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KBS-3H

Summary report of work done during Basic Design

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September 2004

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Preface

This report summarise the results of the work and conclusions of the work done during Basic Design of the KBS-3H project during 2003. The work with the project has continued during 2004 with mainly preparation of Request for Proposal (RFP) documents for the detailed design and manufacturing of the deposition equipment. Further, SKB has signed a contract with a drilling company for drilling of the horizontal deposition drifts late 2004 at Äspö HRL. The work with the buffer issues and the safety case for the KBS-3H concept has also continued during 2004.

During the work with the RFP documents for the deposition equipment and excavation of deposition drifts, some modifications or changes have been done that is not documented in this report. The main changes in the KBS-3H projects are the following:

1. The excavation of the deposition drift at Äspö HRL will not be done with the Wassara water hammer technology as described in the report but with blind raiseboring technology instead.
2. The shell of the super container has been redesign and also the top and bottom plate of the container are perforated and the thickness has been reduced to 8 mm, the same thickness as the container shell, and the designs of the container feet are modified. The use of an electromagnet for holding the super container during the deposition process is therefore no longer feasible with these thin end plates. The electromagnet is now replaced with a mechanical gripper on the deposition machine. These grippes are holding the front feet of the super container during the deposition process.

The reader should therefore be aware that some of the description and conclusion from the Basic Design may have changed somewhat after completion of the Basic Design and that new information may be available as the work with the KBS-3H is progressing. The detailed design is scheduled to start late 2004 and the manufacturing of the deposition equipment is scheduled for completing late 2005. The testing of the deposition process is scheduled to commence early 2006 and reporting and evaluation will take place during 2007.

Stockholm, September 2004

1 Introduction

1.1 General

The purpose of this report is to give an overview of the work done during the Basic Design phase of the KBS-3H project and with highlighting of achievements and outstanding questions after the completion of the Basic Design. The Basic Design of KBS-3H is the second phase of the R&D Program which is carried out together by SKB and Posiva during 2002–2007. The first phase of the project, the feasibility study, was done during 2002 followed by the Basic Design phase performed during 2003. The third phase of project will be focused on the design, manufacturing and demonstration of the concept at Äspö HRL as well as a safety case based on Olkiluto site data. This phase covers the period 2004–2007.

1.2 R&D program for horizontal emplacement, KBS-3H

The KBS-3H project was initiated during 2002, based on the R&D program introduced in /SKB, 2001/. The project is advancing stepwise with new decisions to be taken before start of a new step. KBS-3H is a joint project with Posiva. The Feasibility Study for KBS-3H was decided and performed during 2002. The following Basic Design step was decided in November 2002 to be completed during 2003. The aim of Basic Design is to, as far as possible; verify that KBS-3H is a technically, economically and environmentally feasible and realistic project and that also requirements on long term safety can be fulfilled. This repost is a description of the work done within the Basic Design.

The aim of this report is to give a brief specification of achieved knowledge from Basic Design. The report will also constitute the basis for decision to continue the project or not with detail design and manufacturing of deposition equipment and other equipment necessary for realization of full scale demonstrations of horizontal deposition in long horizontal drifts at Äspö during the period 2004–2007. An attempt to present an overall time schedule for the KBS-3H project is shown in Figure 1-1.

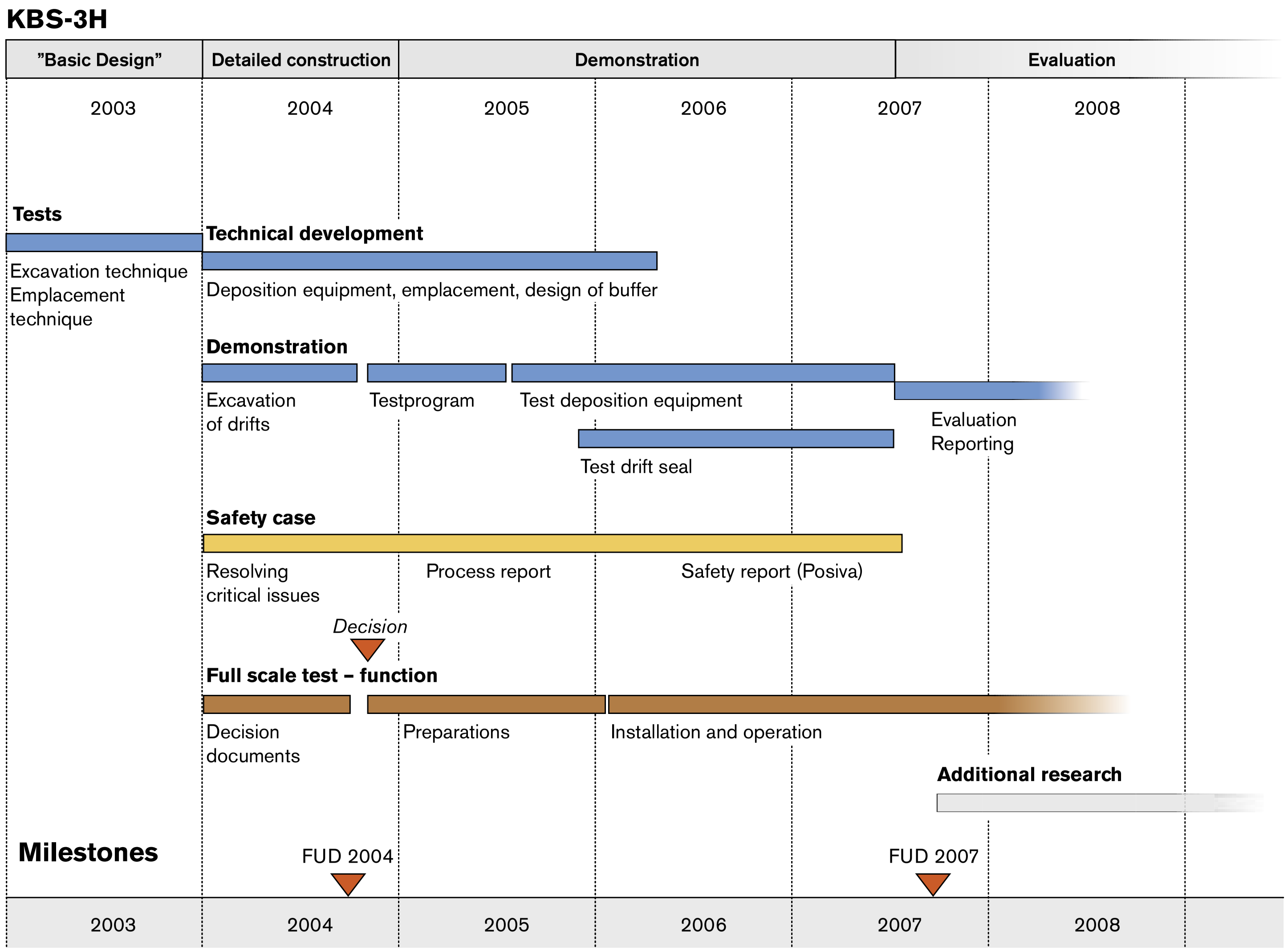


Figure 1-1. Overall schedule for the KBS-3H project.

1.3 Horizontal emplacement, KBS-3H

The horizontal emplacement concept, KBS-3H, has the following main features:

- The general conditions for the repository as depth, environment, etc are same for both vertical and horizontal concepts.
- Copper canister design is the same as for KBS-3V.
- Saturated bentonite buffer density should be the same as for KBS-3V.
- A perforated container, called "super container" containing both canister and bentonite buffer will be used for transport and deposition in KBS-3H. The weight of the super container is in the order of 45 tons.
- The super containers will be placed in an array in the drift with distance blocks of bentonite blocks in between. The distance between canisters is preliminary set to 7.3 m using the Swedish input data on decay heat of the spent fuel, thermal conductivity of the rock, distance between drifts, etc. The distance between canister and drifts will be studied and optimised much later in the project.
- The length of the deposition drift is assumed to be up to 300 m.
- The diameter of the deposition drift is 1.85 m.
- The inclination of the deposition drift is 2° upwards.
- The spacing of the deposition drifts; approximately 40 m.
- Operation area in niche outside the deposition drift.
- A concrete plug will be used to seal the deposition drift at the end.

The major difference between the vertical and horizontal emplacement concept is that several canisters will be placed in the same deposition drift in the horizontal concept compared to the vertical concept Figure 1-2.

The serial emplacement of the KBS-3H concept gives the following implications:

- A deposition tunnel with backfilling material is not needed in the horizontal concept. That means that the total excavated volume of the deep repository plant will be about 50% less. Due to orientation of the canister and somewhat thicker buffer the area needed for KBS-3H will be 10 to 15% larger compared with KBS-3V if all parameters are identical. The reduced volume of excavated will give positive consequences for the environment and reduce investment and operation costs.
- The safety case is different, with an array of canisters with possible intercommunication in the drift and adjacent rock mass which should be compared with the intercommunication in the backfilled tunnel. The array of canisters also gives a different thermal situation to be considered.
- The super container material and the additional (initial) voids in the super container and drift are also added to the safety case.
- Method and equipment for excavating of deposition drifts with high demands on direction, alignment and surface have to be developed and demonstrated.
- A super container for transportation of canister and bentonite buffer has to be designed and demonstrated.
- Method and equipment for emplacement of super containers and distance blocks in deposition drifts have to be developed and demonstrated.
- Method and equipment for retrieval of canisters in long horizontal drifts have to be developed.

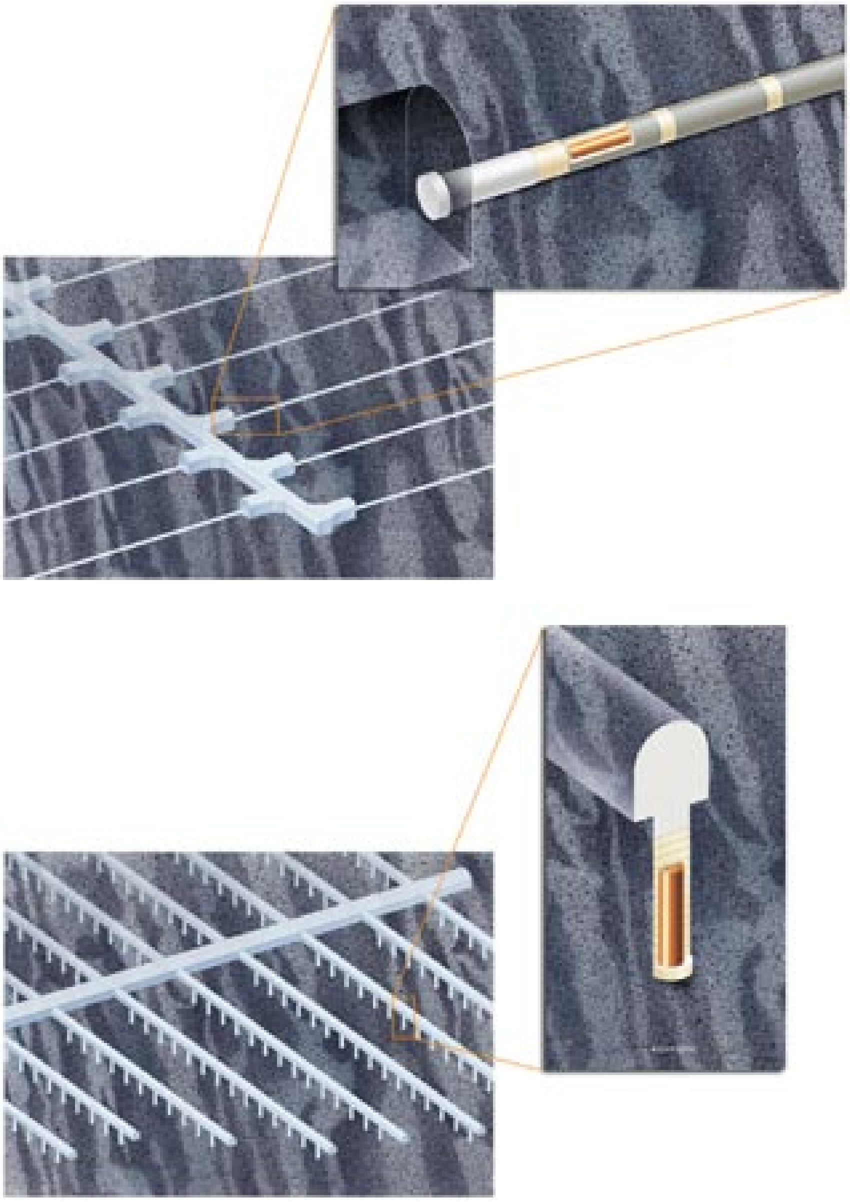


Figure 1-2. *Vertical (KBS-3V) and Horizontal emplacement (KBS-3H).*

1.4 Construction and operation of a KBS-3H repository

1.4.1 Introduction

The three main components of a KBS-3H repository underground layout are the deposition drifts, transport tunnels and the operation chambers, see Figure 1-3. The development of equipment or methods related to the KBS-3H concept in the Basic Design has not indicated any need for major changes of the repository facility compared to early studies of a KBS-3H repository. However, it has been indicated that the extension length of the equipment for excavation and deposition might determining curve radius of transport tunnels and connection to the operation chamber and its lengths to be considered for future underground layout. Also the height of operation camber might need to be increased to contain sufficient space for heavy lifts above the drift opening. Another change is the increase in diameter of the deposition drift for KBS-3H from Ø1.75 m to Ø1.85 m. The diameter of the deposition hole for KBS-3V is Ø1.75 m but due to the chosen emplacement concept with lifting cushions and steel slide plate need a increased diameter, see Section 2.3.

Figure 1-3. Illustration of the main tunnel, niche and deposition drifts.

The following sections briefly describe the most important differences between the two alternatives, KBS-3H and KBS-3V.

1.4.2 Deposition tunnel versus deposition drift

The major difference between the two repository facilities is that the large deposition tunnels, area 30 m^2 with a total length of 30–40 km of the KBS-3V concept are not needed. They are replaced by Ø1.85 m circular deposition drifts, for KBS-3H. The absence of deposition tunnels reduces the excavated rock volume by about 50 percent, or about 900,000 m^3 of solid rock in the Swedish case. This results to less environmental impact during construction, cost savings and reduced need for ventilation and drainage during construction and later on operation. This means that KBS-3H provides a much more efficient disposal of spent nuclear fuel compared to KBS-3V.

In KBS-3V, somewhat larger volumes of rock will be open at the same time. Excavating the deposition tunnels by conventional drill and blast, plus transporting the excavated rock with diesel trucks will entail larger ventilation volumes than needed for KBS-3H.

1.4.3 Transport tunnels and main tunnels

The layout and dimensions of the underground facility will be determined by the spacing between deposition drifts, number of canisters to be disposed of, geological constraints, construction logistics, dimensions of vehicles and equipment for construction and deposition. The deposition machine determines the dimensions of the deposition tunnels and determines the dimensions of the transport tunnels and main tunnels in KBS-3V. The main tunnel referred to are the tunnels from which the deposition tunnels branch off. The preliminary dimensions of the main tunnels are 10 m in width, whereas the transport tunnels can be 7 m in width.

In KBS-3H, the super containers are transported and handled horizontally all the time, meaning that the deposition machinery is smaller. This means that the width of the transport tunnels does not have to be enlarged to the same width as the main tunnels, the deposition drift can branch off from a tunnel of the same width as a transport tunnel. It is assumed that operation chamber of about 15 metres depth will be built in the sides of the tunnel as shown in Figure 1-3. Each tunnel branches off, to allow the deposition drifts to be excavated and to permit docking of the deposition equipment to the drift without interfering with traffic in the tunnel.

1.4.4 Plugging and backfill

Since each deposition drift shall be sealed with a low-pH concrete plug at the operation chamber there is no back-filling operation of deposition or transport tunnels during the disposal operation of the deep repository. This means that the equipment and building for production of back-filling material is not needed until a very late stage of the deep repository.

1.4.5 Groundwater inflow

The planning for the deep repository is based on the view that all construction and operation should be done so that the geological environment of the site can retain its original properties in the best possible manner. This means in practice that the inflow of ground water to the excavated volumes should be reduced as far as possible. Uncontrolled ground water inflow can mean that the chemical buffer capacity of the rock is consumed, i.e. through disintegration of the fracture filling material or that saline ground water, which might be found at a deeper level, could be pumped up to the repository level.

Since a repository based on the KBS-3H design has a smaller total excavated volume, the leakage of ground water into the horizontal deposition drifts should be less and easier to control than the flow of ground water and in KBS-3V.

1.4.6 Installations at ground level

It is assumed that all buildings and installations in the operation area at ground level will be ready for initial operation, both for the KBS-3V and KBS-3H alternatives. The only difference between the alternatives is that the building and equipment for preparing backfilling material will not be needed for the KBS-3H alternative until the final backfill and closure of the deep repository after that all canisters with encapsulated fuel have been disposed of. The equipment for preparing the buffer material will be needed for both alternatives.

1.4.7 Rock transport

During regular operation of KBS-3H, the annual excavation of rock will, in principle, be limited to the amount of rock excavated from five deposition drifts with an approximately length of 300 m each, with the associated operation chamber. The volume of the deposition drifts for KBS-3H amounts to about 4,000 m^3 of solid rock, compared with about 40,000 m^3 of solid rock for KBS-3V.

This means that the extent of rock transportation during regular operation will be very small for KBS-3H compared to KBS-3V.

1.4.8 Ventilation

Since the excavated volume will be less for KBS-3H compared to KBS-3V, the ventilation requirement will also be reduced.

1.4.9 Working environment

The long deposition drifts in KBS-3H entail a difficult working environment if civil or rock works have to be performed in the drifts. This question must be addressed in parallel with technical development of the excavation and deposition equipment. The main goal is to avoid manual work inside the deposition drift as far as possible.

1.4.10 Quality control

In KBS-3H the super container containing the copper canister with spent fuel and bentonite buffer, i.e. the near field of the package, are assembled in a reloading station at repository level which offers good possibilities for inspection and quality control. This should be compared to KBS-3V, where the buffer material, the most important component of the near field is emplaced in the deposition hole, in the deposition tunnel. In the case of KBS-3H, the super containers the buffer and canister are well protected during transportation, in a transportation tube to the launch tube where it is docked to the deposition drift.

Since the canister and the buffer are stored as a single unit in the super container, it is easier to check the canister and buffer during the entire deposition procedure from filling of the supercontainer until it is in emplaced in final place in the deposition drift.

1.4.11 Organisation

The impact on the organisation has not been studied, but it is assessed that the organisation for a deep repository based on KBS-3H could be somewhat smaller, since backfilling of the deposition tunnels is omitted. Excavation of the horizontal deposition drifts will also be less labour intensive than drill and blast the deposition tunnels and subsequent boring the individual deposition holes for individual canisters.

A time study of the deposition cycle indicates that the goal to deposit one canister per day can be achieved also for KBS-3H. It should although be considered to plan for two sets of deposition equipment due to need for back-up during maintenance, repair and establishment at a new deposition drift.

1.4.12 Costs

During both the feasibility and Basic Design study, a cost comparison between KBS-3V and KBS-3H has been carried out. The result showed that there is a significant cost saving potential for the KBS-3H alternative due to reduced rock excavation and less backfilling. However, it is too early to give exact figures of the cost savings before the technical demonstration and the safety analyses of the KBS-3H concept has been carried out and been evaluated.

2 Technical developments

2.1 Excavation technique for deposition drifts

2.1.1 General

The requirements on the excavation of the deposition drift for KBS-3H are high due to the requirements regarding the deposition process, early evolution of the buffer and the long term safety of the concept.

Both TBM and Cluster technique were investigated during the KBS-3H feasibility study. They represent two different technologies with different advantages and disadvantages. They were both regarded as feasible for excavation of the deposition drifts although a test is required in order to verify that the quality requirements can be achieved.

In the end of the feasibility study SKB decided to focus work on the cluster technique based on the following reasons:

- The method has good possibilities to produce a straight drift with a very smooth surface.
- The method does not require people in the drift during boring.
- There is no risk of oil leakage or other polluting of the rock surface during operation.
- The method was expected to be suitable for short tunnels and frequent set-up.

Work during Basic Design was mainly focused on the following two areas:

- The design of the clusters is new and in need of further development and tests.
- How to handle the large water flows required for the water hammers and transport of the excavated rock in the drift.

The TBM technology was regarded as having greater flexibility regarding grouting and reinforcement, but on the other hand, work environment risks was considered greater due to needs to perform manual work in the drift during operation. The wear of cutters is relatively large; especially the outer disc cutters and they have to be changed at short intervals. This affects the total performance of the excavation process.

2.1.2 Cluster technology

General

The KBS-3H Basic Design project included development of equipment for horizontal excavation of deposition drifts with a diameter of 1.85 m and length up to 300 m.

The drilling equipment is designed and manufactured with the aim to fulfil the requirements on the deposition drift. The requirements relate to tolerances on drift alignment, diameter variation, deviation and quality of the rock wall surface. The tolerances are shown in Appendix 1.

Design and manufacturing of the drilling equipment was followed by a test drilling at the end of 2003.The idea of performing an excavation test during the Basic Design phase was to be able to evaluate, and if necessary correct, function, method and technique prior to the planned excavation of demonstration drifts at Äspö HRL.

