canister,  
            • Protect canisters from external processes that could compromise the safety function of complete containment of the spent nuclear fuel and associated radionuclides,  
            • Limit and retard radionuclide releases in the event of canister failure. |
| Host rock | • Isolate the spent nuclear fuel repository from the surface environment and normal habitats for humans, plants and animals and limit the possibility of human intrusion, and isolate the repository from changing conditions at the ground surface,  
            • Provide favourable and predictable mechanical, geochemical and hydrogeological conditions for the engineered barriers,  
            • Limit the transport and retard the migration of harmful substances that could be released from the repository. |
| Closure   | • Prevent the underground openings from compromising the long-term isolation of the repository from the surface environment and normal habitats for humans, plants and animals.  
            • Contribute to favourable and predictable geochemical and hydrogeological conditions for the other engineered barriers by preventing the formation of significant water conductive flow paths through the openings,  
            • Limit and retard inflow to and release of harmful substances from the repository. |

Performance targets

Specific performance targets and target properties have not yet been defined for the KBS-3H method. However, most of the performance targets set for the canister and closure, and some of the target properties set for the host rock in /Posiva 2012b/ apply to KBS-3H. The performance targets for the buffer and Supercontainer are to be defined in the current KBS-3H project phase. The rock suitability criteria and target properties of the host rock will also need to be updated to take into account the differences in the excavated spaces.

The specific requirements arising from the KBS-3H design have been considered during the project phase 2008-2010 and are discussed in the KBS-3H Complementary Studies 2008-2010 report /SKB 2012/, Chapter 3. These proposed requirements will be refined during the current KBS-3H project phase. The following Section is summarized from /SKB 2012/.
3.2 Design requirements to support the safety functions

Requirements on rock volumes for drift construction and canister emplacement

The Posiva RSC programme for KBS-3V is described in Section 4.2.3 of SKB (2012). The KBS-3V RSC criteria will, according to present plans, be updated to also include KBS-3H. However, based on the current planning, the suitability of a certain rock volume for final disposal is likely to be assessed in stages using the classification scales of repository, deposition drift and disposal location within the drift (for KBS-3V, the scales are repository, tunnel and deposition hole), and, at least some of the criteria developed for a KBS-3V repository are expected to be directly transferable to a KBS-3H repository. The repository scale classification applies the site scale model. A detailed scale model based on site scale model and local information becoming available from the rock volume in question is applied for the classification at the tunnel and deposition-hole scale.

The host rock requirements for the KBS-3H are discussed in (SKB 2012), Section 3.3.1. At the repository scale, RSC for a KBS-3H repository are expected to be identical to those defined for a KBS-3V repository. At the scale of a deposition drift and disposal location within the drift, a possible criterion is that there may be no FPI (Full Perimeter Intersection) fractures intersecting the deposition drifts at canister emplacement locations. Such criterion would reduce the probability of rock shear movements that could damage the canisters. Other potential criteria relate to initial inflows to the drifts, both the total inflow to the drift and local inflow into drift sections. These are needed, because high inflows add to the risk of buffer mass loss due to erosion, and are also an indication of a high transmissivity of the fracture from which the inflow occurs, possibly endangering long-term safety.

Requirements common to all engineered components

All engineered system components, including not only the canister and the buffer, but also the auxiliary components discussed later in this chapter, must be designed mutually compatible. Although all components will inevitably undergo physical and chemical changes over time e.g. due to chemical alteration or corrosion, saturation, swelling, none should evolve in such a way as to significantly undermine either the long-term safety functions or the design functions of the others. Thus:

- no component should contain any chemical constituents that lead to significant negative effects on the performance of the others;

- no component should generate gases at rates that could lead to a build-up of potentially damaging gas pressure taking into account the gas permeability of the other components; and

- no component should give rise to mechanical stresses that could lead to significant damage to the canisters; and no component should undergo volume changes due, e.g. to swelling, compaction, corrosion or alteration that could lead to significant changes in density of the adjacent buffer.
In the case of the canister, the buffer and the host rock, significant negative effects include, in SKB terminology, any that compromise their ability to meet their respective safety function indicator criteria and, in Posiva terminology, any that compromise their ability to meet their respective performance targets in the case of the canister and buffer or achieve target properties in the case of the host rock. If these criteria or targets are not met, then a component may not perform its allocated safety functions.

It should be noted that the criteria or targets for the canister, buffer and host rock are largely identical for the KBS-3V and KBS-3H design variants.

Requirements specific to the canister

The functional requirement of resistance to mechanical (isostatic and shear) loads and chemical loads are achieved primarily by the mechanical strength of the cast iron insert and the corrosion resistance of the copper surrounding it, and a manufacture and quality control procedure that ensures a low probability of occurrence of initial defects that could compromise containment. The requirements set in /Posiva 2012b/ are considered to apply for KBS-3H.

Requirements specific to the buffer

The buffer is designed such that, after artificial water filling, it will fill all the void spaces in the deposition drift between canisters and the rock wall. The requirements set in /Posiva 2012b/ are considered to apply for KBS-3H. Additionally in the case of KBS-3H, no items are allowed to be left in or around the distance blocks that may give rise to a hydraulic connection between Supercontainer sections.

Requirements on the buffer/rock interface

Some perturbation to the buffer/rock interface is probably inevitable in the vicinity of the Supercontainers. For example, the buffer material that fills the gaps initially present between the Supercontainer shells and the drift walls will be of lower density than the bulk of the buffer. Such density differences in the buffer will only partially homogenize over time due to internal friction within the bentonite. The Supercontainer shell may also rupture and be pressed against the drift wall by the developing swelling pressure of the buffer within the Supercontainer. Depending on the material selected for the shell, its corrosion may lead to the presence of potentially porous or fractured corrosion products in contact with the drift wall, and there may be chemical interactions of the buffer with these corrosion products. Finally, there may be some thermally-induced rock spalling if the buffer swelling pressure does not develop sufficiently rapidly.

Such potential perturbations mean that there is requirement for disturbance to the buffer/rock interface adjacent to the distance blocks, which have the safety function of separating the Supercontainers hydraulically, in addition to the other safety functions of the KBS-3H buffer. There is also a requirement that disturbances to the buffer in the vicinity of the Supercontainers should extend to only a limited radial distance inwards towards the canisters from the buffer/rock interface, such that the remainder of the buffer between the canister and the rock continues to perform its safety functions. In the current design, the distance from the canister surface to the drift wall is about 0.4 m.
These requirements will be re-evaluated after a performance assessment for the whole drift has been done.

**Requirements on auxiliary components**

In addition to the canister and buffer, implementation of the KBS-3 method entails the introduction of a number of auxiliary components such as grouting materials (cement-based materials or colloidal silica e.g. Silica Sol), spray and drip shields, and rock support structures (bolts, nets, etc.). Further auxiliary components specific to KBS-3H include the Supercontainer shells, filling blocks, compartment plug and the drift plug. Some of these components will degrade significantly over time and so do not serve a long-term safety role. All, however, protect the components that do have safety functions during the operational period and through the early evolution of the repository, and in some cases beyond. Tentative requirements have been set for these components. These requirements will be re-evaluated after a performance assessment for the whole drift has been done.

**The Supercontainer shell**

Following artificial water filling, the buffer inside the Supercontainer must swell and form a tight seal with the drift wall. The perforations in the Supercontainer shell must be such as to allow this to happen. This is needed as to avoid the possibility that pressure differences develop along the drift. Also the likelihood of thermal spalling of rock which is especially a risk in dry drift sections will be minimised by the buffer in contact with rock, as well as the Supercontainer shell getting into contact with rock during the early evolution of the system. In the longer term, the Supercontainer shell will degrade at a rate that depends strongly on the material chosen for its construction, and its degradation products may interact with the buffer. This leads to the following requirements on the Supercontainer shell:

- the properties of the buffer affected by interaction with the Supercontainer shell must be shown to meet the performance targets for the buffer, or, if this is not possible
- the region affected by this interaction should extend only to a limited radial distance into the buffer.

In addition, the Supercontainer shell may undergo volume change as it degrades, affecting the buffer density. These requirements impose constraints on material selection for, and the thickness of, the shell.

**Filling blocks**

Filling blocks are used in drift sections where relatively high initial groundwater inflows render them unsuitable for Supercontainer and distance block emplacement. Their function from a long-term safety perspective is (i), to fill void spaces in the drift, contributing to its mechanical stability, and to confine the buffer as it takes up water, such that its saturated density remains within the range specified by performance target values, (ii), to protect the canisters and buffer from the effects of transient water flows, e.g. piping and erosion, that may occur during the operational period for a drift and the
following period leading to saturation, and (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 provide 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
- The filling blocks shall have a sufficient but not excessive swelling capacity
- The filling blocks shall have a sufficiently low permeability and lateral extent.

The design of filling blocks can be developed to include more erosion resistant materials.

**Compartment plugs, as possible alternative to filling blocks**

Compartment plugs are mainly used to section the KBS-3H drift. An additional use is when the initial inflow into a section is higher than a certain limit; tentatively > 1 litre per minute in a 10 m drift section, two compartment plugs may be installed rather than filling blocks to isolate the fractures responsible for this inflow. This is because of concerns regarding the early mechanical erosion, and longer term chemical erosion, of bentonite in such drift sections. The plugs are installed at both ends of the drift section to be sealed off, and filling material emplaced between them, this filling material is currently not designed. The filling material should be preferably erosion resistant. The function of this entire assembly from a long-term safety perspective is identical to that of the filling blocks, namely (i), to fill void spaces in the drift, contributing to its mechanical stability, and to confine the buffer as it takes up water, such that its saturated density remains within the range specified by performance target values, (ii), to protect the canisters and buffer from the effects of transient water flows that may occur during the operational period for a drift and the following period leading to saturation (e.g. piping and erosion), and (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 provide preferential pathways for radionuclide transport in the event of canister failure.

The filling material for use between two compartments plugs has not been completely defined. The key design requirements for this material are that:

- The filling material between compartment plugs shall have a sufficiently low compressibility.
- The filling material between compartment plugs shall not have excessive swelling pressure.
- The filling material between compartment plugs has to be designed to allow the water flow through without significant mass loss (Anttila et al. 2008, Section 5.7.3 the system of filter zones and transition zones in the design).
- The compartment plugs and the filling material between compartment plugs should 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 should not undergo volumetric changes which might compromise the performance of the adjoining buffer.
- The compartment plugs should not allow the build-up of excessive gas pressure in adjoining drift sections, i.e., to avoid damage to the main barriers.

**Compartment plugs for sectioning the drift, including the adjacent filling material**

Compartment plugs are mainly used to section the drift into two compartments, approximately 150 m long. For installation reasons, these plugs cannot be built right up against the distance blocks, and for this reason transition zones consisting of a transition block and bentonite pellets are required.

The filling material in the transition zone should not have an impact on the distance blocks and ensure the functions of the distance blocks. Another function of transition zone is to seal potential pathways around the plug. In case of water leakage in the transition block section the same respect distances between the fracture and the Supercontainer as presented for filling blocks can be applied. The plug will be positioned in good rock avoiding any water leakages close to it in order to prevent any hydraulic pathways around the plug.

The compartment plugs themselves also have certain specific functional requirements during the operational phase and the period immediately thereafter. In particular, they should:

- provide an adequate drift seal that prevents flow through the plug and rock plug interface, to avoid erosion of buffer by transient water flows during the operational phase;
- be capable of supporting a full hydrostatic pressure after installation for as long as there are void spaces in an adjoining drift; and
- form a confining surface to maintain the Supercontainers and other components in position during operation of each drift.

Design requirements corresponding to these functional requirements are that the plugs should be:

- positioned in good-quality rock sections in the drift, with the forces exerted on rock surfaces being compressive; and
- dimensioned to withstand a one-way pressure of 5 MPa prior to installation of the drift plug, only marginal swelling pressure will occur before the drift is sealed, see Section 3.3.

**The drift plugs**

The function of the drift plugs, similar to the KBS-3V deposition tunnel plugs, is to avoid significant water flows out of the drift, which could give rise to piping and erosion of the buffer, either through the plug itself, or through the adjacent rock. They also keep the buffer in place prior to the backfilling and saturation of the adjacent central tunnel. In the longer term, and over the entire regulatory compliance period, the drift plugs form part of the system of natural and engineered barriers that limit any radionuclide’s transport in the event of canister failure.
The requirements on the drift plugs are similar to those on the KBS-3V deposition tunnel plugs. In particular, the plugs are required to:

- withstand full hydrostatic pressure of 5 MPa plus the swelling pressure of the buffer in the disposal drifts of up to 10 MPa for as long as the adjacent central tunnels are not backfilled, to avoid displacement into the central tunnels, with consequences for buffer density and swelling pressure;
- withstand pressure heterogeneity of 2 MPa (estimated) acting on the plug surface;
- be sufficiently tight, particularly during the operational phase before the central tunnels are backfilled but also afterwards together with the backfill and seals of other openings, so as to avoid loss of eroded buffer materials from the deposition drifts; and
- not give rise to volume changes or to chemical or mineralogical changes in the adjoining buffer that compromises its performance or that of the canisters.

The drift plug is required to stay in place under the applied loads until the adjoining central tunnels are backfilled and saturated. Also in the long-term as noted above they should form part of the natural engineered barriers that limit the transport in the event of canister failure.

### 3.3 Additional requirements from the operational point of view

#### Construction of the deposition drifts

Additional requirements related to operations have been established for the construction of the deposition drifts. Construction begins with the drilling of a pilot hole. Preliminary geometrical requirements including tolerances, for the drift itself, are given in Table 3-2 along with a summary of the reasoning that justifies them.

**Table 3-2. The updated preliminary geometrical requirements for the KBS-3H deposition drift /SKB 2012/.

<table>
<thead>
<tr>
<th>Issue</th>
<th>Requirement</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>&lt;300 m</td>
<td>The repository layout shall be similar to KBS-3V. The length is considered to be feasible from a construction and operational point of view. However, optimisation of this length will be necessary after the KBS-3H technology has been demonstrated.</td>
</tr>
<tr>
<td>Drift diameter</td>
<td>1,850± 5 mm</td>
<td>The drift diameter is based on operational as well as thermal heat flow and buffer density considerations. Rock deformations are negligible.</td>
</tr>
<tr>
<td>Vertical inclination</td>
<td>2º ± 1º</td>
<td>A positive inclination is a prerequisite for water drainage.</td>
</tr>
<tr>
<td>Deviation of pilot hole</td>
<td>&lt;2 m from the nominal position at a distance of 300 m.</td>
<td>A minimum drift spacing of 25 m has been adopted in thermal dimensioning of the Olkiluoto repository layout.</td>
</tr>
<tr>
<td>Steps</td>
<td>≤5 mm</td>
<td>Full-scale laboratory tests have verified that the deposition machine can move properly in the drift for steps of up to 5 mm.</td>
</tr>
<tr>
<td>Roughness</td>
<td>≤5 mm</td>
<td>Full-scale laboratory tests have verified that the deposition machine functions properly for a roughness up to 5 mm.</td>
</tr>
<tr>
<td>Straightness (waviness or deviation from the centre line)</td>
<td>≤10 mm over the length of 6000 mm</td>
<td>The centre line deviation shall be kept within small tolerances to prevent the SC from contacting the rock surface during emplacement in the drift.</td>
</tr>
</tbody>
</table>
Control of groundwater inflow

The groundwater flow out of the deposition drift during its operational period must not be so high that it affects the installation of engineered components. Either pre-grouting in the pilot hole or Mega-Packer post-grouting will be used to limit substantial water inflow into the drift. The grouting will have to be durable for the operational time only. After this time hydrostatic pressure in the drift being equal to the pressure in the adjacent rock mass limits the inflow regardless of the grouting material. For the installation phase it is important to provide conditions where the water flow on the drift floor in the slot (44.5-48 mm) between floor and the components does not reach the bentonite blocks, which would result in erosion. The flow rate that would cause this erosion would have to be several tens of l/min. Use of groundwater controlling techniques is proposed to reduce inflows during the whole repository construction phase in order to avoid drawdown of the water table which could lead to up-coning of salt water. It is also important to ensure that there are no significant connective flow paths between the 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. The tests performed with compartment plug have given very promising results regarding the self-sealing capacity of bentonite pellets preventing water (artificial and leakage water) flow from a sealed drift into open parts of the repository, see /SKB 2012/.

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 in the deposition drifts during Supercontainer and distance block emplacement that could cause movement of these components, or cause rupture or piping and transport of bentonite through buffer, prior to artificial water filling. Following artificial water filling, high hydraulic pressure gradients and gradients in buffer swelling pressure may develop along the drifts, which could potentially lead to phenomena 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 piping and 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, the compartment plug is designed to stay in place under the applied loads (i.e. no significant displacement are allowed) until the next compartment is filled and a further compartment plug or drift plug installed.

Artificial water filling

A favourable initial state of saturation is obtained by using DAWE (Drainage, Artificial Watering and air Evacuation) design methodology. After artificial water filling the buffer should swell uniformly and fill all the open space. The bentonite should have sealed the drift so that there is no flow inside the drift that can cause piping and transport of bentonite.
The artificial water filling system is required to fill all void spaces in the drift compartment at approximately the same time, thus ensuring that the bentonite will swell and seal the drift uniformly. This minimizes the risk of bentonite piping and erosion, as well as water pressure displacement of distance blocks and/or Supercontainers during the saturation phase after sealing of the drift.

**Operation schedule**

The installation of the engineered components in each deposition drift will be carried out in two steps. Installation in the inner section of the drift will take place first. This section will then be sealed with a compartment plug and subsequently water-filled according to the DAWE methodology. Installation in the second compartment - i.e. the section from the compartment plug to the position of the drift plug - will take place, followed by the construction of a drift plug and water filling according to the DAWE methodology. The time from deposition of the first Supercontainer until the drift is sealed and water is filled shall be as short as possible for the reasons stated below:

- The compartment must be filled as fast as possible because of the erosion, cracking of the bentonite in highly humid environment, which are dependent on time
- The compartment plug shall be mounted without delay as well as the artificial water filling thereafter to accelerate the swelling of the bentonite (prevent erosion and spalling). Inadequate sealing around the compartment plug could cause leaking of the artificially filled water from behind the plug into the open drift section and potentially cause erosion of bentonite components in the filled section.
- Filling of the next compartment quickly would mitigate these incidents. Another reason for filling the second compartment and building a drift plug quickly is that the compartment plug is only dimensioned for full hydrostatic pressure assuming that no significant (more than 100 kPa) swelling pressure will occur before the drift is sealed. If the drift is kept open after emplacing the first compartment plug (longer than months), there is risk for increased swelling pressure from filling components and buffer which potentially could compromise the compartment plug.
4 OVERVIEW OF THE KBS-3H DAWE DESIGN

During the Complementary Studies 2008-2010 DAWE (Drainage, Artificial Watering and air Evacuation) was selected as the reference design for KBS-3H defining the way forward for KBS-3H. It provides the basis for technical development, planning, safety analysis, radiation protection and work on environmental influence.

As the name DAWE implicates the design includes techniques to drain the drift, the artificial water filling of the drift and air evacuation during water filling process.

Drainage during installation phase is enabled through the inclination of the drift, which ensures drainage of inflowing water out of the drift. Artificial Watering is performed by short pipes through the plugs, which are used to artificially fill the compartments with tap water, effectively ensuring quick initial swelling of the buffer. The air is evacuated through an evacuation pipe during water filling. All these techniques are described in more details in /SKB 2012/, see also Chapter 9.

4.1 Excavation of drifts, preparatory work

4.1.1 Excavation

4.1.1.1 Reference methods used for the construction of deposition drifts

The reference method for excavating the deposition drifts is full-face horizontal push-reaming technique. Reaming of the pilot hole will be made by using slightly adapted equipment for conventional raise drilling, where the head is pushed and rotated. Stabilizers are necessary to stabilize the drill string, Fig. 4-1.

Horizontal push-reaming generates substantial volumes of muck at a high rate (up to some 3 m³/h) and the rock cuttings need to be removed from the almost horizontal drift using flushing water. Effective mucking was considered at an early stage to be vital for efficient excavation, and several options were successively tested and rejected during the excavation of the test drifts. The removal of the debris using a re-circulated water flow (3000 litres/min) was sufficient to clean the drift at a 2° inclination /Bäckblom & Lindgren 2005/.

The mucking system shall be as presented in Fig. 4-2. A hopper should be fitted to the drift. A pipe with at least 300 mm diameter should be fitted to the cone and graded below the machine foundation. The flush water is led into pipe with outlet in a pump pit (at least 10 m long, 3 m deep and 3 m wide) where a pump lifts the water into a sedimentation container about 20 m² in surface area. The pump pit is regularly emptied
by a digger to a truck. For repository drift excavation, it would be convenient to fit the derrick and steel frame with tyres so the equipment can easily be towed to the nearby drifts to be excavated /Bäckblom & Lindgren 2005/.

Figure 4-2. Set-up for the muck removal /Bäckblom & Lindgren 2005/.

4.1.1.2 Pilot borehole drilling for reaming to full drift diameter

The reference method is to drill a pre-pilot hole (diameter 76 mm) that is reamed to full drift size, with an additional intermediate reaming step to actual pilot hole size (e.g. diameter 311 mm). Pre-pilot holes are drilled with directional core drilling. The bit size of 76 mm is a standard size used in core drillings in the Posiva’s rock characterisation programmes at the present and the tools needed to characterise the drill holes are available. Directional drilling requires two main systems, one that establishes the position of the drill bit in space and a second system that guides the direction of the borehole based on the error in the bit position relative to the theoretical trajectory of the pre-pilot hole /SKB 2012/.

Verification that the geometrical requirements have been met constitutes an important part of the pilot hole / the drift excavation process. If the drift for some reason does not fulfill the geometrical requirements it could imply that deposition is not possible. The measurements should be done stepwise and using proven technology to the extent possible. Special measurement devices cannot be ruled out in future applications /SKB 2012/.

Drift inclination and direction can be measured by using conventional techniques. However, the deviation tools have their limitations with the accuracies they can provide. During the excavation of the 95 metre drift at Äspö HRL during 2005, conventional survey techniques were used with good results. There are a number of systems available on the market, each with its own limitations and special characteristics. Inclination and direction of the drift will be measured as part of the directional drilling process of the pilot hole, where corrections are made when deviations that might lead to the drift not fulfilling the requirements are measured /SKB 2012/.

4.1.1.3 Geometrical tolerances

Acceptable geometrical tolerances for deposition drifts are imposed by the Supercontainers and other drift components. The design basis concerns the straightness, diameter, inclination, waviness, steps and roughness see Table 3-2. This will impose
constraints on the performance of the reference method in terms of the resulting dimensions of the deposition drift.

The tests at the Äspö Hard Rock Laboratory, successfully demonstrated the feasibility of push-reaming in the 15 m and 95 m long drifts /Bäckblom & Lindgren, 2005/. With respect to the geometrical requirements, a diameter change is anticipated due to wear of the periphery cutters. For a 300 m long drift, it is envisaged that the demands placed on the minimum and maximum diameter of the drift will result in careful monitoring of the wear of the cutters and timely exchange of cutters during the course of reaming.

Concerning the smoothness of the drift, the reamer head manufacturers have no documented experience how it may be affected by the reamer head design, e.g. using six instead of four periphery cutters. Furthermore, there are no data available on the marginal extra overbreak that is generated beyond the periphery cutter. The reaming may also generate grooves and steps but it is not fully clear how to design the reamer head and how to operate the equipment to minimize generation of grooves and steps. Fig. 4-3 illustrates the 95 metre full diameter drift at Äspö after reaming /SKB 2012/.

Figure 4-3. The end of the 95 m drift at the Äspö HRL showing the final shape of the face and occasional grooves /SKB 2012/.
4.1.1.4 Control programme
Drift surface requirements, roughness, steps, diameter changes etc. need to be measured. Laser scanning of the drift has been tested in Åspö and found feasible. The method generates huge amount of data from which the surface can be analysed /SKB 2012/.

