KBS-3H Preparations, assembly and installation of the Multi Purpose Test

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SKB

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Abstract

The Multi Purpose Test (MPT) is carried out at the Äspö HRL starting 2011 and is part of the KBS-3H project which is a joint project run by Swedish Nuclear Fuel and Waste Management Co (SKB) of Sweden and Posiva Oy of Finland. The MPT is also part of the LucoeX project and is partly funded by the European Commission.

The test is basically a shortened non-heated installation of the KBS-3H reference design; Drainage, Artificial Watering and air Evacuation (DAWE). The MPT includes the main KBS-3H components; the Supercontainer, consisting of a canister surrounded by buffer blocks inside an outer perforated metal shell, distance blocks and a metallic plug with its transition zone (blocks and pellets), Figure 1-3.

The primary purpose of this report is to provide an overarching presentation of the MPT test, including its design, basic instrumentation, preparatory work on components and in the drift, component assembly and test installation. The report also presents main experiences gained from the work.

Sammanfattning

Det så kallade Multi Purpose Test (MPT), genomförs på Äspö-laboratoriet med start 2011. Testet är en del av KBS-3H-projektet som drivs gemensamt av Svensk Kärnbränslehantering AB i Sverige och Posiva Oy i Finland. MPT är även en del av LucoeX-projektet och är delvis finansierat av Europeiska kommissionen.

Testet är i princip en avkortad installation av KBS-3H:s referensdesign, Drainage, Artificial Watering and air Evacuation (DAWE) utan värmare. MPT inkluderar de huvudsakliga KBS-3H-komponenterna; Supercontainern som utgörs av en kapsel med buffert placerad inuti ett perforerat metalliskt skal, distansblock, och en metallplugg med dess övergångszon (block och pelletar), Figur 1-3.

Huvudsyftet med denna rapport är att ge en övergripande presentation av MPT-testet, inklusive dess design, instrumentering, förberedande arbeten med komponenter och deponeringshål samt montage av komponenter och installation av testet. Rapporten presenterar även viktiga erfarenheter som dragits från arbetet.

Contents

1 Introduction

1.1 General

The common goal of SKB and Posiva is disposal of spent nuclear fuel from Swedish and Finnish nuclear power plants at depth in crystalline bedrock to ensure the safety of human beings and the environment for long periods of time. The method selected for the final repository is the KBS-3 method, Figure 1-1. The reference design is KBS-3V employing vertical disposal of waste canisters, where horizontal disposal of canisters, KBS-3H, is a possible alternative which is being explored and elaborated by the two organisations. SKB's and Posiva's current programmes for KBS-3 are detailed in SKB's RD&D-Programme (SKB 2013) and in Posiva's corresponding programme (Posiva 2010).

KBS-3H development work started in 2001 based on the KBS-3V method with focus on KBS-3H specific issues. The layout of the KBS-3H drift is shown in Figure 1-2. The foremost elements of the design are the inclined horizontal drifts, the Supercontainers which constitute disposal packages made up of a canister surrounded by bentonite buffer with an outer perforated metallic shell, the distance blocks made of bentonite which separate the Supercontainers hydraulically and thermally and the metallic plugs with their accompanying transition zones made up of pellets and bentonite blocks. The compartment plug is designed to withstand the hydraulic pressure and minor buffer swelling pressure and the drift plug is designed to withstand full hydraulic and buffer swelling pressure. Additionally there are filling components which are placed in positions of high water inflows.