Method

The method to achieve a drift which meet the requirements is basically to perform the drilling in three main steps shown in Figure 2-1. The first step is to drill a pilot hole that shall guarantee the overall alignment of the drift and also serve as a guide for the subsequent drilling. The second intermediate step is "production drilling" with the Ø1,440 mm cluster to efficiently excavate the bulk volume of the drift in order to reduce the load on the final cluster. The third and final step is drilling with the Ø1,850 mm cluster ring to achieve the required rock surface quality and drift diameter.

Pilot holes – equipment

The equipment used to drill pilot holes is an Ø254 mm W200 water hammer where steering/balancing was done by Ø251mm stabilizers and ribs on the W200 hammer. The first stabilizer was placed next to the hammer and the second was placed 6 m behind. The first pipe after the second stabilizer had short ribs on both ends, also at Ø251mm.

Ø1,440 mm cluster hole – equipment

The Ø250 mm pilot hole is then reamed using an Ø1,440 mm cluster drill consisting of 12 water hammers, W150, Figures 2-3. Water is transported to the cluster through the drill string. In order to avoid bending of the drill string and the cluster a number of stabilisers keep the string in the central part of the drift. The cluster design is based upon existing clusters on a smaller dimension.

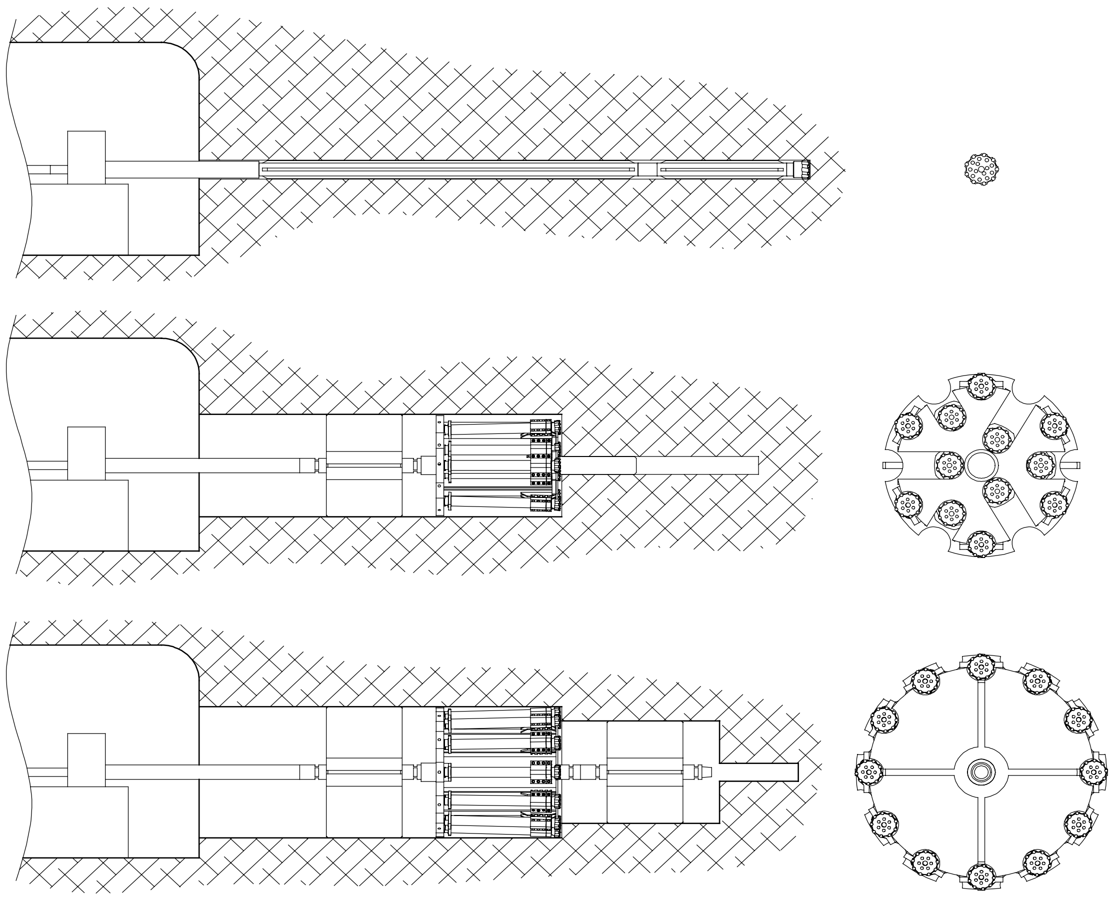


Figure 2-1. *Illustration of the three step excavation sequence of a deposition drift.*

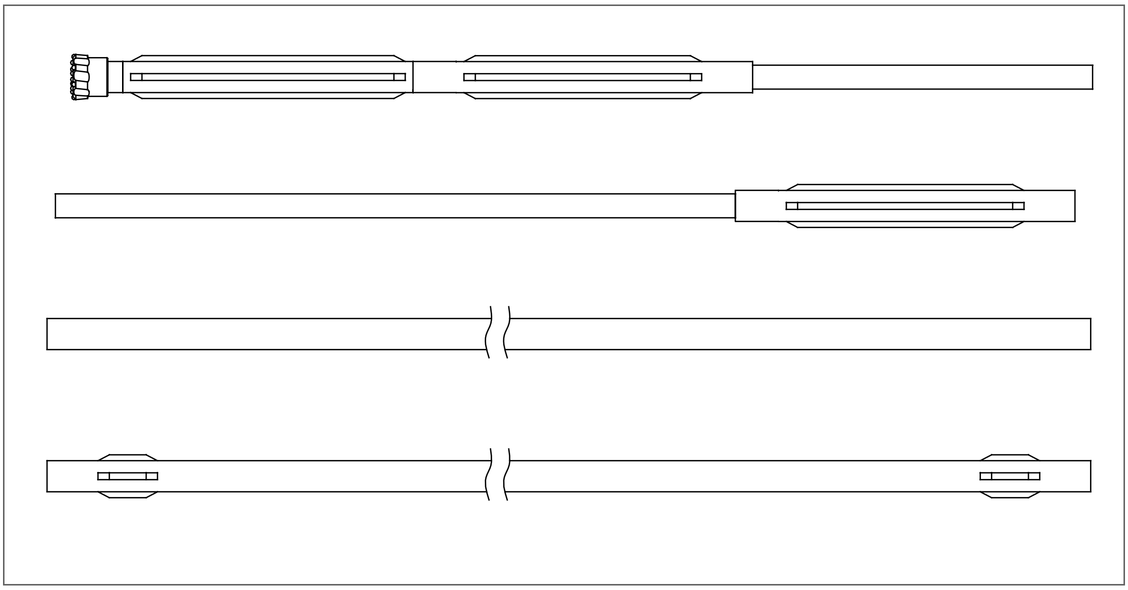


Figure 2-2. Equipment used to drill the pilot hole.

Figure 2-3. Cluster (Ø1,440 mm).

Ø1,850 mm cluster – equipment

A cluster with diameter Ø1,850 mm and with 12 hammers, W150, all drilling in the same path is used to ream the Ø1,440 mm drift. The equipment was especially designed within the project to meet quality requirements on the rock wall surface. The cluster is shown in Figure 2-5.

Figure 2-4. *Bit from outer orbit in the Ø1,440 mm cluster.*

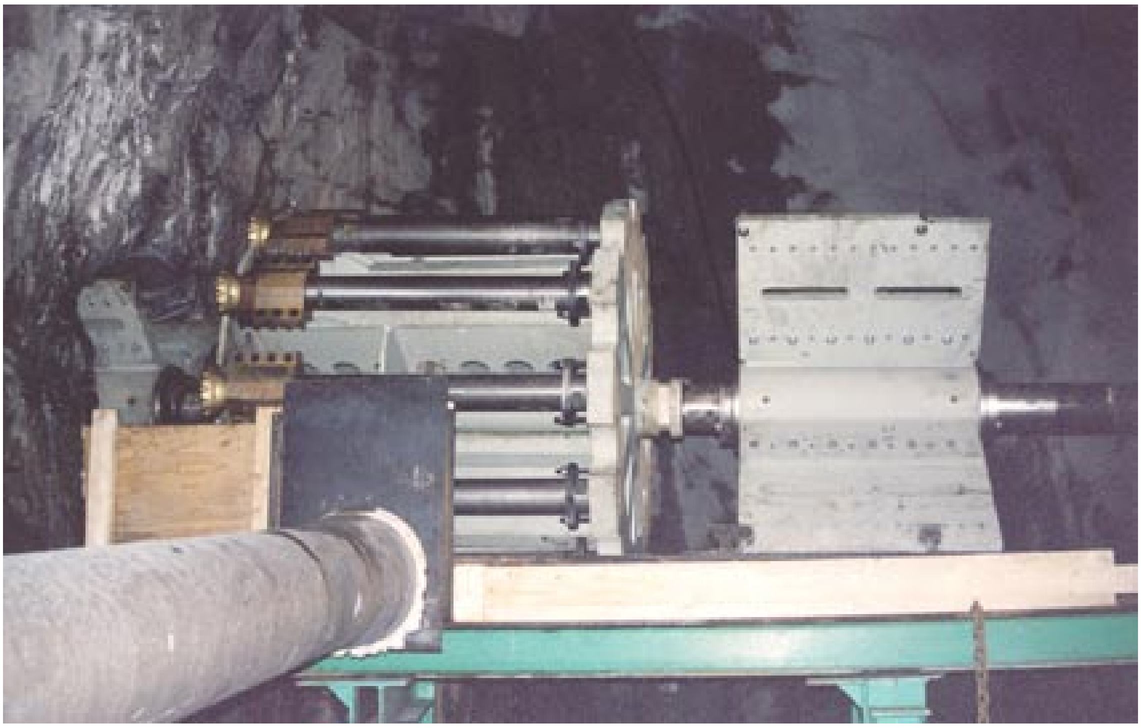


Figure 2-5. *Cluster (Ø1,850 mm) and adjustable guide entering the rock.*

Drill rig and water handling system used during the test of the system

During the test of the cluster equipment in Norway late 2003 the following mechanical equipment and tools were used:

Machine

Horizontal Directional Drilling Rig with 100 ton pullback force and maximum torque 5,5000 Nm. Maximum rotation speed is 85 RPM. Total installed diesel power is 340 kW. Special featured with data acquisition unit for monitoring drilling operation. Drill manager computer tool for assisting operator. Drill pipe modified 6 5/8 API FH to 6 5/8 API REG, length per pipe 8.5–9 meter.

Water pumps for drilling operation

Two 20 feet ISO container each with one Haliburton HT 400 6" plunger pumps; 500 kW, diesel powered. One 10 feet ISO container with two Crown electrical driven frequency controlled pumps. Totally installed electrical power; 265 kW.

Pumps for water handling in the sedimentation basin

Two 5.5 kW Flygt pumps with a capacity of 4.8–5 m^3/minute is used for control of the water level in the sedimentation basin.

Auxiliary equipment

- 20 tons wheel carrier and telescopic truck for lifts and transport.
- Mobile breakout unit for 5–12 connections.
- Hydraulic power pack, 5 kW.
- Compressor 12 m^3/h 6 bar.
- Platform for aligning and handling cluster and stabilizers that was constructed on site.
- Trough for collecting water coming out from the drift, also made on site.
- Handling of cluster was done with a mobile crane 60–70 tons lifting capacity.
- 40 kW fan for evacuating air and exhaust.

Full scale test excavation

A full scale test drilling was performed during October/November 2003 at an underground water treatment plant situated near Oslo. The equipment described above was used at the test. A 40 m long test hole was considered sufficient for testing of the method, equipment and evaluation of the drilling result.

A 42 meter long pilot hole with a diameter of Ø254 mm was drilled with a theoretical start angle of 2° from the horizontal plane. The Ø254 mm pilot hole was reamed up to a total length of only 33 meters with a diameter of Ø1,440 mm using the cluster with 12, W150 Wassara hammers. The drilling had to stop since the inclination of the pilot hole had become too small at the end of the hole to allow evacuation of cuttings by water flushing. Finally the Ø1,440 mm drift was reamed up to a total length of only 14 meters with a diameter of Ø1,850 mm, using the Ø1,850 mm cluster. It was decided to stop the drilling after 14 meters due to time and budget restraints. It was also judged that necessary information could be extracted from the performed drilling.

The power to the clusters was provided by two diesel pumps and one electric pump. The water used was tap water from a 900 m^3 storage tank. The waste water was collected in a concrete sedimentation basin, pumped out and not cleaned and re-circulated. For the real case in a future deep repository cleaning and recirculation will be necessary but in this test case it was more cost effective not to re-circulate the water.

Test results

A number of results could be obtained from the test drilling. The performed tests and results are compiled in Table 2-1.

Table 2-1. Performed tests and results.

No.	Object, etc.	Test, visual inspection, etc.	Result
1	Systems overall performance	Expertise judgement	• Overall performance of the system is according to expectations. • Improvements of lifting devices during assembling are needed to facilitate mobilisation. • The pilot hole had too much deviation. Improvements of stabilisers and balance of the drill string are needed. • Drilling performance during the first reaming (diameter 254–1,440 mm) was good with lower torque than expected. • Drilling performance for the second reaming was good with lower torque than expected. Some interrupting problems occurred due to blocks caving from the first reamed hole that jammed the cluster. Improvements of the cluster design are likely to solve the problem.
2	Rig (frame)	Visual inspection	OK
3	Machine	Visual inspection Evaluation of performance and logged data	Problems with wear and breakage due to vibrations caused by pressure peaks emanating from unstable running hammers. Suggested improvements are damping of pumps, equalization of hammer action, separation of high pressure water pipe and oil hydraulic hoses.
4	Pumps	Visual inspection and evaluation of logged data	Too low pump capacity at maximum load resulted in overheating and wear.
5	Water hammer for pilot hole	Visual inspection Evaluation of performance and logged data	The performance was OK, but the water consumption was too low to flush cuttings appropriate.
6	Bits for pilot	Visual inspection	OK
7	Stabilisers for drilling of pilot hole	Visual inspection Evaluation of performance and logged data	High wear due to insufficient flushing of cuttings. Poor balance probably because of too small stabiliser diameter and not optimized configuration leading to hole deviation.
8	Cluster for Ø1,440 mm hole	Visual inspection Evaluation of performance and logged data	The cluster performance was good except from water leakage at hammer connection welding, which in turn required higher pump capacity.
9	Bits for Ø1,440 mm cluster	Visual inspection	Bits in the middle orbit were worn after 33 m drilling, especially front buttons. Bits in the outer orbit were also worn at the front buttons, see Figure 2-6. Bits in the inner orbit showed very little wear. The wear rate can be improved by optimisation of the bit and button configuration.
10	Water hammers for cluster, Ø1,440 mm	Visual inspection Evaluation of performance and logged data	OK
11	Stabilizers for drilling of Ø1,440 mm hole	Visual inspection Evaluation of performance and logged data	OK. Wheels are not necessary.
12	Cluster for Ø1,850 mm hole	Visual inspection Evaluation of performance and logged data	The cluster performance was good except from occasional jamming due to loose rock pieces sticking between hammer locking clamps and rock wall. Water leakage at hammer connection welding also occurred, which in turn required higher pump capacity.
13	Water hammers for cluster, Ø1,850 mm	Visual inspection Evaluation of performance and logged data	OK
14	Bits for Ø1,850 mm cluster	Visual inspection	No wear of the bits could be seen after only 14 m of drilling.

No.	Object, etc.	Test, visual inspection, etc.	Result
15	Guides for drilling of Ø1,850 mm hole	Visual inspection Evaluation of performance and logged data	OK. Wheels are not necessary. Longer sliding surface area will reduce friction and thus risk for marks on the rock surface.
16	Bore hole quality; hole deviation	Measurement	The inclination had dropped from 2° upwards to 0° after 38 meters and slightly downwards at end of bore hole. Horizontal deviation maximum 10 mm at 26 meters depth. Vertical deviation does not fulfil the requirement.
17	Bore hole quality; roughness	Measurement	OK. Maximum measured roughness from drilling is 4 mm.
18	Bore hole quality; diameter and roundness	Measurement	OK. Maximum measured diameter 1,853 mm and 1.4 mm deviation from roundness.
19	Bore hole quality; waviness	Measurement	Horizontal waviness measured to maximum 2 mm from the centre line. Vertical waviness not possible to evaluate due to pilot hole deviation.
20	Bore hole quality; steps	Measurement and visual inspection	OK, no steps could be found in the bore hole.
21	Bore hole quality; coneness	Measurement	Bore hole length too short for evaluation.

2.1.3 Horizontal raiseboring

General

A literature study of horizontal raiseboring (or horizontal reaming) has been performed as a complementary alternative to the cluster technology. The study was established with the overall objective to ascertain the state of the art concerning horizontal raise boring technique and to identify necessary improvements in order to reach the required specifications for a 300 m long deposition drift.

Method

Horizontal raise boring is an alternative way of using the common so called raise boring technique. Except for the setting up of the equipment, two basic activities are involved, the pilot hole drilling, which is performed from the machine into the break through drift, and the reaming of the raise which is made from the break through drift towards the machine. Figure 2-6 below shows the principles of raise boring technique.

Conclusions from the study

The conclusion of the study was that raiseboring is a mature technology which with small improvements can be used for production of deposition drifts. The necessary improvements are related to the cutter head design:

- Special perimeter cutters that follows the regular cutters making the final trimming of the diameter.
- Diamond coated perimeter cutters.
- Frequent regular changing of perimeter cutters.

The most important issue for the future to meet the SKB tolerances is to initiate discussions with manufacturers in conjunction with representatives from the drilling contractors in order to drive the development work forward.

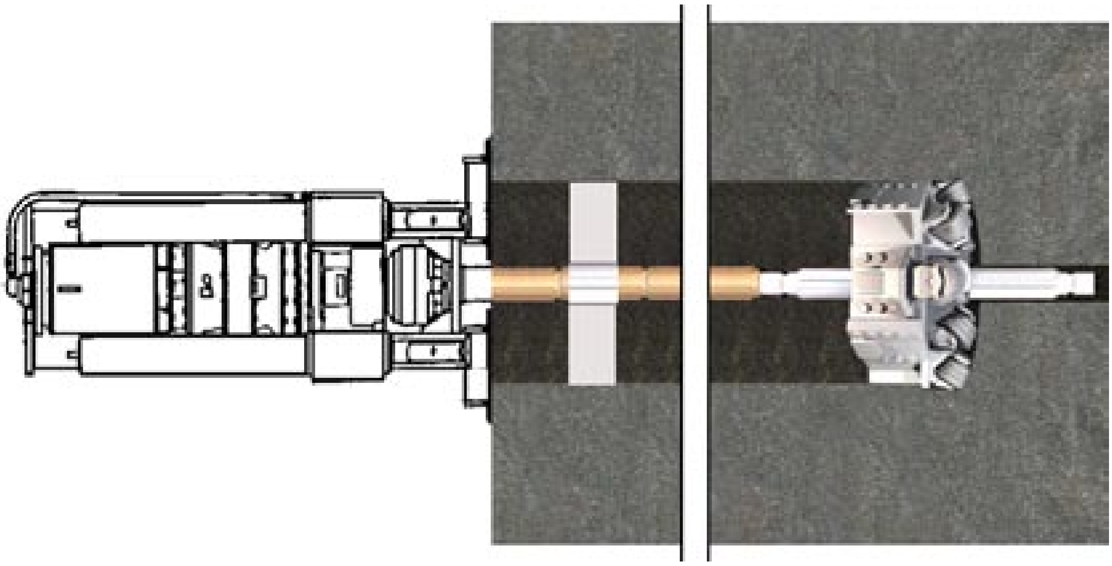


Figure 2-6. The principle set-up of horizontal raise boring equipment.

The overall conclusion of the study is that:

- The equipment is available on the market.
- The contractors are familiar with this kind of tunnelling method showing good records of references, however, the requirements have never been similar to SKB:s set of requirements.
- The cost and time involved is comparable with vertical raiseboring.
- Reaming heads must be developed in order to meet KBS-3H requirements.
- There is a possibility to do blind horizontal raiseboring, in this case the drillrig pushes the drill string instead of pulling it. A set of drill string stabilizers is necessary in order to keep the string in the centre of the drift.

During early 2004 it was decided to select the blind raise boring technique for excavation of the drifts needed for the demonstration at Äspö as this technique is less costly and still meet the requirements for the deposition drifts for the demonstration.

2.2 KBS-3H deposition equipment

Based on the conclusions of the feasibility study SKB has carried out Basic Design of the machine equipment necessary for emplacement of the super container and the distance blocks. The Basic Design has also covered the super container itself

The input from the feasibility study was in short:

- a recommendation that the emplacement of canister and bentonite should be done in one unit, a so–called super container.
- movement along the drift should be supported by lifting cushions which carry the super container on a thin film of air or water. This reduces the friction and enables a relatively simple machine design and a slim super container.
- The super container should be made of as little steel as possible and have a perforation grade of about 60%.

- Functional requirements for the deposition equipment which serves as input data for the Basic Design phase.

Based on these conclusions the KBS-3H Basic Design project has carried out designs of the super container and deposition equipment. As a part of the design work, workshop tests of the aircushion function were carried out.

2.3 KBS-3H super container

2.3.1 General

The super container consists of a perforated steel cylinder with highly compacted bentonite and one copper canister inside, Figure 2-7. The super container has a perforated top and bottom plates and is equipped with two rows of feet along the container. The feet create an about 40 mm slot underneath the container in which the lifting palette and sliding plate will be active.