There are other suitable methods and instruments for inspecting the dimensions of deposition drifts, e.g. geodetic methods. SKB and Posiva will develop a procedure for verifying that the geometrical tolerances in deposition drifts conform to the design basis. Primarily quality control and assurance procedures will be applied to inspect pre-pilot hole’s, pilot hole’s and deposition drift’s positioning and alignment of the drill rigs as well as the conditions related to the drilling operations, e.g. checking cutter conditions. The resulting geometry after drilling will be inspected by one or a combination of measurement methods. A visual inspection of the completed deposition drift is also necessary in order to rule out the occurrence of spalling. Any deposition drift that does not conform to the geometrical tolerances shall be rejected and backfilled.

Detailed information regarding the measurement techniques can be found in /Bäckblom & Lindgren 2005/ as well /Autio et al. 2008/.

4.1.2 Control of groundwater inflow, Mega-Packer
A key issue for horizontal deposition is groundwater control. For long-term safety reasons water inflows ideally have to be measured before any disturbance takes place of the natural inflows, hence pre-grouting is not optimal. Another limitation is that boreholes are not allowed outside the drift contour. To minimise the need for pre-grouting a post-grouting device that can handle the conditions at full repository depth called the Mega-Packer has been developed /Eriksson & Lindström 2009/, see also Section 9.7.

In order to enhance the emplacement conditions in the drift all drift sections that do not meet the positioning inflow criteria, 0.1 l/min per 10 m, will be post-grouted.

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. In fact the limiting factor is the deposition machine which is based on water cushion techniques. There is a limit of water flow rate where the function of the deposition machine might get hampered. With the present design of the slide plate and the lift pallet in the deposition machine (see Fig. 9-3) this limit is about 7 l/min, which can be increased by redesign of the plates allowing water to flow below the plates avoiding wetting of the bentonite blocks to be emplaced with the deposition machine. Consequently, the current estimate is that the total water inflow for the drift can be no more than 10 litres per minute. This means that the water inflow into a drift after all inflow points exceeding the positioning inflow criteria, have been post-grouted with Mega-Packer.

Besides from the operational point of view the reduction of water leakage into the drift by groundwater controlling techniques is needed to avoid drawdown of the water table and mixing of the waters during the whole repository construction phase. It is also important to ensure that there are no significant connective flow paths between the 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 in case the water flow gets in touch with the bentonite components.

4.1.3 Preparatory work in the drift

Before installation of the drift components preparation of the deposition drift is carried out. The preparation of deposition drifts comprises:

- cleaning of the deposition drift,
- inspection of inflow to the deposition drift,
- inspection of potentially discriminating fractures intersecting the deposition drift,
- installation of spray/drip shields if necessary,
- inspection to determine the dimensions of the deposition drift,
- levelling of possible outbreaks with casted low-pH concrete

The spraying, dripping, and squirting of groundwater onto the buffer material during the operation phase is prevented by placing metal spray shields over inflow points, See Fig. 4-4. At single inflow points the shielding can be implemented through the use of stud type nipples (e.g. penny shaped disk attached on the rock surface in the centre of inflow point). Inflow coming from the roof of the deposition drift will be redirected towards the lower half of the drift /Anttila et al. 2008/.

![Principle of using drip shields](image)

**Figure 4-4. Principle of using drip shields /Anttila et al. 2008/.

The material for the shields is titanium. The shields are fastened mechanically with screws into small holes drilled in the rock. Round “penny” type washers are placed in positions of single flow points. The sheets are shaped to follow the rock surface tightly.

Outbreaks caused by geological anomalies from the deposition drift will be levelled with casted low-pH concrete.

4.2 Drift components

4.2.1 Supercontainer

The KBS-3H design is based around the canister and the buffer being emplaced as one unit rather than as in the KBS-3V case, the buffer being installed first followed by the
canister in a separate step. The KBS-3H canister-buffer unit including an outer perforated shell is denoted a Supercontainer. The design and assembly of the Supercontainer is described in detail in the design description 2007 /Anttila et al. 2008/.

The selection of Titanium as the material for the Supercontainer shell was made in the project phase “KBS-3H Complimentary Studies 2008-2010” /SKB 2012/. This material fulfils the long-term safety and operational requirements. Other optional materials that were evaluated were copper together with structural steel. The studies of metal-bentonite interactions are elaborated in Section 5.10.

The Supercontainer is depicted in Fig. 4-5 showing the spent fuel canister surrounded by a bentonite buffer and the perforated Titanium shell. The shell has an outer diameter of 1761 mm, a length of 5525 mm and a thickness of 6 mm. The Supercontainer shell is provided with five pairs of feet with a height of 42.5 to 45 mm and 73.5° spacing. The shell has a perforation of 62 % with 100 mm diameter holes, the end plates are solid. Fully loaded with canister and buffer the weight of the Supercontainer is approximately 46 tonnes.

The Supercontainer is designed to withstand unfavourable load conditions induced by variations in the excavation of the deposition drift. For example, where a step-like unevenness exists on the surface of the deposition drift floor causing uneven load on the Supercontainer.

There should be no big surprises associated with manufacturing the Supercontainer. Bending of plates and making holes in materials of higher tensile strength demand more of the production equipment but this will be taken care of by qualified manufacturers working with qualified procedures. Welding of Titanium contains some specific features and the studies on welding issues are ongoing. However, welding of a Supercontainer shell made of Titanium is not considered to be an issue.

Special care must be taken to ensure that manufacturing procedures are correctly adjusted to the grade of material used and manufacturing is performed in accordance with qualified procedures in order to maintain the desired mechanical properties of the welded units. Titanium is a strong material with good mechanical properties and allows for a thinner Supercontainer shell than using steel. The use of titanium brings additional benefits by enabling a smaller outer diameter for the shell compared to other studied materials. A titanium Supercontainer shell has not been designed in detail but this will be done in the current project phase. Initial FEM- calculations using Titanium grade 3 indicate that the shell thickness can be reduced to 6 mm with acceptable stresses, strains and deformations. The reduction in shell thickness could impact the practicality of production and these aspects will also be addressed in the upcoming studies.
Figure 4-5. The KBS-3H Supercontainer made up of a canister surrounded by buffer rings and blocks with an outer perforated titanium cylinder (shell) to keep the unit together. The top plates of the Supercontainer are not perforated /SKB 2012/.

The buffer is composed of different types of bentonite sections with different dimensions, dry densities and water contents. There are three types of buffer blocks, the ring-shaped blocks around the canister, the solid cylindrical blocks at both ends of the canister inside a Supercontainer and the solid cylindrical distance blocks between Supercontainers.

The buffer inside the Supercontainer consists of a sufficient number of ring-shaped blocks and solid blocks depending on the repository design alternative. The reference designs of the bentonite buffer blocks are presented in Table 4-1 and Fig. 4-6. The densities are given as dry densities.
Table 4-1. Reference buffer blocks inside the Supercontainer /updated from SKB 2012/.

<table>
<thead>
<tr>
<th>Design parameter</th>
<th>Nominal design</th>
<th>Accepted variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid blocks inside the Supercontainer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry density</td>
<td>1,753 kg/m$^3$</td>
<td>±20 kg/m$^3$</td>
</tr>
<tr>
<td>Water content</td>
<td>17 %</td>
<td>±1 %</td>
</tr>
<tr>
<td>Dimensions</td>
<td></td>
<td>±1 mm</td>
</tr>
<tr>
<td>Height: 350 mm</td>
<td></td>
<td>+1/-2 mm</td>
</tr>
<tr>
<td>Outer diameter: 1740 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ring shaped blocks inside the Supercontainer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry density</td>
<td>1,885 kg/m$^3$</td>
<td>±20 kg/m$^3$</td>
</tr>
<tr>
<td>Water content</td>
<td>11 %</td>
<td>±1 %</td>
</tr>
<tr>
<td>Dimensions (mm)</td>
<td></td>
<td>±1 mm</td>
</tr>
<tr>
<td>Height: 1211 mm</td>
<td></td>
<td>+1/-2 mm</td>
</tr>
<tr>
<td>Outer diameter: 1740 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner diameter: 1058 mm</td>
<td></td>
<td>±1 mm</td>
</tr>
</tbody>
</table>

Figure 4-6. Cross-sections of the cylindrical blocks inside the Supercontainer: solid blocks (left) and ring shaped blocks around the canister (right). Ti used as reference. The final thickness of the ring-shaped blocks depends on the selected compaction technique.

4.2.2 Distance block

The distance blocks are placed between the installed Supercontainers in a drift. The reference design of the blocks is presented in Table 4-2 and Figure 4-7. The densities are given as dry densities. The water content of the distance blocks is higher than in the Supercontainer blocks in order to prevent humidity induced cracking during operation.
Table 4-2. Reference buffer block outside the Supercontainer (distance blocks) /SKB 2012/.

<table>
<thead>
<tr>
<th>Design parameter</th>
<th>Nominal design</th>
<th>Accepted variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid blocks outside the Supercontainer (distance blocks)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry density</td>
<td>1,712 kg/m³</td>
<td>±20 kg/m³</td>
</tr>
<tr>
<td>Water content</td>
<td>21 %</td>
<td>±1 %</td>
</tr>
<tr>
<td>Dimensions</td>
<td>Height: 500 mm</td>
<td>±1 mm</td>
</tr>
<tr>
<td></td>
<td>Outer diameter: 1,765 mm</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4-7. Cross-section of the solid cylindrical distance blocks /SKB 2012/.

There are several alternative lengths for distance blocks based on the type of canister (canister spacing), see Fig. 4-8. Two compaction techniques (uniaxial or isostatic) are available and the block lengths to be compacted can be optimized to suit the needs for each canister type. The isostatic compaction technique is described in /Ritola & Pyy, 2012/.

Figure 4-8. The distance blocks are placed between the installed Supercontainers (SC) in a drift. Different distance block alternatives for Finnish spent fuel canisters /Kirkkomäki & Rönqvist 2011/.
The distance block length does not affect the design of filling components, however, it has an impact on the utilization degree of drift.

### 4.2.3 Filling Components

#### 4.2.3.1 General

In drift sections where inflow exceeds the positioning criterion, 0.1 l/min per 10 m, filling blocks made of bentonite are used. In addition to filling blocks there are additional filling components in a drift where void spaces have to be filled.

The KBS-3H drift design includes 5 types of filling components, which are illustrated in Fig. 4-9. The design inside the compartment and drift plug are basically the same and 5 different components have been designed.

- a) Filling inside the drift plug (and compartment plug)
- b) Filling blocks in position of inflows
- c) Filling outside the compartment plug
- d) Filling at drift end
- e) Filling of Pilot hole

![Figure 4-9. KBS-3H drift design with different filling components /SKB 2012/.](image)

The design of filling components is based on the internal friction of the filling material and therefore permanent density gradients will remain in 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.

The filling of the deposition drift outside the drift plug has not been developed and will be part of later backfilling design of the deposition niche and central tunnels.

The design and installation procedure of the plugs (compartment and drift plugs) influences and to some extent determines the design of the adjacent filling components, see Section 4.2.4 for the plug designs. It is assumed that 1.3 m distance is needed between the collar of the plug and the transition block.

The length and diameter of the pilot hole stump at the drift end are approximately 2000 mm and 152 mm, respectively. The design of the filling components is presented with more details in /SKB 2012/.
4.2.3.2 Additional basis for filling component design

Na-bentonite of similar type as used for buffer has been selected to be used in the filling components. This allows the distance blocks and the filling/transition blocks to be merged together.

Material selection was based on engineering judgement and following arguments:

- It is assumed in this design that using the same material as used for buffer but increasing the length of the filling block fulfils the requirements specified for filling components.
- The recent research on erosion issues /SKB 2012/ has shown that Wyoming type Na-bentonite material (commonly referred also as MX-80 type bentonite) used as bentonite buffer in KBS-3H design, can tolerate the erosion during water filling of the drift when the water flows are orders of tens of litres per minute, which together with inflows from rock has been a main concern previously /Anttila et al. 2008/. Inflow from rock is not a main concern in DAWE design alternative because the artificial water filling limits the erosion effect caused by inflows during water filling while erosion takes place mainly at the entrance point. Mechanical erosion due to inflow from rock is also prevented with spray and drip shields. 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 same material for filling components as buffer reduces or eliminates the risk for detrimental or uncertain physical and chemical reactions between filling components and other materials in the drift.
- Use of same material as for buffer gives filling components additional buffering capacity which conforms to the bentonite buffer.
- 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 design of the filling components is based on pellets and cylindrical blocks similar to distance blocks if possible. The blocks can be combined of fixed size thickness cylindrical block or the thickness can be adjusted to specific requirements based on operational aspects. The selection of design for the filling components was based on the following arguments:

- The filling components can be installed using same type of equipment (in principle) as for emplacing Supercontainers and/or distance blocks which has been proven technically feasible and efficient.
- Production of pellets is standard proven technique with plenty of experience available.
- The properties of filling blocks (e.g. density, length) can be dimensioned so that the diameter is the same as for distance blocks.

**4.2.3.3 Filling blocks in positions of inflows**

In the current KBS-3H design, filling blocks (FB) will be placed in drift positions intersected by fractures giving initial inflows to the drift above 0.1 l/min (Figures 4-10 and 2-1). Such drift sections are currently excluded as locations for Supercontainer or distance block emplacement.

![Diagram of KBS-3H drift](image)

**Figure 4-10.** *KBS-3H drift, showing the position of a filling block between split distance blocks and 2 Supercontainers. Note that the inclination of fracture has effect on the length of filling block /SKB 2012/.*

The following modifications have been made to previous schematic design /Anttila et al. 2008/:

- There is a half distance block on both sides of the filling block. This is conform to a situation where there is an inflow of exactly 0.099 l/min (less than the limit 0.1 l/min used to reject it for emplacement of Supercontainer) and a normal distance block is positioned between Supercontainers in this section.
- The length of filling block depends on: a) distance between transmissive leaking fracture (closest point of the fracture affected by inclination of fracture) and b) length of distance blocks. This is based on the principle that the length of filling block sets the transport length (and resistance) from 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 blocks are composed of 0.5 m thick slices based on the present production technique and to simplify the operation. This, however, can be adjusted and optimised if needed.
**Dimensioning**

The length of the filling block 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. 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 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 compartment plug sections, it should be stated that the double compartment plug sections are not ruled out and is still an option /SKB 2012/.

**Table 4-3. Respect distances (L in Fig. 4-10) with respect to inflow rates and allowed components /SKB 2012/.

<table>
<thead>
<tr>
<th>Initial inflow range [litres min⁻¹]</th>
<th>Respect distance [m] and allowed component</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.1</td>
<td>Supercontainer section</td>
</tr>
<tr>
<td>0.1 - 0.5</td>
<td>3 m (filling block + half a distance block on each side)</td>
</tr>
<tr>
<td>0.5 - 1</td>
<td>5 m (filling block + half a distance block on each side)</td>
</tr>
<tr>
<td>&gt; 1</td>
<td>Alt 1. 6 m (filling block + half a distance block on each side)</td>
</tr>
<tr>
<td></td>
<td>Alt 2. double compartment plug sections</td>
</tr>
</tbody>
</table>

The respect distance is measured from the closest point where the fracture plane intersects the drift wall to the Supercontainer, see Fig. 4-10. This applies to both sides of the filling block. The lengths of the filling blocks 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 is increased based on the length of the fracture plane between the two closest points with the specified respect distance to the next SC. This length of the fracture plane is projected to the drift axis. The important parameter here is the angle between the fracture plane and the drift axis.
Other parameters which affect the length of a filling block are the length of the distance block and the inflow rate into the Supercontainer section. As 50% of the distance block length 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. The friction angle for swelling pressures between 1 and 10 MPa is about $\phi=10^\circ$. A nomogram has been developed to determine the length of filling blocks, see Fig. 4-11.

![Figure 4-11](image-url)

**Figure 4-11.** Nomogram presenting the dimensioning of the filling block as a function of the angle between drift axis and the fracture plane in three different inflow range categories, with specific respect distances. The length of the distance block that has been used in this case is 2.874 m (see Fig. 4-8). Friction angle $\phi=10^\circ$ has been used.

### 4.2.3.4 Filling adjacent to the drift plug and on the sealed side of compartment plug

The design for filling components adjacent to the drift plug and the sealed side of the compartment plug are identical. The schematic principle of filling adjacent to drift plug is shown in Fig. 4-12. The key requirements and factors specific to the drift plug and the compartment plug affecting the design of filling components are similar with the exception that the compartment plug is exposed to hydrostatic pressure only and not exposed to significant swelling pressure of buffer and adjoining filling components as the drift plug. This difference was not assessed as having impact on the design of filling these components. The preliminary requirements and prerequisites can be summarized as:

- The drift plug must withstand 5.0 MPa hydrostatic pressure and the swelling pressure of the bentonite inside the drift (10 MPa). The loading from filling should be as even as possible to reduce force heterogeneity on the plug.
- In case of compartment plug the plug must withstand only hydrostatic pressure and insignificant swelling pressure of order of few tens of kPa’s.
- It shall be tight assuming the largest allowed water leakage past the plug specified tentatively as 0.1 l/min. The compartment plug was tested in full-scale at ÄSPÖ HRL, see /SKB 2012/. 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 tentative requirement.
- It shall not under its working time or afterwards affect fulfilment of requirements of the neighbouring distance block section. Especially the density of adjacent distance block must not be affected.
- The function of drift plug is needed for a long time, whereas function of compartment plug is needed for a relatively short time (order of weeks until 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 micro-fractures.
- In order to be able to build the plug an empty space of 1.3 m is needed inside the plug in order to emplace the cap of the plug.

The design is based on the following principle:

- The empty volume on the sealed side of the drift plug is filled with pellets resulting in lower density.
- A section of highly compacted blocks called transition blocks are placed between the pellet filled volume and 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.

![Figure 4-12. Schematic drawing of filling components of the sealed side of the drift plug /SKB 2012/](https://via.placeholder.com/150)
**Dimensioning**

The design implies that the distance block adjacent to filling section is unaffected by the swelling in the transition zone (containing transition blocks and pellets) and corresponding compression of the pellets filling. Since the pellets filling has a much lower density than the transition blocks there will be a transition zone between the distance block and the plug where the density gradually changes. The required length of the transition zone is determined by the density gradient in the transition zone caused by the swelling of the transition blocks into the pellets filling. If some density deviation could be allowed in distance blocks, the length of transition zone could be made shorter. Due to mainly friction between the bentonite and the rock surface the swelling of the transition zone will be restricted to a certain distance that in a simplified way can be estimated with equations that are derived from force equilibrium in axial direction.

The compartment plug and the lead-through are not included in the analysis since they assessed as being negligible to design. Only the filling between the plug and the distance block will be studied. The length of the transition zone will be dimensioned so that the density of the swelled and homogenized transition zone in contact with the distance block section will be the same as the density of the distance block section assuming that no axial swelling of the distance block section takes place. The dimensions of the transition zone and the expected swelling pressure on the plug were determined in the calculations.

The problem can be treated either numerically with FEM calculations or analytically in a simplified way. The analytical solution has been used at this stage, Table 4-4 shows the results and the calculations are presented in /SKB 2012/.

*Table 4-4. Results of the calculations (in these calculations the cap was measured from the cap of the plug to the transition block, i.e. conservatively) /SKB 2012/.*

<table>
<thead>
<tr>
<th>Friction angle $\phi$</th>
<th>Total length of the transition zone $L_T$</th>
<th>Length of transition block $L$</th>
<th>Swelling pressure on the plug</th>
</tr>
</thead>
<tbody>
<tr>
<td>5º</td>
<td>8.1 m</td>
<td>6.8 m</td>
<td>2.33 MPa</td>
</tr>
<tr>
<td>10º</td>
<td>5.8 m</td>
<td>4.5 m</td>
<td>1.40 MPa</td>
</tr>
<tr>
<td>20º</td>
<td>4.0 m</td>
<td>2.7</td>
<td>0.46 MPa</td>
</tr>
<tr>
<td>30º</td>
<td>3.2 m</td>
<td>1.9 m</td>
<td>0.20 MPa</td>
</tr>
</tbody>
</table>

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 $\phi=10^\circ$, which thus can be used as dimensioning value. 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 would motivate to use $\phi=5^\circ$. 
**Design**

Since the rock surface is not expected to be smooth a friction angle value of $\phi=10^\circ$ yielding a transition block length of 4.5 m is used in the design. The design based on that is shown in Fig. 4-13. The material properties used in the design are as follows:

- Dry density of the pellets filling zone $\rho_{dp}=1000$ kg/m$^3$
- Dry density of the transition blocks $\rho_{dt}=1712$ kg/m$^3$
- Average dry density of the transition zone $\rho_{dt}=1635$ kg/m$^3$

The design of highly compacted bentonite blocks used in transition blocks are similar to the filling blocks presented above.

![Figure 4-13. Transition zone on the sealed side of the drift plug /SKB 2012/.](image)

**4.2.3.5 Filling on drift entrance side of the compartment plug**

The schematic principle of filling adjacent to drift entrance side of the compartment plug is shown in Fig. 4-14. The key requirements and factors specific to the compartment plug and affecting the design of filling components can be summarized as:

- The water leakage flowing from the sealed side to the open side is specified not to exceed 0.1 l/min (a tentative requirement). The compartment plug was tested in full-scale at Åspö 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.
- It is considered beneficial that the swelling pressures of filling components exerted to compartment plug after full saturation from both sides of compartment plug would be roughly equal. This would therefore not lead to any major displacements of plug after long periods of time when the structural strength of the plug has disappeared by e.g. corrosion.

The geometries and initial conditions are identical on both sides of the compartment plug with the exception that the thickness of the pellet filled section is 1.0 m on the entrance side.

The design is based on the following principle:

- A compacted high density transition zone with blocks similar to filling blocks is placed next to compartment plug.
- The empty volume between the compartment plug and transition blocks is filled with pellets resulting in lower density.
- The pellets are installed via a hole in the transition blocks. The hole is filled afterwards with a compacted bentonite cylinder to plug and seal it.
- As filling components absorb water and swell, there will be a transition zone from the compartment plug to the distance block with a density gradient.

**Figure 4-14** Schematic drawing of filling components in drift entrance side of a compartment plug /SKB 2012/.

**Dimensioning**
The criteria for dimensioning the transition zone are basically the same as presented for the sealed side of the drift plug. The length of the pellet filling is, however, shorter, 1.0 m counted from the crown of the cap. The length of the transition zone will be hence dimensioned so that the density of the swelled and homogenized transition zone in contact with the distance block section will be the same as the density of the distance block section assuming that no axial swelling of the distance block section takes place.

The calculations related to the dimensioning are presented with more details in /SKB 2012/.

**Design**
The required length of the transition blocks on the entrance side of the plug, where the dimensioning length of the pellets filling is 1.15 m (inside the plug), will be \( L = 4.25 \text{ m} \) for \( \phi = 10^\circ \). The corresponding swelling pressure on the on the plug will be 1.38 MPa.

Since the rock surface is not expected to be smooth a \( \phi = 10^\circ \) yielding a transition block length of 4.25 m is proposed to be used in the design assuming 1.15 m length of pellet filling section. The design based on that is shown in Fig. 4-15. The material properties used in the design are as follows:

- Dry density of the pellets filling zone \( \rho_{dp} = 1000 \text{ kg/m}^3 \)
- Dry density of the transition blocks \( \rho_{dt} = 1712 \text{ kg/m}^3 \)
- Average dry density of the transition block zone \( \rho_{d} = 1635 \text{ kg/m}^3 \)
The design of highly compacted bentonite blocks used in transition blocks is similar to the filling blocks presented above.