The KBS-3H reference design is called Drainage, Artificial Watering and air Evacuation (DAWE). The DAWE design utilises that the KBS-3H components are installed on feet's so that inflowing water drains underneath them. When all components are installed in a 150 m section the voids around the components in the section are artificially filled with water through the compartment or drift plug while the air is evacuated.
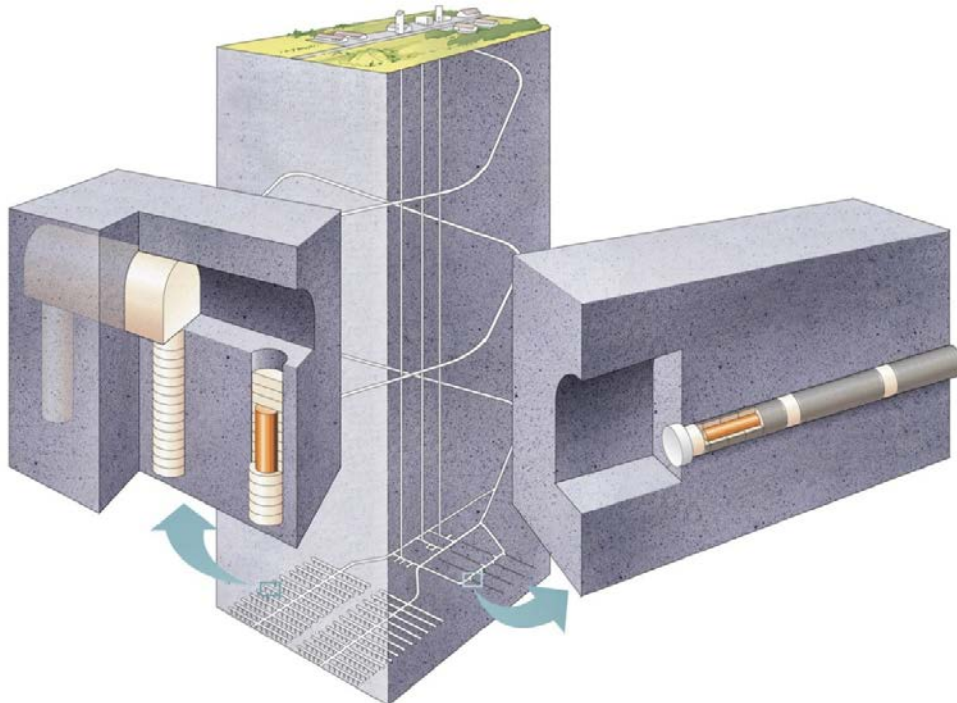
Figure 1-1. *Schematic illustration of the KBS-3 method with its three barriers: the canister, the buffer and the rock. The vertical reference design is illustrated to the left and the horizontal alternative to the right.*
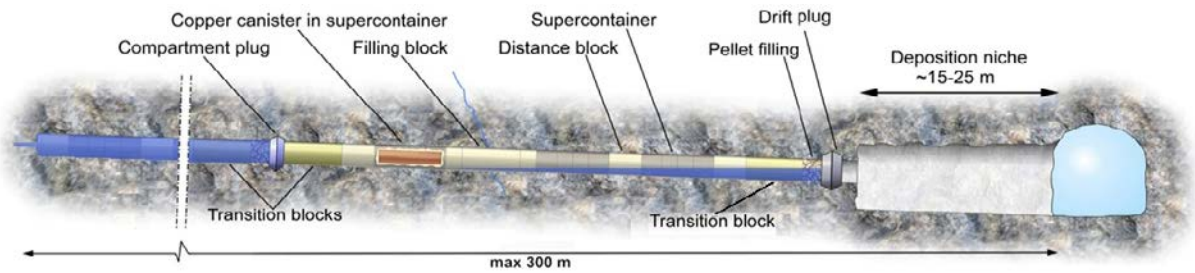
Figure 1-2. *Illustration of the KBS-3H design, the current figure illustrates the water filling of the second compartment.*

Further details on the KBS-3H design; including premises, requirements, safety assessments, construction and operation etc. can be viewed in KBS-3H Complementary studies, 2008–2010 (SKB 2012).

The KBS-3H design has been developed jointly by SKB and Posiva since 2002. This report has been prepared within the project phase "KBS-3H – System Design 2011–2016".