The preliminary design was considered to fulfil the requirements regarding long term safety and early evolution of the buffer material surrounding the copper canister. As a part of the KBS-3H project an extensive analysis of the super container strength and behaviour during emplacement has been performed using the Finite Element Method. The results of the analysis show that the super container will withstand the different load cases that will act on the container during the installation process in the drift. The analysis show however the importance of how the feet are designed and some changes have been done compared to the first design.

The property of the buffer material and the distance plugs are however not finally stated. This may change the presumptions for the detailed design of the super container.

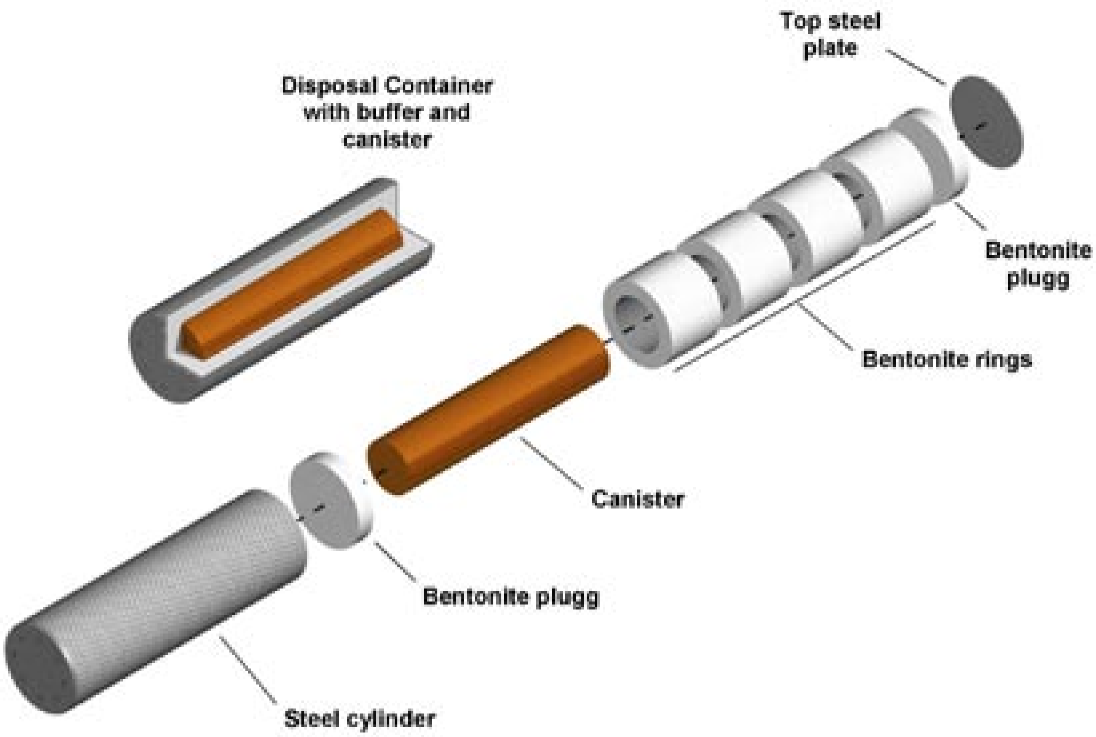


Figure 2-7. *Exploded view of perforated super container.*

2.4 Distance block

Distance blocks are used to separate super containers from each other in order not to exceed the maximum canister temperature. The distance block will also create a hydraulic cell surrounding each canister. The blocks are not designed in detail during the Basic Design phase, but will most likely consist of compacted bentonite with complementary sealing collars. The sealing collars are necessary in order to reduce the risk of piping and erosion if high water flow or water pressure is expected during the early swelling and saturation phase of the bentonite block. The dimensions of the blocks will be dependent of the chosen engineering solution to transport and emplace the blocks in the drift and also the minimum allowed distance between canisters due to thermal effects.

2.5 Deposition equipment

2.5.1 General

During 2003 the deposition equipment of the KBS-3H concept has undergone Basic Design. The equipment will be used for a full-scale demonstration at Äspö Hard Rock Laboratory not for a future deep repository. For economical and practical reasons some simplifications are made, this means that some of the requirements which will apply to a future deep repository are not included in the list of functional requirements. The equipment will for instance not be designed for radiation from a canister with spent fuel however, the presence of radiation will be considered to some extent during selection of materials etc.

The main objectives for the Basic Design of deposition equipment have been:

- Establishment of descriptions and drawings of deposition equipment, complete enough for ordering the detailed design and manufacturing of the equipment.
- Verification that the lifting cushion principle is feasible for horizontal emplacement of disposal super containers.

The following equipments have been included in the Basic Design:

- Deposition machine including lifting palette.
- Transportation tube.
- Start tube.
- Connecting gate enabling connection of the equipment to the drift.

Equipment for handling of distance blocks was originally included in the Basic Design but dimensions and geometry of distance blocks have not been possible to fix due to ongoing laboratory tests. Therefore, the design of such equipment was excluded from the Basic Design and moved to the next design phase.

The Basic Design has resulted in drawings and mechanical analyses of the different parts of the deposition equipment as well as general design of electrical- and control systems. The workshop tests of the lifting cushions have also been performed and reported.

2.5.2 Basic Design results

The design is based on alternating relative movement of super container and slide plate. The super container is provided with feet. In the space which is created underneath the super container, a slide plate and a lifting cushion pallet are installed, Figure 2-8.

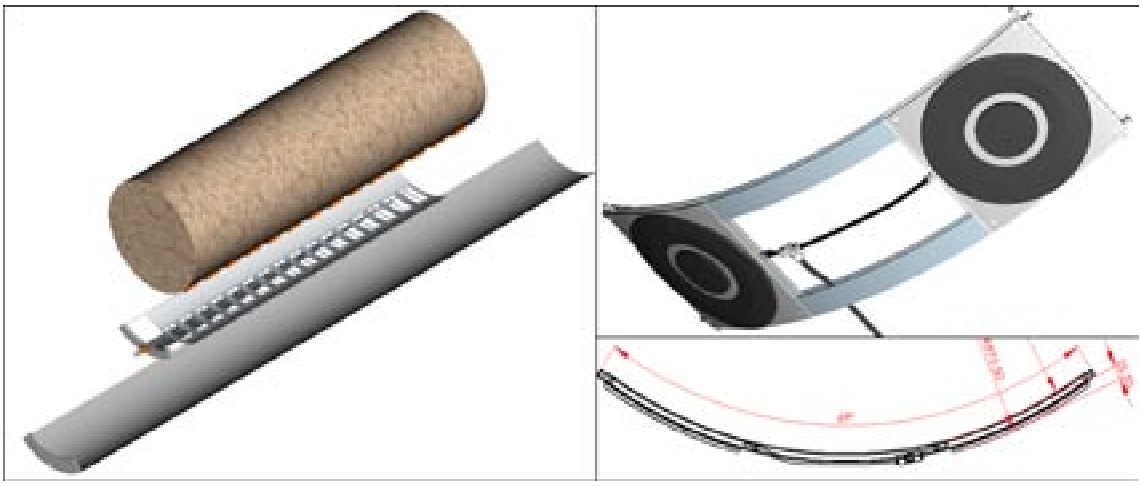


Figure 2-8. *Super container with cushion pallet and slide plate (left hand) plus a cushion element (right hand).*

The slide plate is used to give the cushions a smooth surface to slide on. The cushion pallet consists of several co-operating cushions. Originally, the idea was that the cushions would be ordinary aircushions but during the design process it was considered more energy efficient to use water as the media in the cushions.

Movement in the deposition drift is arranged as follows:

1. When the lifting cushions are activated, the super containers are lifted from the parking feet and float on a thin film of water.
2. The deposition machine then push the super container forwards one stroke about one and a half metres on the slide plate.
3. The pressure is reduced and the super container lands on the parking feet.
4. At this stage, the super container rests securely on its parking feet and the deposition machine can pull itself and the slide plate forward by retaining its grip on the super container.

The above is repeated until the super container is in the correct position in the deposition drift. After this, the machine is released from the super container and the machine rolls out from the deposition drift on its own wheels. The principle for transportation in the deposition drift is shown in Figure 2-9.

An overview of the deposition equipment at the start position in the operation chamber outside the deposition drift is shown in Figure 2-10. The emplacement phase is shown in Figure 2-11.

Description of the Deposition Machine

The deposition machine forms a unit with the sliding plate and water cushion module. The deposition machine is wheel driven. The wheels are only driven when the machine is docked to the disposal super container in the deposition tunnel and when the machine backs out of the tunnel when the disposal super container has been placed in the correct deposition position.

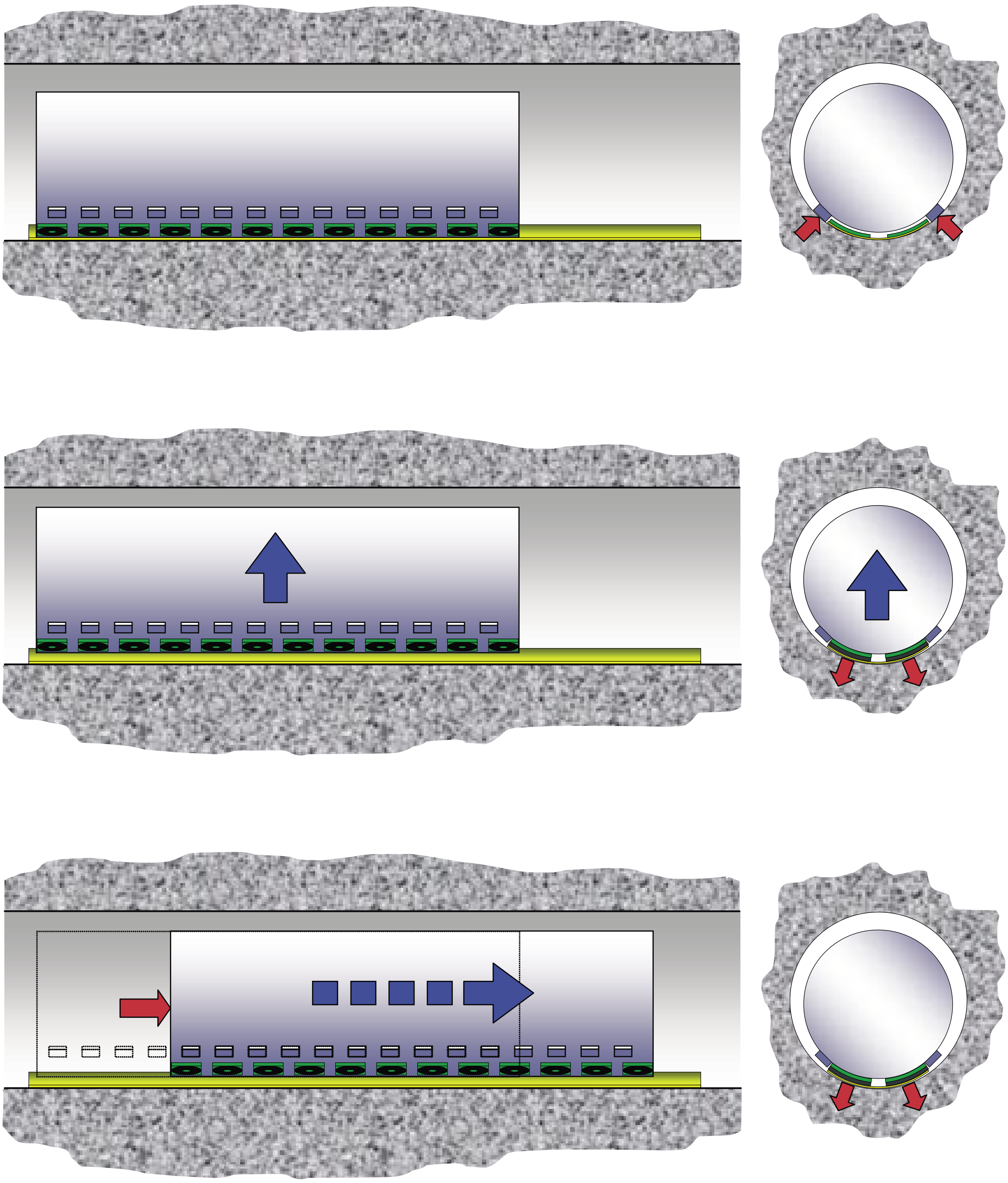


Figure 2-9. Transportation principle in deposition drift

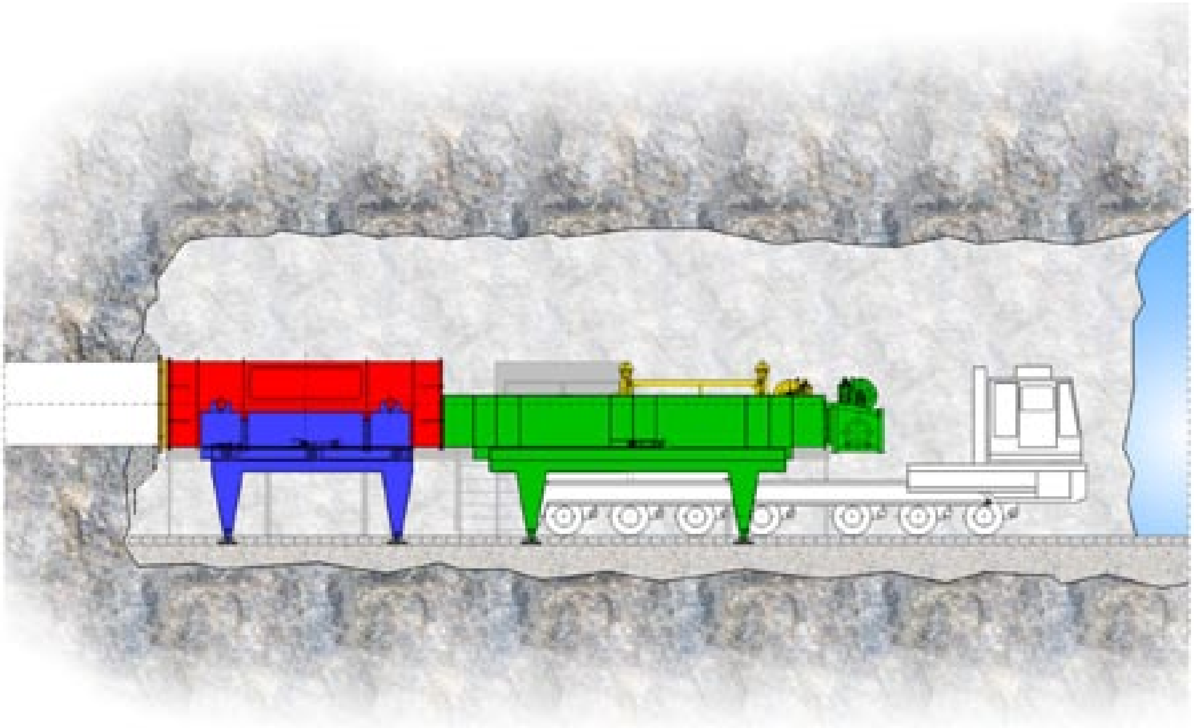


Figure 2-10. Deposition equipment outside the deposition drift, transport tube (red), start tube (green) and the deposition machine (yellow)

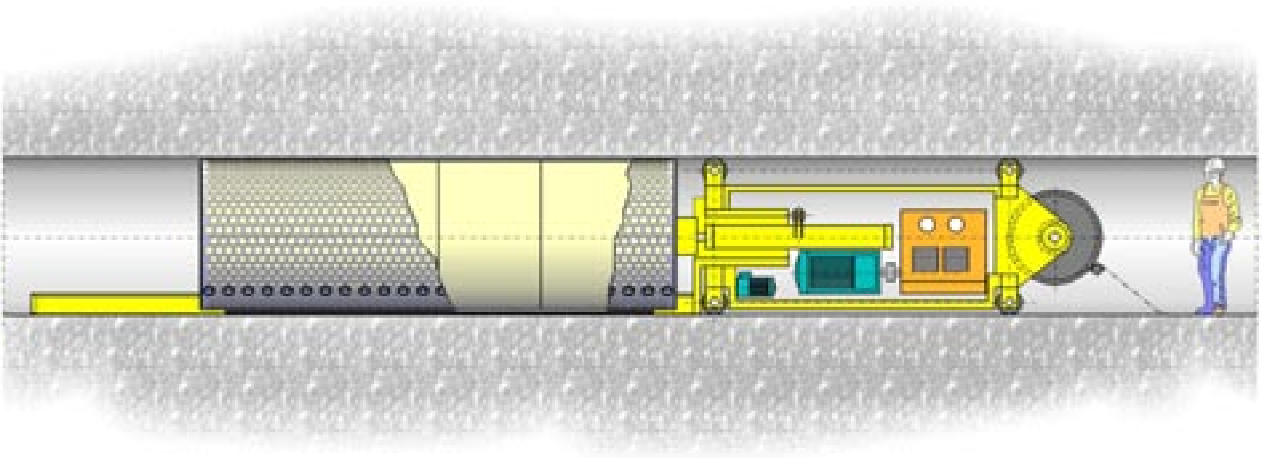


Figure 2-11. Deposition equipment and super container in the deposition drift

When deposition super containers are moved and when the slide plate is moved, a linear actuator on the front of the machine is used. The front part of the actuator is mounted to an electromagnet, which is locked to the end plate of the super container. The electromagnet is released when the super container is in its final position. The machine is connected to the slide plate during the entire process in the deposition drift.

In case of a power loss, the super container will be lowered and the electromagnet will be released. If considered necessary the whole deposition machine can be pulled out to the niche using a steel wire that always is connected to the machine in the aft.

During 2004 the system with an electromagnet for connecting the super container with the deposition machine was replaced by a system of mechanical grippers. These grippers are holding the front feet of the super container during the deposition process.

The estimated average time for a disposal of a super container in the final emplacement plant assuming a length for the deposition hole of 300 meters is 14 hours and 40 minutes.

The main frame of the deposition machine consists of steel beams with rectangular cross sections. The water tank with its pumps and piping is located at the middle of the machine. Rotating wheel rings are placed on each side of the machine. The slewing rings are equipped with locking device, or with restricted rotary motion. The driving machinery that drives the machine is placed on the aft ring. The driving machinery consists of a motor with an integrated worm gear that drives four connected wheels placed 90 degrees apart. The electrical actuator and its two guiding shafts are placed in the front part of the machine and are attached to the machine with links to allow movements. The front of the actuator and the guiding shafts are attached to the stand that carries the electromagnet. The lifting palette with the water cushions is connected to this stand and the sliding plate is connected to the frame with a flexible link.

The complete assembled deposition machine, including lifting palette and sliding plate, is parked in the start tube between the super container disposals. When transporting the machine, the palette and sliding plate must be disassembled from the machine and moved under the machine in the space between the machine and the start tube.

Water supply system

The water supply system consists of a 750 litres water tank, main pump, drainage pump, strainers, valves and piping. The main pump supplies the lifting palette with water with a pressure of approximately 0.5 MPa and a flow of 200 litres per minute.

When lifting the super container during the disposal operation a 3-direction valve controls the flow to the lifting palette. When placing the super container on the drift floor, the water is directed to the sump for the drainage pump. The main pump is controlled by a frequency converter and reduces the speed when the palette is not activated to reduce the power consumption.

The water that passes the water cushions is collected on the sliding plate and flows backwards on the plate to a pump sump. This is achieved due to inclination of the drift of 2 degrees. The drainage pump transports the water back to the tank. The drainage pump is continuously in operation and is fed with water from the main pump when the lifting palette is deactivated to avoid try operation and damages on the pump.

Super container control

It is of great importance that the super container always is correctly orientated with the parking feet located downwards at starting position. A tilt sensor detects the horizontal alignment of the super container.

When the lifting palette is activated it has an almost frictionless contact to the sliding plate. This is illustrated in Figure 2-12 below.

The more heavy components of the deposition machine is placed as low as possible to achieve a low centre of gravity. This will counteract possible rotation of the super container during lifting. An additional adjustable counterweight is placed on the machine to compensate any unbalance of the super container. The counterweight is also placed low

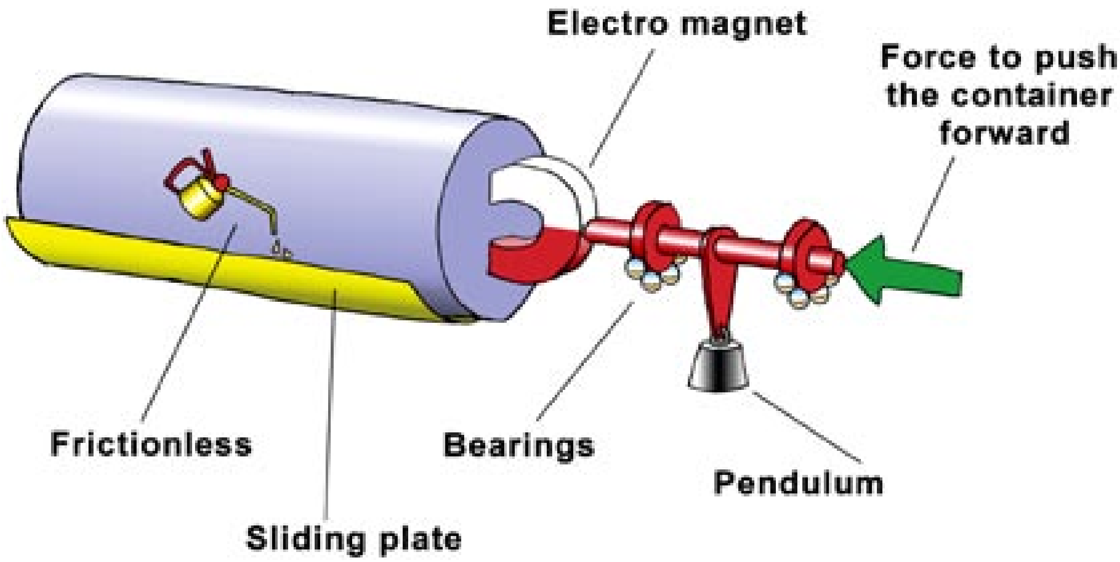


Figure 2-12. Principal function of super container control.

to achieve the best effect. The weight is made of lead and has a mass of 750 kg. The weight is moved with an electrical actuator.