![Diagram of filling on entrance side of compartment plug](image)

**Figure 4-15.** Design of filling on entrance side of compartment plug. Note that the hole for filling can be made shorter if needed depending on the emplacement technique. Note also that in this figure the dimension of the pellet filling section is measured from the top of the cap instead of from the collar. This results a conservative length for the whole transition zone, see [SKB 2012](#).

**Uncertainties and important issues**

There are several issues including uncertainties in the design of filling components that will have to be addressed in the upcoming project phases.

In layout adaptation of KBS-3H repository water leaking (0.1 l/min or more) long fractured zones or fractures with a strike in the direction of the axis of the drift should be avoided if possible because they have a significant impact on the positioning of Supercontainer sections and lower drift utilization efficiency. Fracture striking perpendicular to the drift should also be avoided to mitigate the impact of earthquakes and needs consideration in case of buffer components.
The dimensioning of filling components adjacent to drift plug and compartment plug are based on mathematical calculations and include uncertainties such as the friction angle to be used for the calculations and assumptions that hysteresis has no significant influence on the swelling. The assumption of hysteresis and better definition of the expected effect should be verified in the next project phase taking into account different possible wetting and saturation alternatives. The calculations were based on the assumption that high density buffer filling can maintain density and swelling pressure difference for long periods of time, which is related to homogenization of buffer.

The concept of filling blocks in high inflow sections (> 1.0 l/min) differs from previous design with the double compartment plug section /Anttila et al. 2008/, which is kept as an optional design, and the viability should be evaluated from safety point of view.

The possible consequences of post-glacial erosion were not considered in the filling component design work since there is not adequate design basis for incorporating that into design. Based on present results, there appears some effect but the degree of effect and design factors to manage it are not yet understood sufficiently for engineering purposes. However, there is potential to develop erosion resistant design that could mitigate or solve this issue.

4.2.4 Plugs

4.2.4.1 Compartment plug

The compartment plugs of KBS-3H are used to hydraulically separate and seal sections (~150 m) of the drift and they also enable the water filling procedures of DAVE, the detailed requirements are presented in /SKB 2012/. The plug consists of three components; the fastening ring which is cast into a rock notch using low-pH concrete, the collar, which is attached to the fastening ring and finally the cap. The collar is fastened to the fastening ring by welding as is the cap to the collar. The plug is designed so that the welds do not carry any load, thus only function as a seal. Possible leakage is expected at the boundary between the Titanium components and the concrete casting securing the titanium to the rock as well as at the boundary between rock and concrete. The design of the steel plug is illustrated in Fig. 4-30 and elaborated in /Anttila et al. 2008/. Due to the material change from steel to Titanium the design will be updated.

During 2009 and 2010 the compartment plug was tested in the 15 metre long drift, DA1622A01, at the -220 metre level at Äspö HRL. The objective was to verify the ability to divide a KBS-3H drift into hydrological separated compartments. A steel compartment plug was used for testing.

The acceptance criterion had since earlier project phases been tentatively specified as a maximum water leakage of 0.1 l/min through the plug at hydrostatic pressure of 5 MPa, this corresponds to an older limit set up for the Compartment plug that relates to the Basic Design where a flow of 0.1 l/min was the limit set for flow from one Supercontainer section to the next and hence also set as a limit for a Compartment plug into the next Supercontainer section. The final target will, however, be to prevent advective flow through the plug and a much lower criterion is foreseen. A leakage value of 0.002 l/min was achieved in the full-scale compartment plug test at 5 MPa water pressure, see /SKB 2012/.
Figure 4-16. The compartment plug design. In this test a one sided plug is installed and tested. The only difference between a one and two sided plug is the opposite cap on the two sided plug /SKB 2012/.

4.2.4.2 Drift plug

During 2010 the positive results from the compartment plug tests led to a re-evaluation of the method used to seal the KBS-3H drifts. It was proposed that a redesigned compartment plug, using a suitable material, could fulfil the function of the previous drift end plug structure made of concrete described in /Anttila et al. 2008/. Among the advantages of such a change would be the reduced amount of concrete used in the drift, reduction of the installation steps, and an increase in the utilization degree enabling a possible extra canister position in each drift.

The requirements on the drift plug are equal to the requirements on the previously used drift end plug; see /SKB 2012/. These requirements are considerably higher than those specified for the compartment plug on which the new design is based, both regarding the pressure tolerances and durability. This is because the compartment plug has a function only during the installation phase, whereas the drift plugs must withstand the full hydrostatic pressure and the swelling pressure, and be sufficiently tight to form a part of the system of barriers. Therefore the drift plug requires water tightness and the ability to withstand 5 MPa hydrostatic pressure and 10 MPa uniform swelling pressure resulting from buffer and filling components. In addition, it is required to withstand a localized variability of 2 MPa in swelling pressure (estimated) which is assumed to be caused by e.g. uneven wetting and swelling.

The compartment plug design has been modified in order to fulfil the preliminary drift plug criteria. The drift plug design utilises a different rock notch profile, a sturdier collar and a cap with increased strength. The design is illustrated in Fig. 4-17.
To make sure that the design fulfils the criteria, the new drift plug will be manufactured in titanium. The drift plug is required to stay in place under the applied loads (no significant displacement allowed) until the adjoining central tunnels are backfilled. In the layout adaptation work /Kirkkomäki & Rönqvist 2011/ this time is estimated to be in the order of 30 years at maximum and the requirement is up to 100 years /Saanio et al. 2012/.

A FEM-analysis has been carried out during the design phase, and the input parameters are summarised in Table 4-5.

**Table 4-5.** FEM-analysis parameter values for the drift plug-design based on Titanium alloy grade 12.

<table>
<thead>
<tr>
<th>Design data</th>
<th>Geometry of the model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water pressure</td>
<td>Diameter of the cap</td>
</tr>
<tr>
<td>Swelling pressure</td>
<td>5 MPa (uniform)</td>
</tr>
<tr>
<td>Heterogeneous pressure</td>
<td>1650 mm</td>
</tr>
<tr>
<td>-2 MPa (eventually acting on casual areas)</td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Height of the cap</td>
</tr>
<tr>
<td>Safety factor on load (EC)</td>
<td>Thickness of the membrane</td>
</tr>
<tr>
<td>Titanium grade 12 (ASTM)</td>
<td>400 mm</td>
</tr>
<tr>
<td>1.00 (water pressure)</td>
<td>36 mm</td>
</tr>
<tr>
<td>1.35 (swelling pressure)</td>
<td></td>
</tr>
<tr>
<td>Material safety factor</td>
<td>Thickness of grout layer</td>
</tr>
<tr>
<td>1.0 (titanium grade 12)</td>
<td>40 mm</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The analysis showed that the stresses on the cap are below the acceptance level. According to analysis the drift plug will withstand a load of 22 MPa before failure of the components is expected, which indicates that it will take the design loading of 15 MPa with a high degree of confidence.

The maximum stress in the grouting layer is calculated to be 84 MPa, which is acting on a very limited area. The average stress is 48 MPa. Concrete strength depends on the mixture used, but the tests done so far on low-pH concrete indicate strength of approximately 88 MPa.
The highest compression stress in the rock is 44 MPa. In addition to the stresses from the plug, stresses from other sources exist after deposition, i.e. in situ rock stresses, and excavation (drift, V-notch) induced stresses as well as thermally induced stresses.

The conclusions of the calculations made /SKB 2012/:

- The plug shape and contact pressure has very minor effect on spalling probability because it affects mainly in direction of drift axis, which is perpendicular to the maximum stresses caused by in situ stress and thermal stress.

- The highest compressive stresses take place in the bottom of plug notch. The possible damage is limited to small volume and has no effect on the plug performance. This damage can already take place at the time of notch cutting, but propagation by thermal stresses is unlikely because the plug structure prevents the dilatancy of failed/damaged rock.

- In Olkiluoto, spalling/damage is evident at the time of maximum thermal stresses regardless of in situ stress level. This spalling/damage reduces remarkably the contact surface area of the plug and makes it discontinuous. If the plug will take pressure at the time of maximum thermal stresses then this reduced support surface should be taken into account in the plug design. The results of Posiva’s Olkiluoto Spalling Experiment (POSE) will be used in updating the plug design, see /Siren 2011/.

- The practical extend of plug stress effect zone is quite short and it disappears after 1 m – 1.5 m from the plug in a direction of the drift axis. Further, regardless of the location of the central tunnel, plug and notch are going to be constructed in the area which can be damaged at the time of maximum thermal stresses around the drift itself. If this damage is probable, the only possibility is to take it into account in the plug design. Estimate for modified contact area can be obtained and calculated based on the given spalling depth and shape. Finally, if the plug is situated further than 1.5 -2.0 times the diameter of the central tunnel, no combined negative or positive stress effects are assumed.
5 ASSESSMENT OF LONG-TERM SAFETY

A safety assessment of a KBS-3H repository at Olkiluoto was published in 2007 /Smith et al. 2007a/, and is summarised below.

Another focus of the studies within the KBS-3H programme has been on both experiments, modelling and scoping calculations to improve the understanding of the processes related to the interaction of the Supercontainer shell material with the buffer in the deposition drift and the potential associated disturbances at the buffer/rock interface (Chapter 5.2).

The findings of the KBS-3H safety studies performed within the joint SKB-Posiva RDD programme are summarised in this section.

5.1 Summary of the safety assessment for a KBS-3H type repository at Olkiluoto

A safety assessment of a KBS-3H repository at Olkiluoto was performed within the Posiva-SKB joint programme in the years 2004-2007. The aims of the safety assessment for KBS-3H were to assess:

(1) Whether there are safety issues specific to KBS-3H with the potential to lead to unacceptable radiological consequences and

(2) Whether the KBS-3H is a promising method for spent fuel disposal at a site with the broad characteristics of Olkiluoto from the long-term safety point of view.

The assessment was based on the preliminary reference repository design, termed the Basic Design. At the time of selection of the reference design for long-term safety studies, no major differences between the selected reference design Basic Design and the design alternative, termed DAWE (Drainage Artificial Watering and air Evacuation), had been identified that were relevant to long-term safety. The Basic Design with the Supercontainers and bentonite distance blocks kept in place by fixing rings, the compartment plugs to seal off high inflow drift sections, thus dividing the drift into isolated compartments, and the drift sealing steel-reinforced low-pH concrete drift end plugs is presented in /Autio et al. 2007/.

The safety assessment includes a description of the initial conditions within and around a KBS-3H deposition drift, based largely on the design specifications of the repository, on the Olkiluoto site reports, and on a repository layout report. It also includes a description of processes that may occur within and around the repository over time, and a description of the evolution of the repository in successive time frames, including a description of the main uncertainties affecting this evolution. The features, events and processes (FEPs) considered in KBS-3H process descriptions have been checked for completeness by auditing them against the SR-Can Process Reports and FEP database, and also against the international FEP database maintained by the OECD / NEA. The descriptions of processes and repository evolution over successive time frames provide the basis for the identification of evolution scenarios, an assessment of canister longevity and the analysis of radionuclide release and transport in the event of canister failure.
5.2 The safety concept, safety functions, performance targets and target properties

According to the safety concept for the KBS-3 method, long-term safety is achieved by isolating the spent fuel deep underground, and containing its radionuclides by a system of multiple barriers, both engineered and natural, which ensure that no single harmful event or deficiency of the system may endanger the ability of the system to provide safety.

The long-term safety principles are described at Level 2 of the VAHA (VAHA is Posiva’s requirements management system) as follows, see /Posiva 2012b/:

1. The spent fuel elements are disposed of in a repository located deep in the Olkiluoto bedrock. The release of radionuclides is prevented with a multi-barrier disposal system consisting of a system of engineered barriers (EBS) and host rock such that the system effectively isolates the radionuclides from the living environment.

2. The engineered barrier system consists of
   a) canister to contain the radionuclides as long as these could cause significant harm to the environment
   b) buffer between the canisters and the host rock to protect the canisters as long as containment of radionuclides is needed
   c) deposition tunnel backfill and plugs to keep the buffer in place and help restore the natural conditions in the host rock
   d) the closure, i.e. the backfill and sealing structures to decouple the repository from the surface environment.

3. The host rock and depth of the repository are selected in such a way as to make it possible for the EBS to fulfill the functions of containment and isolation described above.

4. Should any of the canisters start to leak, the repository system as a whole will hinder or retard releases of radionuclides to the biosphere to the level required by the long-term safety criteria.

The safety concept, as depicted in Fig. 3-1, is a conceptual description of how these principles are applied together to achieve safe disposal of spent fuel in the conditions of the Olkiluoto site. Due to the long-term hazard of the spent fuel, it has to be isolated from the surface environment over a long period of time. The KBS-3 method provides long-term isolation and containment of spent fuel by a system of multiple barriers, both engineered and natural, and by ensuring a sufficient depth of disposal (the key safety features of the system in Fig. 3-1). All of these barriers have their roles in establishing the required long-term safety of the repository system. These roles constitute the safety functions of the barriers (see Table 5-1). The surface environment is not given any safety functions; instead it is considered as the object of the protection provided by the repository system.

Most radionuclides in the spent fuel are embedded in a ceramic matrix (UO₂) that itself is resistant to dissolution in the expected repository conditions. The slow release of
radionuclides from the spent fuel matrix is part of Posiva’s safety concept. Moreover, the near-field conditions should contribute to maintaining the low solubility of the matrix.

Implementation of the KBS-3 method also entails the introduction of a number of additional barriers because of engineering, operational safety or long-term safety needs. Long-term safety needs arise, for example, because implementation involves the construction of a system of underground openings, including access tunnels and shafts, that would significantly perturb the safety functions of the host rock unless backfilled and sealed during closure. These closure components with long-term safety functions include:

- backfill of underground openings, including the central tunnels, access tunnels, shafts, and other excavations, and
- drillhole plugs, mechanical plugs, long-term hydraulic plugs at different depths and plugs near the surface.

The safety functions of the main barriers (canister, buffer and rock) are largely identical in KBS-3H and KBS-3V. However, in case of the KBS-3H variant, the buffer has the additional safety function of separating the Supercontainers hydraulically one from another, thus preventing the possibility of preferential pathways for flow and advective transport along the buffer/rock interface. This is required because the buffer/rock interface near to the canisters may locally be perturbed by a number of processes.

The safety functions of the EBS components and host rock are summarised in Table 3-1.

The discussion about additional components and their role in the KBS-3H variant, such as filling components and plugs, will be worked out in the ongoing project phase, and will be summarised in the Design Basis report for the KBS-3H variant.

Performance targets have been defined for critical parameters determining the long-term performance of the engineered barriers, and these have been justified and presented in the Design Basis report for the KBS-3V design / Posiva 2012x/. These are largely common to KBS-3H and KBS-3V.

The target properties for the host rock are common to KBS-3H and KBS-3V. Target properties contributing to the performance of the engineered barriers and retention of radionuclides are defined for the host rock as part of a set of rock suitability classification (RSC), which has been set for the KBS-3V variant. The RSC for the KBS-3H variant will be evaluated and defined during the next RDD programme.

If the performance targets are achieved, and target properties are present, then the repository barriers are expected to fulfil their respective safety functions. If plausible situations can be identified where the performance targets or target properties are not achieved, then the consequences of loss or degraded performance of the corresponding repository barrier or barriers must be evaluated as part of the safety assessment.
5.3 Assessment basis and methodology

Theoretical or conceptual understanding of relevant features, events and processes (FEPs) and their interactions forms the basis for assessing the long-term safety of the proposed repository and producing a safety case. The current understanding of FEPs is documented, to a large extent, in various versions of the Process Report /Gribi et al. 2007/, /Miller & Marcos 2007/). A new FEP-report for the KBS-V variant is being compiled /Posiva 2012c/.

The scientific understanding supporting the assessment is synthesised in a Process Report /Gribi et al. 2007/ and in an Evolution Report /Smith et al. 2007b/. The features, events and processes (FEPs) considered in these reports have been checked for completeness by auditing them against the SR-Can Process Reports and FEP database, and also against the international FEP database maintained by the OECD / NEA. The Process and Evolution Reports provide the basis for the selection of the scenarios potentially leading to radionuclide releases, and for calculation cases to evaluate the consequences of releases, the analysis of which is described in the Radionuclide Transport Report /Smith et al. 2007c/. The Complementary Evaluations of Safety Report /Neall et al. 2007/ provides additional arguments related to long-term safety. A Biosphere Analysis Report /Broed et al. 2007/ was produced in parallel to these reports, using input from the Radionuclide Transport Report.

In spite of the all favourable features which ensure the performance of the system according to set performance requirements, features, events and processes that could potentially lead to canister failure, or degrade the capacity of the repository to limit radionuclide transport in the event of canister failure, cannot be excluded. These various uncertain features, events and processes are taken into account in the definition and formulation of scenarios. Climatic scenarios provide the framework within which the internal evolution of the disposal system can be described. The disposal system comprises the repository system and the overlying surface environment.

In the assessment for KBS-3H the base scenario included all lines of evolution of the disposal system giving no release of radionuclides, and all lines of evolution of the surface environment during the first several thousands of years were included in the base scenario (the time window for which a quantitative dose assessment is required by Finnish regulations). Disturbance scenarios included those lines of evolution of the disposal system that include radionuclide release and hence to the possibility of exposure of humans and other biota to ionising radiation, they were developed for KBS-3H by combining repository assessment scenarios and dose assessment scenarios. Repository assessment scenarios were developed for lines of evolution of the repository system leading to canister failure and radionuclide release. These generally have a low probability of occurrence. Dose assessment scenarios described the potential fate of radionuclides in the surface environment. They include lines of evolution of the surface environment, and lines of evolution for how humans and other biota inhabit and use the surface environment during the time window for quantitative dose assessment (at least several millennia), taking regulatory guidelines into account.

In the KBS-3H safety assessment, a “deterministic” modelling approach assessing the impact of specific model and parameter uncertainties has been adopted, involving:
- defining and modelling separate base calculation cases for each identified canister failure mode;

- identifying alternative conceptual assumptions and parameter values consistent with current scientific understanding;

- defining and modelling variant calculation cases (i.e. sensitivity cases, “what if” cases, and complementary cases) that incorporate these alternatives either individually or in combination.

5.4 Evolution of the disposal system

The starting point for the description of disposal system evolution is a description of its initial state, which is when direct control of that part of the repository ceases. In principle, the initial state is a range of conditions prevailing at the time of emplacement that meet the requirements set in the Design Basis / Posiva 2012b/. In the Description of the Disposal System for KBS-3V /Posiva 2012d/, the initial state has been defined as follows:

“the state when the direct control over that specific part of the system ceases and only limited information can be made available on the subsequent development of conditions in that part of the system or its near-field”.

The conditions for the surface environment predicted for the year 2020, upon the emplacement of the first canister, define the initial state of the biosphere, and are based on forecasts from the terrain and ecosystems development modelling /Posiva 2012e/. The initial state of the near-field rock and, to some extent, the broader geosphere, is determined - or at least constrained - by the rock suitability classification (RSC - still under development) that are applied in locating suitable rock volumes for repository construction and for canister deposition. The initial state of the geosphere will differ from the undisturbed conditions in the bedrock due to the effects of repository construction (including the construction of the underground rock characterisation facility ONKALO). These effects are quantified by means of rock mechanics, thermal and groundwater flow modelling, including modelling of the transport of dissolved chemical species.

Largely similar processes occur within a KBS-3H deposition drift, although there are some processes that are specific to each variant, and it is in the early, transient phase that most of the significant differences in evolution between the KBS-3V and KBS-3H variants arise. For example, particularly in tight KBS-3H drift sections, the gas generated by the corrosion of steel components external to the canister (principally the Supercontainer shell made of steel used in the assessment) may accumulate at the buffer / rock interface, resulting in a prolonged period during which inflow of water from the surrounding rock will be limited, which will delay saturation of the buffer.

During the period of early evolution, the shoreline will be displaced away from the Olkiluoto site due to continuing land uplift, even in case of global average sea level rise resulting from climate warming. As a result the surface environment will change and the fresh water infiltration will change the groundwater composition.
In the longer term, disposal system evolution could be affected by any future major climatic changes and, in particular, by the development of permafrost and ice sheets. The formation of ice sheets could result in large water pressures and hydraulic gradients in the subsurface. The retreat and melting of ice sheets would result in the possibility that large volumes of meltwater could be forced into deeper parts of the bedrock. Furthermore, post-glacial earthquakes may occur following the retreat of the ice sheet, giving rise to stress changes in the rock that trigger shear movements on smaller-scale fractures that intersect the deposition drifts.

5.5 Difference analysis approach

The scientific basis of the safety assessment includes around 30 years of scientific R&D and technical development in the Swedish and Finnish KBS-3V programmes. Much of this scientific basis is directly applicable to KBS-3H. This has allowed KBS-3H safety studies and the safety assessment to focus on those issues that are unique to KBS-3H, identified in a systematic “difference analysis” of KBS-3H and KBS-3V /Gribi et al. 2007/. In both alternatives, the system evolves from its initial state through an early, transient phase towards a state, in which key safety-relevant physical and chemical characteristics (e.g. temperature, buffer density and swelling pressure) are subject to much slower changes than in the transient phase. Long-term safety assessment starts from the time of emplacement of the first canisters in the repository. This is also the starting point for the early evolution of the system.