1.2 Multi Purpose Test (MPT)

In 2004–2005 two deposition drifts (Ø 1.85 m) were excavated at the −220 m level of the Äspö Hard Rock Laboratory (Äspö HRL), Sweden; one 15 m long and one 95 m long (Bäckblom and Lindgren 2005). The 95 m drift has been used to test and further develop a horizontal deposition machine for disposing full scale concrete dummy distance blocks and fully deployed (dummy) Supercontainers, while the 15 m drift has been used to test the compartment plug (SKB 2012).

The Multi Purpose Test (MPT) is the next step of the KBS-3H development and integrates the key disposal components, including the Supercontainer, distance blocks, compartment plug, transition block and pellets filling. It utilises the innermost 19 m of the 95 m drift at the Äspö HRL and for the first time introduces buffer manufacturing (Johannesson 2014), assembly and deposition of KBS-3H bentonite components and closure by way of a compartment plug, followed by monitoring of the early buffer evolution. The MPT project also includes upgrading and rebuilding of the control system the deposition machine (Ojala and Von Numers 2015).

The MPT started 2011 and the installation was completed end 2013 and the monitoring is now ongoing. The original time schedule was to dismantle and evaluated the MPT end 2014 but the dismantling and analysis of results is now postponed and the new date is not yet decided. It is also part of the LucoeX project and is partly funded by the European Commission.

The test is basically a shortened non-heated installation of the KBS-3H reference design (DAWE), including the main KBS-3H components as shown in Figure 1-3 and 1-4. The test is installed according to DAWE after which the test conditions are monitored. Dismantling and analysis will be carried out at a later stage and the timing for this will be dependent on the measured data and projections made on evolution of the experiment.
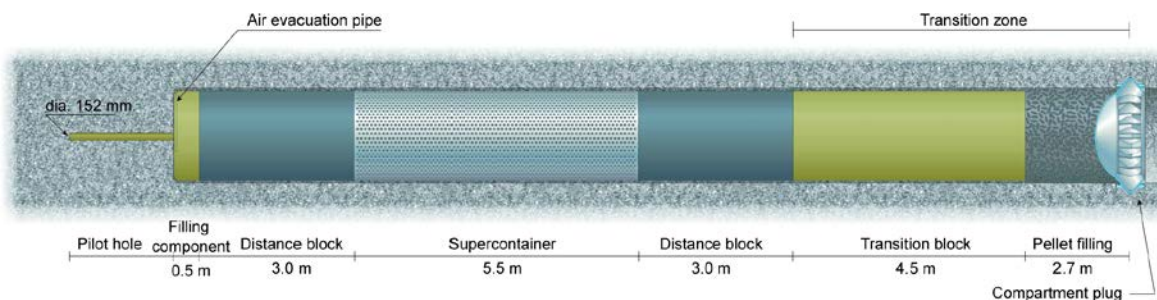
Figure 1-3. *Schematic illustration of the MPT layout.*
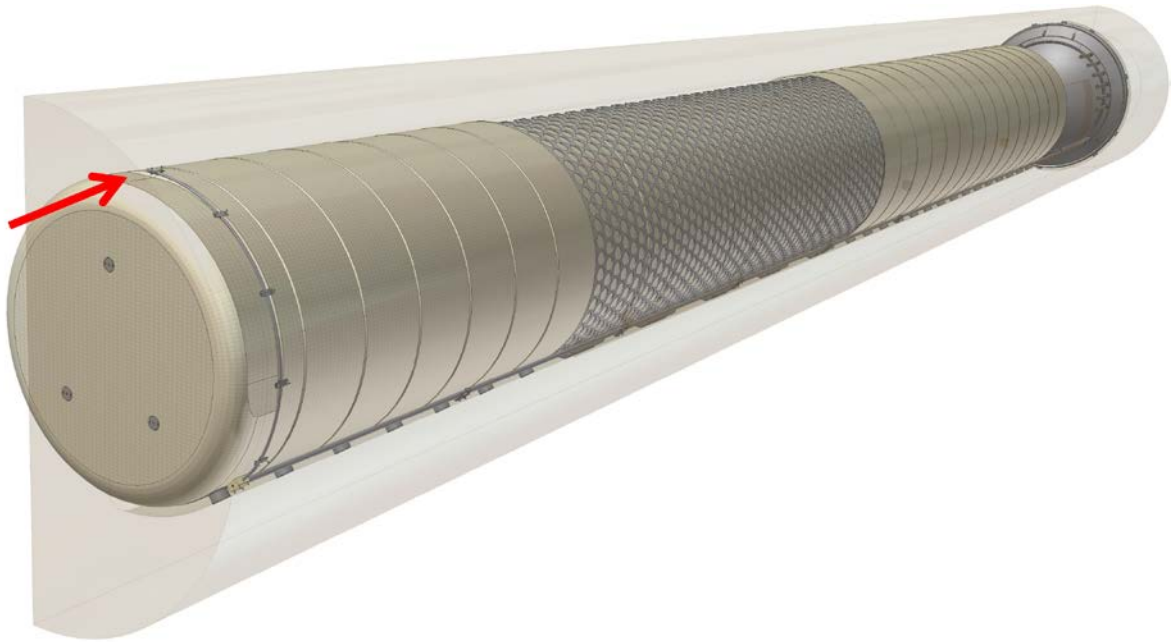
Figure 1-4. *3D illustration of the MPT where the air evacuation pipe can be seen going to the highest point of the drift (red arrow).*