The electromagnet attached to the rear end plate of the super container transfer the unbalance torque to the two guides on the sides of the actuator that are mounted to the frame of the machine.

When the lifting palette is activated and the super container is lifted, the super container will naturally align itself in the centre of the deposition drift. At the same time the low centre of gravity for the equipment counteract the torque from the unbalance. To ensure that the sliding plate also align under the super container the joint to the machine is flexible sideways. Two wedges on each side of the sliding plate will help the plate to align under the super container when they are pressed against the parking feet when moving the plate forward.

Description of transport tube

The transport tube consists of a steel cylinder reinforced at each side with rings plus four rings on each side of the four trunnions. Each trunnion has two lifting spots, one for the lift at the reloading station and one for the placing in the cradle. Both ends of the tube are machined to ensure an accurate docking to the docking flange at the deposition drift opening and to the start tube. The hatches are provided with fast locking devices and are designed to withstand the load from the super container.

The deposition drift opening is provided with a gating flange embedded in concrete. A machined docking flange is assembled to the flange. The end of the transport tube will dock to the docking flange.

Cradle for the transport tube

The cradle is made of steel plates and designed to fit the transport tube and the support frame. The cradle is provided with four minor support positions that correspond to the trunnions on the transport tube.

Two hydraulic actuators, one on each side, operate the cradle to dock to the docking flange. The actuators are assembled with brackets to the cradle and to the support. The cradle is also provided with slide plate bearings between the cradle and the support to simplify the tube docking to the docking flange.

The cradle is fixed to the support with manual locking pins that are used during transport and whenever the transport tube is parked.

Support for the transport tube

The support is made of steel plates and designed to fit the cradle and the transportation vehicle. The feet of the support have conical pins that fit into connection blocks embedded in concrete in the floor of the niche outside the deposition drift. Using the finished support when placing the connecting blocks embedded in concrete ensures the locations of the connecting blocks. Brackets for the hydraulic actuators are attached to the upper plates of the support. The two locking devices for parking and transportation are located at the ends of the upper plate. The hydraulic control unit with pump, valves and oil receiver are also mounted on the upper plate of the support.

Description of the start tube

The start tube consists basically of three different parts.

1. A cradle where the deposition machine is placed.
2. A support for the cradle, including hydraulic actuators on each side.
3. A reversal module for emergency reversal of the deposition machine.

The cradle consists of a half-cylindrical steel plate frame. The front end of the cradle is designed to fit to the transport tube when docking. The deposition machine is placed in the cylinder when it is not in operation in the drift. A flange for mounting the reversal module is provided at the rear end of the cradle.

A chain feeder moves the sliding plate from its parking position under the deposition machine to its operating position in front of the machine.

Two hydraulic actuators for docking to the transport tube are located on each side of the cradle. The cradle is also provided with slide plate bearings between the cradle and the support to simplify the tube docking to the docking flange.

The cradle is fixed to the support with manual locking pins that are used during transport and whenever the transport tube is parked.

Support for the start tube

Basically the support for the launch tube has the same design as for the transport tube.

Reversal module

The reversal module is used if there is a malfunction on the deposition machine and the machine cannot travel out from the drift by itself, for example at power loss. A wire is always connected to the rear end of the machine from the winch.

The reversal module consists of a welded frame made of square hollow profiles. The frame has supports for assembly of a cable-drum for collecting the cable and a motor driven winch. Brackets are also provided for mounting the module to the cradles rear flange.

Power supply and control system

The deposition system is divided in two parts, niche and deposition machine. A PLC is included for each part. To those PLC sensors, signals and supervised objects are connected.

From the control room, located in the operation chamber, the operator can follow the deposition process via monitors and a SCADA system. It is also possible to remote control the deposition machine, docking or connecting the transport tube and the start tube from the control room, or from another place in the chamber or the deposition drift.

All components must be chosen for high enclosure and for corrosive environment use.

Electrical power supply, 3x400VAC TN-S-system with priority, and UPS with power backup supplies the operation chamber and the deposition machine. The UPS power backup will have enough power capacity to supply the deposition equipment in case of power loss to get the deposition machine out from the drift.

2.5.3 Test of lifting cushions

The technique of moving cylindrical objects with aircushions has never been carried out before and for that reason a testing has been performed. The test rig and is shown in Figure 2-13.

The first tests showed that the air-consumption was considerable and would require impractical large need of power (~70–100 kW) to the compressor. A large power input in this application will result in heat problems for the equipment in the deposition drift. At the same time, a short test of water as working fluid showed promising results with only 5–8% of the power needed for air.

Therefore a decision was made to perform a test with water instead of air.

The tests gave good results and all requirements on the equipment were fulfilled. The total lifting height of the cushions at the test was ~22 mm, but more lifting height (~5–10 mm) which might be achieved by optimisation of the cushion-design would be desirable.

Some other conclusions were made from the testing, such as:

- The time for lifting and landing of the water cushions takes a long time (~10–20 seconds).
- Local jets of water may occur and this must be considered when designing the water cushion palette in order to protect the bentonite from getting wet.

The main conclusion from the tests is that the technique of moving cylindrical objects with water cushions is well functioning.

Figure 2-13. *Air cushion test rig.*

2.6 Buffer design

2.6.1 General

KBS-3H and KBS-3V are very similar with respect to the behaviour of the bentonite buffer. However, there are some differences that require special attention. The overall objective of the buffer behaviour investigations is to form a basis for future decisions of buffer and super container design. The following processes had to be investigated for determining the feasibility of the concept:

1. Piping and erosion phenomena of the swelling bentonite.
2. Sealing ability of the distance plugs.
3. Effects of super container corrosion on the bentonite, both mechanically and chemically.
4. Mechanical interaction between the super container and the buffer during the homogenisation of the bentonite and breakage of the super container.
5. Near field thermal and hydraulic evolution.

These processes are studied in a number of projects. Some of the studies started during the KBS-3H Feasibility Study phase in 2002 while others started during the KBS-3H Basic Design phase, 2003 and are still running. These studies are presented in Section 2.6.3.

Early results from tests started during the KBS-3H Feasibility Study have indicated that piping can occur at certain flow rates and pressure levels. It was also shown that the bentonite buffer in the super container will permeate the perforations to distribute and fill the void between super container and rock wall evenly.

2.6.2 Critical issues

The most critical issues are related to the post-emplacement, early phase behaviour and performance of the bentonite buffer in the distance blocks and in the perforated steel super container. Re-saturation and swelling of the bentonite should result in individual sectioning for each canister and filling of the gap between the perforated super container and rock with swollen, impermeable clay preventing groundwater flow along the drift.

One critical issue has been to find limiting values on ground water flow and pressure increase for the sealing ability before saturation of the buffer. Those values are needed to be able to evaluate and decide course of action for super container design and distance block design or alternative solutions.

2.6.3 Buffer experiments

Tests and modelling have been introduced to give basic knowledge about both interaction between bentonite and the perforated super container and piping and erosion phenomenon. Guided by early results from basic tests and critical issue considerations, tests of the sealing ability of distance blocks have also been started. The tests and modelling have been structured in the following way:

1. Test scaled 1:10 of a simulated part of a deposition drift with two canisters (2002), see Figure 2-14.
2. Large-scale test of the interaction between the bentonite and the perforated deposition super container (2003–), see Figure 2-15.

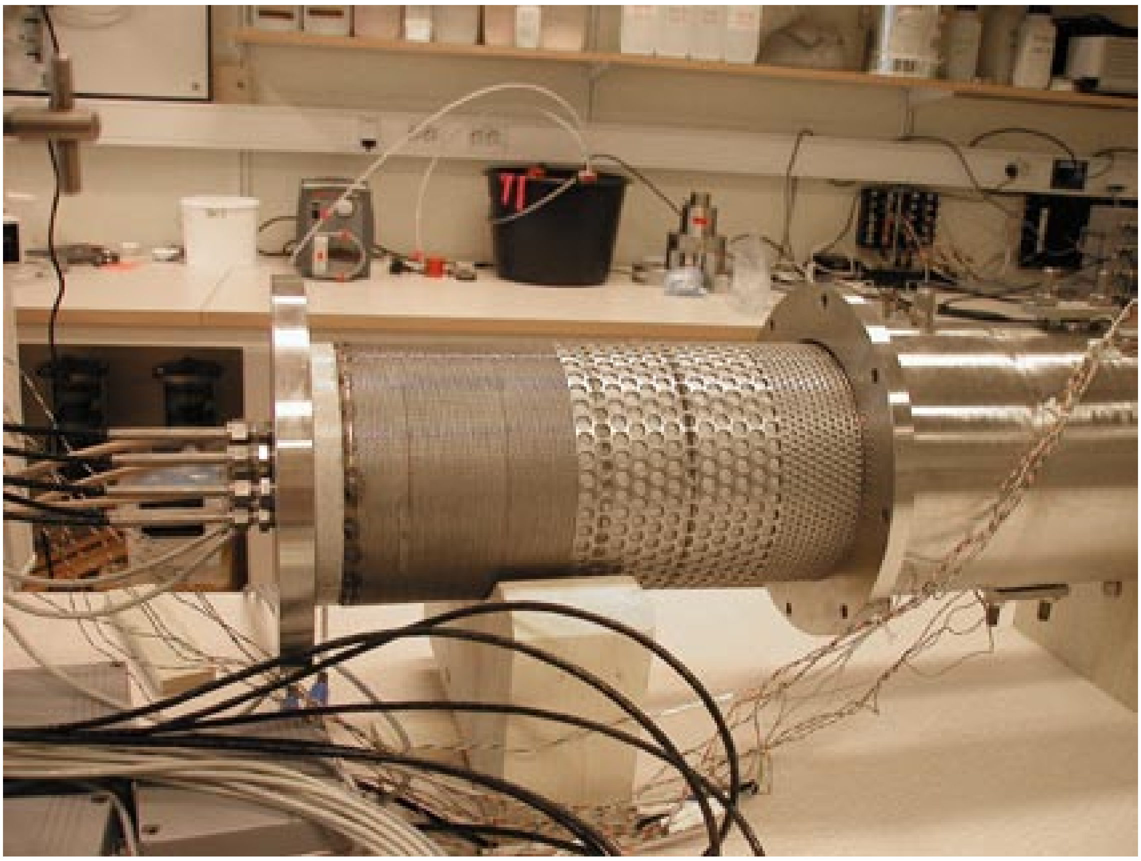


Figure 2-14. *The outer tube equipped with different sensors and perforated super container*

3. Investigation of sealing/piping/erosion phenomena during wetting of the buffer material, see Figure 2-16 and Figure 2-17.
   a) Basic laboratory tests (2002).
   b) Study of processes and scenarios (2003–).
4. Modeling
   a) Modeling of the interaction between the bentonite and the perforated deposition super container.
   b) Modeling of temperature conditions for design purpose.
   c) Modelling of the wetting of the small scale test (1).
   d) Modelling of the wetting and the bentonite swelling in the full scale test (2).
   e) Conceptual modelling of wetting scenarios (3b).
   f) Modelling of the piping and erosion phenomena (3b).

Scale Test 1:10

The test is scaled 1:10 of the exact geometry planned for the concept at the beginning of 2002. The equipment consisted of an outer steel tube with lids in the end parts, two perforated steel super containers with welded end plates, two canisters and bentonite blocks. The bentonite was saturated artificially by filters placed in the periphery of the outer tube. Total pressure, pore water pressure and relative humidity were measured in several points on the outer tube and on one of the canisters. The equipment was designed to withstand an inner total pressure of 10 MPa.

Large-scale test of the interaction between the bentonite and the perforated deposition super container

The large scale test has been postponed because the same test equipment was needed for the investigation of sealing/piping/erosion for distance blocks. The latter was given a higher priority since it was considered a more critical issue.

In order to test some critical functions in full scale, a large-scale model of a part of the perforated steel super container and the distance block is planned. A test with the following ingredients will be performed:

- Perforated super container, buffer thickness and all slots in full scale but no canister.
- Up-scaling of a part of the test scaled 1:10.
- Flow testing in the same way as for test scaled 1:10.
- Dismantling and sampling after finished test.

The duration of the test is preliminarily intended to be about 2 years but may be prolonged since the test will be far from completely water saturated after that time.

The design of the test equipment and test set up is shown in Figure 2-15.

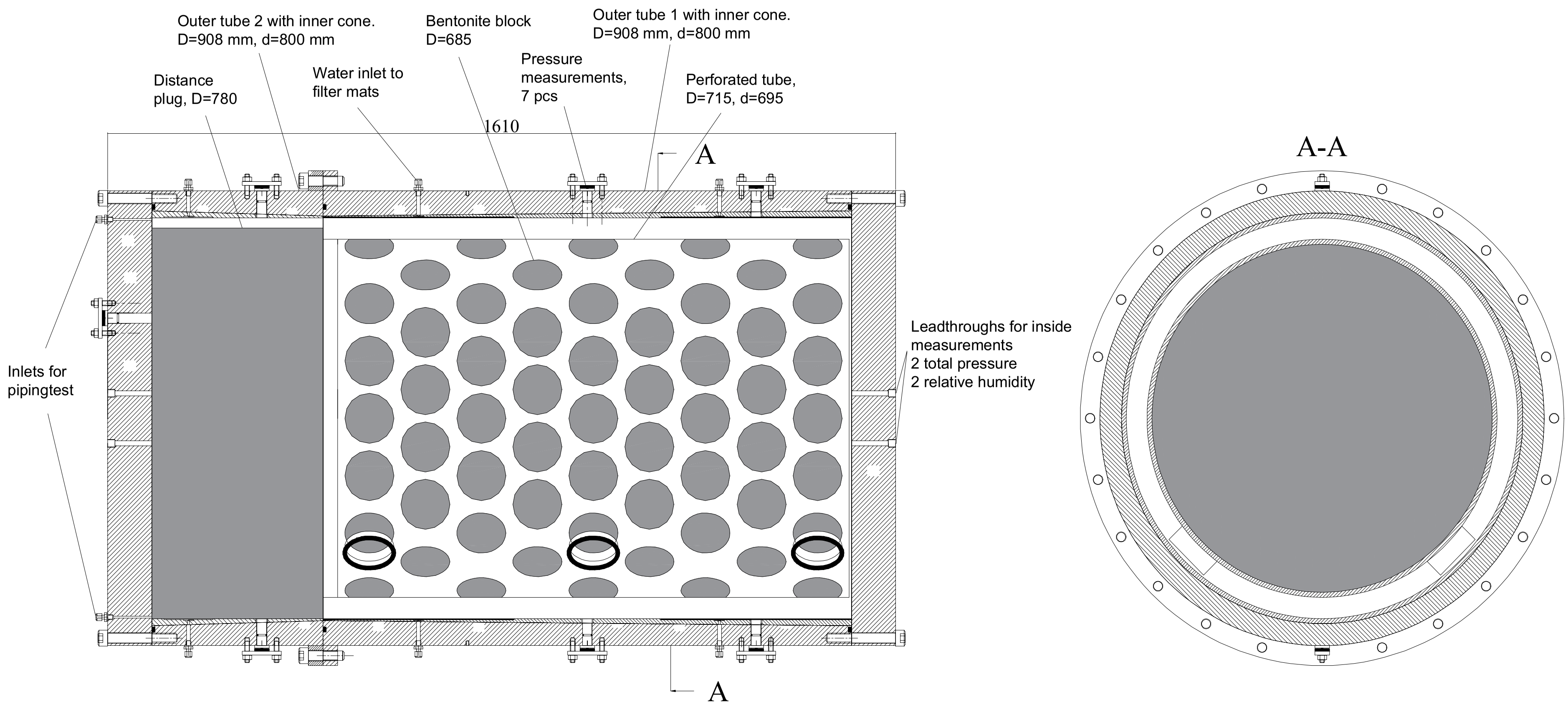


Figure 2-15. *Large scale test set-up.*

Investigation of sealing/piping/erosion phenomena

The sealing and piping/erosion phenomena are very complex and need to be tested in realistic environment since the theoretical understanding is not enough today. The sealing/piping/erosion phenomenon has therefore been further investigated in a study with the following ingredients:

- Modelling of inflow and piping scenarios both conceptually and in the laboratory.
- Performing scaled tests with realistic inflow properties.
- Simulating the function of the distance plugs for preventing piping.

Water inflow into the deposition tunnel will take place and will contribute to the wetting of the buffer. However, if the inflow is localized to fractures that carry more water than the bentonite can adsorb, there will be a water pressure in the fracture acting on the buffer. Since the swelling initially form a gel, which increases its density with time the gel may be too soft to stop the water inflow. The result may be piping in the bentonite and a continuous water flow and erosion of bentonite. There will be a competition between the swelling rate of the bentonite and the flow and erosion rate of the buffer.

In order to investigate this phenomenon a series of test have been performed, starting with basic laboratory tests and continuing with scenario studies and tests of sealing techniques. The following values of the conceptual hydrogeological conditions at a deposition drift have been used as reference for the sealing tests:

- Equivalent water inflow rate is 0.1 lit/min per canister position.
- Water pressure build up maximum is 2 MPa.
- Water pressure build up rate is 0.1 MPa/hrs.

The basic laboratory tests used a final design according to Figure 2-16. A bentonite block with 49 mm diameter was put into a super container with 50 mm diameter so that a 0.5 mm slot was formed between bentonite and super container. The block had a height of 120 mm. The water was led through a hole drilled at the centre of the bentonite block and was let out through a slot at the opposite end.

A part of the dismantled test equipment for the test scaled 1:10 has been used for testing the sealing scenarios. In order to simplify the test the entire perforated steel super container package was replaced by a dummy super container of PVC. Only the distance block was simulated with bentonite.

Water was filled in one point above the super container. The rate of filling was adapted to the scale 1:10. Outside the distance block the next super container was simulated with the lid of the test tube and a slot at the periphery of the lid.

The tests started with water filling until no more water entered. The water filling was in all tests followed by leakage through the plug. When the leakage and the water inflow stopped the pressure increase was started.

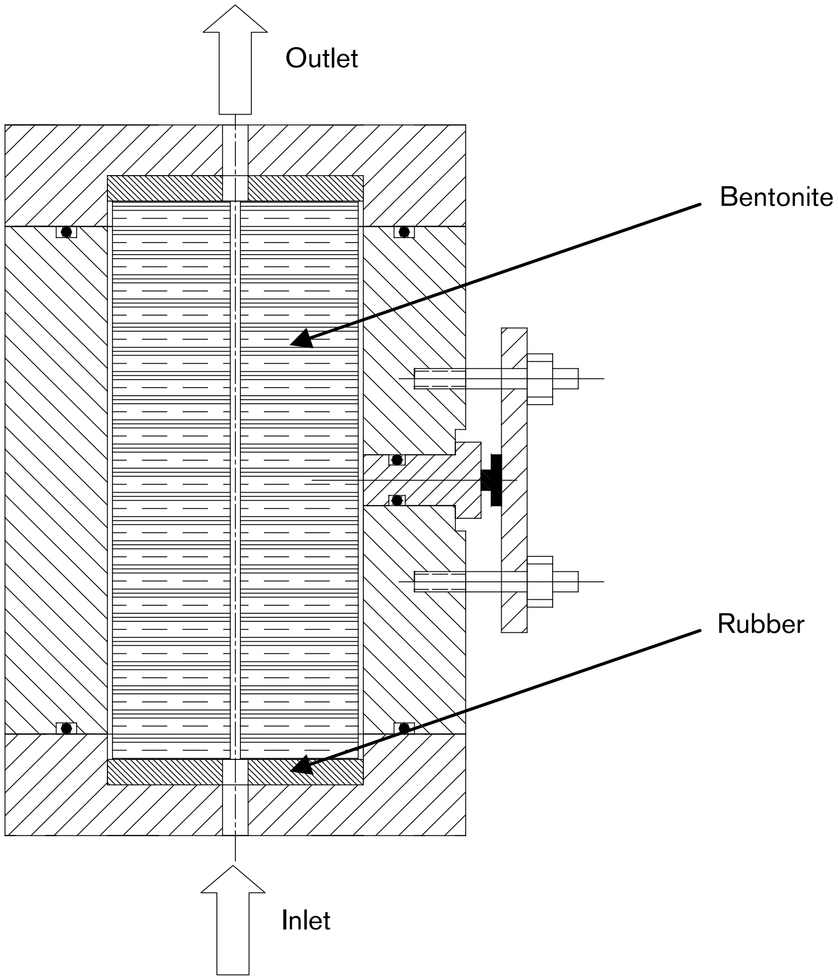
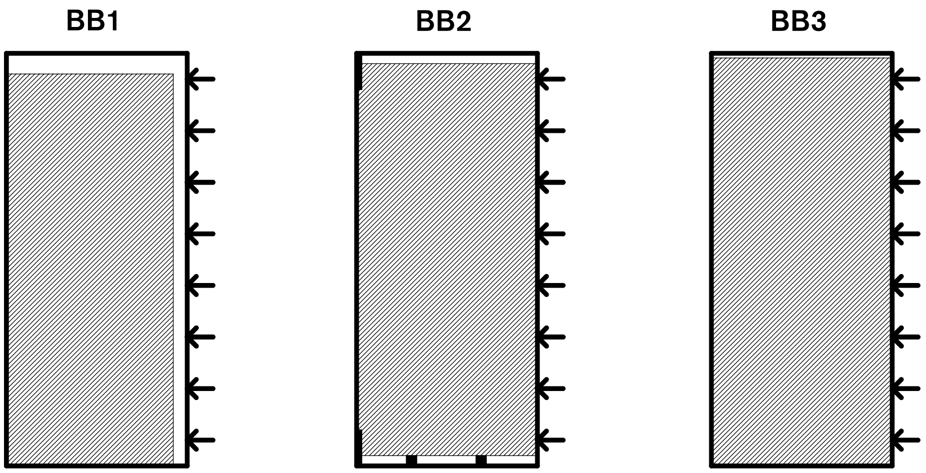


Figure 2-16. *Basic laboratory test set-up.*

The sealing tests in scale 1:10 resulted in the conclusion that the distance blocks works properly for sealing water inflow at the reference case. However, the open slot is due to the scale effect only 2–4 mm, so it is not unlikely that it does not work in full scale with the slot width 2–4 cm. The slot width is thus unfavorable in full scale. On the other hand the block is also 10 times thicker and the filling time is 10 times slower, which is in favor of the full scale.