The difference analysis (see Table 5-1) has shown that most of the differences between KBS-3H and KBS-3V relate to internal processes involving KBS-3H-specific components, such as the Supercontainer and other structural components, and variations in hydraulic conditions in KBS-3H deposition drifts and their immediate environment (Supercontainer-buffer-rock interface, near-field rock, drift plugs). Many of these differences affect the early, transient phase of repository evolution, when significant mass and energy fluxes will occur as a result of the various gradients created by repository construction and emplacement of spent fuel, although some differences also occur at later times. For example, the radionuclide transport paths from a failed canister are affected by the differences in the geometry and backfilling of the KBS-3H deposition drifts compared with the KBS-3V deposition tunnels.
<table>
<thead>
<tr>
<th>System components / (groups of) processes</th>
<th>KBS-3V</th>
<th>KBS-3H</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Buffer</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piping / erosion by water and gas, chemical erosion</td>
<td>Within deposition hole at buffer / rock interface in the case of high initial inflow rates (however, the holes can be selected individually and those with larger inflows will be rejected). Also, in the longer term, chemical erosion is possible in the event of an influx of glacial meltwater. Loss of buffer around one canister due to piping/erosion or chemical erosion by glacial meltwater will not affect the buffer around neighbouring canisters.</td>
<td>Piping/erosion may affect buffer density at bentonite / rock interface in canister sections with high initial inflow rates and in canister sections adjacent to these; mitigating the effects of piping / erosion is considered to be a major challenge in the design of KBS-3H and has led to the consideration of two candidate designs and various design alternatives. Deposition drift sections with inflows larger than a specified limit are not used for deposition - but sealed tightly. This will affect the utilization degree of deposition drifts. Design is still under development /Autio et al., 2007/. Chemical erosion is possible in the event of an influx of glacial meltwater. Loss of buffer around one canister due to piping/erosion or chemical erosion by glacial meltwater may affect the buffer around neighbouring canisters, since the buffer density along the drift will tend to homogenize over time.</td>
</tr>
<tr>
<td>Displacement of buffer / distance block (leading to a reduction in bentonite density)</td>
<td>Swelling of buffer from deposition hole into deposition tunnel above the hole may lead to lowering of bentonite density. Rock stress distribution leads to risk of rock slabs at mouth of deposition hole.</td>
<td>Axial displacement of distance block by hydraulic pressure build-up may lead to the lowering of bentonite density and must be counteracted by a rapid emplacement rate and by the use of steel plugs and steel rings * bolted to rock, as described in the current reference design /Autio et al., 2007, Börgesson et al., 2005/. Axial displacement due to heterogeneous swelling is limited by friction and by drift end plug.</td>
</tr>
<tr>
<td>Iron / bentonite interaction</td>
<td>Relevant only for failed canisters</td>
<td>In addition to the processes relevant to KBS-3V, significant geochemical interactions between supercontainer shell and buffer will take place (iron / smectite interaction, iron-silicate formation, cation exchange, etc.). These processes may affect the buffer density, swelling pressure, hydraulic conductivity and other properties. The effects are locally limited at early stages, but may develop with time and affect larger parts of the buffer /Johnson et al., 2005; Carlson et al., 2006; Wersin et al., 2007/.</td>
</tr>
<tr>
<td>Gas transport and possibly gas-induced porewater displacement</td>
<td>Relevant only for failed canisters</td>
<td>In addition to the processes relevant to KBS-3V, significant gas effects are expected (Johnson et al., 2005) due to anaerobic corrosion of supercontainer shell and other steel components (retarded resaturation, air trapping, gas dissolution / diffusion / advection, gas pressure build-up, gas leakage, gas pathways along drifts, etc.). During this early phase, no radionuclide transport is expected.</td>
</tr>
</tbody>
</table>
### System components / (groups of) processes

<table>
<thead>
<tr>
<th></th>
<th>KBS-3V</th>
<th>KBS-3H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effects of engineering and stray materials (other than EBS materials, host rock and groundwater)</td>
<td>Effects of concrete bottom plate, stray materials, bentonite pellets.</td>
<td>Effects of steel rings*, rock bolts, steel feet, water / gas evacuation pipes, grouting, spray and drip shields, cement.</td>
</tr>
</tbody>
</table>

### Supercontainer and other structural components within the deposition drifts

<table>
<thead>
<tr>
<th></th>
<th>KBS-3V</th>
<th>KBS-3H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel corrosion and formation of corrosion products</td>
<td>N / A</td>
<td>For the expected steel corrosion rate, complete conversion to oxidised species occurs within a few thousand years.</td>
</tr>
<tr>
<td>Gas generation by anaerobic corrosion of steel</td>
<td>N / A</td>
<td>Gas generation rates are significant although the overall amount of gas produced is moderate; for the effects of gas, see buffer.</td>
</tr>
<tr>
<td>Effects of volume expansion (magnetite formation)</td>
<td>N / A</td>
<td>Volume expansion of corrosion products may increase buffer density and swelling pressure.</td>
</tr>
<tr>
<td>Ion release to bentonite porewater</td>
<td>N / A</td>
<td>Leads to iron / bentonite interaction.</td>
</tr>
<tr>
<td>Effect of supercontainer on water flow paths along the periphery of the drift</td>
<td>N / A</td>
<td>The physical properties of the corroded supercontainer shell have not been evaluated. Although the porosity and hydraulic conductivity of the corrosion products may be low, the possibility that fracturing could lead to the formation of pathways for water flow and advective transport cannot currently be excluded. Selected radionuclide transport calculation cases cover the case of a disturbed buffer/rock interface due to the presence of iron corrosion products in contact with bentonite.</td>
</tr>
<tr>
<td>Displacement of supercontainer / buffer by swelling of distance blocks</td>
<td>N / A</td>
<td>See buffer</td>
</tr>
<tr>
<td>Breaching of supercontainer shells by bentonite swelling</td>
<td>N / A</td>
<td>The supercontainer shell may be breached by the different forces due to bentonite swelling acting inside and outside the supercontainer shell (secondary effect, because the supercontainer has no safety function).</td>
</tr>
</tbody>
</table>

### Deposition drift, central tunnel, access tunnel, shafts, boreholes

A major difference is in the geometry and backfilling of the KBS-3H deposition drifts compared with the KBS-3V deposition tunnels. In KBS-3H, supercontainers are emplaced along relatively narrow deposition drifts, separated by compacted bentonite distance blocks. In KBS-3V, deposition holes are bored from relatively large diameter deposition tunnels, backfilled with swelling clay or clay / crushed rock mixture.

For other underground openings (access tunnel, shafts, boreholes) no major differences have been identified. Differences of the most important system components and processes and their possible implications have been covered above.

### Geosphere
### System components / (groups of) processes

<table>
<thead>
<tr>
<th></th>
<th>KBS-3V</th>
<th>KBS-3H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas transport, gas-induced porewater displacement</td>
<td>Relevant only for failed canisters</td>
<td>Gas formation related to corrosion of the supercontainer shell and implications of the corrosion gases. Limited storage volume and transport capacity within deposition drift, combined with increased gas generation (rates and total amount). Gas dissolution / diffusion / advection in groundwater, gas pressure build-up, gas-induced porewater displacement, capillary leakage. For tight canister sections: gas transport along drift (EDZ) to the next transmissive fracture, possibly involving reactivation of fractures in near-field rock, when minimal principal stress is exceeded.</td>
</tr>
<tr>
<td>Transmissive fractures and flow conditions</td>
<td>The selection of deposition holes locations is more flexible than in KBS-3H because rock sections with larger inflows can be rejected.</td>
<td>Local variations in groundwater flow conditions along the drift may lead to variable saturation time for the buffer along the drift.</td>
</tr>
<tr>
<td>Mechanical stability of the drift / tunnel</td>
<td>High stresses at the mouth of deposition holes and at the top of backfill tunnel</td>
<td>Lower rock stresses than in KBS-3V because the deposition drifts can be better adapted to the stress field.</td>
</tr>
<tr>
<td>Orientation of fractures</td>
<td>KBS-3V is more sensitive to sub-horizontal than to sub-vertical with respect to potential damage to the engineered barrier system by rock shear.</td>
<td>KBS-3H is more sensitive to sub-vertical fractures than to sub-horizontal fractures with respect to potential damage to the engineered barrier system by rock shear.</td>
</tr>
</tbody>
</table>

*steel rings (fixing rings) were used only in BD to avoid displacement of the distance blocks prior to the installation of compartment and drift end plugs.

### 5.6 Formulation of release scenarios

The majority of canisters are expected to provide complete containment of radionuclides over hundreds of thousands of years. However, since the possibility of one or more canister failures cannot currently be excluded over a million year time frame, the consequences of canister failure have to be assessed, taking into account uncertainties in the mode of failure and subsequent radionuclide release and transport processes.

Repository assessment scenarios explore the consequences of various uncertain features and perturbing processes that could potentially lead to canister failure, or significantly degrade the capacity of the repository system to limit radionuclide transport in the event of canister failure. Relevant features and processes are those that have the potential to compromise the capacity of the repository system to meet its performance targets, or to significantly perturb the target properties of the bedrock.

Potentially relevant features and processes as arising internally within the disposal system or due to events external to the disposal system has been identified and analysed.
- The possible presence of penetrating and non-penetrating defects in the canisters or other defects that could lead to early releases.
- Processes leading to missing, loss or redistributed buffer mass.
- Processes leading to perturbation of the buffer / rock interface.
- Gas generated internally within the canister.
- Buffer freezing.
- Canister failure due to isostatic load.
- Migration of oxygen to repository depth.
- Loss of buffer due to exposure to glacial meltwater.
- Canister failure due to rock shear.

The processes and system evolution for a KBS-3H repository, and the difference analysis with KBS-3V, indicates that most safety issues are common to the two alternatives, but that there are also differences. Often, these are differences in the significance to, or potential impact of, an issue to each of the alternatives. Key safety issues that were judged to have a different significance for or potential impact on, KBS-3H compared with KBS-3V, concern mainly the early, transient evolution of the repository. They include

(i) piping and erosion during repository operations and drift saturation;
(ii) steel components external to the canister, their corrosion products and their impact on mass transport;
(iii) impact of gas from the corrosion of steel components external to the canister;
(iv) interactions involving leachates from cementitious components and EBS;
(v) thermally-induced rock spalling; and
(vi) expulsion of water and dissolved radionuclides from a defective canister interior by gas.

Issue (i) is a critical issue for repository design as well as safety. Design measures have been taken to limit the possibility of significant piping and erosion during early evolution of the buffer. In the absence of other more significant perturbations to mass transport in the buffer or at the buffer / rock interface (see below), scoping calculations indicate that limited piping and erosion will not lead to canister failure by copper corrosion within a million year time frame. This is due to the limited sulphide concentration in the groundwater (although the variability and evolution of groundwater sulphide concentration with time is still being studied).

Issues (ii) and (iii) are related to the steel components present in the drift, and major effort has been put on studies for understanding of this process and also on studies of alternative materials to be used to limit the perturbation at the buffer/rock interface (see Section 5.2).

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

Issue (vi), expulsion of water and dissolved radionuclides from an initially penetrated canister by gas, is a possibility if the defect is located on the lower side of the horizontally orientated canister. In this case, it is possible that gas generated principally by corrosion of the insert will become trapped above water lying in the lowest part of canister, and gas pressure will build up until it is sufficient to expel the water and dissolved radionuclides into the buffer. Scoping calculations indicate that the more likely situation is that water entering the canister will be completely consumed by corrosion of the cast iron insert, and there will be no gas-induced displacement of contaminated water through the defect into the saturated bentonite. The possibility of expulsion of contaminated water by gas cannot, however, be completely excluded, and its impact on radionuclide release and transport has been addressed.

5.7 Assessment of release scenarios

The majority of canisters are expected to provide complete containment of radio- nuclides for hundreds of thousands of years in all identified scenarios. However, since the possibility of one or more canister failures cannot currently be excluded over a million year time frame, the consequences of canister failure have to be assessed, taking into account uncertainties in the mode of failure and subsequent radionuclide release and transport processes. Thus, a range of assessment cases - i.e. specific model realisations of different possibilities or illustrations of how a system might evolve and perform in the event of canister failure - has been defined and analysed in terms of hazard to humans and to other biota. The assessment cases address each identified canister failure mode: (i), an initial penetrating defect, (ii), canister failure due to corrosion and (iii), canister failure due to rock shear. For each canister failure mode, a base calculation case is defined, together with a number of variant calculation cases that illustrate the impact of individual uncertainties, or uncertainties in combination.

In evaluating the assessment cases, extensive use has been made of SR-Can parameter values and model assumptions, except where these are affected by differences in the materials to be disposed of in Finnish and Swedish repositories, and differences between conditions at Olkiluoto and those at the Swedish sites considered in SR-Can. Where differences arise, the selection of parameter values and model assumptions has been made largely according to “expert judgement”, based on considerations such as use in previous assessments, additional data gathering and laboratory studies. In the case of more recent developments in the understanding of the Olkiluoto site are used to
provide additional support for the parameter values selected (for example, in terms of their conservatism).

As noted above, there are a number of features and processes that could significantly affect the characteristics of the buffer/rock interface. Some, such as thermally-induced rock spalling, are important for KBS-3V as well as KBS-3H, although the presence of the Supercontainer shells and their corrosion products gives additional potential sources of perturbation for a KBS-3H repository. The impact of a perturbed buffer/rock interface on radionuclide releases to the biosphere in the event of a single canister failure is illustrated in Fig. 5-2 (case PD-SPALL addresses thermally-induced rock spalling PD-FEBENT1-3 address other potential processes, including iron-bentonite interactions). A perturbed buffer/rock interface increases the calculated release ratio by no more than about an order of magnitude with respect to the base calculation case for the canister with an initial penetrating defect (PD-BC) in which an ideal, non-perturbed interface is assumed.

Another key issue for KBS-3H is expulsion of contaminated water from the interior of a failed canister by gas. Water entering the canister through the point of failure will corrode the canister insert. Any residual water will accumulate at the bottom of the internal void space within the canister. Corrosion will also generate gas, which will accumulate above this water. Gas pressure will increase until the gas eventually forces its way out of the canister through the point of failure. In so doing, it will also force out water, provided the water entering the canister is not entirely consumed by corrosion, and provided the point of canister failure lies below the gas-water interface. Water expelled in this manner may be contaminated with radionuclides. In the case that failure is due to the presence of a weld defect, this scenario is more plausible for KBS-3H than for KBS-3V. This is because the weld is near the top of the canister and, in KBS-3V; the canisters will be emplaced vertically upright. Any defect will therefore always be above the internal gas-water interface in KBS-3V, but not necessarily in KBS-3H.

The calculated release rate maximum for this KBS-3H case (PD-EXPELL) is more than an order of magnitude higher than that of the base calculation case (PD-BC). This case also gave the highest annual dose to the most exposed individual, with a maximum of about $2 \times 10^{-2}$ mSv occurring at about 5,000 years. This is a factor of 5 below the regulatory constraint of 0.10 mSv for the most exposed persons. For all other assessment cases, the annual dose maxima range from $5 \times 10^{-4}$ to $3.5 \times 10^{-3}$ mSv, and are thus around two orders of magnitude below the regulatory constraint, even though the annual doses as calculated are likely more conservative quantities than required for the comparison.
Figure 5-2. Overall release ratios in all four calculation cases addressing perturbations to the buffer / rock interface and in the base calculation case (PD-BC) for the KBS-3H safety analysis /Smith et al. 2007c/.

The highest calculated release ratio maximum occurred in a case addressing canister failure by copper corrosion, in association with an influx of glacial meltwater and loss of buffer mass by chemical erosion, coupled to an assumption of low transport resistance and saline geochemical conditions in the geosphere at later times. In this case, the release ratio maximum is more than an order of magnitude below the regulatory constraint. However, there are significant uncertainties associated with this scenario, e.g. whether substantial buffer mass loss by chemical erosion could occur at all, and, if it does, the number of canister positions that are likely to be affected. The development of a better understanding of chemical erosion is a priority for work for both the KBS-3H and KBS-3V variants.

5.8 Compliance with regulatory requirements

The regulatory requirements for the long-term safety of a geological repository in Finland are set out in detail in YVL Guide D.5 (version 4, 22.9.2010), which also specifies the quantitative dose and release criteria to be met by the repository. To date, only in the case of canister failure due to rock shear have the consequences of multiple canisters failures been estimated. The estimated geo-bio flux arising from multiple canister failures (estimated number of potentially affected canisters being in the order of 10 to 20 of 3000 canisters) in this scenario, which conservatively disregards the application of rock suitability criteria to avoid fractures with the potential to undergo damaging shear movements (criteria are still under development), nevertheless complies with the regulatory geo-bio flux constraint.
The studies to date already indicate that, except a few unlikely circumstances affecting a small number of canisters, spent fuel is expected to remain isolated, and the radionuclides contained within the canisters, for hundreds of thousands of years or more, in accordance with the base scenario. Nevertheless, a small number of canister failures within a million year period cannot be excluded. The planned disposal system provides a series of barriers that delay and attenuate the releases from a failed canister, such that any exposure of humans and other biota to radioactivity is highly unlikely to cause harm. To demonstrate that this is the case, scenarios have been developed and analysed, taking into account the various uncertainties affecting the rates of release of radioactive substances from failed canisters and their subsequent migration through the geosphere and transport in the biosphere.

The low radionuclide calculated release rates to the biosphere and resultant annual doses imply that any radiological consequences of these releases will be negligible. Other safety indicators have also been used to place these results in perspective. The radiotoxicity flux, for example, is a measure of the hazard associated with a flux of radionuclides, and can be used to compare releases from the repository with radionuclide fluxes arising from other, natural sources (Fig. 5-3).

Beyond the million year time frame, slow corrosion of the copper shell, the detrimental effects of multiple periods of glaciation or some other mechanism will eventually lead to failure of all the canisters and the release of some radioactivity to the surrounding rock. The radioactivity that is initially present in the repository will, however, decay to a much reduced levels before this happens.

**Figure 5-3.** Radiotoxicity flux from the KBS-3H repository into the biosphere for the penetrating defect base calculation case (case PD-BC in the KBS-3H safety assessment) compared with a range of naturally occurring radiotoxicity fluxes (see text and Appendix B, /Neall et al. 2007/ for further explanation).
5.9 Conclusions from the safety assessment

Overall, the conclusions of the long-term safety assessment of a preliminary design for a KBS-3H repository for spent nuclear fuel at Olkiluoto are as follows. It should be noted that although this report and /SKB 2012/ are being finalised during 2012, the requirements presented in both reports represent the status at the end of the Complementary Studies phase, early 2011. Updates and changes have been made to some of the requirements during the finalisation of the report but these will be reported in the new project phase.

1. In the absence of any initial penetrating defect in the canisters, no canister failures should occur during the first several thousand years after canister deposition provided the repository system evolves as expected. Thereafter, the processes that are potentially the most detrimental to repository safety are related to glacial conditions. This was also a main conclusion arising from SR-Can in the case of a KBS-3V repository for spent fuel at two Swedish sites, but the importance of some geosphere properties may differ, e.g. the KBS-3H design is more sensitive to sub-vertical fractures with respect to potential damage to the engineered barrier system by rock shear.

2. Safety issues related to a future change to glacial conditions at the Olkiluoto site are generally the same as those identified in SR-Can for the KBS-3V design at Swedish sites, the most significant being canister failure due to rock shear in the event of a large, post-glacial earthquake and loss of buffer from exposure to glacial meltwater, which may lead to early failure of some canisters by corrosion. There are, however, some differences compared with SR-Can and KBS-3V, e.g. the probability of, and possibility of avoiding by design, fractures that can undergo rock shear movements that damage canisters in the event of a large post-glacial earthquake. Furthermore, in the case of KBS-3H, loss of buffer around one canister due to exposure to glacial meltwater may affect the corrosion rate of neighboring canisters, since the buffer density along the drift will tend to homogenize over time. This also means that the impact on buffer density and on the corrosion rate of the first canister will diminish with time. In the case of KBS-3V, on the other hand, buffer loss around one canister will not affect the state of the buffer around the other canisters.

3. A difference analysis has shown that the key differences in the evolution and performance of the KBS-3H and KBS-3V designs relate mainly to the engineered barrier system and to the impact of local variations in the rate of groundwater inflow on buffer saturation along the drifts. The safety functions of the geosphere are generally not expected to differ significantly between the two designs.

4. No features or processes that are specific to KBS-3H have been identified that could lead to a loss or substantial degradation of the safety functions of the engineered barriers over a million year time frame. However, the degree to which fractures with the potential to undergo shear movements that damage the engineered barriers in the event of a large earthquake can be identified and avoided remains to be evaluated, and may be different for KBS-3H compared with KBS-3V.
5. Particularly in tight drift sections, the gas generated by the steel components of the KBS-3H repository external to the canister in the current reference design (principally the Supercontainer shell) may accumulate at the buffer / rock interface, possibly resulting in a prolonged period during which significant inflow of water from the surrounding rock will be limited and the buffer will remain only partially saturated.

6. The timing of eventual canister failure by corrosion may be affected by perturbations to the buffer / rock interface caused, for example, by the presence of the steel Supercontainer shell and its corrosion products. The issues related to the impact of iron and its corrosion products on the buffer bentonite are potentially detrimental to the safety functions of the buffer and subject to significant uncertainties. Hydrogen generation during the first thousands of year may also affect the corrosion of the canisters via its effect on the microbial reduction of sulphate to sulphide, but the sulphides formed may be precipitated as iron sulphides by reacting with the iron corrosion products, thus reducing the flux of sulphide to the canister surface. The conclusions from the analyses performed are that these perturbations are not expected to lead to canister failure by corrosion within a million year time frame.

7. Radionuclide release from the repository near field in the event of canister failure may also be affected by perturbations to the buffer / rock interface, but in all cases releases are limited and comply with Finnish regulatory criteria. Only single canister failure cases have, however, been considered and the possibility of multiple canister failures must be addressed in future studies.

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

The performed safety assessment has some important limitations, including the implementing of the Basic Design, which has later been replaced by DAWE the design. Nevertheless, it can be concluded, based on the present safety assessment, that the KBS-3H design variant offers potential for the full demonstration of safety for a repository at Olkiluoto site and for the demonstration that it fulfills the same long-term safety requirements as KBS-3V. Studies are being undertaken to address remaining critical scientific and design issues and the further development of the DAWE design alternative to avoid the possibility of distance block displacement or deformation, which could lead to significant piping and erosion, as well as studies of iron / bentonite
interaction and the possible use of alternative materials, such as titanium for the Supercontainer shell and some other engineered structures in the drift (see Chapter 5.2).

In general, the calculation results indicate that differences in the geometry and transport paths considered in the analysis of the KBS-3V and KBS-3H design variants have only a minor impact on calculated releases and doses. The focus of the analysis was on uncertainties that are specific to the KBS-3H variant, or have different implications for KBS-3H compared with KBS-3V. In this sense, the analysis was more limited in scope than in the 2009 safety analysis of a KBS-3V repository. The biosphere analysis for KBS-3H is also more limited than in the 2009 safety analysis of a KBS-3V repository, in the sense that only a single biosphere scenario has been applied, and compliance with all regulatory constraints was not fully assessed.

5.10 Assessment of long-term material buffer interaction

Different structural components are planned to be used in the KBS-3H deposition drift. Early in the KBS-3H development programme, it was already recognised that the physical and chemical effects of the corrosion products of the Supercontainer shell made of carbon steel need to be evaluated. The main issue noted is the possible alteration of bentonite and loss of boundary transfer resistance between the buffer and the fracture in the host rock due to the interaction of iron from the Supercontainer shell with the bentonite buffer. One of the main concerns noted by the authorities (STUK and SSM) in their review of the KBS-3H safety assessment was the impact of iron and its corrosion products on the performance of the buffer.

Iron has been the reference Supercontainer shell material in earlier studies of the KBS-3H variant. Key long-term safety issues for a steel Supercontainer shell are the uncertain impacts of the Fe(II) and hydrogen that will be released as the shell corrodes on the bentonite buffer. In the Complementary studies of horizontal emplacement KBS-3H 2008–2010, copper and titanium have also been studied as alternative materials. Studies have addressed their corrosion rates and the impacts of their corrosion products on the buffer. Studies of iron-clay interactions have also continued.

The evaluation presented in this chapter focuses on the Supercontainer since it is the KBS-3H specific component (compared with the reference design, KBS-3V) which will have the greatest influence on long-term safety in a KBS-3H repository. It is closest to the canister and will also represent the main part of the KBS-3H additional components.

There is no required safety function of the Supercontainer shell and therefore the only assessment that needs to be made is related to how the Supercontainer shell affects the bentonite with respect to its desired long-term performance.

5.10.1 Fe-clay interaction

The relevance of iron corrosion and iron-bentonite interaction has already been recognised early in Posiva’s programme. A preliminary review study on natural analogues was documented by /Marcos 2003/. A pioneer experimental corrosion study in compacted MX80 bentonite was conducted by /Carlson et al. 2006/. In this study, both corrosion and processes in the bentonite were investigated. The main outcome from this study was that the corrosion process was profoundly affected in the compacted
bentonite samples with large fraction of the corroded iron transferred to the clay. The nature of this iron, however, could not be unambiguously identified. Results from swelling pressure and hydraulic conductivity measurements suggested that the bentonite close to the iron was altered by cementation effects.

In a follow up study, a combined literature review and modelling effort was undertaken and documented in a Posiva report /Wersin et al. 2007/. The focus therein was to present and to discuss the effect of the Supercontainer shell on the bentonite buffer in the KBS-3H disposal concept taking the Olkiluoto site as case study. The main results were:

- From a mass balance viewpoint, the interaction of the steel shell with the buffer could lead to transformation of 10-30 % of montmorillonite, resulting in a maximum swelling pressure decrease from 7 to 2 MPa.
- A preliminary coupled diffusion-reaction model under Olkiluoto-specific conditions indicated that the effect on the buffer is much smaller than derived from mass balance. This arises principally because of (1) slow corrosion rate of iron, (2) the low solubility of iron corrosion products and (3) diffusion-limited mass transfer of iron in the buffer. Thus, the altered zone between the iron source and the unaffected buffer was predicted to remain spatially limited to a few cm for very long times.
- Given the proximity of the physically affected zone around the Supercontainer to the tunnel boundary, however, the potential impacts of this zone need to be considered in performance assessment.

Under these premises, three new studies were launched in the complementary study stage (2008-2010). The scope of these studies is to (1) improve process understanding of Fe-clay interactions within the KBS-3H framework and (2) evaluate the extent of alteration of the bentonite buffer.