A guiding principle for the MPT has been to keep it as straightforward as possible, this was done to minimise the risk that the main objectives, see Section 1.2.1, or the timeframe was compromised, for example, heaters are not used, effectively keeping the number of variables down.

The MPT is a sub-system test and will if SKB and Posiva choose to continue the KBS-3H development be followed by a full KBS-3H system test at repository level. Such a system test would include multiple and heated canisters together with all the KBS-3H disposal components.

1.2.1 MPT Objectives

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

Initial verification of the design implementation and component function is the main objective.

The test also provides important experiences from working in full scale at in situ conditions, thus enabling the recognition of potential implementation issues of the DAWE design.

1.3 Purpose and scope of this report

The current report presents the MPT design, its basic instrumentation setup and work done concerning the

- drift characterisation and preparations,
- compartment plug,
- pre-test with a distance block including technical details for the assembly, transportation and installation,
- assembly of a Supercontainer, two distance blocks and a transition block,
- installation of the components and a compartment plug.

Experiences from the work are presented throughout the report. The final chapter concerning possible future KBS-3H demonstrations also includes technical recommendations based on those experiences.

In situ results of the MPT are presented in KBS-3H Initial data report for the Multi Purpose Test (Pintado et al. 2016).

1.4   Geometrical references

When "different sides" of the cylindrical drift are mentioned in this report, they are defined with the viewer assumed standing outside of the drift and looking in towards the drift end. It is noted that when a sensor is installed on a bentonite block, in the assembly facility, with the viewer standing in front of the block, with the blocks feet towards him, the right side of the block will eventually end up on the left side when the component is installed in the drift, Figure 1-5.

When mentioning clockwise positions, it is assumed that the viewer is standing in front of, and looking on to the object, with three o'clock to the right and nine to the left.