The only way to investigate the scale effect is to do full-scale tests. During 2003 three such tests were performed. The first test was only using the bentonite block with a large gap of 4 cm at the roof for sealing. Since the lid of the equipment prevented the block from moving it acted as a steel collar, which was not water tight against the rock. In the second test the block was centered yielding an overall slot of 2 cm and a watertight steel collar was introduced to reduce the slot between rock and block. The third test was similar to the first but the slot was reduced to 4 mm. Figure 2-17 shows the principles of the tests.



Leaking supporting ring	Sealed supporting ring	Leaking supporting ring
Block not centered	Block centered	Block not centered
Large slot + axial slot	Large slot	Small slot
No pellets	No pellets	No pellets
No container dummy	No container dummy	No container dummy
Test result: 0 (do not work)	Test result: 2 (function OK)	Test result: 1 (OK, but test problems)

Figure 2-17. Three large scale leaking tests performed during 2003.

2.6.4 Results

Results from scale 1:10 test

Density of the bentonite was measured before and after the test. The saturated density before was 2,041–2,048 kg/m^3 and after 2,040 kg/m^3.

Relative humidity (RH) was measured in one point on the periphery of the bentonite and in 5 points on the surface of the instrumented canister. The relative humidity on the periphery reached approximately 98%. The five inner sensors never reached a RH more than 95%, which was not expected.

Total pressure was measured in 9 points on the outside of the steel tube and in 5 points on the surface of the instrumented canister. The final measured total pressure varied between 5 and 14 MPa, which was a rather high scatter. Especially the pressure outside the perforated steel tube varied a lot, which may be explained by the influence of the steel tube.

Pore pressure was measured in one point on the outside and two on the canister surface. These results are shown in the same diagram as the total pressure. Unexpected high water pressure was measured at one point on the canister surface. The measured water pressure is most likely caused by gas pressure and not water pressure. Such a gas pressure can result from shut-in air that has been compressed by the suction of the buffer. This may also partly explain why RH never reached 100% on the canister surface. Visual inspection during dismantling after one year showed that the perforated steel super container had been completely covered by the swelling bentonite permeating through the holes. It also showed that the swelling pressure had ruptured the super container at certain locations.

Results from investigation of sealing/piping/erosion phenomena – basic lab tests

Four parameters were investigated; water flow, water velocity, water pressure and channel diameter. The main results are accounted for in Section 2.7.

Results from investigation of the sealing/piping/erosion phenomena – study of processes and scenarios in scale 1:10 test

Possible flow rates and water pressures were investigated to find limits for piping. The results are shown in Table 2-2.

Results from investigation of the sealing ability in full scale test

Possible flow rates and water pressures were investigated to find limits for piping with and without additional water tight steel collar.

The tests were started and water filled with a rate that would correspond to the reference case. In the first test it turned out that the leakage was very strong and the filling rate had to be rather high. After about 8 days no more water could be filled and the pressure increase started. The progress of the test is shown in Figures 2-18 and 2-19.

Figure 2-18 shows that the leakage was very high before no more filling was possible. 110 liters of water had leaked through when the pressure build up test could start. At first the pressure increase rate 50 kPa/h was tried. After about 1.5 days these tests had to be interrupted because piping occurred over and over again. Then the rate was decreased to 5 kPa/h. This rate worked until after 10 days there was piping at the pressure 1.2 MPa.

Test with an additional water tight steel collar

In the second test the filling rate was adapted so that the slots were filled after 3 days. Then the water pressure was increased with the rate 50 kPa/h. The progress of the test is shown in Figure 2-20 and Figure 2-21.

Table 2-2. Compilation of the piping tests in the scale 1:10.

Test No.	Time until stop leakage (h)	Leakage before test start (l)	Water pressure increase rate (kPa/h)	Pressure at breakthrough (kPa)	Comments
1a	10	3.5	–	No breakthrough	10 kPa water pressure
1b	–	–	9,300	No breakthrough	Left 62 hours before test
2a	6.3	1.1	500	Breakthrough at 22 kPa	
2b	–	–	50	No breakthrough	Left 20 min. before test
3	4.5	2.0	50	No breakthrough	
4	6.7	1.8	250	Breakthrough at 1,100 kPa	Shootout!
5	5.3	2.0	50	No breakthrough	New geometry
6	6.2	2.5	50	No breakthrough	No axial slot
7	26.3	0.1	250	No breakthrough	Filling rate 0.001 l/min.

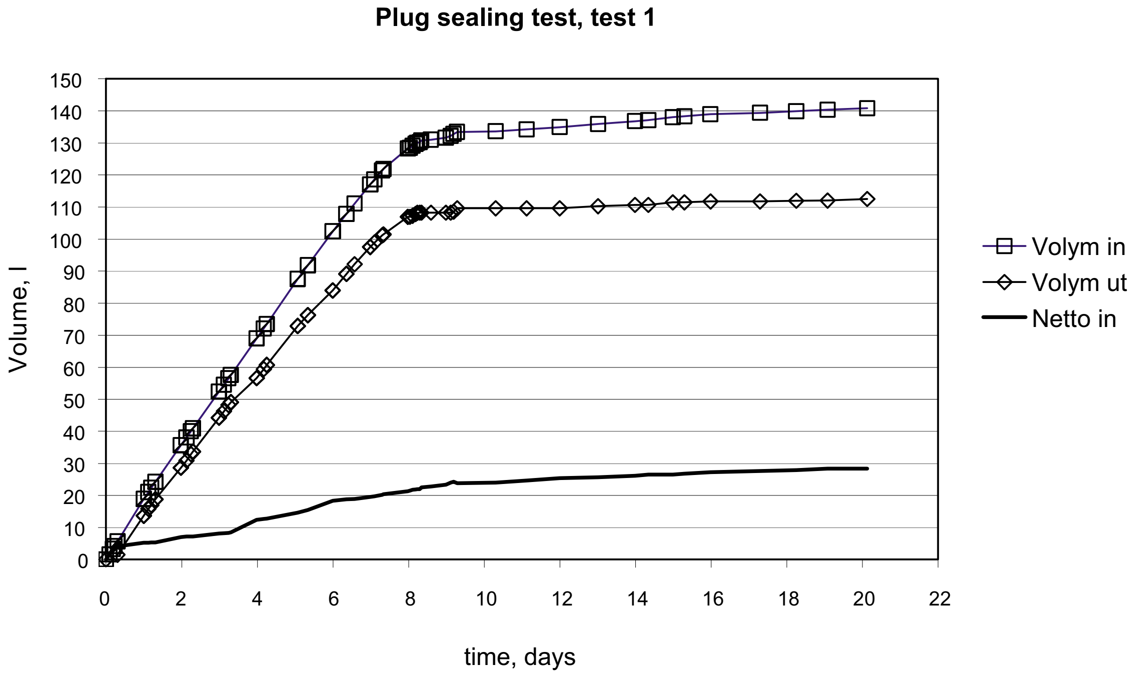


Figure 2-18. *In- and outflow of water as a function of time during the filling and pressure increase.*

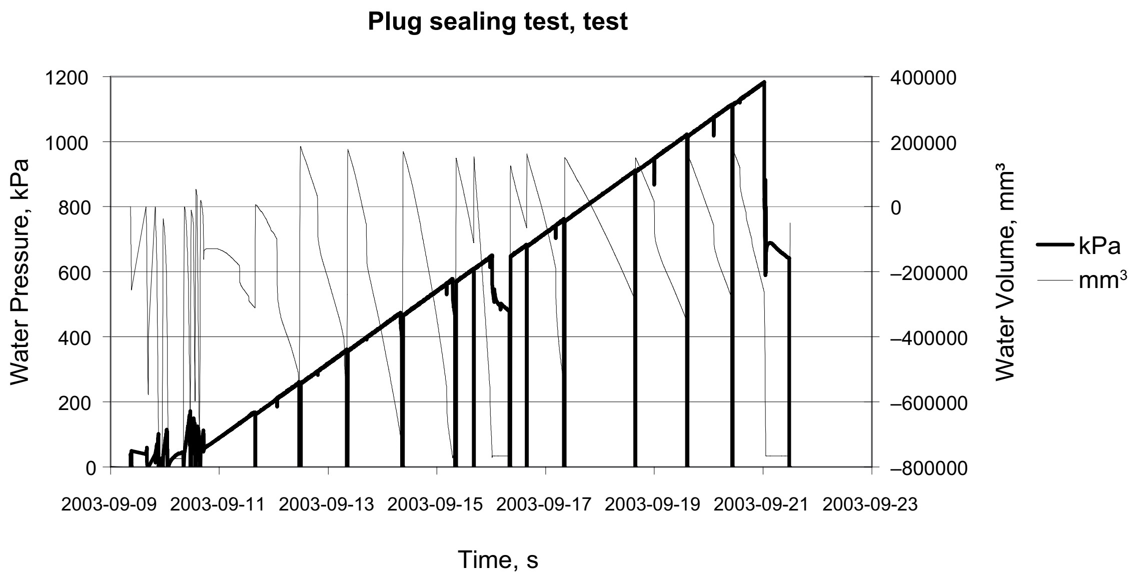


Figure 2-19. *Water pressure increase and inflow volume as a function of the dates.*

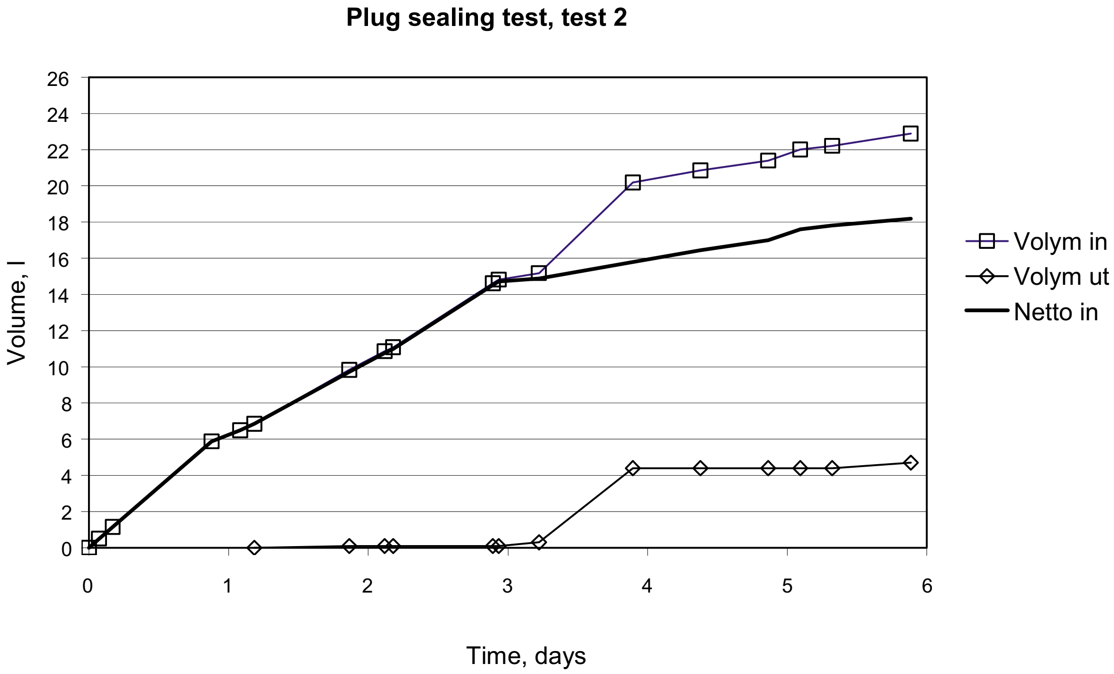


Figure 2-20. *In- and outflow of water as a function of time during the filling and pressure increase*

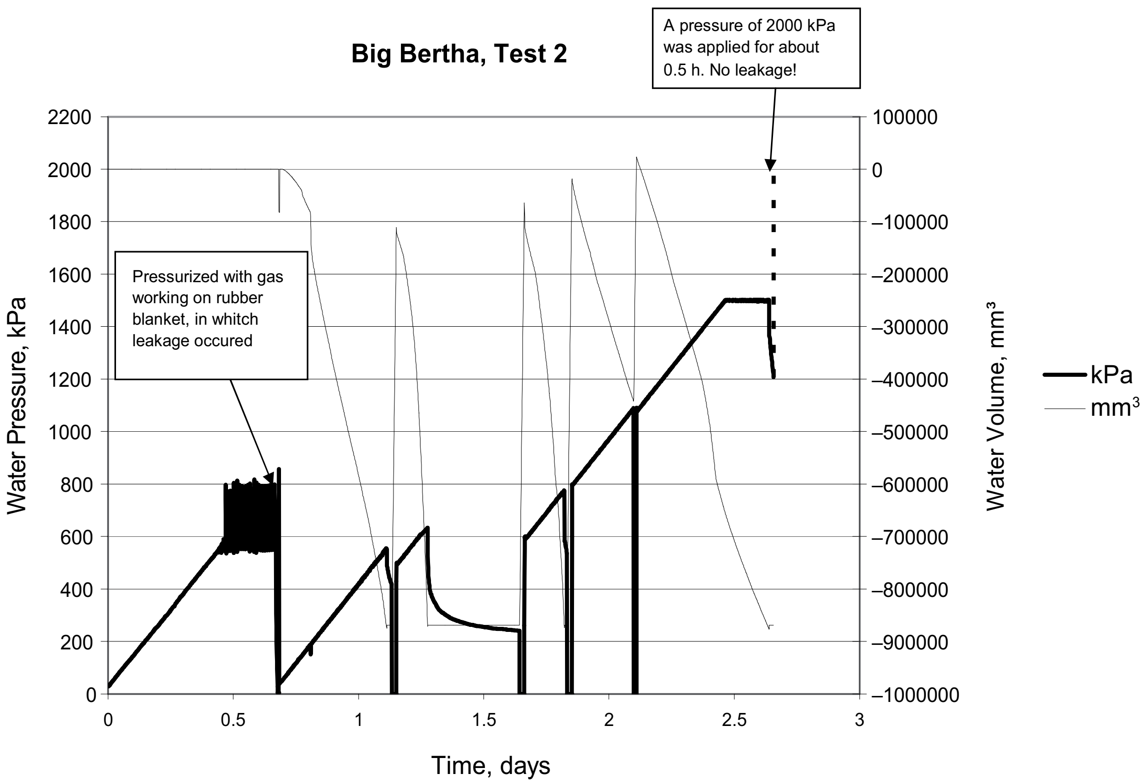


Figure 2-21. *Water pressure increase and inflow volume as a function of time.*

Figure 2-20 shows that there was no leakage during filling, but some leakage appeared at the beginning of the pressure increase. The net inflow during the pressure increase is mainly caused by filling up air pockets. Due to technical problems the water could not be filled continuously during the whole test. However, the pressure could be raised until 1.5 MPa with the intended rate and without piping. After a few hours rest the pressure was increased to 2 MPa without piping.

Test with leaking steel collar and 4 mm slot

In the third test a technique for using a bentonite block that can be adapted to fit the diameter of the tunnel with only a few millimetres slot was simulated. In spite of some technical problems the results were good and the water pressure 2 MPa was resisted without piping.

2.7 Technical development – conclusions

2.7.1 Excavation technique

During the KBS-3H Basic Design project SKB performed detailed design, manufacturing and a test drilling with the Cluster equipment. The overall performance of the system (cluster frames with water hammers, drill rig and high pressure pumps) was more or less according to expectations. The drift produced during the test drilling met the requirements except for the pilot hole alignment. This indicates that the cluster frames with water hammers work as expected. The reliability of pilot hole drilling accuracy still needs to be verified by further tests.

The overall performance of the system did not fulfil the expectations due to poor availability. It is important to remember that this was the very first test of cluster drilling in this dimension and there is a large improvement potential. Important experiences of the cluster drilling system were made, such as: drilling parameters, handling of water, handling of the heavy equipment, forces and vibrations in the system.

The test also showed the need for some minor redesign of especially the Ø1,850 mm cluster to better handle fractured rock. There is also a need to design supporting equipment which will make the handling of the equipment easier and thus improve the availability.

The important conclusion is that SKB have shown that cluster technique can produce drifts which meet the requirements. During early 2004 it was decided to select the blind raise boring technique for excavation of the drifts needed for the demonstration as this technique is less costly and still meet the requirements for the deposition drifts for the demonstration at Äspö.

2.7.2 Super container for buffer and canister

The developed design of the super container fulfils the requirements regarding functionality and strength. However, some improvements and optimizations are recommended for the next design phase, for instance a larger space between the super container and the rock surface floor will give a better safety margin so the deposition process, hence, the parking feet should be redesigned. It is also recommended that the super container design should be optimized with respect to manufacturing aspects and production cost.

2.7.3 Deposition equipment

The main conclusion of the KBS-3H Basic Design project is that the technique with a lifting palette, using water as a working fluid for the cushions, is feasible for reduction of friction and therefore enabling the horizontal emplacement of heavy super containers in a drift with small gaps.

The developed design of the deposition machine, start tube, transport tube and the other ancillary equipment is believed to fulfil the functional requirements. However, the result of the design work during Basic Design can be improved and optimisations of the equipment would be done during the Detail Design phase.

The problem with heat release during transportation in the deposition drift has been a key issue that may cause a problem. However, it is believed that actions can be taken to solve this problem by protection of sensitive equipment, i.e. control equipment, or by increasing the cooling effect of the air in the drift.

Another problem that needs to be studied further is the risk for jamming the lifting palette under the super container due to tolerances and deflection of the super container. Some development of the water cushions to increase the lifting height is believed to solve this problem.

2.7.4 Buffer design

The main conclusion from the scale 1:10 test is that the bentonite has swelled and homogenized very well also outside the perforated super container although there are still some differences in void ratio. The buffer was close to water saturation although there are still missing a few percent probably due to enclosed air.

Conclusions and comments derived from the results of the basic laboratory tests of the sealing/piping/erosion phenomena:

- Very low water pressure is required to cause piping and erosion at constant water pressure (2–4 kPa).
- Very little water flow is required to cause piping and erosion at constant water flow (less than 0.001 l/min.).
- The processes are complicated with many variables and dependencies.
- The values 2–4 kPa and 0.001 l/min. are probably conservative since they are combined with either high rate of water pressure increase or high water flow rate.
- The hydraulic function of the rock is very important.
- After long time the sealing will be helped from other wetting parts and is expected to tighten all leaks if the swelling pressure is higher than the water pressure.
- The distance plug is thus expected to function if the water flow is not so high that the erosion reduces the density but it may take years.

One conclusion from these early tests is also that more realistic flow and pressure regulations should be used in further testing and that the complexity of included parameters calls for scenario simulations.

The conclusions from the scale 1:10 sealing tests were that the filling rate and the water pressure increase rate are very important for the sealing ability. With the basic inflow scenario 0.1 l/h and 100 kPa/h the distance plug seems to work in the scale 1:10, i.e. when the slot between the rock and the plug is 2–4 mm.

The conclusions of the full scale sealing tests are that the scale effect is strong and the large slot 2–4 cm, which is expected between drift and top of the distance blocks, cannot be sealed according the desires at the reference scenario. Thus, either the slot must be reduced to about 4 mm or an engineering sealing must be made. The test showed that the collar sealing worked and that it is possible to fulfil the requests.

3 Thermal analyses

3.1 General

The deep repository will contain thousands of heat-generating canisters. A design maximum temperature of 100°C has been prescribed for the canister surfaces. In order to keep the canister surface temperatures below that limit, the spacing between nearby canisters cannot be arbitrarily small. That spacing must on the other hand be kept at a minimum in order to limit the extension of the repository such that it can be accommodated within the given rock volume. This means that it is necessary to derive reliable relations that show how the canister surface temperature depends on the canister power, on the thermal resistance between canister and rock, on the canister spacing and on the rock thermal properties. This issue is relevant for KBS-3H as well as for KBS-3V.