1) **Analysis of long-term Fe-bentonite interaction tests**

Reliable predictions for iron-bentonite interactions and their effects on the buffer's long-term performance hinge on reliable experimental data. Long-term studies are very valuable in this regard, because, if performed under consistently anoxic conditions, are more representative of processes occurring in the EBS after repository closure. Within the KBS-3H program, solid and liquid samples from two entirely different types of long-term experiments were analysed: batch experiments carried out at JAEA in Japan and diffusion-type experiments carried out at VTT in Finland. The applied methods, results and interpretation of this study are documented in detail in /Kumpulainen et al. 2010/.

In the following the main conclusions from this experimental study are summarised:

The batch experiments, albeit representing extreme and unrealistic conditions, enabled to gain relevant process understanding on montmorillonite transformation, Thus, bentonite in (direct) contact with a large source of zero-valent Fe induces high pH and
low Eh conditions as well as transformation to a non-swelling 1:1 clay (presumably berthierine).

Diffusion-type experiments, representing more-realistic repository conditions, revealed very limited changes in the clay fraction and a very limited zone affected by cementation (< 2 mm), but no effect with regard to clay alteration. The corrosion rate of iron was estimated to be about 1.5 μm/a, in agreement with previous corrosion studies in compacted bentonite (e.g. /Smart et al. 2004/). The corrosion reaction generated an increase in iron (predominately Fe(II)) in the clay close to the contact. The most likely form of this Fe-pool is a mixed Fe(II/III) hydroxide green-rust type phase. Results confirmed the large pH buffering capacity of the bentonite which helps to counteract the alkalinity generated by the corrosion reaction.

2) Sorption/diffusion of Fe(II) in bentonite

Sorption and diffusion of Fe(II) in bentonite has been studied in co-operation by VTT Technical Research Centre of Finland (VTT) and the French Geological Survey (BRGM).

Sorption was studied by determining the distribution coefficients in batch experiments. Two types of purified MX-80 bentonite were used in the experiments. One of them was purified at BRGM (MX_{BRGM}) and the other one at VTT Finland (MX_{VTT}). Experiments were also carried out with synthetic smectite, which did not include iron, prepared at BRGM (SB_{BRGM}). The sorption experiments were carried out under low-oxygen conditions in an anaerobic glove-box. Radioactive isotope (^{55}Fe) was used as a tracer in the experiments. The experiments were carried out in 0.3 M and 0.05 M NaCl solutions as a function of pH, and in 0.3 M NaCl solution buffered at pH 5 as a function of added Fe(II) concentration. The batch experiments were modelled with a cation exchange /surface complexation model including Fe(III)/Fe(II) redox reactions.

The results from the sorption study reveal the generally expected pH dependence of Fe(II) sorption, but also the influence of the purification treatment of the bentonite. The data could be adequately modelled with a “conventional” non-electrostatic surface complexation model, but including assigned standard redox potentials for the structural iron for the different clays.

Diffusion of Fe(II) was studied in anaerobic conditions with the non-steady-state diffusion experiment method, where the tracer is introduced as an impulse source between two bentonite plugs. The isotope ^{55}Fe was used as a tracer in the diffusion experiments. The experiments were carried out at pH 5 and 8 in purified sodium bentonite MX_{VTT}. The experimental times of the diffusion experiments were 310 days. Parallel samples to the diffusion experiments were prepared for measurement of pH in bentonites. The samples were prepared in the same way as the diffusion samples, but without ^{55}Fe activity. Two IrOx electrodes were placed in the bentonites at the distance of 6 mm from each end.

After 310 days the diffusion experiment of each pH was finished and the activity profile in the bentonite determined. The activity was found within 0.5 mm from the initial source. Due to the short diffusion distance only two points were available for the
calculation of the diffusion coefficient. The diffusion profiles are shown for the pH 8 test in Fig. 5-4. The measured $D_a$ was $6.4 \cdot 10^{-16}$ m$^2$/s at pH 5 and the value calculated from $K_d$ was two magnitudes higher. It may be that there is a slow sorption process, which does not appear in the short sorption experiment but slows down the diffusion. At pH 8 the measured $D_a$ was $3.7 \cdot 10^{-16}$ m$^2$/s while the calculated one varied from $5 \cdot 10^{-16}$ to $5 \cdot 10^{-18}$ m$^2$/s depending which separation techniques was used in the sorption measurement. The pH in the bentonite changed slightly during the experiments.

![Diffusion at pH 8](image)

**Figure 5-4.** Measured activity profile in the diffusion sample at pH 8 and modelled profiles with different $D_a$ values.

The following conclusions can be drawn:

- It could be demonstrated that a sorption/redox model enables to predict Fe(II) sorption onto montmorillonite. However, the redox properties of clay structural Fe are not constant. They seem to depend on the clay structure but also on the clay “history” reflected for example in their Fe(II)/Fe(III) ratio.

- Both measured and calculated diffusivities show rather low values. No complete matching is obtained between the calculated and measured $D_a$, however.

3) **Reactive transport modelling of the iron front**

This modelling study carried out in 2010-2011 is documented in /Birgersson & Wersin 2011/, a Posiva WR currently under review. It is based on the preliminary reactive transport modelling study conducted in 2006/2007 /Wersin et al. 2007/. Recent advances in experimental, modelling and thermodynamic data were taken into account for this update. A particular aspect was the consideration of the potential effect of pH increase during corrosion. Without the clay, the anoxic corrosion reaction is commonly
perceived as being pH neutral (e.g. /Grauer 1984/). However, in the presence of clay, an increase in pH could in principle occur by slow precipitation of corrosion products and concomitant scavenging of Fe(II) by the clay surface. A further aspect was the use of a new thermodynamic database elaborated by the French Geological survey (BRGM) which includes a number of clay minerals and potential alteration product phases.

The scope of the 1D transport model was to simulate the Fe-clay interactions and accompanying geochemical reactions in the buffer as a result of the corrosion of the steel. The powerful and versatile code CrunchFlow /Steefel 2006/ was applied, specifically aimed at reactive transport modelling in porous media. It considers coupling of porosity and diffusivity (porosity update feature) and has a well-established kinetic dissolution / precipitation rate formulation based on the transition state theory implemented in the code. The mineral rates were taken from /Palandri & Kharaka 2004/ and various other sources as outlined in /Birgersson & Wersin 2011/. As highlighted also in other modelling studies on Fe-clay interactions, the precipitation rates of many of the potentially forming mineral phases are poorly constrained. In particular, this includes precipitation of corrosion products, such as magnetite or mixed Fe(II)/Fe(III) hydroxide (green rust). Therefore, a major aspect in this modelling exercise was to analyse the effect of different precipitation rates of potentially forming corrosion products (magnetite, green rust, goethite, FeS and pyrite). Different test cases, a base case and alternative cases were defined.

The modelling results can be summarised as follows:

- Complete corrosion of the iron shell occurs after about 5000 years. For the base case, the predominant sink for the corroded iron is green rust iron and very little interaction of Fe(II) with the clay has occurred. Thus, montmorillonite remains virtually unaffected by the corrosion reaction. After this time period, very little further alteration takes place, because of the low solubility of the corrosion phase.

- Assuming magnetite or goethite to form as main corrosion product (instead of green rust) yields a very similar picture, thus showing little Fe-clay interaction and very restricted alteration of montmorillonite. Released Fe(II) reacts with the clay and forms predominantly berthierine. The extent of the altered zone is about 2 cm. As for the other cases, not much interaction occurs once the zero-valent iron has been corroded.

- The largest effect on montmorillonite alteration is predicted for the case where sulphate reduction is included. This could occur for example in the interface zone between the rock, the corroded shell and the buffer where the swelling pressure is reduced. The effect on montmorillonite is indirect via increase in pH from the global redox reaction:

\[ 4Fe + 10H^+ + SO_4^{2-} \rightarrow FeS(s) + 3Fe^{2+} + 4H_2O \]  

This pH increase which cannot be fully compensated by the formation of corrosion products leads to the dissolution of montmorillonite and subsequent precipitation of the zeolites. The extent of the altered zone after 5000 years is somewhat larger, about 5 cm.
As with the other test cases, no significant further alteration occurs once the corrosion reaction has ceased.

The main conclusions from this experimental study can be summarised as:

The results confirm previous ones in that the extent of montmorillonite alteration is predicted to remain spatially limited to a few centimetres from the iron source. The largest impact occurs during the initial corrosion reaction where clay dissolution may be triggered by the generation of OH-. The pH buffering reaction in the clay as well as from carbonate reservoir in the surrounding host rock will limit the increase in pH. The largest effect predicted from reactive transport modelling is the case where (microbially-induced) sulphate reduction would occur. Because of hostility of the compacted clay environment towards microbial activity, sulphate reduction will be limited, if occurring at all, to the interface zone between the host rock, shell and the clay buffer.

The modelling exercise highlights that the main uncertainties are reaction kinetics of minerals and thermodynamic data of clays. In spite of these uncertainties, the results are robust with regard to predicting the extent of montmorillonite alteration. The main factors limiting this process are: the diffusional constraints, the effective pH buffering processes in the EBS system and the low solubility of corroded iron products.

5.10.2 Cu-clay interaction

The summary of the review study by /King & Wersin 2012/ on interactions between a copper Supercontainer shell and the bentonite buffer is presented below.

1) Review study

Copper corrosion strongly depends on the redox conditions in the near-field. Initially, oxic conditions will prevail and the Cu material will corrode to Cu(II) species due to reactions with residual molecular O₂ trapped in the pores of the buffer and the gap between the buffer and the rock. The corrosion rates will be rather high (of the order of several to tens of μm/yr initially) and depend, besides O₂ levels, on chloride concentrations in the groundwater, decreasing with increasing Cl concentrations. The total amount of corrosion during the aerobic phase is determined by the amount of atmospheric O₂ trapped initially in the repository. During the oxic period the initial oxygen present in the buffer surrounding the canister and in the gap between the shell and rock will corrode a maximum of 70 mol of copper (0.4 % of the total mass of the shell). Upon depletion of the residual O₂, anaerobic conditions will be established leading to an entirely different corrosion behaviour. The corrosion rate will decrease and the main corrosion agent will be sulphide derived from the groundwater. Moreover, a further sulphide source induced by microbially-driven sulphate reduction at the buffer/rock interface cannot be ruled out. Under these conditions, copper sulphide (Cu₂S) will be formed and Cu(I) species will predominate.

On the basis of literature data and site-specific information corrosion rates for Olkiluoto and Forsmark conditions for the anaerobic conditions after oxygen depletion were estimated as summarized in Table 5-2. This highlights that initially Cu shell corrosion rates at closure after oxygen depletion are estimated to be similar for both sites. Due to
the higher sulphide levels at Olkiluoto, higher long-term corrosion rates are expected at this site. The pessimistic highest corrosion rates would occur in case of high sulphide concentrations based on the estimates of a high sulphide production rate in the backfill for a KBS-3V type repository at Olkiluoto /Pastina & Hellä 2006/ and low buffer densities with a sulphide diffusivity in bentonite as in the bulk solution which might arise from slow homogenization of the buffer material in the shell/rock interface region. Note that for these rates microbially-induced sulphate reduction is assumed to occur, which significantly contribute to HS\(^{-}\) fluxes and Cu corrosion rates.

From the estimated long-term anaerobic corrosion rates, corresponding \(H_2\) production rates were derived (Table 5-2). For the Olkiluoto site, these are relatively low \((8 \times 10^{-7} \text{ m}^3 \text{ H}_2 \text{ STP m}^{-2} \text{ yr}^{-1})\) for the realistic case, hence range where gas can escape in dissolved form. Only for the pessimistic case \((4 \times 10^{-3} \text{ m}^3 \text{ H}_2 \text{ STP m}^{-2} \text{ yr}^{-1})\) the calculations suggest that the formation of a separate gas phase is possible.

**Table 5-2. Estimated upper Cu shell steady-state corrosion rates for realistic (high) buffer density and conservative (low) buffer density.**

<table>
<thead>
<tr>
<th>Olkiluoto</th>
<th>Forsmark</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At closure after oxygen depletion</td>
</tr>
<tr>
<td>HS(^{-}) concentration (mol/L)</td>
<td>(2 \times 10^{-5})</td>
</tr>
<tr>
<td>Total steady-state sulphide corrosion rate of copper supercontainer shell (µm/yr); buffer density 2000 kg/m(^3)</td>
<td>(6.4 \times 10^{-4})</td>
</tr>
<tr>
<td>Pessimistic case; Total steady-state sulphide corrosion rate of copper supercontainer shell (µm/yr) very low buffer density and high diffusivity of HS(^{-})</td>
<td>(1 \times 10^{-1})</td>
</tr>
<tr>
<td>Range of (H_2) production rate (m(^3) STP-m(^{-2})-yr(^{-1}))</td>
<td>(8.4 \times 10^{-7}) to (3.79 \times 10^{-3})</td>
</tr>
</tbody>
</table>

The interaction processes between corrosion-derived Cu and the bentonitic clay can be assessed by various means. From the evaluation of diffusion-type studies a contrasting behaviour for Cu(II) and Cu(I) can be deduced. At high dissolved \(O_2\) concentration and/or low \(Cl^-\) concentration, dissolved copper exists primarily in the Cu(II) oxidation state. Cupric species are strongly sorbed by the clay, resulting in high interfacial total copper concentrations and steep concentration profiles. Conversely, at low \([O_2]\) and/or high \([Cl^-]\), the Cu(I) oxidation state is stabilised, in the form of dissolved \(CuCl_2^-\) species. Being an anion, the \(CuCl_2^-\) is not strongly sorbed and diffuses relatively rapidly through the bentonite, resulting in the extended copper concentration profiles.

The strong affinity of Cu(II) to the smectite mineral surface is confirmed by numerous sorption studies. Spectroscopic data indicate covalent binding of Cu(II) at edge surface
sites. Under thermal treatment (T > 200 °C) Cu(II) is incorporated in the interlayer structure (mainly in hexagonal cavities) which, at high Cu(II) loadings has a strong impact on the bulk properties of bentonite and leads to significantly reduced swelling capacity. The relevance of this process for KBS-3H type conditions is considered to be small in spite of remaining uncertainties with regard to long-term effects. The impact of Cu(II) on the buffer was estimated from simple diffusion-retardation considerations and the total amount of available residual O2. Thus, a diffusion distance of 2 - 6 cm into the buffer was deduced. The amount of Cu(II) taken up by the clay in this zone was estimated to be rather small compared to its cation exchange capacity.

The interactions of Cu(I) with the clay are much weaker than those of Cu(II) species. However, a systematic investigation on potential uptake of Cu(I) to clay surfaces is lacking so far.

From the above considerations it can be inferred that the main process affecting the buffer is corrosion resulting from interaction of the Cu surface with sulphide and leading to an insoluble Cu2S layer of approximately 2-3 times the volume of the original shell. Bentonite within a few cm of this layer may also contain a small amount of copper sulphide due to the conversion of aerobic corrosion products that had diffused away from the shell prior to the onset of anaerobic conditions. There is no evidence that bulk properties of the bentonite (swelling pressure, hydraulic conductivity or sorption capacity) would be adversely affected by interaction with copper corrosion products. In addition, because of the very low solubility of Cu2S, dissolved Cu porewater concentrations will be very low (< 10⁻⁹ M). The possible changes in bulk properties are thus limited to an interfacial zone of <3 cm enriched in Cu2S between the Cu source and bentonite source. The extent of this zone is estimated from the assumption of complete corrosion of the Cu shell and accounting for the molar volume of Cu2S. The hydraulic properties of this zone are uncertain.

Because of its exposure closer to the rock, the Cu shell may corrode at a higher rate compared to the Cu canister, in particular if microbial activity were to occur in the rock/shell region. The Cu shell will moreover limit the flux of HS⁻ to the canister by the corrosion process until it has completely corroded. The period for this corrosion process depends on HS⁻ groundwater concentrations and buffer density and is estimated to be between 2'400 and 1.5 x 10⁷ years.

In summary, the impact of Cu derived corrosion from the shell on the buffer's performance is expected to be very limited from the review study. The main uncertainties derived from this assessment include potential interaction processes between Cu(I) and the clay, such as for example the possibility of oxidation to Cu(II) by structural Fe(III) and simultaneous reduction of Fe(III) to Fe(II), as well as the bulk properties of the copper sulphide corrosion layer. There are also uncertainties in the bulk properties of the copper sulphide corrosion layer and of a few centimetres of bentonite adjacent to this which may contain a small amount of copper sulphide, produced from aerobic corrosion products that had diffused away from the shell prior to the onset of anaerobic conditions. The consequences of a disturbed buffer/rock interface for long-term safety are discussed later in this section.
2) Copper corrosion in compacted MX-80

In the long-term experimental study reported by Kumpulainen et al. 2010/, compacted saturated bentonite samples partly containing a cast iron cylinder in the centre were in contact with copper vessels. The main focus was the study of iron-bentonite interactions which is presented in more detail in the following section. A side aspect of the study was the analysis of copper profiles in the bentonite samples extracted after 8.2 years of reaction time in order to estimate Cu corrosion rates. For this purpose, four profiles were analysed with aid of acid digestion of the slices cut perpendicular to the Cu source followed by ICP-OES analysis.

The results are summarized in Table 5-3. These show consistent corrosion rates for all four samples, with an average corrosion rate of 0.035 μm/a. It should be noted that this calculated corrosion rates omit possible precipitated corrosion products at the metal surface. From visual inspection (shiny surface), however, the amount thereof is presumably negligible. The time-averaged corrosion rate is likely due to some initial oxygen present in the system which upon depletion is much smaller. This experiment thus represents early transient phase of evolution of the system going from oxic to anoxic conditions.

The obtained corrosion rates are somewhat lower than those reported from the LOT A2 experiment at Åspö /Karnland et al. 2009/ who estimated rates of 0.14 - 1.8 μm/a. A further corrosion study in compacted Ca bentonite /Kim et al. 2007/ reported a corrosion rate of ~0.2 μm/a. In both of these studies, conditions evolved from aerobic to anaerobic conditions, thus reflecting a "mixed" corrosion rate. The comparison of corrosion rates suggests that conditions in the study of Kumpulainen et al. 2010/ were more reducing than the two other ones although also in this case initially conditions were oxic, thus, causing higher corrosion rates until oxygen was consumed from the system. Sulphide was not measured in the system and therefore it is not known if sulphide was present in the long-term and affected Cu corrosion rates.

Table 5-3. Calculated Cu corrosion rates from Cu concentrations in study of Kumpulainen et al. (2010). For all calculations background in MX-80 Cu concentration conservatively assumed to be zero.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cu conc. background (wt%)</th>
<th>Cu conc. interface layer (wt%)</th>
<th>Thickness of layer c (mm)</th>
<th>Cu corrosion rate (μm/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6c</td>
<td>&lt;0.04</td>
<td>0.12</td>
<td>1.5</td>
<td>0.036</td>
</tr>
<tr>
<td>19c</td>
<td>&lt;0.04</td>
<td>0.09</td>
<td>2</td>
<td>0.034</td>
</tr>
<tr>
<td>20c</td>
<td>&lt;0.01</td>
<td>0.09</td>
<td>2</td>
<td>0.038</td>
</tr>
<tr>
<td>29b</td>
<td>n.m.*</td>
<td>0.08</td>
<td>2</td>
<td>0.03</td>
</tr>
</tbody>
</table>

* not measured

5.10.3 Ti-clay interaction

Titanium metals display very low corrosion rates (< 1 nm/a) over a large range of chemical (pH, Eh, salt content) conditions /Hua et al. 2004/. The corrosion behaviour is governed by the low solubility of tetravalent TiO₂ which forms a passive surface corrosion layer under both oxic and reducing conditions. The dependence of the composition and properties of the titanium oxide film on electrochemical potential has
been extensively studied. The different factors controlling film growth are understood, as are the associated corrosion processes /Shoesmith 2006/. Amongst all the common engineering alloys, Ti is perhaps the only one believed to be immune to microbially-induced corrosion /Little et al. 1991/.

The interactions between titanium and clay have been barely studied so far. Preliminary long-term data obtained by Prof. Olefjord and co-workers from Chalmers (S) in the 1980ies (as part of SKB's canister program) indicates similar corrosion rates in compacted bentonite compared to those measured in water, i.e. \( \leq 1 \text{ nm/a} /\text{Mattsson \\& Olefjord 1984/}. \) So far, no work on reaction products from this interaction process has been carried out. Even the speciation of Ti in natural clays is uncertain. In principle, five possible reaction products resulting from Ti-clay interactions are possible: (i) Ti sorbed to the clay surface via cation exchange or specific adsorption, (ii) Ti incorporated in the octahedral or tetrahedral clay structure, (iii) Ti precipitated as separate TiO\(_2\) or mixed (Fe, Ti) oxide, (iv) Ti precipitated as separate silicate phase and (v) polymerized as cross-linked TiO\(_2\) units in the interlayer (Ti pillared clay). The latter two transformation products would have the strongest impact on the buffer, but are improbable on the basis of current knowledge. The geochemistry of Ti, its behaviour in natural environments, with a particular focus on clay-rich ones, and possible interaction processes with clays are outlined in detail in /Wersin et al. 2010/. In the second part of that report, the preliminary Ti-bentonite interaction study is documented.

**Preliminary batch study on Ti-clay interactions**

The scope of this preliminary and pioneering study was to shed more light on Ti-clay interaction processes and on the Ti species resulting from these interactions. Because of the known very low corrosion rates of Ti alloys, a main focus was to analyse the reacted clay materials with advanced spectroscopic techniques. Synchroton-based x-ray absorption spectroscopy (XAS) and \( \mu \)-XRF were the main tools applied for this purpose.

Two series of batch experiments were conducted, the results of which are presented in /Wersin et al. 2010/ and summarised below. Currently, a third series of batch tests is foreseen.

**1st series of batch tests & spectroscopic baseline study:**

In these tests, purified MX-80 powder (2g) was reacted with Titanium nanopowder (2g) or with Ti foil in 0.1 M NaCl solutions (100 mL) previously purged with N\(_2\) at room temperature. The Ti nanopowder was contained in a dialysis bag (Spectropore 7) in order to facilitate separation of the two solid materials after reaction. The samples were centrifuged after about 4 months of reaction time and both solution and solid were analysed.

The XRF bulk analysis of the raw and purified MX-80 showed a Ti content of about 0.1 wt\%, in agreement with previous studies. This indicates that Ti is not removed by the purification procedure. Rokle bentonite (raw) showed a considerable higher content (~2.5 wt\% Ti).
The results from solution analysis indicate, as expected, low Ti concentrations low, even for samples adjusted initially to extreme pH conditions (pH 2 and pH 12). The measurable Fe concentration (expect for the high pH sample) indicates that in fact anoxic conditions were achieved.

XAS analysis on clay reference samples and selected reacted batch samples was carried out at the Swiss Light Source (SLS), Paul Scherrer Institute (Switzerland). The reference samples included purified MX-80, raw Rokle bentonite, Opalinus Clay, illite du Puy as well as Ti standard minerals rutile, anatase and titanate (CaTiSiO₅). The XANES (x-ray absorption near edge structure) spectra for Rokle bentonite and Opalinus Clay are depicted in Fig. 5-5. These reveal the same spectral features as for anatase, thus indicating that Ti in these clay materials occurs predominately as small TiO₂ particles. A different result was obtained for illite du Puy and MX-80 bentonite which show similar spectra as that of CaTiSiO₅ (Fig. 5-6). This suggests that Ti in these latter clay materials is bound in the clay structure (presumably in the octahedral layers).

![Figure 5-5. Ti XANES spectra of two natural Ti-clay materials (Rokle Clay, compared to anatase TiO₂. Note the close match of the pre-edge features.](image-url)
Figure 5-6. XANES spectra of MX-80 and Illite du Puy, compared to that of titanate.