The drift where the MPT section is located is referred to as the 95 m drift (rounded up from 94.5).
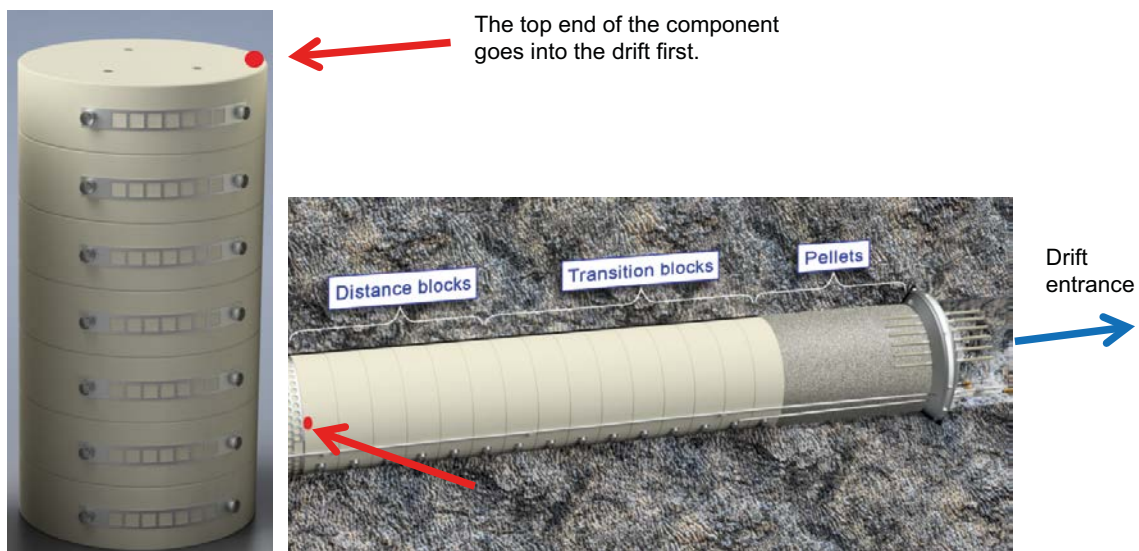
Figure 1-5. Illustration of how a sensor on the 'right' in the assembly hall ends up on the 'left' in the drift. The red arrow marks a theoretical sensor and the blue arrow marks the drift entrance direction.

2 MPT design, instrumentation, basic equipment and constraints

This chapter outlines the MPT design, its components, expected evolution and the selected instrumentation. It also introduces basic equipment that has been developed earlier and the constraints of the test setup.

2.1 Test set up and components

The MPT design is presented in Figure 1-3. It includes a Supercontainer flanked by bentonite distance blocks on both sides and a compartment plug with its accompanying transition zone made up of a section filled with bentonite pellets and a bentonite transition block. Each component is described in the subsections below.

2.1.1 Supercontainer

The Supercontainer is made up of the canister surrounded by bentonite buffer rings and blocks that are placed inside a metallic shell. In the MPT a carbon steel shell is used but in the reference design titanium is employed for long term safety reasons. In the long term, the steel could potentially affect the bentonite buffer in a negative way but for a short-time test like the MPT this effect is expected to be very limited. For detailed buffer requirements and manufacturing, cf. Johannesson (2014). Figure 2-1 illustrates the MPT Supercontainer and its components.

2.1.2 Distance blocks

Figure 2-2 illustrates the distance blocks which are placed to separate Supercontainers thermally and hydraulically and are made up of bentonite blocks with feet attached for deposition in the drift. The reference feet are 46 mm high and basically centres the distance blocks in the drift which allows the deposition machine to get in underneath and lift them. The feet also keep the bentonite away from the drift floor so that water can drain underneath them. For the MPT slightly higher feet, 49.5 mm, were used due to wear on the deposition machine's lifting equipment. In the MPT case, one foot is placed on each distance block segment. Installed feet can be seen in Figure 7-4. In the MPT steel feet are used rather than the reference design which is titanium, with the argumentation being the same as for the Supercontainer steel shell. Additionally, in the MPT a rod system is used to hold the composite distance blocks together, see Section 6.1.1 for details.