For the horizontal deposition concept KBS-3H, the tunnel diameter is an additional design parameter. For the design considered at present (October 2003), this parameter has been fixed at a value of 1.85 m. The canisters are identical to those of KBS-3V. The canisters will be fitted together with bentonite envelopes in cylindrical steel super containers which will be kept centred in the tunnel by use of support devices. The steel super containers will have an outer diameter of 1.765 m, which means that there will be a 42.5 mm annular space between the super container and the rock wall. Geometries are shown in Figure 3-2. The steel cylinders will be perforated to allow for saturation of the bentonite through water uptake in liquid or vapour form from the steel/rock space. Between the steel super containers there will be bentonite distance blocks. The length of these blocks is the design element that will be used to set the canister spacing at the selected value. The presence of a high-conductivity material, i.e. the steel, and the annular steel/rock space will influence the way heat is transferred from the individual canisters to the near-field rock. For the thermal development of the canister and the buffer, these conditions and the horizontal orientation of the canister are the main differences between KBS-3H and KBS-3V.

In addition to the annular space between steel cylinders and rock wall, there will be clearances between the canister and the bentonite, and between the bentonite and the steel cylinder. For the design being considered now, these clearances, or slots, will have an average width of 5 mm. This gives a total internal slot width of 10 mm, which is the value assumed to apply for the canister/bentonite slot in the KBS-3V concept. As far as these slots are concerned, the difference between the KBS-3V concept and the KBS-3H concept is that the 5 mm slot between bentonite and cylinder will close and disappear very soon, provided that there is some access to water in liquid or vapour form. For the 5 mm gap between canister and bentonite, the same conditions apply as for the 10 mm gap in the KBS-3V concept, i.e. the gap will not close until a substantial fraction of the bentonite has been almost completely saturated. Figure 3-1 shows the geometry of a KBS-3H tunnel schematically.

Thermal analyses have been carried out by Clay Technology /Hökmark and Fälth, 2003/ and VTT /Ikonen, 2003/, especially investigating, the effects of the emplacement gaps (canister – bentonite, bentonite – steel super container, steel super container – rock) on the thermal evolution of the KBS-3H type repository (Figure 3-2).

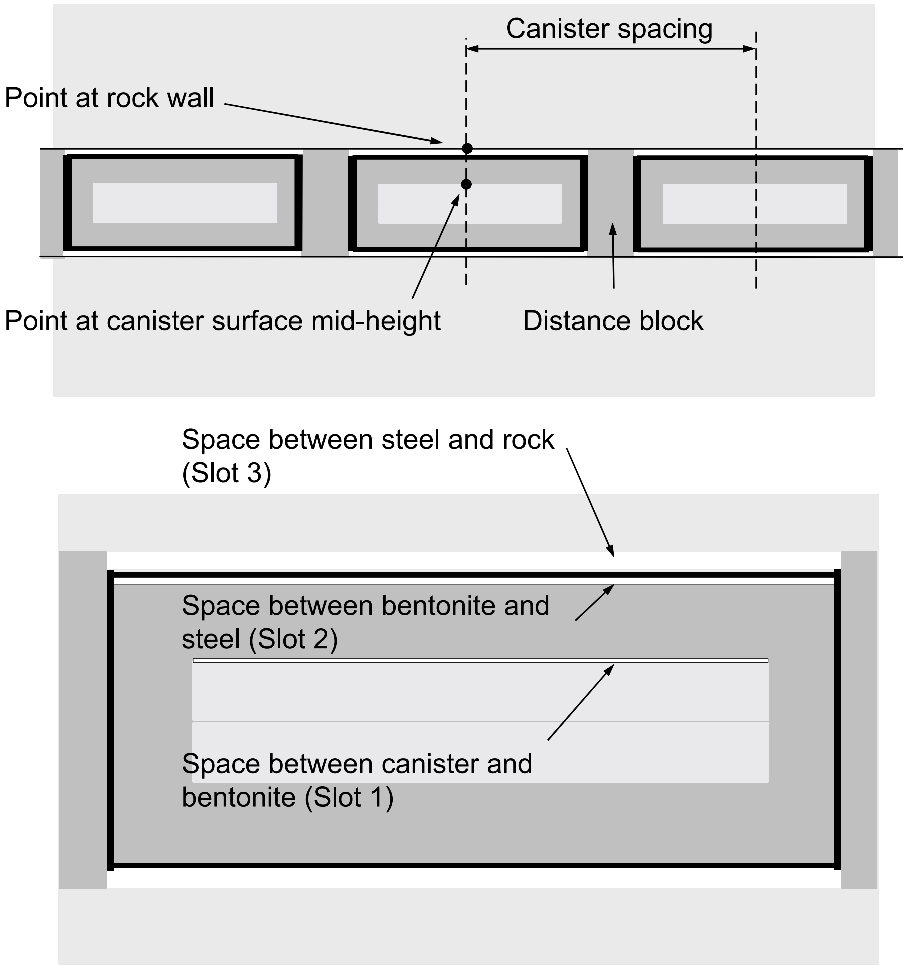


Figure 3-1. *Schematics of a part of a KBS-3H tunnel.*

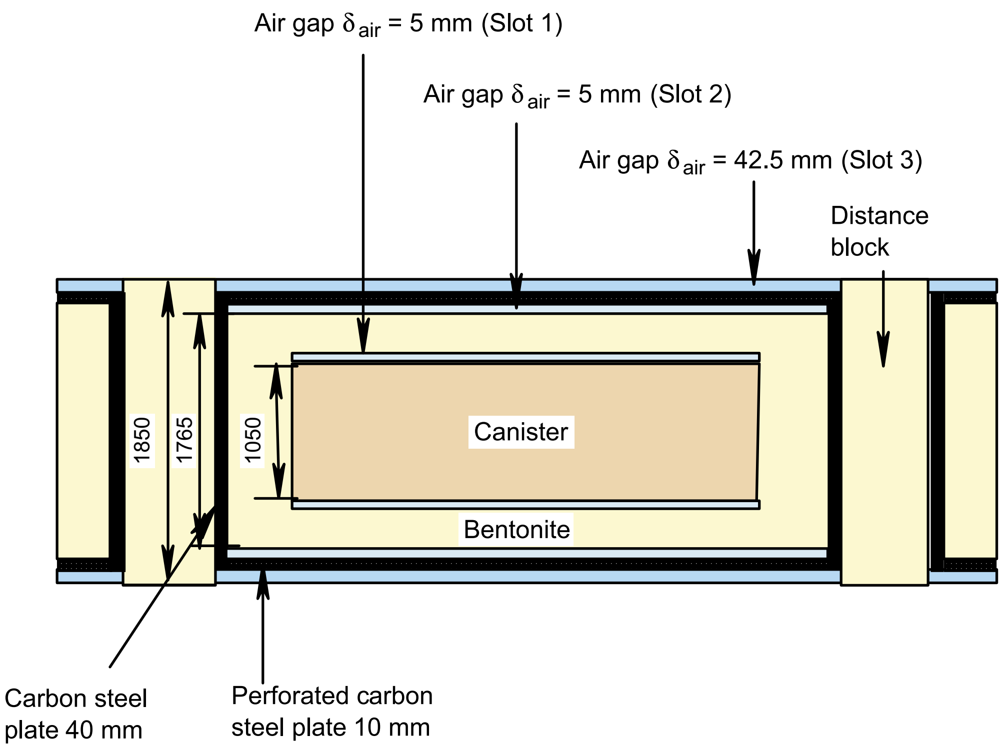


Figure 3-2. *Geometrical data used in the thermal analysis /Ikonen, 2003/.*

3.2 Analyses

The maximum canister surface temperature has been calculated /Hökmark and Fälth, 2003/ for a sufficiently large number of cases to allow for derivation of reliable relations between maximum canister surface temperature and canister spacing for different assumptions regarding canister power, rock thermal properties, etc. These relations are given as nomograms.

The results are obtained using combinations of analytical and numerical solutions.

Figure 3-3 shows a part of a KBS-3H repository. Because of the more complex heat transfer conditions around the canisters, a numerical model was used to calculate the temperature contribution from the local tunnel, i.e. the studied tunnel. The contributions from all other tunnels are then calculated using a line source solution and superposed on the numerically calculated local tunnel temperature field.

The analytical expressions used /Hökmark and Fälth, 2003/ are based on "textbook" solutions of the temperature development around a time-dependent line heat sources, and on the hypothesis that heat transport in crystalline rocks is mainly linear heat conduction. This allows for use of the superposition law, which makes it possible to include the total effect of any number of canisters.

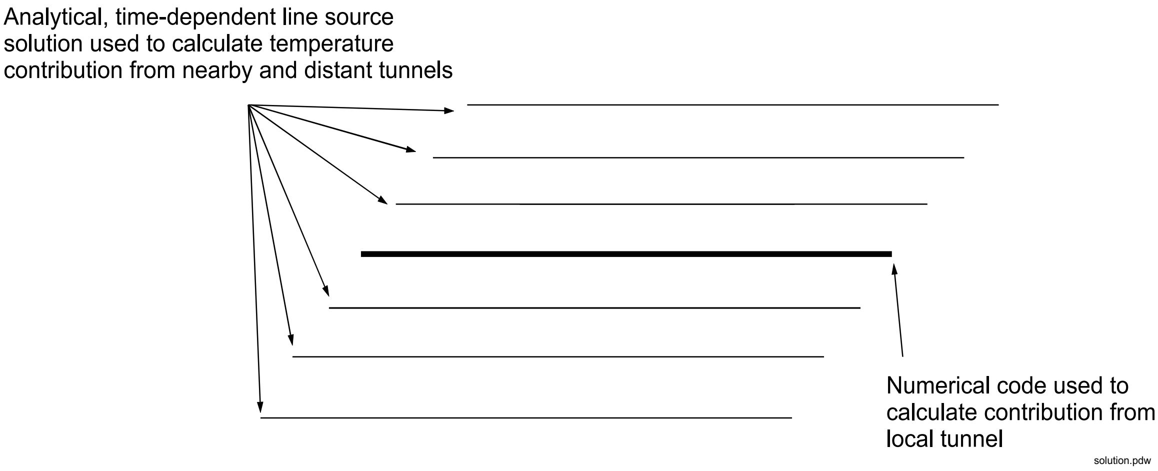


Figure 3-3. *Principles of KBS-3H thermal analysis /Hökmark 2003/.*

3.3 Results

3.3.1 Results from Clay Technology

Canister surface temperatures at different canister spacing have been calculated for several cases /Hökmark and Fälth, 2003/. Results for case d) described in Table 3-1 has been accounted for in this section. See Figure 3-4.

Table 3-1. Case descriptions.

Case	Slot 1 (Between canister and bentonite)	Slot 2 (Between bentonite and steel supercontainer)	Slot 3 (Between steel super container and rock)	Bentonite conductivity W/(mK)	Comment
a)	Air-filled	Air	Air-filled	1.0	Worst case
b)	Bentonite	Bentonite	Air-filled	1.0	
c)	Bentonite	Bentonite	Water-filled	1.0	
d)	Bentonite	Bentonite	Water-filled	1.1	Best case
e)	Air-filled	Bentonite	Air-filled	1.0	Conservative/realistic

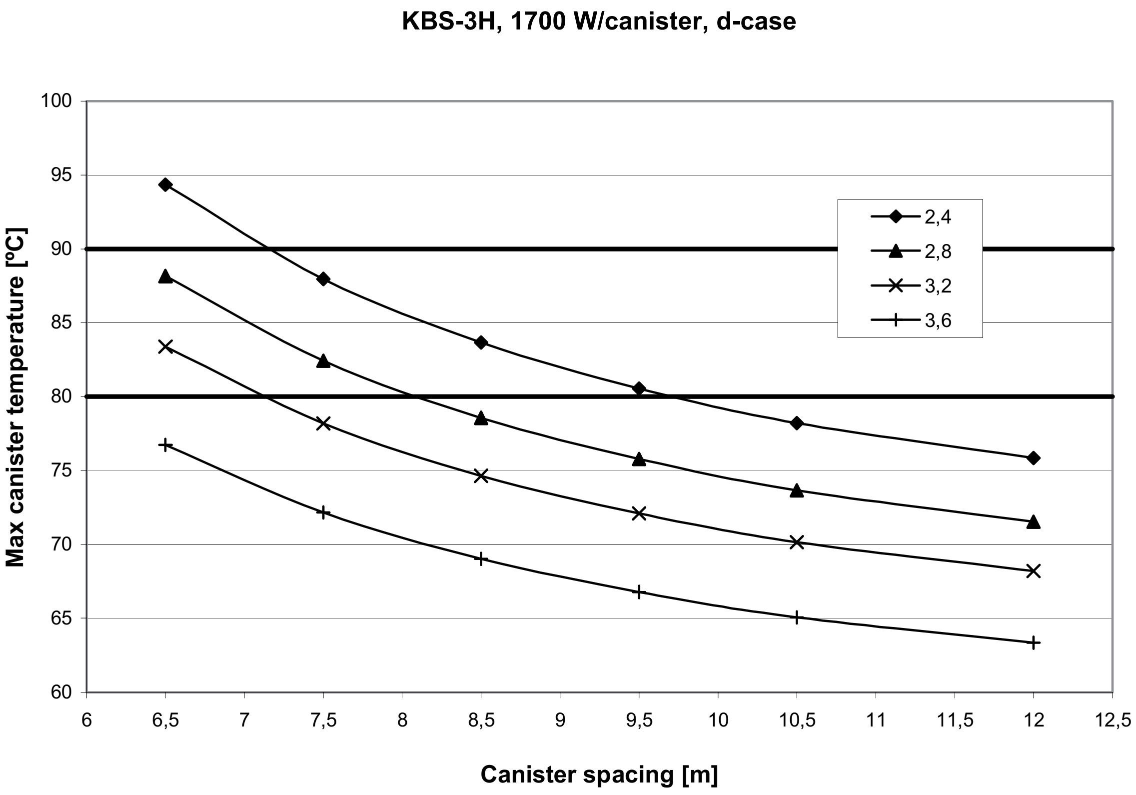


Figure 3-4. Max canister temperature as a function of canister spacing. The legend gives rock thermal conductivity in W/(mK). /Hökmark and Fälth, 2003/.

3.3.2 Results from VTT

VTT's calculations were verified against the analyses performed by Clay Technology. In the verification case, the two analyses provided maximum temperatures very close to each other. After the peak temperature (which was reached after about 10 years), the decrease in the temperature at the canister surface was, however, somewhat slower in VTT's analysis, Figure 3-5.

To limit the maximum temperature at the canister surface to below 90 °C (providing a safety margin of 10 °C to the design basis maximum temperature of 100 °C), the c-c spacing of disposal super containers containing BWR fuel with a total initial heat power of 1,700 W per canister needs to be 11 metres (i.e. the length of the distance blocks between two disposal super containers needs to be 5.35 metres) if the drift spacing is 25 metres in the Olkiluoto rock. With a drift spacing of 40 metres, the c-c spacing of the super containers needs to be 8.7 metres (length of the distance blocks 3.05 metres).

Heat transfer over an air-filled canister – bentonite gap depends significantly on the emissivity of the copper surface, which depends strongly on the quality of the surface. The emissivity value used in the thermal analyses may be overly conservative.

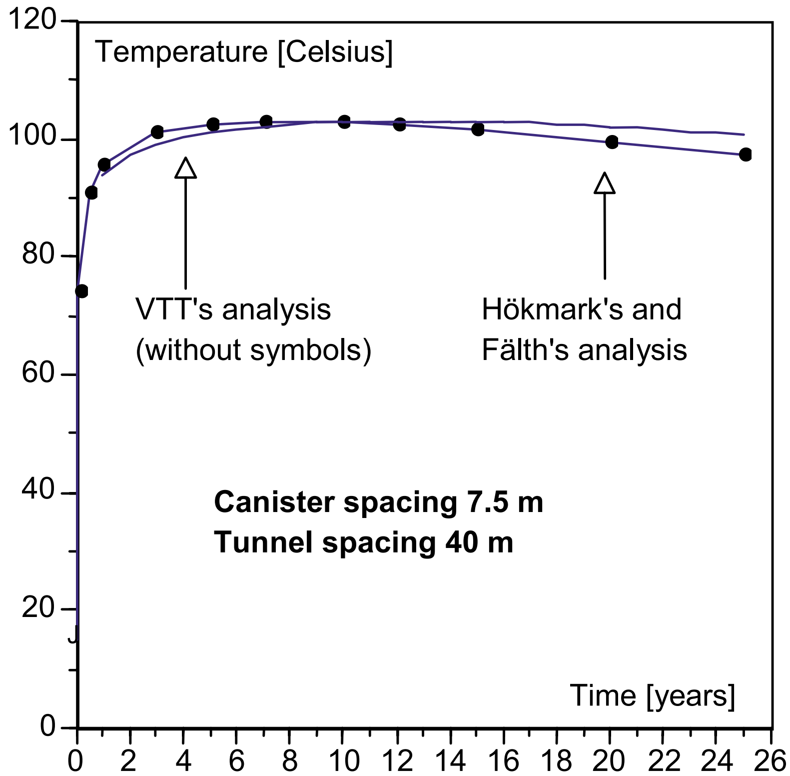


Figure 3-5. *Temperature histories in the verification case of the analyses by Clay Technology and VTT /Ikonen 2003/.*

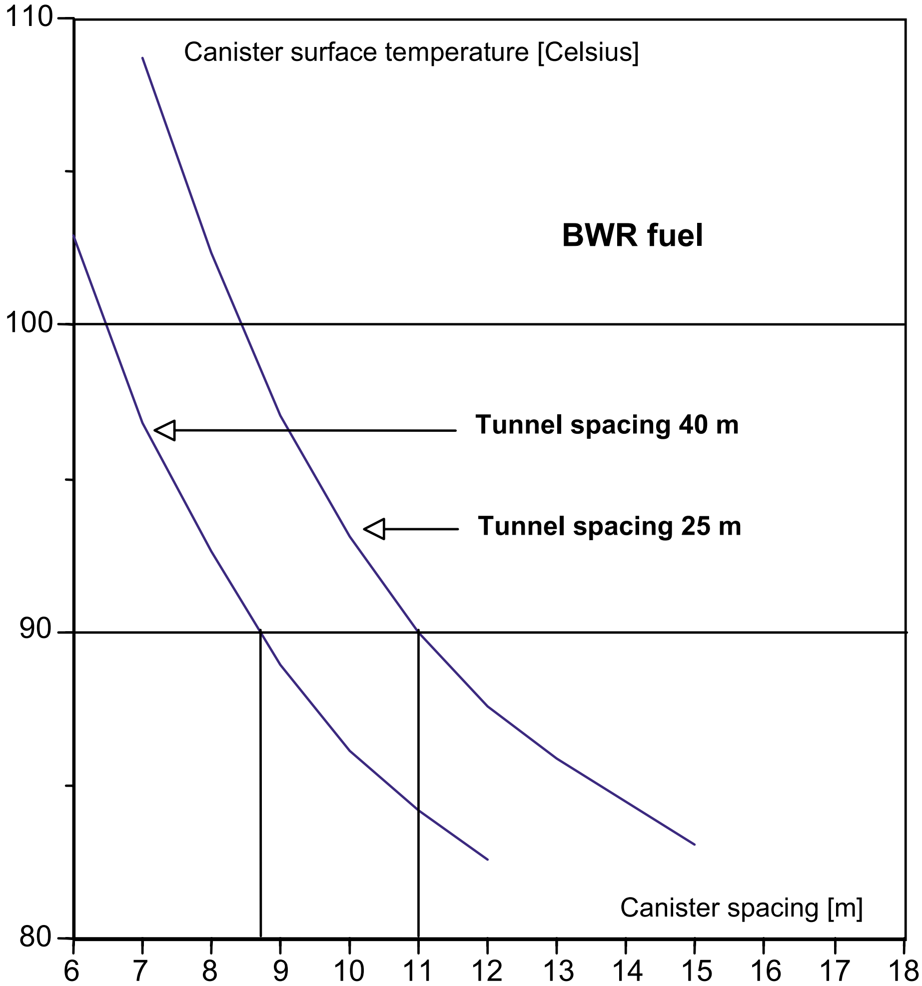


Figure 3-6. *Maximum surface temperature of a BWR canister with an initial heat power of 1,700 W as a function of canister spacing, when the tunnel spacing is 25 or 40 metres /Ikonen, 2003/.*

3.4 Conclusions

3.4.1 Conclusions by Clay Technology

Clay Technology has arrived at the following major conclusions from the thermal analyses /Hökmark and Fälth, 2003/.

- The determination of temperature margins is a key issue. For systems that give high temperatures (low conductivity rocks) with gentle slopes of the spacing/temperature curves close to the threshold intersection, smaller margins would bring the required canister spacing down significantly.
- The temperature offset between canister surface and bentonite, in particular, is difficult to predict. For KBS-3H, a 10°C margin seems to be sufficient.
- If the outer KBS-3H gap can be assumed to be water-filled and the KBS-3V canister/bentonite gap must be assumed to be 15°C, then the KBS-3H concept will require less total tunnel length than KBS-3V.
- The initial power is important. Raising the power from 1,545 W/canister to 1,837 W/canister means that the spacing must be increased by about 5 m for a high-temperature case.

- The initial temperature is important independently of concept comparisons. The initial undisturbed rock temperature was set at 15°C as a reference. An initial temperature of 12°C, as in the Forsmark site application, would be equivalent to moving all thresholds up by 3°C, meaning space savings of between 0.6 m and 2 m.

3.4.2 Conclusions by VTT

VTT´s analyses confirm the general results and conclusions of the thermal analyses by Clay Technology, /Hökmark and Fälth, 2003/. In addition they provide design data for KBS-3H type repository (containing spent fuel from the Finnish power plants) at the Olkiluoto site, which is planned to be used as a reference site for the KBS-3H safety case.