The XAS analysis of the reacted MX-80 samples indicated no difference with regard to the unreacted material. From the obtained XANES and EXAFS spectra in combination with the XRF results it could be concluded that the amount of Ti that reacted from the corrosion process was too small to yield any information on Ti speciation. This was true for all studied samples, including also the high and low pH ones.

2nd series of batch tests:

The main scope of these series was to enhance Ti transfer from the metal to the clay, thus to enable spectroscopic analysis of the Ti released from corrosion and taken up by the clay. For this purpose, synthetic "Ti-free" montmorillonite produced by hydrothermal synthesis was used as starting material. From elemental analysis (determined by XRF) and thermal gravimetry analysis (TGA), the following structural formula could be derived: \( \text{Na}_{0.34}[\text{Al}_{1.64}\text{Mg}_{0.37\pm 0.09}\text{Si}_{4.00}][\text{Si}_{4.00}]\text{O}_{10}(\text{OH}_{1.95}\text{F}_{0.05})\text{4H}_{2}\text{O}, \) where \( \square \) stands for vacancy. This confirms that the synthesised product is dioctahedral smectite. A further difference with regard to the 1st series is the higher temperature (80 °C) at which experiments were conducted, in order to increase corrosion and transfer rates to the clay. Other than that, the experimental procedure was very similar: the synthetic montmorillonite was contacted with Ti nanopowder and foil in 0.1 M NaCl solutions in a N\(_2\) purged glovebox for about four months.

The results from solution analysis generally confirm those obtained for the 1st series. Ti concentrations were very low (< quantification limit). On the other hand, the sample with purified MX-80 exposed to Ti nanopowder for 17 months revealed higher Ti concentrations of about 5 mg Ti /l. The same trend was observed for Fe, where the
purified MX-80 sample displays a Fe concentration of about 200 mg/l, or about 3.5 mM. The initial pH of the synthetic montmorillonite exposed to 0.1 M NaCl was rather low (~5.1) which is explained by the preparation behaviour of this material /Wersin et al. 2010/. At the end of experiment, however, all samples showed pH values close to 7.

Micro-XRF analysis, which was carried out with a focussed x-ray beam, showed extremely low Ti concentrations for the synthetic montmorillonite, contrary to purified MX-80 (Fig. 5-7). This confirmed the suitability of this material to study Ti-clay interactions.

Figure 5-7. Synchrotron-based XRF spectra showing the Ti content of different synthetic clay samples after exposure to Ti. For samples 20 and 23 the Kα and Kβ emission lines of Ti are clearly visible. The other samples exhibit Ti contents at the limit of detection (less than two-fold the background count rate) and are statistically indistinguishable from blank samples.

Another result of this analysis was the identification of small Ti metal particles on the clay surfaces for samples with Ti nanopowder (emplaced in dialysis bags). The remaining surface did not show any or showed only extremely low concentrations of Ti. This indicates that the samples were contaminated with metal Ti nanoparticles by the experimental procedure. The analysed sample with bentonite exposed to Ti foil showed measurable Ti concentrations (sample 23), which is not attributed to any experimental artefact. This was confirmed by preliminary XAS analysis which indicated a different coordinative environment for Ti than that of Ti metal (Fig. 5-8). In fact, the XANES spectrum is similar to that of titanate, thus suggesting that Ti occurs in the clay structure
or is surface-bound. This result for one sample can only be regarded as preliminary at this point and needs to be supported by further data.

**Figure 5-8.** MicroXANES spectra recorded for sample 23. a) microXANES of a localized contamination hot spot. Spectrum is indicative of metallic Ti. b) microXAS of the homogeneous Ti content induced by the corrosion exposure. Characteristic single pre-edge feature points towards a Ti speciation similar to the Ti coordination environment found in CaTiSiO₅ (titanite).

The following conclusion can be drawn from the preliminary Ti-clay interactions study:

- Titanium is a very inert material forming a very insoluble TiO₂ corrosion layer under both oxic and anoxic conditions. As revealed from previous studies, including a long-term study in compacted bentonite /Mattson & Olefjord 1984/, the corrosion rate of Ti metals is very low, in the range of 1 nm/a or lower.
- Spectroscopic analysis on a number of natural and purified clay materials showed that Ti occurs either as small TiO₂ particles (e.g. Rokle bentonite) or is incorporated in the clay structure (MX-80). Differences in Ti concentration or speciation do not appear to affect the bulk properties of bentonite, as indicated from the study of /Karnland et al. 2006/.
- Because of the high Ti background concentration, meaningful experiments on Ti-bentonite interactions are difficult. The use of synthetic "Ti-free" montmorillonite yielded promising results in this regard. This material is recommended in future experiments to unravel the speciation of Ti transferred to the clay via the corrosion process.
- Preliminary data suggest that Ti released from corrosion is in fact transferred to the clay. This, however, needs to be supported by further data in order to allow for conclusive results. The experimental setup with Ti nanopowder, however, proved not suitable because of experimental artefacts induced. Further batch tests with coarser grained Ti material are recommended.

A third series of optimised tests is foreseen for the period 2012-2014.
5.10.4 Summary comparison of the three metal materials

Table 5-4 summarises corrosion rates and related properties for Fe, Cu and Ti in their function as Supercontainer shell materials. The highest corrosion rates are exhibited by metallic iron which is unstable in water. The associated volume increase of the metal structure depends on the molar volume of the corrosion product formed: for magnetite the volume increase by a factor of 2 whereas for iron sulphides or green rust it is larger. For Cu and Ti, the volume is expected to increase by a factor of about 2. The rate of hydrogen production which is directly linked to the corrosion rate is highest for iron, where the formation of a separate gas phase is possible. For Ti, the hydrogen production rate is very low in view of the low corrosion. For Cu, the corrosion rates and H₂ production strongly depend on sulphide levels (see Section 5.2.2).

Table 5-4. Comparison of corrosion rates and related properties for Fe, Cu and Ti as Supercontainer shell materials.

<table>
<thead>
<tr>
<th></th>
<th>Fe</th>
<th>Cu</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>anoxic corrosion rate</td>
<td>0.5 - 2</td>
<td>0.001 - 0.5*</td>
<td>≤0.001</td>
</tr>
<tr>
<td>(µm/a)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>expected corrosion product(s)</td>
<td>magnetite, GR, FeS_{1+x}</td>
<td>Cu₂S</td>
<td>TiO₂</td>
</tr>
<tr>
<td>volume increase factor (relative to metal)</td>
<td>2 - 4</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>H₂ production rate</td>
<td>high</td>
<td>low - medium</td>
<td>low</td>
</tr>
</tbody>
</table>

* upper limit based on sulphide concentration of 1·10⁻⁷ mol/l (rather than 3.6·10⁻⁴ mol/l proposed in King & Wersin 2012)

5.10.5 Impact of hydrogen formed

Hydrogen is generated by the corrosion of all potential shell materials. Due to its very low corrosion rate Titanium will slowly release only minor amounts of H₂ which will dissipate via diffusion. Copper corrosion in the presence of sulphide will produce H₂, but the rates of H₂ production will generally be small, such that H₂ will be transported away in dissolved form. Only under very conservative assumptions (i.e. large HS⁻ fluxes, and low buffer densities), H₂ generation may be sufficiently high in the tighter sections of Olkiluoto for copper, such that a separate gas could form /King & Wersin 2012/. In the case of iron, the highest hydrogen fluxes will be induced (e.g. /King 2008/), which may lead to a separate gas phase and large hydrogen partial pressures, depending on the hydraulic properties of the surrounding rock.

Hydrogen may eventually influence the porewater chemistry of the buffer bentonite, but the expected largest impact is due to the use of hydrogen as an energy source in the microbial reduction of sulphate to sulphide.
Hydrogen is generated by the corrosion of all potential shell materials, but only in the case of iron is the expected generation rate high enough to lead to the formation of a separate gas phase and, in relatively tight drift sections, potentially large hydrogen partial pressures may form that may affect bentonite porewater chemistry. The impact of microbially-mediated processes involving H₂ on porewater chemistry depends on the interplay of kinetically-controlled microbial redox reactions and iron corrosion, mineral dissolution / precipitation (e.g. calcite) and diffusional processes. Moreover, the geochemical conditions in the rock surrounding the buffer will strongly affect the extent of microbial activity. Preliminary considerations of relevant chemical reactions, scoping calculations and the results from reactive transport modelling indicate that the presence of hydrogen, together with corroding iron, will render porewater more alkaline and lower the redox potential. Thus, analysis from a recently updated thermodynamic model for compacted bentonite /Wersin et al. 2012/, and taking into account surface reactions in the clay, the carbonate system and the precipitation of corrosion products, indicate that porewater pH will be buffered to slightly alkaline values (7.9 - 8.8), and will be unaffected by large hydrogen partial pressures. These findings are further supported by reactive transport calculations using the CrunchFlow code. Microbial processes may also generate or consume hydrogen, and one important aspect is that SRB may use hydrogen for reduction of sulphate to sulphide.

Microbial processes generating or consuming H₂ occur in deep groundwaters and are relevant at Olkiluoto, where at repository depth and below sulphate reducing bacteria (SRB), methanogens, iron reducers, acetogens, nitrate reducers and manganese reducers have been identified /Pedersen 2008/. SRB may utilize H₂ for the sulphate reduction reaction and release hydrogen sulphide. Thus, high hydrogen favours sulphate reduction, which at low H₂ levels occurs mainly from the oxidation of dissolved organic matter (DOC).

5.10.6 valuation of the consequences of disturbed buffer/rock interface

In the safety analysis of a KBS-3H repository /Smith et al. 2007a, 2007b/, radionuclide transport calculations were carried out in which the buffer/rock interface was considered to be significantly perturbed, e.g. by the presence of the Supercontainer and its corrosion products or by thermally-induced rock spalling. In these calculations, the interface zone was treated as a “mixing tank” of effectively infinite hydraulic conductivity, due to the absence of data on its likely spatial extent and bulk properties.

In the Complementary studies of horizontal emplacement KBS-3H 2008 –2010, scoping calculations have been carried out to illustrate more realistically the impact of perturbations to the buffer/rock interface on flow around a deposition drift and mass transfer between the KBS-3H buffer and flowing water. The calculations have shown that use of the “mixing tank” flow rate is conservative in all cases considered. These include cases where flow is parallel to the deposition drift as well as perpendicular to the drift, and in which the host rock is treated as either an equivalent porous medium or as a fractured medium. It has also been shown that various more realistic approximations to the flow through the interface zone and to the consequent radionuclide release rates to the rock could be used if values for the quantity Kₒᵣ (the product of zone thickness and hydraulic conductivity) could be obtained experimentally. The most appropriate approximation will depend on whether diffusion or advection is
the dominant process moving radionuclides out of the interface zone into the rock. The dominant transport process needs to be checked on a case-specific basis.

5.10.7 Summary

Establishing evidence on the long-term performance of the buffer including interaction with other materials was one of the main objectives of the recent KBS-3H project phase.

From the safety perspective, the most important aspect is the Supercontainer shell-clay interaction, which also has been the focus of these studies. When comparing the metal-clay interactions a number of questions have been discussed related to the corrosion properties, solubility, diffusion and sorption properties, evidence from natural analogues and known impact on physical properties of the clay and finally also the remaining uncertainties.

- The corrosion behaviour of all metals is well known. The corrosion rate and production rate of hydrogen is lowest for Ti and highest for Fe, for which the possible risk of formation of a gas phase in very dry sections is thus also the highest. Solubility for all metals is low, but lowest for Cu and Ti.
- Ti is present as TiO₂ and in the clay structure in bentonites in various amounts, but these clays do not show any differences in the physical properties.
- Fe is known to react with bentonite by sorption and formation of non-swelling silicate phases. Cu as Cu(II) is very reactive at high temperatures, but Cu(I) reactivity towards the clay is low as indicated from diffusion profiles. Natural analogues also suggest a low reactivity for Cu(I). Ti is considered to be one of the most inert materials on earth and one of the most corrosion-resistant materials.
- Reported impact on physical properties of bentonite is highest for Fe, but very little is known about the impact of Cu and Ti. The extent of impact seems to be limited for all metals, due to the low corrosion rate and solubility for Cu and Ti, low solubility and slow diffusion rate for Fe. The range of impact according to modelling studies is expected to be 3-5 cm for Fe(II) and 2-3 cm for Cu.
- For all materials (Cu, Fe and Ti) there remain a number of uncertainties related to process understanding, formation of phases, diffusion and sorption, and possible impact on the physical properties in relevant repository conditions.

Titanium is expected to be the most inert, having lowest corrosion rate and lowest rate of production of hydrogen. In addition, this element is already present in various amounts in natural bentonites which have been shown to display favourable properties as buffer materials.
6  KBS-3H LAYOUT ADAPTATION TO OLKIUOTO SITE

6.1 General

In this chapter the technology, layout and stepwise implementation of the final repository at Olkiluoto bedrock in KBS-3H concept are described.

In KBS-3H concept the canisters are going to be emplaced one after another in 150 – 300 metres long deposition drifts. Canisters are transferred to the repository level along the canister shaft. In the reloading station at the disposal level the canisters are packed in Supercontainers. The Supercontainers are transported in a transport shielding tube to the disposal area by a transfer vehicle. The transfer vehicle is based on self propelled modular transporter (SPMT).

At the disposal area the Supercontainers are installed into the deposition drift with a deposition machine. The Supercontainers are moved on top of a very thin water film with a lift pallet. The force needed to push them forward in the deposition drift is relatively small compared to the weight of the Supercontainer. The deposition machine pushes the Supercontainers in 1.5 metre long steps. The Supercontainers cannot be installed into the deposition drifts one after the other because of the thermal dimensioning. The bentonite distance blocks are installed between Supercontainers. The length of the distance blocks vary from 3 to 5 metres. Distance blocks are installed into the deposition drifts with the deposition machine just like the Supercontainers.

6.2 Site information

The description of the Olkiluoto site is given in various references, but a detailed description is given in the “Olkiluoto Site Description” /Posiva 2011/ concentrating on the host rock and in the Biosphere Description” /Posiva 2012f/ for the surface environment. A very concise description is given e.g. in /Posiva 2012b/.

6.3 Layout adaptation

6.3.1 General

The updated layout adaptation to the Olkiluoto site was done using the same principles as in the KBS-V adaptation /Kirkkomäki 2009/ in 2009. The total amount of canisters was 2,820 (5,600 tU). The drift spacing was 25 m and the canister spacing varied from 7.2 m to 10.6 m depending on the canister and spent nuclear fuel type. The layout was carried out assuming a one-storey repository design.

The bedrock model /Hellä et al. 2009/ was the same as in the KBS-3V adaptation /Kirkkomäki 2009/, see Fig. 6-1. It is based on the data /Posiva 2009a/ that was available in 2009. The latest data and bedrock model are a slightly different, but in this work it was decided to use the same bedrock model so that the two adaptations were made comparable. The principle of having two parallel central tunnels, a tunnel pair, used in the KBS-3V adaptation /Kirkkomäki 2009/ was also used in this work. The deposition drifts are connected to the parallel central tunnels. The distance between the central tunnels is about 20 metres. The purpose of using the parallel tunnel principle is to ensure the maximum flexibility in construction and operation phases.
The two parallel central tunnels provide also efficient emergency exit facilities. In KBS-3H there are interconnections between the two tunnels in every 25 metres i.e. the locations of deposition niches. In the case of KBS-3V there are interconnections in about every 100 metres. The central tunnels are separated in two different fire compartments. This allows quick movement from one fire compartment to another in the event of an accident.

The length of the deposition niche is about 23 metres. The distance between the central tunnels is about the same and the niches can be made between the central tunnels. This configuration gives the opportunity to operate two deposition drifts from one niche. This saves excavation volume and gives better efficiency of the use of the deposition area.

Figure 6-1. The major fractured zones (gray) at Olkiluoto according to the 2009 research data, ONKALO (green) and coastline (blue) /Kirkkomäki 2009/.

The layout adaptation to the Olkiluoto site for 3H variant will be updated, see /Posiva 2012a/. The upcoming update will include the 3H-specific features like assembly and reloading station as well as the storage rooms for Supercontainers and other drift components.

Application of Rock Suitability criteria (RSC) for KBS-3H layout adaptation together with the subsequent needs for any potential characterization methodology specific to 3H concept will be introduced in a later stage /Posiva 2012a/.

6.3.2 Stepwise construction of the underground repository

The KBS-3H layout adaptation to the Olkiluoto site is presented in Fig. 6-2. There are 122 deposition drifts and the total length of drifts is 31.6 km. The total length of the central tunnels is 9.2 km. The total excavated volume of the disposal facility is 920 800 m³. The volume of the deposition drifts is 84 800 m³ and the central tunnels
441 000 m³. The total volume of the disposal facility is not going to be excavated at once. It has been divided into eight excavation phases, Fig. 6-3. Building of the underground research facility ONKALO is the first one. It begun in year 2004 and has been completed. ONKALO rooms will form the basis for the rest of the disposal facility. The implementation of the disposal facility will commence with extending the ONKALO facility. Before the disposal of the canisters is started, the central tunnels and deposition drifts that are needed in the first deposition stage will be constructed. The total excavated volume of the preparation stage is 182 900 m³. During the operational stage more central tunnels and deposition drifts are constructed in six excavation stages with an average excavating volume of about 52 500 m³, see Table 6-1.

Figure 6-3. KBS-3H layout adaptation to the Olkiluoto site /Kirkkomäki & Rönnqvist 2011/. The layout area shown is between fractured zones R20 and R21, see Fig. 6-1.

6.3.3 Excavated volumes in 3H and 3V

Excavated volumes between the two concepts have been compared by Kirkkomäki & Rönnqvist /2011/. The work included KBS-3H layout adaptation based on the same amount of canisters and the same rock model as was used for the same work for KBS-3V /Kirkkomäki 2009/. The objective was to make the two adaptations comparable. Additionally the same minimum canister spacing was used. In both adaptations the same utilization degree was deployed i.e. 10 % more canister positions than the actual number of canisters (2 820 pcs.) were included in the drifts. The total lengths of deposition drifts in KBS-3H and deposition tunnels in KBS-3V are quite similar.

The total excavated volume in the 3H variant is about 200 000 m³ smaller than in the 3V variant. The most significant difference is caused by the total volumes between deposition drifts and deposition tunnels. The total volume of the deposition drifts in 3H is below 100 000 m³ whereas the total volume of deposition tunnels including the vertical deposition holes is about 5-folded i.e. close to 500 000 m³, see Table 6-2.
The total volume of parallel central tunnels in the 3H variant is clearly larger, difference being 135 600 m³, than in the 3V variant. For the KBS-3V layout the total volume of the central tunnels is only 287 200 m³, see Table 6-2. This is due the more straightforward layout adaptation of the area NE of the technical rooms in the 3V concept. Additionally the maximum length of the deposition tunnels is 50 metres longer than the maximum length of the deposition drifts. This combined to the shape of the deposition area and the orientation of the deposition drifts makes it impossible to use efficiently the same layout in KBS-3H. To cover the deposition area efficiently the layout of the central tunnels has to be more complex. In the 3V variant the NE repository area is covered with only one parallel central tunnel pair in the SW-NE direction. In the 3H variant covering the same area an increased length of central tunnels is needed.

Table 6-1. Excavation phases of the underground disposal facility excluding the volume of the deposition drifts /Kirkkomäki & Rönnqvist 2011/. Phases 1 to 6 are shown in Fig. 6-4.

<table>
<thead>
<tr>
<th>PHASE</th>
<th>VOLUME (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ONKALO</td>
<td>337 921</td>
</tr>
<tr>
<td>Preparatory phase</td>
<td>182 940</td>
</tr>
<tr>
<td>Phase 1</td>
<td>47 384</td>
</tr>
<tr>
<td>Phase 2</td>
<td>59 981</td>
</tr>
<tr>
<td>Phase 3</td>
<td>57 141</td>
</tr>
<tr>
<td>Phase 4</td>
<td>44 896</td>
</tr>
<tr>
<td>Phase 5</td>
<td>68 781</td>
</tr>
<tr>
<td>Phase 6</td>
<td>36 926</td>
</tr>
<tr>
<td>TOTAL</td>
<td>835 970</td>
</tr>
</tbody>
</table>

In Olkiluoto’s case the footprint is just slightly larger in KBS-3H design compared to KBS-3V. The same tunnel/drift spacing (25 m) between deposition tunnels/drifts was used. In KBS-3H design the length of the drifts is limited to 300 m and in KBS-3V the corresponding maximum length of a deposition tunnel is 350 m. The total excavated volume of the repository was about 921 000 m³ for KBS-3H design and about 1 166 000 m³ for KBS-3V. There are 122 deposition drifts in the underground repository and the total length of the drifts is 31.6 km. The total length of the central tunnels connecting the deposition drifts is 9.2 km. In both designs the utilization degree was estimated to be the same. The layout was designed for a number of canister positions that is 10 % higher (3 102 pcs.) than actually needed (2 820 pcs.).

The average open volume of the underground repository during the operational stage is about 577 000 m³. The average open volume of the repository does not differ in the H- and V-concepts. The largest open volume during the operational phase at a time in the disposal facility is about 695 700 m³. That is 77 % from the total volume. Minimum open volume during the operational phase is 520 900 m³, which is 58 % from the total volume. The average open volume during the operational phase is 577 100 m³.
**Table 6-2.** Comparison of the excavated underground volumes in the repository between the two concepts /Kirkkomäki & Rönqvist 2011/.

<table>
<thead>
<tr>
<th>Description</th>
<th>KBS-3H</th>
<th>KBS-3V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of deposition drifts/tunnels</td>
<td>122 pcs.</td>
<td>105 pcs.</td>
</tr>
<tr>
<td>Total length of the deposition drifts/tunnels</td>
<td>31 547 m</td>
<td>31 244 m</td>
</tr>
<tr>
<td>Average length of the deposition drifts/tunnels</td>
<td>259 m</td>
<td>298 m</td>
</tr>
<tr>
<td>Maximum length of the deposition drifts/tunnels</td>
<td>300 m</td>
<td>350 m</td>
</tr>
<tr>
<td>Total volume of the underground repository</td>
<td>920 769 m$^3$</td>
<td>1 166 398 m$^3$</td>
</tr>
<tr>
<td>Total excavated volume of the underground repository excl. deposition drifts/holes</td>
<td>835 970 m$^3$</td>
<td>1 114 301 m$^3$</td>
</tr>
<tr>
<td>Total volume of the deposition tunnels</td>
<td>-</td>
<td>436 681 m$^3$</td>
</tr>
<tr>
<td>Total volume of the deposition drifts/holes</td>
<td>84 799 m$^3$</td>
<td>52 096 m$^3$</td>
</tr>
<tr>
<td>Total volume of the central tunnels</td>
<td>440 976 m$^3$</td>
<td>287 201 m$^3$</td>
</tr>
<tr>
<td>Access tunnel, shaft connections, shafts</td>
<td>280 216 m$^3$</td>
<td>280 216 m$^3$</td>
</tr>
<tr>
<td>Technical rooms</td>
<td>78 284 m$^3$</td>
<td>73 730 m$^3$</td>
</tr>
<tr>
<td>Storage for low and intermediate level waste</td>
<td>36 494 m$^3$</td>
<td>36 494 m$^3$</td>
</tr>
<tr>
<td>Maximum volume of open space in the repository</td>
<td>695 723 m$^3$</td>
<td>698 771 m$^3$</td>
</tr>
<tr>
<td>Minimum volume of open space in the repository</td>
<td>520 861 m$^3$</td>
<td>513 259 m$^3$</td>
</tr>
<tr>
<td>Average volume of open space in the repository</td>
<td>577 104 m$^3$</td>
<td>595 812 m$^3$</td>
</tr>
</tbody>
</table>

*) During operation; **) The volumes of the deposition drifts/holes not included
Figure 6-4. Construction phases of the underground disposal facility in Olkiluoto, a) ONKALO, b) preparatory phase and c) – h) excavation phases 1 - 6 /Kirkkomäki & Rönnqvist 2011/. 
7 ONGOING STUDIES TO SOLVE IMPORTANT ISSUES FOR THE LONG-TERM PERFORMANCE OF A KBS-3H DRIFT

7.1 Focus for the next years in the safety work

The KBS-3H project has now established a new reference design, DAWE, and to enable a comparison between KBS-3H and KBS-3V it must now be demonstrated that this design can fulfil the same long-term safety requirements as KBS-3V.

The safety work will be carried out in a stepwise approach. Two issues that could possibly be more troublesome for KBS-3H than for KBS-3V and on which there are not much studies carried out will be addressed early in the KBS-3H System Design phase; these are chemical erosion and earthquake compression shear. The latest input from SR-site will be used to carry out KBS-3H specific scoping calculations of these issues. The selected reference design (DAWE) is expected to function well, taking care of these issues, and unless the calculations indicate otherwise the next step will be initiated, namely a full drift performance assessment (PA).

The drift performance assessment is expected to present the evidences to support that the set performance requirements will be met. The PA report presents the analysis of the performance of the drift under the most likely line of evolution and evaluates the fulfilment of safety function indicators and indicator criteria (SKB), and performance targets and target properties (Posiva) by taking into account the uncertainties in the expected line of evolution. The Design Premises (SKB)/Design Basis (Posiva) will be updated in conjunction with this work by consideration of the recent KBS-3V safety assessments (SR-Site and Posiva KBS-3V safety case) as well as the experience from the earlier KBS-3H safety assessment and especially by considering all components in the drift and the expected thermal, hydrologic, mechanical, geochemical boundary conditions during the evolution of the system.

In parallel with carrying out the drift performance assessment the KBS-3H specific production lines will be produced. These reports will present how the KBS-3H repository is designed, produced and inspected. They will provide the background and sources to the principles to be applied in the design, the functions of the KBS-3H repository and the barrier functions of the engineered barriers and rock. The range of possible initial state for the barriers as constrained by the requirements and implemented according to specifications is presented in the production lines reports including deviations and uncertainties. Further, the methodology to substantiate detailed design premises for the engineered barriers, underground openings and other parts of the KBS-3H repository will be presented.

Earlier layout adaptations, have been based on the KBS-3V layout, i.e. the central tunnel etc. have been the same. In the KBS-3H System Design phase the updated layouts shall address possible optimisations with regards to the horizontal alternative. This means optimisation in relation to e.g. long fractures and rock stress.

The remaining buffer issues are intended to be solved by calculations and large/lab-scale tests to a level that corresponds to what has been achieved in KBS-3V.
The activities presented above will all produce the basis for the safety assessment that will be carried out for Olkiluoto in the coming years. Still a large part of the analysis can be based on reporting for the KBS-3V, such as site and canister data. Many of the issues to be included will be similar to KBS-3V and results from SR-Site and Posiva’s safety case for KBS-3V will be possible to introduce directly in the KBS-3H safety assessments. The focus in the future work will still be on more KBS-3H specific issues, especially related to the evolution and performance of the whole drift and the multiple canister failure modes. But the analyses will be carried out at as complete as for KBS-3V in order to be able to make a full evaluation of the two variants at the decision-making step.

The main basis for further development has been produced within the project but an important input to the planning of the upcoming project phase has been the evaluations carried out by the authorities. SSM has done an evaluation of the joint research, development and demonstration (RD&D) programme carried out by SKB and Posiva in 2002-2007. SSM required its external expert group BRITE (the Barrier Review, Integration, Tracking and Evaluation) to evaluate the reporting. /SSM 2009/. A comprehensive list of key issues are discussed and brought forth by the authorities in this report. Some of the issues have been handled in the current project phase but some require additional studies and full-scale tests to confirm feasibility and confidence in the KBS-3H design.

STUK has also carried out a review of the KBS-3H Safety Case reporting, they raise several critical issues relevant for both KBS-3V and KBS-3H and a number of specific issues for the KBS-3H long-term safety /STUK 2009/. Some of these issues are closely connected to design and the operational period and will hence require full-scale testing to be fully resolved. A number of the issues are related to a better quantification of the number and timing of canister failures, and analyses of multiple canister failures. A specific question raised was the comparison of the impact of rock shear on the KBS-3H vs. KBS-3V. The request for the analyses of consequences of the dilute glacial meltwater intrusion for the KBS-3H alternative as compared to KBS-3V was also raised by both authorities.

The issues brought forth by the authorities are well in line with Posiva’s and SKB’s planning and the issues are recognised as important in the development work towards a KBS-3H repository, such as to handle the possibility of multiple canister failures; to handle the combined effects of more than one disruptive event or process; to ensure all relevant uncertainties are identified and their impacts assessed, including the potential use of probabilistic methods; and to assure quality in the various steps in the production of the safety case.

The feasibility and quality of technical solutions will also be demonstrated by tests and experiments. In this way, a comprehensive safety case will be developed to support a final decision to implement the facility.
7.2 Chemical erosion of the buffer

The chemical erosion of buffer caused by dilute groundwater is an important process, which will be studied primarily within KBS-3V project in the EU-project called “BELBAR” that was started March 1, 2012. Chemical erosion is regarded as a critical issue, which is common between 3V and 3H projects. It may potentially have a significant impact on the design of KBS-3H repository system. The 3H specific study in the study will be included in a later stage /Posiva 2012a/.

7.3 Impact of rock shear (compression shear) on the buffer and the canister

The conclusions of the performed modeling of one of the most severe cases of rock shear through KBS-3H are that the difference in consequences of the rock shear between KBS-3H and KBS-3V repository design alternatives is insignificant at the same type of shear. It has also been concluded that the consequences of the uncertainties regarding the differences between the two models are insignificant. This means that the results and conclusions of the extensive investigations and modeling exercises of a rock shear in KBS-3V can also be used for KBS-3H.

Regarding the second calculation that concerned skew compression shear, the stresses in the welds in the lid were higher than corresponding stresses in the welds in all the modelled cases for KBS-3V. This needs to be considered in the Safety Assessment of KBS-3H /Posiva 2012a/

7.4 Homogenization of buffer

The issue of homogenization of buffer after erosion must be considered as remaining unresolved. Efforts in terms of improving the material models and improving the calculation technique will need to be made in the coming years in order to address this issue conclusively. This issue is common between 3V and 3H projects.

7.5 Buffer erosion in the early evolution – experimental studies on piping and erosion, water transport in a drift

The transient behaviour, especially water absorption rates with respect to time is currently not well specified and there is no experimental information available on this. Main issues in the work are to increase understanding of the process of internal piping and erosion rates and to get representative estimates for the time period required to reach the fulfilment of the performance requirements. Improvement of conceptual understanding of the water transport process is required for the development of modelling techniques.

The issues will be addressed e.g. by small size experiments to study desiccation, piping and erosion followed by long experiment (8 m) at 1:10 scale representing heterogeneous inflow including erosion measurements. Whether buffer in a Supercontainer can “steal” water from distance blocks and would they then lose their function (support/counter pressure) will be addressed experimentally.
7.6 Thermal spalling of the rock during the thermal transient period/POSE

For the most likely in situ stress conditions the excavation of the deposition drifts will not induce spalling at Olkiluoto /Lönnqvist & Hökmark 2007/. After a few years of heating thermal spalling is almost certain to occur in case there is no counter pressure induced by swelling of buffer.

There will be a significant mechanical pressure acting on the rock surface which would indicate that the issue of thermally induced spalling could be mitigated/avoided for the reference design with artificial water filling /SKB 2012/.

The results should be considered indicative, because no thermo-mechanical calculations were carried out. To confirm the preliminary results and to minimize the uncertainties full 3D thermo-mechanical analyses for the KBS-3H design and should be carried out.

This issue must be addressed after the report on POSE experiment will be finalized.

7.7 Other important issues

For other important issue see /SKB 2012/ and /Posiva 2012a/.

The design of filling components has been introduced in the previous project phase. Issues regarding the erosion resistivity and homogenization will be addressed in the current project phase via modelling work, scoping calculations and experimental work. The studies on the erosion resistivity of the filling component material will be focussed on those components placed in the inflow points. The transition zone behind the plugs will be tested in connection with the Multi Purpose Test at Äspö.
8 ONGOING DEMONSTRATION WORK

The planned demonstrations are continuation to the full-scale tests that have been carried out during the previous project phases. In the previous KBS-3H project phase, 2004-2007, two drifts were constructed using push reaming at the -220 level at Äspö HRL – one 15 metre long drift and one 95 metre long drift both with a diameter of 1850 mm. The drifts were used to test grouting with the Mega-Packer and the deposition equipment. The drifts have also been used during the project phase Complementary Studies 2008 – 2010; the longer drift has been used for continued testing of the deposition technique and deposition equipment while the shorter drift has been used for testing of the compartment plug. The Mega-Packer tests were also been finalised during the Complementary Studies project phase 2008 – 2010, see /SKB 2012/, /Anttila et al. 2008/.

The planned demonstrations during 2013-2015 are presented in /Posiva 2012a/.

8.1 Multipurpose test (full-scale) at Äspö at -220 level

A full-scale demonstration test called Multi Purpose Test, “MPT” is included in the EC LucoeX project (2011-2014). The test will be performed at the Äspö HRL, KBS-3H test site at the -220 m level in the 95 m long deposition drift DA1619A02, that was excavated earlier, see Figures 8-1 and 8-2. This drift has been used for testing the deposition machine during the last few years.

The objectives of MPT are to test the system components in full scale and in combination with each other to obtain an initial verification of design implementation and component function. This includes the ability to manufacture full scale components, carry out installation (according to DAWE design) and monitor the initial system state of the MPT and its subsequent evolution.

Figure 8-1. The drift components in the drift section that is used for MPT-test.
8.2 Drift excavation (including drilling of pilot hole) experiment at the deposition level/Äspö

In the previous project phase it was concluded that the pilot-hole can be drilled either by directional core drilling, or bored by rotary crushing as the main alternatives even if percussion drilling also should be feasible. A standard diameter used for core drilling is 3” (76 mm). This hole needs later to be reamed to the final pilot-hole diameter, proposed to be minimum 311 mm (12” ¼). Another alternative is to drill the full diameter of the pilot-hole using rotary crushing techniques.

Directional core drilling requires two main systems, one that establishes the position of the drill bit in space and a second system that guides the direction of the borehole based on the error in the bit position relative to the theoretical trajectory of the borehole /SKB 2012/.

As the steering equipment did not function as planned in the pilot hole boring in the previous project phase 2004-2007 and the pilot holes was bored with the blind technique, which met the geometrical requirements set for the pilot hole. However, the pilot hole was only 95 m long and it still needs to be demonstrated that the requirements can be met with 300 m long pilot holes /Bäckblom & Lindgren 2005/.

A test site is planned to be located at Äspö where the first 100 metres of the pilot hole will be reamed to the full drift diameter.

8.3 Mega-packer test at the repository level

Successful test of the Mega-packer have been completed earlier at the -220 metre level of the Äspö Hard Rock Laboratory /Eriksson & Lindström 2008/. The tests successfully demonstrated the ability to seal conductive fractures and fractured zones with both high
and low inflows, see /SKB 2012/ and /Anttila et al. 2008/. The groundwater pressure at repository depth proposed by both Posiva and SKB is higher than at the -220 metre level so it has been recommended to perform additional tests at the repository depth to verify the Mega-Packer function further at a more relevant depth and hydraulic pressure.

The Mega Packer system is presented in Section 9.7. See also /Posiva 2012a/.

**8.4 Characterization of the pilot/investigation hole at Äspö at the deposition level**

**8.4.1 Borehole deviation**

A crucial issue regarding the strict geometrical requirements for the deposition drifts is the straightness of the 300 m long pilot hole before reaming it to full drift size, see Table 3-2. The pilot hole can be achieved by either directional core drilling (hole diam. 76 mm), which is the reference option at the moment or using a full-face boring machine (hole diam. 152 mm), preferably with a steering option, to make a pre-pilot hole. These holes will then be reamed to the full pilot hole size, diam. about 300 mm, which is large enough for the reamer head needed to enlarge the pilot hole to the full drift diameter, the allowed range being 1850-1855 mm. Reaming of a hole of any size is not considered an issue as long the hole to be reamed is straight enough.

As there is no available technique to measure deviation and inclination of a long borehole with a precision provided e.g. by laser technique after the line of sight has been lost in the hole, the available deviation measuring tools must be tested and calibrated to achieve the best results. The objective is to test if this is adequate in terms of the requirements set for the drift. For this purpose a deviation facility, a 300 m long pipe with accurate coordinates, is being developed at Äspö HRL on the surface. This facility will enable testing and evaluation of different available deviation measurement equipment. A preliminary outlining is presented in /Posiva 2012a/.

The work with the deviation facility is ongoing and the first 60 meter of the 76 mm part has been finalized. That section has a vertical curvature exactly matching the KBS-3H requirements, as illustrated in Fig. 8-3.

![Figure 8-3. Illustration of the vertical waviness of the first 60 m of the deviation facility.](image-url)
8.4.2 Other characterizations

The applied detailed site investigation methods applied for KBS-3V will be updated to meet the KBS-3H needs. The principal differences are expected to lie in the type of pilot boreholes used for deposition drifts (drilling technique, diameter of hole etc.) and the associated site characterisation data (characterisation techniques and quality in results). For the hole size 76 mm there are tools available to carry out the hydrogeological and the geophysical measurements that are needed. For the hole size 152 mm the measuring tools available are much more limited.

There may be differences between 3V and 3H in the way different site characterisation methods and the Observation method are implemented during excavation/reaming of a deposition drift, and after it has been excavated/reamed. Posiva staff working with RSC will be involved in the work to ensure RSC is taken into account in a suitable way. It is foreseen that the data handling systems developed for 3V will largely be applicable also to 3H. In the work one of the objectives is to establish the RSC criteria for KBS-3H. This work will be started in 2013 /Posiva 2012a/. These criteria will affect e.g. the utilization degree of the drifts as well as the characterisation methods needed in the pilot holes and in the excavated drifts.
9 KBS-3H SPECIFIC SYSTEM DESCRIPTIONS

The work on the KBS-3H-specific systems will be initiated in a later stage in the project, see /Posiva 2012a/. The work includes system descriptions in line with STUK’s YVL Guide “B1 draft 2”.

In this chapter the most important 3H specific systems are presented and described.

9.1 Deposition drift

Excavation of the drift and the design of the drift components have been presented above in Sections 4.1 and 4.2, respectively.

The Fig. 9-1 presents the principle how a deposition drift is composed of drift components: Supercontainers, distance blocks, plugs including both the compartment plug and the drift plug, filling blocks and other filling components. The more detailed description of each component has been given in Sections 4.2.1-4.2.4, see also /SKB 2012/. The deposition of the drift components is done through the deposition niche that is located between the two parallel central tunnels. From the deposition niche another drift can be excavated to the opposite direction.

The compartment plug, divides the drift into two compartments. The drift plug seals the entire drift. The canister is located in the Supercontainer surrounded by bentonite buffer and perforated Titanium shell.

The distance blocks are placed between the Supercontainers to separate them hydraulically and thermally.

In drift sections where inflow exceeds the positioning criterion, 0.1 l/min per 10 m, filling blocks made of compacted bentonite are deployed. In addition to filling blocks there are additional filling components in a drift adjacent to the plugs and in the rear part of the drift, see Section 4.2.3.

Figure 9-1. The parallel central tunnels with the deposition niche in between. The drift is excavated from the niche with a slight inclination upwards enabling drainage during installation /translated from Posiva 2012/.

9.2 Deposition niche

Deposition niches will be excavated between the two parallel central tunnels allowing the space for drilling and boring equipment when excavating the drift at both ends of the niche. The drift spacing is 25 m (c-c).
After the drifts have been excavated with the techniques presented in Section 4.1.1, drift entrance structures will be constructed at the entrance from the deposition niche to a drift, see Figures 9-2 and 9-5. The entrance structure is used for docking the transport shielding tube to the drift. Its function is to act as a supporting structure between the tunnel wall and the transport shielding tube, but also as a radiation shield.

The drift entrance structure is constructed by casting a concrete collar around the drift entrance. An Adjustment ring will be placed inside the collar. The Adjustment ring will be adjusted with the centre line of the drift and grouted. The Steering ring will be attached next. The transport shielding tube will be docked to the Steering ring.

![Drift entrance structure diagram](image)

**Figure 9-2. The deposition drift entrance structure /Kirkkomäki & Rönnqvist 2011/.**

### 9.3 Deposition of the drift components

The deposition of the Supercontainers and other drift component is performed with the deposition machine, see Fig. 9-3. The prototype, described by /Halvarsson 2008/, has been tested at the Äspö HRL /SKB 2012/. The deposition equipment is composed of the actual deposition machine and the support, the slide plate and the lift pallet, see Fig. 9.5.

The Supercontainer is pushed forward with the deposition machine using water cushion technique, see Fig. 9-4. The lift pallet moves on the top of a thin water film between the slide plate and the lift pallet. For more detailed description of the deposition machine and its function see /Halvarsson 2008/.
There has been some upgrading with the deposition machine done during the past few years:

- Mechanical updates to the deposition machine was done during 2011 and spring 2012
  - New cushions, additional sensors, filters and pumps etc. was changed
- Sensor system and corresponding software updates were completed in May 2012
The machine handling was initially reasonably free from interruptions and manual intervention but this was temporary and the balance of the Supercontainer is currently problematic.

The current conclusions of the deposition machine are:

- The ability of the control system to balance the machine is rather limited. It can only cope with imbalances when the machine mechanics are accurately adjusted. The previous successful control, however, proves that such a machine adjustment exists.
- The correct mechanical setting of the machine has not been found despite two weeks of sliding plate and palette adjustments. This indicates that the correct adjustment interval is very narrow or that the adjustment depends on some currently unknown parameters.
- The most problematic feature is that the sliding plate and pallet have to be disassembled from the machine for the deposition of every distance block or Supercontainer.

*Figure 9-5. The transport shielding tube moved between the drift entrance structure and the deposition machine. After opening of the gamma gate the emplacement of the Supercontainer into the drift can be started /Kirkkomäki & Rönnqvist 2011/.*

The work is ongoing to achieve repetitive and quality assured depositions. The deposition machine is under upgrading process and it will be used for MPT-test, a demonstration at Äspö HRL during 2013, see /Posiva 2012a/.

**9.4 Central tunnel**

Transportation of the Supercontainers and other drift components to the deposition drifts is managed through the central tunnels. The other of the two parallel central tunnels belongs to the controlled area and the other one to uncontrolled area. The tunnel
profile is similar to the 3V design, but 700 mm higher due to the dimensions of the transfer vehicle with the transport shielding tube.

![Diagram](image)

**Figure 9-6.** The KBS-3H central tunnel profile that is 700 mm higher than that of 3V. Other dimensions are the same between the two variants /translated from Posiva 2012g/.

### 9.5 Reloading station

In the reloading station the canister, the perforated Supercontainer shell and the buffer between the canister and the shell will be packed together forming a Supercontainer. The Supercontainer will be placed in the transport shielding tube with gamma gates on both ends standing on the transfer support. The Supercontainer will be transported with the transfer vehicle to the deposition area, see Figures 9-5, 9-7 and 9-9. The conceptual design of the reloading station is presented in /Kirkkomäki & Rönnqvist 2011/.

### 9.6 Transportation

#### 9.6.1 General

Canisters are transferred to the disposal level along the canister shaft. In the reloading station at the disposal level the canisters are packed in Supercontainers. The Supercontainer consists of a perforated protective cylinder made of titanium, bentonite buffer blocks and a copper canister.
The Supercontainers are transported in a transport shielding tube to the disposal area by a transfer vehicle along the central tunnels. At the disposal area the Supercontainers are emplaced into the deposition drift with a deposition machine as presented above in Section 9.3. The Supercontainers are moved on top of a very thin water film with a lift pallet. The force needed to push them forward in the deposition drift is relatively small compared to the weight of the Supercontainer. The deposition machine pushes the Supercontainers in 1.5 meter long steps.

### 9.6.2 Transfer vehicle

The Supercontainers are transferred from the reloading station to the deposition area or to the intermediate storage to wait for disposal. The total weight of the Supercontainer and the transport shielding tube is about 60 tons. The transfer vehicle is based Self Propelled Modular Transporter (SPMT), which are widely used all over the world in very large and heavy transportations, see Fig. 9-7.

The speed of the vehicle is 4-5 km/h. For more details of the vehicle, see /Kirkkomäki & Rönnqvist 2011/.

Loading the Supercontainer to the transfer vehicle, transfer to the deposition area and deposition take place always in the controlled area of the repository. The transfer vehicle collects the Supercontainers from the reloading station located close to the technical rooms.

At the deposition area in the deposition niche the transfer vehicle is aligned with the deposition drift in front of the drift entrance. The vehicle is moved and the transport shielding tube is left standing on the transfer support, see Figures 9-5 and 9-8. After the Supercontainer has been emplaced the transfer vehicle will take the empty transport shielding tube together with the transfer support to the reloading station to collect the next Supercontainer.

![Figure 9-7. Transfer vehicle based on Self Propelled Modular Transporter /Kirkkomäki & Rönnqvist 2011/](image-url)
Figure 9-8. The transport shielding tube with the Supercontainer inside turned to the horizontal position on the transfer support /Kirkkomäki & Rönnqvist 2011/.

Figure 9-9. Conceptual presentation of the reloading station /Kirkkomäki & Rönnqvist 2011/.
9.7 Post-grouting with Mega-Packer

9.7.1 General

A key issue for horizontal deposition is groundwater control. For long-term safety reasons water inflows ideally have to be measured before any disturbance takes place of the natural inflows, hence pre-grouting is not optimal. Another limitation is that boreholes are not allowed outside the drift contour. To minimise the need for pre-grouting a post-grouting device that can handle the conditions at full repository depth called the Mega-Packer has been developed.

In order to enhance the emplacement conditions in the drift all drift sections that do not meet the positioning inflow criteria, 0.1 l/min per 10 m, will be post-grouted using colloidal silica.

9.7.2 Mega-Packer description

The Mega-Packer, Fig. 9-10, denotes equipment consisting of a large tube of 48 mm steel, 1970 mm long (with a grouting length of 1590 mm) and with a diameter of 1820 mm, only slightly smaller (30 mm) than the drift (e.g. 15 mm gap between the Mega-Packer and the drift wall when centred). It has packers sealing off both ends. The packers are inflated with water at a pressure required to resist grout penetrating out between the packers and the rock wall during grouting. The steel tube has connections for valves, so that the hoses for grouting and measurement equipment can be connected. Colloidal silica is the preferred grout but low-pH grouts can also be used, the residual layer of grout on the drift wall is removed after the grouting. To grout longer fractured zones, two Mega-Packers can be connected and used simultaneously. The current design allows for this connection but the function has not been included in the tests that have been carried out.

Figure 9-10. The Mega-Packer positioned outside the 95 m drift at Äspö HRL /Eriksson & Lindström 2009/.
9.7.3 Previous experiences

The tests that have been carried out have demonstrated that the Mega-Packer has the potential of sealing horizontal drifts below the set-up criteria of 0.1 l/min per 10 metres. This is in line with earlier theoretical studies. The premises constraint by the test site, a drift which was pre-grouted with cement, with low groundwater pressures have, however, likely affected the results considerably and tests at the repository level will be required to ensure full confidence in the Mega-Packer post-grouting technique, this is also planned in the current project phase /Posiva 2012a/.

However, given the conditions at the -220 m level the sealing capability was at least as good as a well performed traditional pre-grouting using colloidal silica and show a better sealing capability than what has been noticed with traditional post-grouting.