Experimental measurements of the copper surface emissivity are recommended due to the great importance of this parameter for the heat transfer over an air-filled gap, and thus maximum surface temperature of the canister, in the early phase.

An area that deserves further studies is the internal temperature inside the canister and thermal expansion of the cast iron insert and the copper casing. In this respect the horizontal deposition concept is somewhat more favourable than the vertical concept for two reasons; in the horizontal concept the initial contact area of the insert and casing is larger, and the distance over which the heat must be conducted in iron, which has significantly lower heat conductivity than copper, to reach the copper casing is shorter.

4 Safety Case

4.1 Introduction

This section focuses on the long-term safety studies for the KBS-3H concept. The main challenges and critical issues for the safety case of KBS-3H are related to the early phase evolution of the disposal system, the performance of the buffer in the distance plugs and in the perforated steel super container, and their potential effects on the long-term performance after the eventual saturation of the deposition drift. The other system components will in principle remain similar with KBS-3V and, thus, the work being performed for KBS-3V is also essential for the KBS-3H Safety Case.

The SC studies are being done in a close co-operation with the technical development subproject with the experiments and demonstrations. In Chapter 3.2 buffer studies being done at Clay Technology are discussed.

The overall goal of the long-term safety studies is a SR-Can type safety assessment of the KBS-3H concept in 2007 with Olkiluoto as the reference site. The main tasks are:

- To describe the processes of importance in the KBS-3H concept and compile a Process Report for KBS-3H.
- To perform process-level modelling, such as thermal, mechanical and chemical evolution analyses.
- To evaluate and resolve the critical issues related to the early evolution of the system, in close co-operation with the technology and demonstration subprojects.
- To perform radionuclide transport analyses.
- To compile the Safety Case for the KBS-3H concept with Olkiluoto as the reference site.

The first milestone in 2003 included an external expert review of the KBS-3H design from the point of view of post-emplacement behaviour and safety assessment. Evaluations of critical issues were initiated by thermal analyses of the system (Chapter 3), by investigations on chemical effects of the disposal super container and its corrosion products (Section 4.3), and by an evaluation of the effect of the distance between a water-conducting fracture and canister defect on solute transport (Section 4.4) were carried out. The evaluation of the most critical issues should be finished by mid 2005.

A process report for KBS-3H is planned to be finalised by mid 2006. Process-level modelling such as thermal, mechanical, gas-related and chemical evolution analyses will be carried out in combination with desk studies and laboratory experiments by mid 2006. Radio nuclide transport analyses are planned to be carried out in 2006–2007. The analyses are mainly "what if" type analyses of consequences of potential deviations from the designed post-emplacement and post-closure states and also consequences of potential deviations from the planned post-closure behaviour of the engineered barrier system (EBS). Finally the compilation of the Safety Case is planned to be carried out by mid 2007.

4.2 External expert review

4.2.1 Description of task

In order to get more insights into the feasibility of the novel KBS-3H concept with the perforated steel super container as well as additional input to the direction of future safety case studies it was decided to perform external expert reviews by experts familiar with the horizontal disposal concepts in crystalline rock.

The task defined was to review the KBS-3H design, from the point of view of post-emplacement behaviour and performance of the disposal system, as well as a review of the preliminary safety assessment (and its internal review).

4.2.2 Performance of review and main results

The external expert review was done by experts at NAGRA, ENRESA and NUMO. By having several experts involved in the work a diversified and comprehensive view was expected.

The documents being reviewed were:

- KBS-3H – Summary of results of Feasibility Study, Recommendations for continued work.
- Buffer and Safety assessment.
- Internal Review of Preliminary Safety Assessment of KBS-3H.
- A summary of buffer studies of KBS-3H.
- Safety Case Issues identified in the subproject plan.

The results were presented at a follow-up meeting in July. The produced review documents were compiled into a Posiva R&D report /Snellman, 2004/.

The main conclusions from the reviews were:

- Overall, the KBS-3H concept was considered as a feasible alternative to the KBS-3V disposal system.
- The review strengthened the earlier identified most important areas for further studies and stressed also the needs to focus on the early evolution of the system.
- It was foreseen that the long-term safety can be fulfilled by the KBS-3H concept.

4.2.3 Remaining issues

Some significant issues and demonstration work, which need to be addressed in the future, were identified. Recommendations for further work on design issues are due to:

- The behaviour of the system prior to emplacement, e.g. the thermal behaviour before emplacement considering the time requirement for assembling and handling.
- More detailed analyses of the layout, especially by consideration of thermal effects (complementary thermal analyses have been done in 2003, see Chapter 3).
- The sealing capacity, piping and erosion constitute the most critical issues regarding the efficiency of the buffer and distance blocks. Clear arguments and evidence should be found (demonstration complemented with modelling) for absence of piping and erosion for the full range of possible inflow rates of groundwater into the deposition drift. The

critical zone regarding piping and erosion is the distance block area. Filling of the gap between the distance block and rock as well as the gap between the perforated super container and rock with pellets was recommended by the reviewers. Thereby also uncertainties related to assumptions regarding the heat transfer across gaps could be reduced.

- The need for low-pH cement for sealing and plugging of the deposition drift is obvious.

Recommendations for further work on Safety Case issues are due to:

- Mitigating measures to reduce the probability of piping and erosion in the immediate post-emplacement phase is a key issue also for the Safety Case.
- The gas build-up and migration, the corrosion of the steel super container introduces a complex set of gas issues in safety assessment, such as gas bubble transport and transport of volatile radio nuclides, accumulation of gas along the top of the drift, and its effect on groundwater transport.
- Chemical and physical effects of corrosion product build-up. Interactions between the buffer and the super container. The effect of Fe(II) uptake on the swelling pressure of bentonite needs to be evaluated as well as the effects of corrosion products on the transport conditions along the periphery of the drift.

4.3 Interaction between the disposal super container and bentonite

The release of iron from the super container and exchange from Na^+ to Fe^{2+} or Fe^{3+} may influence the swelling properties of the bentonite for parts with lower density to an appreciable extent. Transformation of montmorillonite towards chlorite due to an uptake of iron in the hydroxyl layers has also been suggested to be a possible process.

In order to get insight into the possible changes in the properties of bentonite, that might result due to iron-bentonite interaction and to evaluate the physico-chemical conditions in which changes take place, as well as to search for suitable natural occurrences/analogues of iron-bentonite a study was performed by Helsinki University of Technology /Marcos, 2003/. The review indicated that:

- The bentonite transformation to chlorite or berthierine as a result of interaction with iron is a high temperature process and can be ruled out at temperatures below 85°C. It was reported that this kind of change would require either the starting smectite mineral in bentonite to be saponite or nontronite or the temperature to rise very high, close to 300°C in case the starting mineral were montmorillonite.
- Ion exchange from Na^+ to Fe^{2+} was reported but no data was found on the resulting changes in properties of bentonite.
- The mode of occurrence of the structural iron in bentonite, either as Fe^{2+} or Fe^{3+} has profound implications for the swelling properties of bentonite, the swelling pressure being clearly lower and the hydraulic conductivity indicated to be higher for the Fe^{2+} form.

Greek and Spanish deposits of bentonite being affected by iron-rich solutions coming from faults and other discontinuities were identified. A plan was set up to study the bentonite outcrop in Cabo de Gata, Almeria, Spain for the role and form of iron and the change in basic properties of bentonite (swelling, CEC etc.) as a result of interaction with iron and iron-oxyhydroxides. Sampling was done in November 2003 and analyses and evaluation of the potential site/samples for a further study is going on and will be reported by the end of January). It remains to be seen whether the Spanish or some other natural analogue can give relevant information on the potential changes in physical properties of bentonite, such as swelling and hydraulic properties, and ion exchange properties due to iron-bentonite interaction.

Direct evidence of the penetration of iron as Fe^{2+} into bentonite, most probably by ion exchange has been found in recent studies on the anaerobic corrosion of carbon steel in contact with bentonite at temperatures of 30°C and 50°C /Smart et al. 2003/. A more detailed study on the mode of iron present in bentonite is foreseen in the coming studies (another project by SKB), which are planned to be reported in 2004.

4.4 Solute transport in the saturated state

VTT Processes has carried out an analysis of equivalent flow rates from a defective canister into a rock fracture intersecting the deposition drift as a function of the transmissivity of the fracture and its distance from the defective part of the canister /Nordman and Vieno, 2004/. Equivalent flow rate, which concept has been used in the SR 97 and TILA-99 safety assessments, gives the steady state release rate of a stable species from the canister interior into the geosphere when a constant concentration of one unit per litre is assumed to prevail in the canister interior.

The results show that in the fully-saturated state the release rates from the deposition drift remain fairly low, even if the canister is assumed to have a large defect and even if a rock fracture with a rather high transmissivity (10^{-7} m^2/s) is assumed to intersect the drift just opposite the defect in the canister. The obtained equivalent flow rates are lower than in the TILA-99 assessment, where significant releases take place via the upper part of the KBS-3V deposition hole and the tunnel assumed to be backfilled with a material, where significant flow of groundwater was assumed to take place. The dominant barrier for the releases is the boundary layer (film) resistance between the stagnant pore water of the buffer and the groundwater flowing along the fracture intersecting the deposition drift.

The analyses have been made assuming that piping and erosion of the buffer do not take place at the mouth of the rock fracture. Transient releases of radio nuclides will, of course, be affected also by the distance between the defect in the canister and the rock fracture intersecting the deposition drift and the half-life and decay chain of the radio nuclides.

4.5 Re-evaluation of the list of critical issues

As stated in the preliminary safety assessment the KBS-3H concept does not suffer from the problems related to the tunnel backfill in KBS-3V, but on the other hand has a more complex early evolution of the near-field and some long-term issues that need deeper analyses. Also the deposition process appears to be more complicated.

There is a number of issues that need to be evaluated for the assessment of the long-term safety of the concept. The main Safety Case issues identified at the out-set of the long-term safety studies in the Basic Design phase are due to:

- The system behaviour and state during and after emplacement and closure operations.

- Behaviour and performance of the distance block and the buffer in the disposal super container. The performance of the buffer is closely related to the treatment of water conducting features intersecting deposition drift, and by that to the principles and effects of grouting.
- Thermal and mechanical evolution.
- Mechanical, chemical and gas-related effects of the steel supercontainer.

Issues, which also need to be addressed, although classified as not so important and urgent, are due to:

- Performance and effects of the drift seal, and the backfill and seals in the tunnels and access routes.
- Gas generation related hydro-mechanical processes in and around a defective Cu-Fe canister.
- Effects of climatic change and glacial cycle.
- Effects of earthquakes.
- Radionuclide transport analyses.

Based on the external reviews and studies performed in 2003, the list of Critical Issues has been updated as a part of the Basic Design phase and issues for coming studies are discussed in the following section.

4.5.1 Outstanding issues and future work

The most important Critical Issue for coming studies is the demonstration of the proper early phase behaviour of the bentonite in the distance block and the super container, especially to rule out the piping and erosion risk. Provided that the planned saturated and swollen state of the buffer is achieved, and the deposition drifts can be positioned in the bedrock properly, the long-term performance and safety of KBS-3H is expected to be similar or even better than that of KBS-3V, thanks to the absence of the backfilled tunnels in the vicinity of the canisters.

The *issues* to be addressed in future studies are;

System behaviour and state during and after emplacement and closure operations

- emplacement of the disposal super container and distance block,
- emplacement of the next disposal super container and distance block,
- sealing of the deposition drift,
- closure of the repository.

For each stage the behaviour and the planned state of the disposal system after the operation should be described. Also the behaviour of the system prior to emplacement, e.g., the thermal behaviour before emplacement considering the time requirement for assembling and handling need to be analysed. Potential deviations from the designed behaviour and initial states after the operations should be analysed in a systematic manner. Due to remote controlled operations and difficulty of visual inspections, and taking into account the long operation phase of the repository (similar with KBS-3V), monitoring may become a (technical) issue.

Behaviour and performance of the distance block and the buffer in the disposal super container

- The sealing capacity, saturation and swelling of the buffer and distance blocks need further investigation. How and when will the deposition drift become tight? What are the properties of the bentonite buffer within the disposal super containers and deposition drift in the radial and axial directions during and after the saturation and swelling process? This is a key critical issue for the KBS-3H concept.

In some of the laboratory experiments and tests, the performance of the distance blocks has been unsatisfactory. Piping and erosion of the bentonite have taken place at rather low pressure (with high inflow rate) or low inflow rate (at high pressure) of water. The experiments suggest that, in the worst case, substantial amounts of bentonite could be eroded and potentially transported out of the deposition drift during the saturation phase. These experiments need to be carefully evaluated and reasons for the piping and erosion need to be explained. Clear arguments and evidence should be found (demonstration complemented with modelling) to rule out the possibility of piping and erosion for the full range of possible inflow rates of groundwater in the deposition drift. For the piping and erosion problem, the spatial distribution of maximum expected inflows from bedrock and the largest inflows, which the buffer can tolerate, must be estimated. Methods to prevent axial flow of water in the deposition drift, and piping and erosion of buffer during the saturation phase are further developed and tested in the Technical development subproject. The problems in KBS-3H are especially related to both large inflows and singular point-sources with lower flows. Possibly discrete fracture network (DFN) modelling could be used. The performance of the buffer is also closely related to the treatment of water conducting features intersecting the deposition drift and by that, to the principles and effects of grouting.

This will also be a question about system optimisation. There may be possibilities to make small changes which could improve the performance, for example larger buffer thickness, longer distance blocks, optimisation of the dimensions or new technical solutions, optimisation of the deposition procedure etc., which may lead to a better long-term performance. Alternative technical solutions being studied in the Technical development subproject are expected to give insight to the solving of the problem.

Thermal and mechanical evolution

- Effects of the disposal super container on the performance of bentonite, its corrosion (e.g. volume expansion by a factor of at least two due to corrosion products), as well as potential dissolving and migration away of corrosion products (which, however, are expected to have low solubility in the repository conditions) need to be taken into consideration.
- Effects of spatially (in radial and axial directions) and temporally varying properties of the bentonite in the disposal super containers and deposition drift need to be taken into consideration, too.
- Also the processes, such as risk for displacement of the distance block due to water pressure build-up (pushing effect) between the distance block and the buffer (container package). The effect of the build-up of water pressure after the distance block has stopped the water inflow from fractures intersecting the drift, need to be evaluated.
- Stress analyses scenarios for the canisters should be done, as the scenarios and magnitudes of the stresses for KBS-3H might be different than for KBS-3V, such as in the event of shear stress arising from displacement along a fracture zone, intersecting the deposition drift, and the effect of glacial loading.

Analyses of the effects of the emplacement gaps (canister – bentonite, bentonite – steel super container, steel super container – rock) on the thermal evolution of a KBS-3H type repository and assessment of the minimum and optimal distances between the disposal drifts and the deposition super containers has been performed for Olkiluoto. Heat transfer over an air-filled canister – bentonite gap depends significantly on the emissivity of the copper surface, which depends strongly on the quality of the surface. The emissivity value used in the thermal analyses may be overly conservative. Experimental measurements of the copper surface emissivity are in progress.

Another area that deserves further studies is the internal temperature inside the canister and thermal expansion of the cast iron insert and the copper casing. In this respect the KBS-3H concept is somewhat more favourable than the KBS-3V concept for two reasons: in the horizontal concept the initial contact area of the insert and casing is larger, and the distance over which the heat must be conducted in iron, which has significantly lower heat conductivity than copper, to reach the copper casing is shorter.

Effects of the disposal super container

- effects of gas build-up and migration,
- chemical and mechanical effects of corrosion and corrosion product build-up at the expected groundwater conditions,
- effects of the corrosion products on the transport conditions along the periphery of the drift need to be evaluated,
- hydraulic effects and potential formation of preferential pathways within bentonite,
- saturation and swelling of bentonite from the perforated super container and mechanical impacts are discussed in above items.

The hydrogen gas formation due to the super container corrosion introduces a complex set of gas issues, such as gas bubble transport and possible co-transport of volatile radio nuclides, accumulation of gas along the top of the drift, and its effect on groundwater transport, which need to be analysed. Released gas may accumulate along the top of the emplacement tunnels (EDZ), where it may affect groundwater transport. Also mechanical effects of the corrosion process need to be evaluated. The main corrosion product will be magnetite. SKB's currently running experimental program to determine the mechanical properties of magnetite, which is formed at high pressures, may give some indications about the hydraulic properties as well.

Laboratory experiments on steel corrosion in bentonite (another project by SKB) are expected to give information on the mode of iron uptake in bentonite. The review on iron interaction with bentonite and/or smectite in nature and in laboratory indicated that bentonite transformation to chlorite or berthierine as a result of interaction with iron is a high temperature process and can be ruled out at temperatures below 85°C. It remains to be seen whether the analogue from Almeira, Spain or some other analogue site can be used to investigate the role and form of iron in bentonite and the possible changes induced in the basic properties of bentonite. The extent of ion exchange Na^+ to Fe^{2+}/Fe^{3+} and the resulting changes in physical properties (swelling, hydraulic conductivity) and ion exchange properties of bentonite should be studied. Even with the uncertainties, this seems unlikely to play an important role in the buffer performance, because most of the thick buffer layer between the canister and the super container would not be influenced by any such interaction. The only case in which the combined physical and chemical effects of the presence of the corrosion products may play a significant role is with respect to the transport conditions along the tunnel boundary.

Treatment of water conducting features intersecting deposition drift, principles and effects of grouting

It is likely that deposition drifts will intersect fracture zones and leaking fractures, which need to be grouted to ease construction and emplacement operations, and thus generally more grout in the near-field is expected for the KBS-3H vs. KBS-3V. The principles of isolating disposal super containers from such water conducting features need to be clarified, and the effects of these features and grouting materials (both cement and non-cementitious based materials) injected in the rock around the drift need to be evaluated, especially their implications on buffer alteration. There might be a need for specific assessments for KBS-3H in addition to the assessments to be carried out in the POSIVA-SKB-NUMO project on low-pH cementitious and non-cementitious grouts. The methods to limit groundwater flow along the drift are one of the key questions in the studies on the Behaviour and performance of the distance block and the buffer in the disposal super container.

Performance and effects of the drift seal, and the backfill and seals in the tunnels and access routes

- Chemical and mechanical interactions of the drift seal and buffer.
- Degradation of the seals.
- Effects of saline groundwater.

Gas generation related hydro-mechanical processes in and around a defective copper-iron canister

- In KBS-3H, a scenario where water intrudes in a defective canister and is later expelled out of the canister because gas generation due to corrosion of the cast iron insert is more likely than in KBS-3V. This is because in KBS-3H the defect in the canister may occur in the underside weld region, whereas in KBS-3V the most likely location of a defect is in the weld of the lid in the upper end of the canister.

Effects of climatic change and glacial cycle

- No significant differences to KBS-3V.
- Maximum isostatic canister pressure during a glacial load.

Effects of earthquakes

- The situation differs somewhat from KBS-3V as the frequency of fracture intersections per canister position is larger due to a large fraction of (sub)vertical fractures. The bedrock deformations caused by earthquakes appear normally in existing vertical fractures and fracture zones. Therefore the deformation is more likely to deform the horizontal long holes than shorter vertical holes which can be positioned with more flexibility.
- A need for Olkiluoto site-specific evaluation of the effect of fracture density.

Radionuclide transport analyses

- In general no significant differences to KBS-3V in the “as designed” state. “What if” analyses need to be done for potential deviations and mishaps.

- The properties and effects of the EDZ around the drilled deposition drift need to be evaluated. The possible effects of collapse of rock blocks, spalling of rock surfaces. The situation differs from KBS-3V.
- Effects of the super container/corrosion products need to be evaluated.

Positioning of the deposition drift

It is assumed that the KBS-3H deposition drift can be positioned in bedrock sections where there are no horizontal fractures parallel to drifts, which may deform as results of the excavation of the drifts and therefore may form continuous flow paths parallel to the deposition drift. The positioning of drifts and feasibility of adaptation to bedrock needs to be evaluated in the Demonstration subproject. Horizontal fractures and fracture density need to be evaluated for the site (Olkiluoto).

5 Site for demonstration at Äspö HRL

5.1 General

A need for a future demonstration site for the KBS-3H concept was foreseen in the KBS-3H Feasibility Study. Therefore, it was decided to investigate a suitable location and prepare such a site at Äspö HRL. The work was performed as a subproject within KBS-3H Basic Design.

5.2 Site selection

Four main criteria were established for comparison of possible location candidates for the demonstration site:

- Provide enough space for machinery and auxiliary equipment, choice of technique for water treatment from drilling and need for complementary excavation of "niche".
- Geological and hydrogeological prerequisites.
- Risk for disturbance of experiments in progress and/or operation of Äspö HRL.
- Public information services at Äspö HRL.

The following locations were chosen for further evaluation:

- TASO (tunnel), –420 m level.
- NASA 2715A (niche), –350 m level.
- NASA 1623A (niche), –220 m level.
- TASM (tunnel), –70 m level.

The locations of the alternatives are shown in Figure 5-1. Locations of the demonstration site below the –420 m level have been omitted since the special terminal vehicle for canister transports etc, can not operate in the TBM tunnel and also because severe influence of experiments in progress can be expected.

Evaluation of the criteria was based on an investigation of the four possible demonstration sites. A criterion for location of the demonstration site compared to a real repository was added to the evaluation. The criteria were evaluated and given marks from 1–3, where 3 is best. The result was summarized in Table 5-1.