Some practical problems were noticed during testing, but these were managed and all together the method should have good production capability.

9.8 Drainage during operation

Use of Mega-packer for groundwater control reduces inflow leakages into the drifts and reduces potential rate of mechanical bentonite erosion 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 plug or the drift plug is installed. Spray or drip shields, thin titanium sheets, will be mounted in positions of water spraying or dripping in order to protect the buffer against mechanical erosion allowing the leakage water to flow freely down the drift walls to the floor.

Regarding the highest allowed inflow rate into the drift compartment the weakest link is the deposition machine, which is working with water cushion techniques. Also the bentonite components will be transported with the deposition machine into the drift. Possible contact between water and the bentonite components has to be avoided during the transportation. By modifying the plates the allowed inflow rate is about 10 litres per min. This figure is after the inflow sections that exceed the inflow positioning criterion, 0.1 l/min per Supercontainer section including both the Supercontainer and the distance block, have been post-grouted.

9.9 Artificial wetting and air evacuation

A favourable initial state of saturation is obtained by using artificial water filling so that the buffer should swell uniformly and fill all the open space. The bentonite should seal the drift and reduce the flow inside the drift that can cause piping and transport of bentonite.

The artificial watering system is required to fill all void spaces in the drift compartment at approximately the same time, thus ensuring that the bentonite will swell and seal the drift uniformly. This minimises the risk of bentonite piping and erosion, as well as water pressure displacement of distance blocks and/or Supercontainers during the saturation phase after sealing of the drift.
The water filling of the compartment is carried out with three pipes that extend through the plug (compartment plug and drift plug) into the transition zone underneath the transition block that is located between the pellet filling section and the first distance block, see Fig. 9-11. The wetting starts after the plug has been mounted in place.

**Figure 9-11.** Main components of the water filling system with short pipes through the compartment plug (similar design for the drift plug). The three short water filling pipes lead the water past the pellet filling section underneath the transition block. Perspective view orthogonal to drift axis and view parallel to drift axis, facing the plug /SKB 2012/.

The only remaining long pipe is the air evacuation pipe that stretches the length of the compartment. For air evacuation it is preferable to use the maximum pipe size that can be safely placed in the drift taking into account the space required for the deposition machine, including shifting from side to side which has been observed in the test runs at Åspö. The diameter must be large enough in relation to the inflow rate of water, max 3l/sec. It has been calculated that an optimal diameter for the air evacuation pipe would be 33.7 mm x 2.0 mm (DN 32). The air evacuation pipe will be installed at the lower part of the drift, but in order to function in a proper way the end part at the rear section of the compartment needs to be turned upwards to the top of the drift, where the air will accumulate. This will be achieved by a separate pipe (diameter 17.2 mm) which will be fixed on the end face of the compartment as shown in Fig. 9-12. When removing the long air evacuation pipe the coupling will allow it to be released from this bottom pipe, which will be left inside the drift.
Figure 9-12. Location of the air evacuation pipe at the rear end of the compartment. The short pipe in the rear part of the compartment that is turned upwards to the roof is needed because the air is accumulated in the upper part of the inclined drift /SKB 2012/.

The air evacuation pipe will be fixed on the drift surface by drilling small holes in the rock and grouting a support made of titanium. It is also possible to anchor the supports with tight holes without using grout, which would reduce somewhat the amount of grout in the drift (approximately 10 kg / 150 m pipe). The mechanism of the support is designed so that the pipe can easily be pushed in and will not hinder removal of the pipe. Spacing of the supports will be 3 metres. The air evacuation pipe will consist of 6 m long pipes which are connected using a screw type coupling.

The diameters of the shorter water filling pipes are also set at 33.7 mm x 2 mm (DN32), these will be made of stainless steel.

It is assumed in design that a favourable initial state of saturation is obtained by using draining, artificial water filling and air evacuation as for buffer components. After artificial water filling the inflow into the drift is reduced significantly because the water pressure in the drift becomes practically same as in the surrounding bedrock. As a result there is only minor pressure gradient between the drift and surrounding host rock. The water filling will accelerate the swelling of bentonite and the nearly simultaneous water filling and buffer swelling in the whole drift is beneficial regarding piping and erosion. As a result all void spaces in the drift compartment are filled at approximately the same time, thus ensuring that the bentonite will swell and seal the compartment uniformly.
The operation of the drift needs to be such that there will be no significant water pressure build-up in the deposition drifts during emplacement that could cause movement of components and other adverse effects /SKB 2012/.

Following artificial watering, 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 piping and 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 a further compartment plug or drift plug installed.

9.10 Pipe removal

Part of the air evacuation pipe will remain permanently at the drift end as well as at the end of the compartment closer to the drift entrance and will be considered in the design. Pipe removal is no longer regarded as an issue after the short water filling pipes were introduced in the design of the artificial water filling leaving only one long pipe, the air evacuation pipe, to be removed from the compartment. The pipe removal is described in /SKB 2012/.
10 DESCRIPTION OF THE FACILITY AT REPOSITORY LEVEL

The spent nuclear fuel accumulated from the nuclear power plants in Olkiluoto in Eurajoki and in Hästholmen in Lovisa will be disposed of in Olkiluoto. Facility complex will be constructed to Olkiluoto, and it will include two nuclear waste facilities according to Government Degree 736/2008. Nuclear waste facilities are encapsulation plant constructed to encapsulate spent nuclear fuel and disposal facility consisting of underground repository and other underground rooms and above ground service spaces. The repository is planned to be excavated at a depth between 400 - 450 metres. Access routes to the disposal facility are an inclined access tunnel and vertical shafts. The encapsulated fuel is transferred to the disposal facility in the canister lift. The canisters are transferred to the reloading station for the assembly of the Supercontainers. From the reloading station located in the area of the technical rooms the Supercontainers are transferred in a transport tube via central tunnel to a deposition niche and deposited in a horizontal deposition drift. Two parallel central tunnels connect all the deposition drifts and central tunnels are inter-connected by the deposition niches that are located between the parallel central tunnels. The spacing between the inter-connections is the same as the drift spacing i.e. 25 metres. This solution improves the fire safety of the underground rooms and allows flexible logistics and closing of the deposition drifts in stages at the operational phase of the repository.

An underground rock characterization facility, ONKALO, is excavated at the disposal level. ONKALO in designed and constructed so that it can later serve as part of the repository. The goal is that the first part of the disposal facility will be excavated after the phase of construction permit in the 2010’s and operation will start in 2020’s. The fuel from 4 operating reactors as well the fuel from the fifth nuclear power plant under construction has been taken into account in designing of the disposal facility. According to the information from TVO and Fortum, amount of the spent nuclear fuel is 5 440 tU. Disposal facility is being excavated and closed in stages over the long operational time of about 100 years. The maximum amount of spent fuel to be disposed of is 9 000 tU according to the Decision-in-principle.

Since the two variants of the KBS-3 method, KBS-3V and KBS-3H, differ from each other only partially the same designs are applicable for the common parts. The most important differences are connected to the deposition tunnels including the vertical holes in the KBS-3V variant versus the horizontal deposition drifts including the drift components in KBS-3H variant. Another clear difference in KBS-3H compared to the vertical variant is how the Supercontainers are assembled in the reloading station and transferred to the deposition area.

For the KBS-3V variant the designs of disposal facility are presented as located in Olkiluoto based on investigation data of the bedrock, see e.g. /Saanio et al. 2012/ and part of description is applicable for the KBS-3H variant. The KBS-3H specific disposal facility description will be compiled in a later stage of the current project phase /Posiva 2012a/.

The location of the disposal facility will be revised when more information on the bedrock has been gained. More detailed data of the bedrock will be obtained with above ground investigations from investigations in ONKALO and investigations during the
excavation of the repository and long operation time of the disposal facility. The facility is planned so that technical development can be flexibly utilized. The total volume of the disposal facility is approximately 0.921 million m$^3$ in the layout adaptation that was made for 5600 tU of spent fuel. The maximum open volume in the repository was about 0.696 million m$^3$, because the disposal facility is excavated and backfilled in stages.

The disposal facility is divided into the controlled area and the uncontrolled area. The Supercontainers are always handled and deposited into the drifts in the controlled area. The excavation, construction and backfilling of central tunnels are carried out in the uncontrolled area. Extensive material transfers, such as transfers of excavated rock and backfilling materials are transported in the access tunnel. Separate ventilation systems are provided for the controlled and the uncontrolled area.
11 DESCRIPTION OF OPERATION INCLUDING OCCUPATIONAL AND OPERATIONAL ASPECTS

11.1 Occupational safety

11.1.1 Performed analyses

An occupational safety studied was carried out during the “Complementary Studies 2008-2010” project phase; the objective was to identify potential occupational safety risks, which can occur during each operation in deposition work with DAWE design in KBS-3H. The analysis was performed using "what-if"-methodology where possible risk were identified and classified due to consequence and probability category 1 to 5.

The risk analysis highlighted the differences identified in KBS-3H compared to KBS-3V. This relates, for instance to fire and evacuation, welding in confined space, traditional occupational safety and radiological risks. The scope of the occupational safety analysis comprised the risks which can occur:

1. During preparation of the drift
2. In the reloading station
3. During deposition work when filling compartments with distance blocks and Supercontainers

The study showed a number of identified events. Some of these were considered “unacceptable”, and require suitable safety measures to be reduced to an acceptable level. These are presented in Table 11-1 together with recommended safety measures in Table 11-2.
**Table 11-1.** Risks identified as unacceptable in the studies carried out, Table 11-2 shows the recommended solutions.

<table>
<thead>
<tr>
<th>Event</th>
<th>Cause</th>
<th>Consequence</th>
<th>Technical barrier</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Falling rocks, flying stones</td>
<td>Excavation of notches, drilling, reaming work</td>
<td>Serious injury person</td>
<td>Personnel protective equipment</td>
<td>6.1.5, 6.2.1</td>
</tr>
<tr>
<td>Shielding gas hose breaks</td>
<td>Welding in narrow space</td>
<td>Asphyxiation</td>
<td>Local ventilation outside</td>
<td>6.1.1, 6.1.3, 6.1.4</td>
</tr>
<tr>
<td>Gas cylinder leakage / rupture</td>
<td>Rounded bottom of the hole, narrow space</td>
<td>Displacement of oxygen, asphyxiation</td>
<td></td>
<td>6.1.1, 6.1.3, 6.1.4, 6.1.6</td>
</tr>
<tr>
<td>Welding fumes</td>
<td>Arc welding in confined space</td>
<td>Intoxication</td>
<td></td>
<td>6.1.1, 6.1.3, 6.1.4, 6.1.6</td>
</tr>
</tbody>
</table>

**Table 11-2. Recommended safety measures**

<table>
<thead>
<tr>
<th>No</th>
<th>Area</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1.1</td>
<td>Ventilation</td>
<td>The ventilation system shall be sufficiently dimensioned for the final operation.</td>
</tr>
<tr>
<td></td>
<td>Design</td>
<td>The estimated amount of air contaminants in form of radon, dust, inert gases etc. shall be taken into consideration when dimensioning the ventilation system. Exhaust device and fresh air injection should be considered. The fan equipment used outside the drift shall be of an explosion-proof design. The concentration of contaminants in the supply air should be substantially below the occupational exposure limit values.</td>
</tr>
<tr>
<td>6.1.2</td>
<td>Alarm system</td>
<td>An alarm to warn for unforeseen fan/ventilation system stop and risk for fire shall be installed.</td>
</tr>
<tr>
<td>6.1.3</td>
<td>Emergency exits</td>
<td>Normally, underground work shall have at least two separate emergency exits. Installation of a rescue chamber designed for the actual number of workers is mandatory. Equipment giving access to respiratory air shall be provided. As an alternative a mobile rescue chamber can be used. All emergency exits shall be clearly marked.</td>
</tr>
<tr>
<td>6.1.4</td>
<td>Oxygen deficiency</td>
<td>It is recommended to measure the concentration of oxygen content in the air in order to assess the level of risk. The oxygen concentration in the breathing air shall not be lower than 18 % vol.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>If there is a risk for oxygen deficiency, or heavy concentrations of air contaminations, compressed air equipment is necessary.</td>
</tr>
</tbody>
</table>
### Falling stones/flying rocks

The use of helmets and other necessary personnel protective clothing is mandatory.

### Welding in confined space

The main risks during arc welding in confined space are electricity, fire due to splash, contaminated air with welding gases and radiation.

- Splash can cause fires and burns. Protective clothing should be of suitable material.
- To avoid the electric shock use protective equipment, shoes with rubber soles and leather gloves.
- Protection from arc welding rays. UV radiation from the arc is dangerous. Use protective clothing and suitable welding helmet.
- During TIG welding ozone gas is produced. It is irritating to the respiratory system. Use local exhaust, which is moving in the welding direction during longer welding.
- Tungsten electrode emits small radioactivity. It should be placed in closed container before welding work starts.
- The air in the welding area should be monitored for amounts of welding fumes. Mechanical ventilation of exhaust hood is required.
- Place the source of electricity at least 1 m away from the welder.
- Gas cylinders shall be chained in upright position.
- For work in a confined space a special work permit for classified welders is required.

### Personnel protective equipment

- It is mandatory to use safety helmets with chinstrap, safety shoes with protective toe caps and nail-proof soles during work with preparation of the drift.
- Other personnel equipment which shall be used includes hearing protectors, safety goggles, breathing protection, and protective clothing and leather gloves.

Measures were also suggested for lower graded risks. The main causes of potential risks are connected to the work in confined space:

1. Risk for falling rocks/stones during preparation of drift
2. Fire in the deposition drift
3. Risk for asphyxiation during arc welding
4. Dust
5. Loss of lighting
6. High noise level
11.1.2 Conclusions

For the risk areas fire, asphyxiation and dust, a well functioning ventilation system is the most suitable physical barrier. In the area of reloading station the work is fully automated and remote. The physical involvement of personnel is small. The main activities are performed in the controlled environment. This area can be compared to the industrial site from the operating point of view. In the risk matrix this area is from the operating point of view, considered as a low risk area. The risks during deposition work are mostly connected to the welding of fastening rings during installation of compartment plugs. Well functioning ventilation system and additional physical barriers including monitoring of oxygen concentrations in the breathing air are necessary.

As the design premises/basis are not fully developed there are some identified uncertainties that need to be investigated further. Most uncertainties are related to the welding during installation of fastening rings in the deposition drift. To fulfil long-term safety criteria both from operational and occupational safety point of view it is recommended to investigate this area in more details.

Furthermore, the most critical physical barrier is the ventilation system. The dimensioning of the system for the final operation including the long-term consequences of welding in confined space should be further investigated.

The organisational safety is another issue, which should be worked out for the final deposition design in details according to the safety directives.

11.2 Operational safety

11.2.1 Performed analyses

A pre-study of a safety analysis for the operational safety was carried out during the Demonstration phase / Anttila et al. 2008/. This study was updated during the “Complementary Studies” project phase with DAWE as the reference design. The analysis was again carried out as a “What-if” analysis with the objective to identify possible damage sequences for copper canisters of spent fuel which can give radiological consequences. The risks were analyzed and mapped in a matrix with consideration to the variables: event, consequence, cause, measure and detection. The analysis was a comparative study where only the operations that deviate from the KBS-3V method were analyzed.

The following steps in the deposition process were included in the analysis:

• Preparation of drift, when the main activities are: excavation, characterisation, sawing of plug notches and installation of fastening rings and the air evacuation pipe

• The reloading station in the controlled environment for Supercontainer assembly

• The deposition area and deposition work

The sequence for these three working areas was studied in detail (the transport from the surface down to the reloading station was not analyzed since it is the same as for the KBS-3V alternative). A panel of experts on the KBS-3H design was formed and an
analysis meeting was arranged in order to identify and discuss risks related to the KBS-3H design. The following conclusions were drawn from the different steps:

11.2.1.1 Preparation of drift
The following additional risks, compared to KBS-3V were identified for this part of the process:

• Too high inflows of groundwater to the drift will give problems with eroding buffer when the Supercontainers and distance blocks are deposited. It is important that the rock characterisation is made properly and that the zones with high water inflows are grouted.

• It is technically a more complex task to excavate a 300 m long drift and to manage the water inflows in it.

• During the preparation of a drift several components are installed; fastening rings for the plugs, an air evacuation pipe and spray and drip shields to block water from coming in contact with the buffer. If these are incorrectly installed and not identified by inspection it can affect the deposition process in a negative way.

11.2.1.2 The reloading station
The following additional risks, compared to KBS-3V were identified for this part of the process:

• Lowering of the copper canister into the Supercontainer.

• Lift of the transport tube used for Supercontainer transports.

• Longer radiation exposure time. Though, the copper canister is always in the controlled environment when it is moved.

11.2.1.3 The deposition area and deposition work
Compared to KBS-3V the following advantages were identified:

• During deposition the deposition machine lifts the Supercontainer with water cushions and the lifting height is very low. There is no risk for dropping the canister.

• The fire load on the deposition machine is less for KBS-3H. Fire cannot be spread to other material than the deposition machine and cables.

The following disadvantages from a safety/availability point of view were identified:

• It is not optimal to use the deposition machine for transporting distance blocks in the drift. The stepwise movement of the blocks might cause cracks in the bentonite near the feet attachment. Alternative machines should be considered. A KBS-3H machine inventory will be developed early in the current project phase to clarify these potential needs. The implications in drift operation and costs should also be included in upcoming work.
• The air evacuation pipe can get stuck in the swelling buffer. The air evacuation pipe may act as flow path for water and might erode buffer in zones where it has not swollen yet.

• Compared to KBS-3V the KBS-3H alternative will probably have lower availability. The canisters are deposited in a sequence in the same drift, hence it will be a more complex task to correct a failure event, e.g. unwanted wetting of the buffer or mechanical failure to the deposition machine and buffer degradation.

11.2.2 Conclusions and recommendations
KBS-3H mainly differs from KBS-3V concerning the preparation of the drift, the reloading station and activities in the deposition area. And although separate risk were identified for the reloading station the controlled assembly of the Supercontainer in the controlled environment (compared to the mounting of bentonite into the deposition hole in the KBS-3V method) is considered an advantage. The lower lifts of the deposition machine inside the drift is also favourable from a safety analysis point of view compared to the higher lifts with strict precision requirements of KBS-3V. The main disadvantage is that if a failure occurs in a deposition drift there is a higher probability that several copper canisters will be affected.

The deposition machine is primarily designed for optimal transport of Supercontainers but is also used for transport of distance blocks and filling components in the current design. It might be better to deposit the distance block with a different type of machine, e.g. designed like a forklift in order to avoid repeated lifting and lowering of the distance blocks and filling components during the transport in the drift. This issue will be addressed in the current project phase by developing a KBS-3H machine inventory.

Several risks that were identified were connected to the power supply and function of water pumps and a clear recommendation for redundancy can be given.

The analysis that was carried out focused on the operational safety. However, some of the failure events could possibly influence the long-term safety; these were identified but were not systematically studied. In order to ensure that all aspects of the long-term safety have been covered it is necessary to consider all design premises/basis and assess whether there are events during operation that could affect these, this will be done in the current project phase.

11.3 Retrievability and reverse operation
Retrievability was studied in the earlier, Demonstration phase / Anttila et al. 2008/ and has not been studied further during the recent “Complementary Studies” project phase. A brief presentation of the technique is, however, given here to include the whole picture.

It is assumed that, at any time during the operation period of the repository after disposal of Supercontainers or installation of other equipment in the drift, it should be possible to retrieve/remove emplaced components from the drift due to the following considerations:
• The waste disposal process itself must be reversible in the event a serious error or accident takes place during emplacement.

• Supercontainer recovery could be necessary as a result of Supercontainer fault occurring during or after emplacement.

• Supercontainer recovery could be necessary if the repository does not function correctly.

• Retrievability is required by the licensing requirements in Finland.

• Future generations might have an interest in retrieving emplaced material.

There are two main scenarios, either the components have absorbed water and has started to swell or they are intact and not affected by water. For the case with no swelling, prior to the artificially wetting, the deposition machine can be operated in reverse (so-called “reverse operation”) - this has also been successfully demonstrated at Äspö HRL using Supercontainer dummies.

In the case where the bentonite buffer has absorbed water, reverse operation may not function properly and other means will be required for Supercontainer recovery, i.e., retrieval.

Due to the different barriers (components/material) that will be introduced into the deposition drifts, a number of different techniques will be required for their removal and ultimate retrieval of the canisters. The different techniques proposed for removal of these barriers include:

- Removal of drift plug
- Removal of filling materials
- Removal of distance block, buffer materials
- Cutting the Supercontainer end plate
- Removal of bentonite inside the Supercontainer
- Retrieval of the canister.
- Removal of the Supercontainer shell
- Cleaning of the drift

The removal of the various barriers will take place through a combination of different techniques. It is proposed that the titanium components are removed by means of hydrodemolition methods and water cutting. The removal of bentonite can be carried out using hydrodynamic/chemical methods, which have already been tested for retrieval of a KBS-3V canister. Alternatively, hydrodemolition methods can be used; however, this would require tests to verify that the method will not damage the copper canister. The
work carried out during the Demonstration phase concluded that it is possible to remove the Supercontainer and other components after installation.
12 SUMMARY

The KBS-3H design is a variant of the KBS-3 method and an alternative to the KBS-3V design, which is the reference design for both Posiva and SKB. In KBS-3H multiple canisters containing spent fuel are emplaced in parallel, 100 – 300 m long, horizontal deposition drifts at a depth of about 400 -500 m in the bedrock whereas the KBS-3V design calls for vertical emplacement of the canisters in individual deposition holes.

The established DAWE (Drainage, Artificial Watering and air Evacuation) reference design for KBS-3H contains that leakage water is self-drained at the bottom of the drift during the installation phase. The empty space between the deposition drift wall and the Supercontainer, distance blocks and filling components inside a sealed compartment is artificially filled with fresh water after installation phase. The water filling is done to accelerate the swelling of the buffer in distance blocks and in the Supercontainers. It is done rapidly and simultaneously in the entire compartment which basically removes the risk of inhomogeneous swelling and subsequent buffer displacement. The swelling pressure induced by the artificial water filling may be sufficient to mitigate the thermally induced spalling of rock. Together with the water filling the trapped air in the drift is removed with air evacuation pipe. The artificial water filling will also ensure a well defined initial state, which is beneficial for evaluating long-term safety aspects.

In addition to the deposition drifts in KBS-3H versus deposition tunnels and vertical deposition holes in KBS-3V, the horizontal concept differs from the vertical concept with respect to the reloading station and the activities in the deposition area. From the operational point of view the industrialised process during construction and disposal e.g. the controlled assembly of the Supercontainer in the reloading station enabling an easier quality assurance of the materials closest to the canister, compared to the mounting of bentonite into the deposition hole in the KBS-3V method, is considered an advantage. However, separate operational risks have been identified for the reloading station. The lower lifts of the deposition machine inside the drift is also favourable from a safety analysis point of view compared to the higher lifts with strict precision requirements of KBS-3V.

Regarding the present safety assessment it can be concluded that the KBS-3H design alternative offers potential for the full demonstration of safety for a repository at Olkiluoto site and for the demonstration that it fulfills the same long-term safety requirements as KBS-3V. Studies are being undertaken to address remaining critical scientific and design issues and the further development of the DAWE reference design.

In general, the calculation results indicate that differences in the geometry and transport paths considered in the analysis of the KBS-3V and KBS-3H design variants have only a minor impact on calculated releases and doses. The focus of the analysis was on uncertainties that are specific to the KBS-3H variant, or have different implications for KBS-3H compared with KBS-3V. In this sense, the analysis was more limited in scope than in the 2009 safety analysis of a KBS-3V repository. The biosphere analysis for KBS-3H is also more limited than in the 2009 safety analysis of a KBS-3V repository, in the sense that only a single biosphere scenario has been applied, and compliance with all regulatory constraints was not fully assessed.
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