It was decided to prepare a demonstration site at the –220 m level based on the recommendations from the evaluation. The site at –220 m level was described as follows in the investigation:

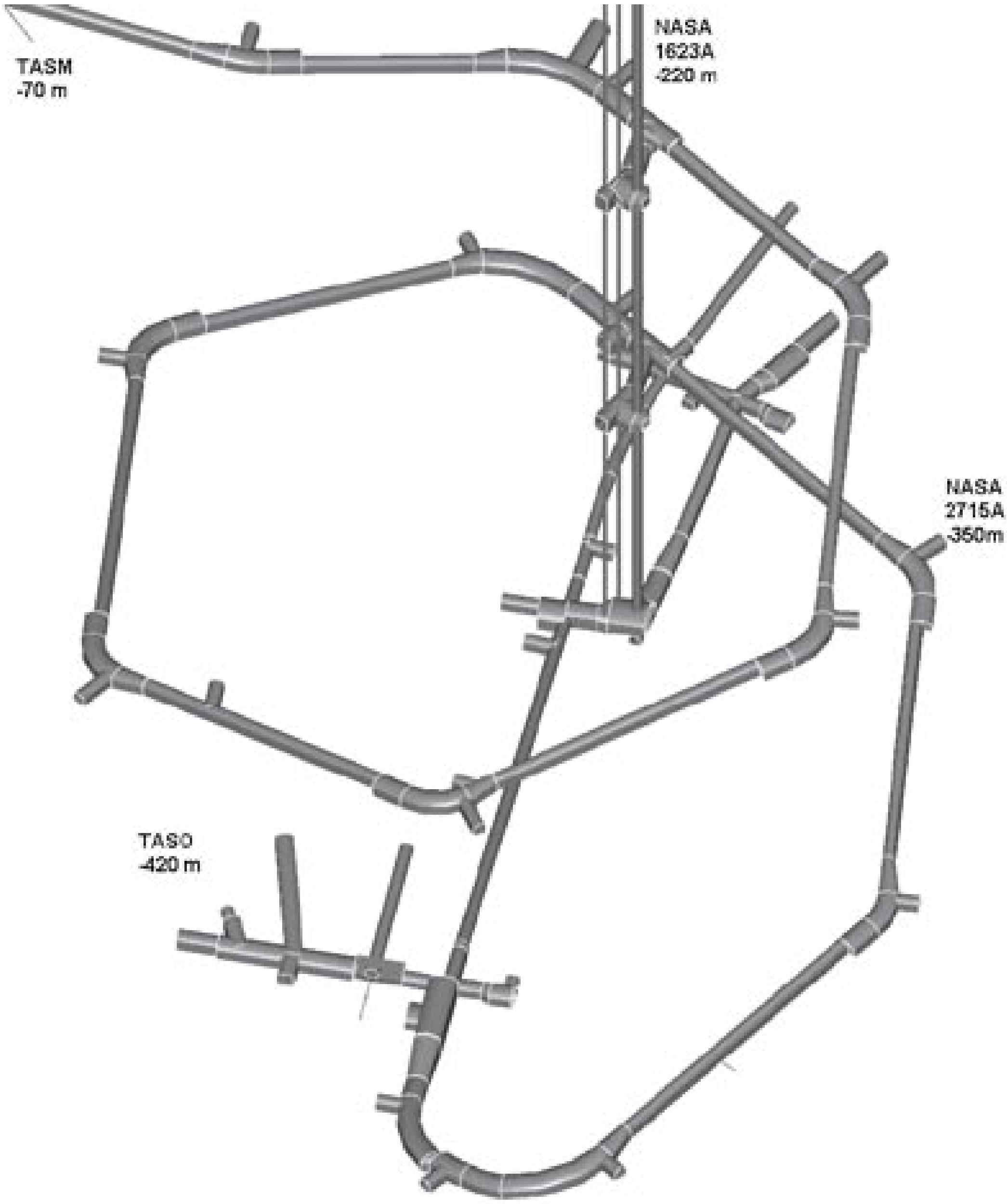


Figure 5-1. Alternative locations of demonstration site for KBS-3H at Äspö HRL.

Table 5-1. Evaluation of test locations.

Criteria	TASO –420	NASA 2715A –350 m	NASA 1623A –220 m	TASM –70 m
Excavation	1	1	3	3
Ventilation	1	2	2	3
Space for machinery	1	1	3	2
Water supply	1	1	3	3
Sedimentation	1	1	3	3
Geology and hydrogeology	2	1	3	(2)
Disturbance of other experiments	1	2	3	3
Operation of Äspö HRL	3	1	1	1
Information service	3	1	2	1
Realistic conditions compared to real repository	3	2	1	1
Total marks	17	13	24	22

Space for machinery

- The existing chamber has to be extended by excavation. (least excavation of the four alternatives).
- Good water supply (water can be taken from the Baltic Sea).
- Sufficient space for arrangement of pumps and separation plant.
- It is possible to utilize the existing pump plant for water transport from pump sump, PG3, to a settling basin at ground level.
- A settling basin at ground level means that it will not be necessary to invest in a lamella sedimentation plant. Tubing for water to the drill site will be required.
- The existing ventilation is sufficient for drilling and blasting of deposition holes.

Geological and hydrogeological assumptions

- The joint system NEHQ3 might influence the demonstration. The NE system is normally relatively tight but can be in connection with water conductive zones in (N)/NW.

Risk for disturbance of experiments in progress and operation of Äspö HRL

- The site will not disturb other experiments.
- A 6 kV cable is passing the chamber, which could disturb PG3.

Information activities

- The vicinity to the elevator makes the location suitable from an information service point of view. It will also be possible for visitor busses to stop where the tunnel is leveled at –220.

5.3 Design

The demonstration site is designed to accommodate vehicles, machinery and auxiliary equipment for drilling of three deposition holes and for demonstration of deposition and also plug sealing. A plan view of the niche with three deposition holes and deposition equipment is shown in Figure 5-2. The original intention was to use one of the 30 m long deposition holes for construction of a drift seal and the other for possible future tests of buffer saturation. The 100 m long deposition hole is meant to be used for tests of deposition equipment. All deposition holes will be used to test the excavation technique and method.

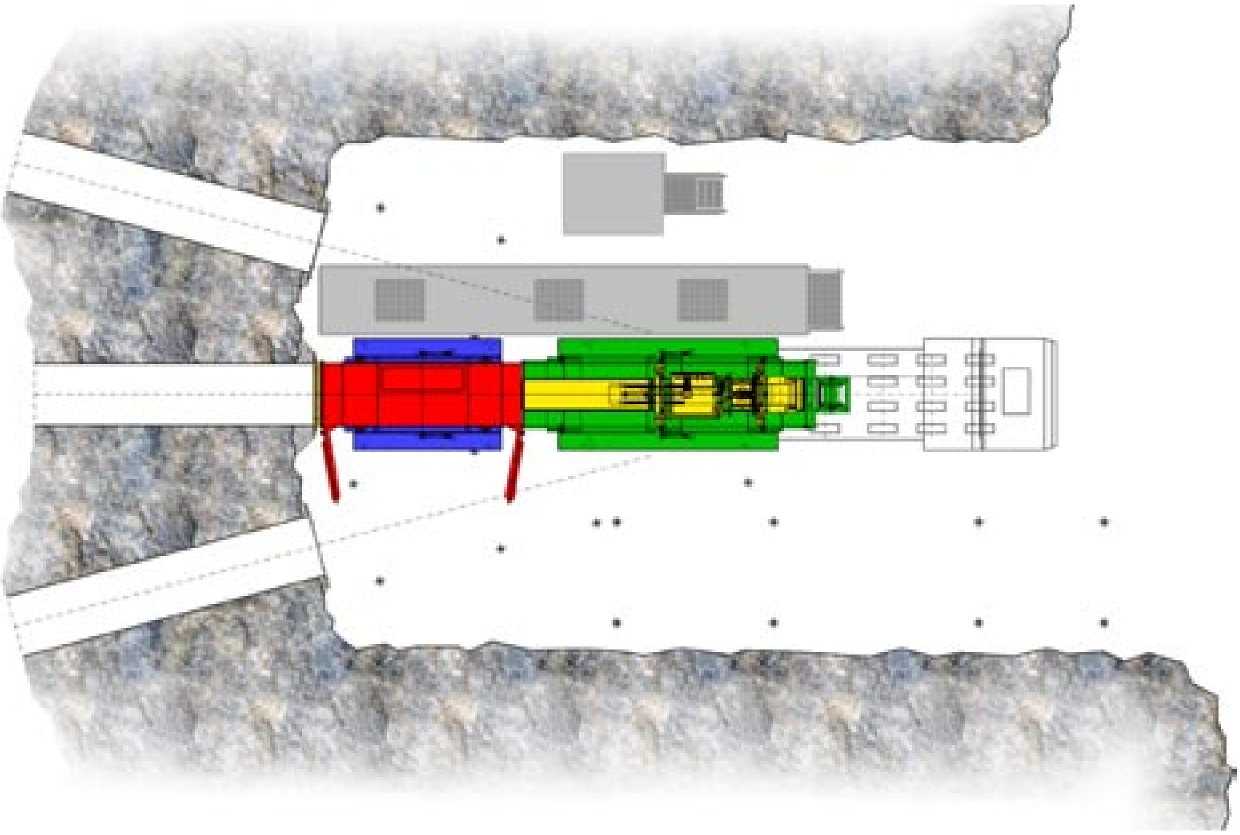


Figure 5-2. *Plan view of demonstration site for KBS-3H at Äspö HRL*

5.4 Geological site description

Core drilling has been performed to investigate the rock mass in the planned deposition drifts. Results from mapping with the Boremap system is obtained from three horizontal cored boreholes drilled at –220 m level. The boreholes KA1616A01 (30 m long, Ø56 mm), KA1619A01 (100 m long, Ø76 mm) and KA1621A01 (30 m long, Ø56 mm) are shown in Figures 5-3 and 5-4. The holes were mapped with respect to lithology, structures and fractures.

The boreholes consist mainly of granodiorite (Äspö diorite). The granodiorite is intruded by several dykes or veins of red, fine grained granites and coarse grained pegmatite. The boreholes, especially KA1619A01 also contain some granite (Småland granite) and several small xenoliths of greenstone (meta-basite).

The boreholes KA1616A01, KA1619A01 and KA1621A01 are relatively poor in natural open fractures. The overall fracture frequency is only 1.2, 1.2 and 0.9 fractures per meter respectively. Two fracture sets were observed: 310/80–90° and 025/80° (in coordinate system Äspö96, see Figure 5-5).

No crushed zones were observed. Two sections with frequent occurrence of open fractures are observed in KA1619A01. One is at 27.9–29.0 m (8.2 fractures per meter) and the other at 34.9–35.9 m (14 fractures per meter). KA1616A01 and KA1621A01 have no densely fractured sections.

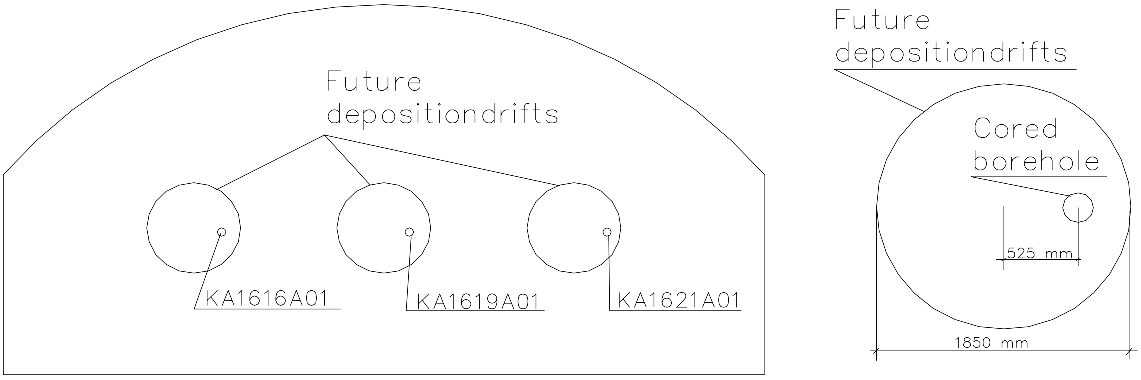


***Figure 5-3.** The cored boreholes in NASA 1623 at Äspö HRL.*

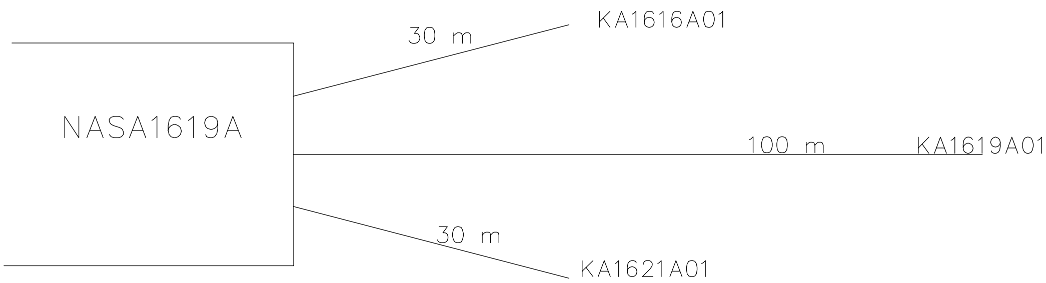


***Figure 5-4.** Top view of the cored boreholes.*

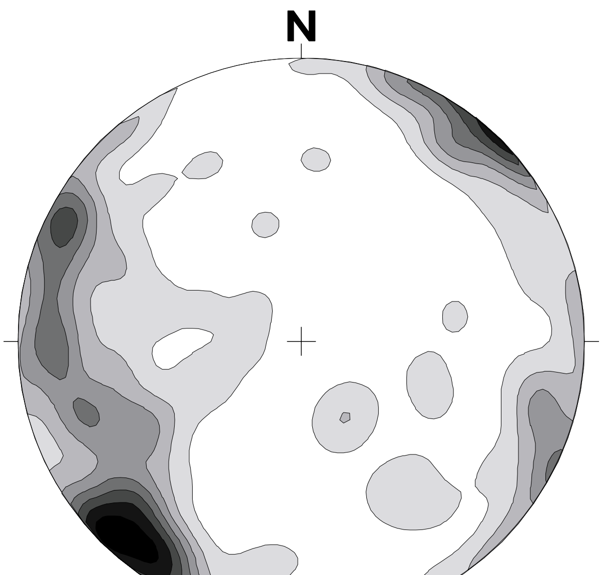


***Figure 5-5.** Contoured pole to plane stereogram showing natural open fractures (N=156 of 179 in total).*

The conclusion of the mapping is that the bedrock in KA1616A01, KA1619A01 and KA1621A01 is sound and has few open fractures. It has also relatively few deformation zones, and those that can be found are usually very small (millimeter scale).

The same orientations of the interpreted sealed fractures (mostly by epidote) and the brittle-ductile shear zones indicate that they are formed during the same deformation phase. It is possible that some displacement has taken place also along the sealed fractures, but signs of movement have not been found.

6 Fulfilment of Basic Design objectives

6.1 General

A number of objectives were expressed during the planning of the KBS-3H Basic Design project. The objectives were based on knowledge from the preceding Feasibility study and a realistic eligible level of knowledge before the subsequent project phase.

6.2 Objectives and fulfilment

The overall objective is to develop the KBS-3H concept to the same level of knowledge as KBS-3V. Three main objectives with diversified directions were identified during the project planning. The main objectives in turn were broken down in sub-objectives. The break down structure is shown in Table 6-1. Fulfilments of the objectives are accounted in Table 6-2, Table 6-3 and Table 6-4.

Table 6-1. KBS-3H Basic Design objectives.

Development of KBS-3H concept Technical development	Safety Case	Äspö Demonstration site
Cluster Technology • Detailed design of cluster equipment and water treatment plant • Manufacturing of cluster equipment • Test drilling with cluster equipment • Investigations of different methods to grout during the excavation process	External reviews of preliminary design and safety assessment	Preparation of demonstration site • Extension of existing niche by excavation
Deposition Technology • Conceptual design of deposition equipment • Description of deposition process • Analysis of reliability in operation process • Work shop test of lifting cushions	Evaluation and resolving of critical issues related to system behaviour • Study of thermal effects • Study of chemical effects • THM analysis	Characterization of rock • Core drilling • Mapping
Buffer design • Investigations in order to define the maximum water inflow rate to a canister position • Start of full scale test in order to verify assumptions regarding early evolution of buffer.		Grouting of characterisation holes in order to reduce water inflow • Grouting
Horizontal raise boring • Investigation of the feasibility to use horizontal raiseboring for production of deposition drifts.		

Table 6-2. KBS-3H Basic Design – fulfilment of technical development objective.

Technical development	Fulfilment of objective
Cluster Technology	
• Detailed design of cluster equipment and water treatment plant • Manufacturing of cluster equipment • Test drilling with cluster equipment • Investigations of different methods to grout during the excavation process	• A cluster has been designed as planned. No special design was needed for a water treatment plant since the water was not re-circulated. • Two cluster frames have been manufactured as planned. • Test drilling with cluster has been performed as planned. • An investigation of the possibility to perform grouting of the deposition drift has been performed as planned.
Deposition Technology	
• Conceptual design of deposition equipment • Description of deposition process • Analysis of reliability in operation process • Work shop test of lifting cushions	• Conceptual design of deposition equipment has been performed as planned. • Description of the deposition process has been performed as planned. • No regular analysis was performed since it was considered premature at the present state of the design. An external expert review of the concept was performed during the design work. • Two tests of lifting cushions was performed, only one was planned from the beginning but there was a need for complementary information regarding the function of the cushions when the media was water.
Buffer design	
• Investigations in order to define the maximum water inflow rate to a canister position • Start of full scale test in order to verify assumptions regarding early evolution of buffer.	• Investigations commissioned as planned but could not be finalized within the Basic Design. The investigation continues in the next phase. • Buffer tests have been carried out but not exactly according to the original plan.
Horizontal raise boring	
• Investigation of the feasibility to use horizontal raiseboring for production of deposition drifts	• Investigation of the "state of the art" has been performed as planned.

Table 6-3. KBS-3H Basic Design – fulfilment of safety case objective.

Safety Case	Fulfilment of objective
External reviews of preliminary design and safety assessment	• External reviews and safety assessment were performed by NAGRA, NUMO and ENRESA as planned and reported in an Posiva working report
Evaluation and resolving of critical issues related to system behaviour • Study of thermal effects • Study of chemical effects • THM analysis	• Thermal effects have been studied as planned. • Chemical effects have been studied as planned. • A THM analysis has been performed as planned.
Re-processing of critical issues	• A revision of the list of critical issues has been carried out.

Table 6-4. KBS-3H Basic Design – fulfilment of Äspö demonstration site objective.

Äspö Demonstration site	Fulfilment of objective
Preparation of demonstration site	
• Extension of existing niche by excavation	• A niche with dimension 15*25 meters has been prepared .
Characterization of rock	
• Core drilling • Mapping	• Core drilling for rock characterization has been performed as planned. • Mapping was performed as planned.
Grouting of characterisation holes in order to reduce water inflow	
• Grouting	• Grouting was postponed to the next phase of the R&D program since the requirements regarding groundwater inflow has not been determined.

7 Conclusion

This section sumarises the conclusions drawn after the completion of the KBS-3H Basic Desgn project. The conclusion has been divided into the following categories:

- Technical development.
- Demonstration.
- Long term safety.

7.1 Technical development

During 2003 the KBS-3H concept has been further developed in the Basic Design project. Main milestones related to technical development have been:

- Manufacturing and test of the cluster technology.
- Basic Design of deposition equipment including workshop test of the lifting cushion device.
- Design of the super container.

Work has also included continued research regarding buffer design and methods for sealing of deposition drifts as well as further studies regarding horizontal raiseboring.

The results indicate that there are good possibilities to design and manufacture the equipment necessary for construction and operation of a repository based on the KBS-3H concept. It is however after the completion of the demonstration at Äspö one can draw conclusions about the overall performance of the concept and do further optimizations. The research regarding the behaviour of the buffer during operation and just after operation has shown that there are many factors affecting the function of the buffer and that it is difficult to design a simple but still robust system. The research activities are planned to continued in the next phase.

7.2 Safety case

During 2003 NUMO, ENRESA and NAGRA have reviewed the existing material regarding the difference in long term safety performance between KBS-3V and KBS-3H. The results indicate that the concept is sound for further development although one must remember that the information is limited and that the planned work regarding the early evolution of the buffer and the processes following the saturation of the bentonite buffer will add more information which in turn may change the conclusion. During 2003 Posiva who is responsible for work related to the long term safety started the research regarding critical issues of the KBS-3H concept.

7.3 Demonstration

At SKB:s research facility Äspö a KBS-3H demonstration site has been excavated at 220 meters depth. The site is 15 times 25 meters and will enable excavation of three drifts, present plans indicate that 2 drifts will be excavated in the first step. During 2003 characterisation of the rock at all three deposition drift positions have been carried out. The characterisation verifies the early assumptions regarding the rock mass quality.

7.4 Continuation of the R&D program

In December 2003 SKB:s board decided to continue the R&D program with the next step, demonstration and preparations for a site specific safety case. This means that SKB aims at completion of the R&D program according to the original plans and a thorough evaluation of the KBS-3H concept by 2007. However, work is proceeding stepwise and the project results are continuously evaluated.

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Appendix 1

Tolerances for excavation of deposition drift