For detailed buffer requirements and manufacturing view KBS-3H Manufacturing of buffer and filling components for the Multi Purpose Test (Johannesson 2014).
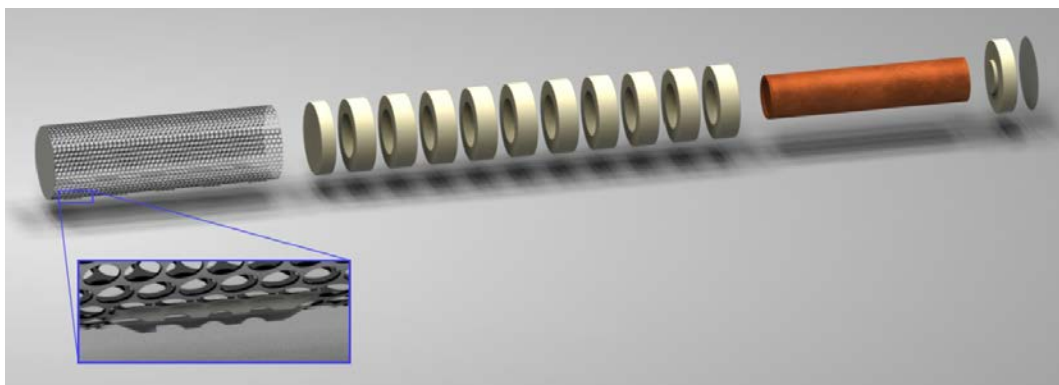
Figure 2-1. *Schematic illustration of the Supercontainer. Due to current limitations in the height of the bentonite press the 'rings' employed in the MPT are shorter than in the KBS-3H reference design.*
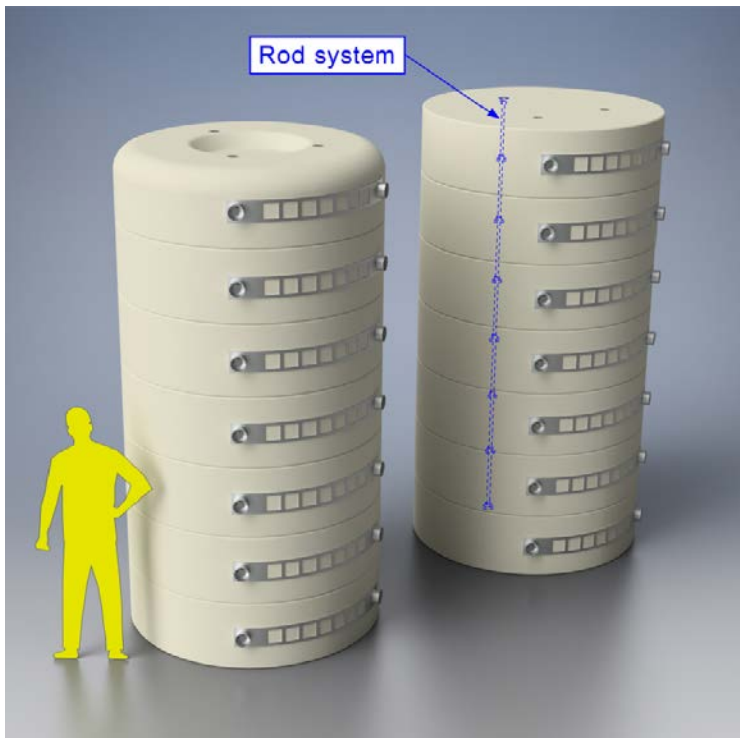
Figure 2-2. Schematic illustrations of the distance blocks with their feet. Seven 0.5 m segments are held together in the MPT making up 3.5 m composite components, six of the seven blocks represent distance block segments. The top block on the left component in the illustration is the innermost filling component which is shaped as the drift end and was installed together with the inner distance block. The bottom block of the right component in the illustration is from the transition zone and was installed together with the six distance block segments in order to make up more evenly sized components.

2.1.3   Compartment plug

A 300 m long drift should according to the KBS-3H reference design be sectioned into two compartments using a compartment plug located at 150 m, while a drift plug which is of similar design, but significantly sturdier is used to seal the entrance to the disposal drift. The separation into two compartments is done for practical reasons related to the air evacuation procedure employed. For the MPT a compartment plug is used, cf. Figure 2-3. The argumentation behind selecting the compartment plug rather than the heavier drift plug was that the MPT is a short term test located at the −220 m level of Äspö; hence the ground water and swelling pressure will not require the sturdier drift plug. In addition, the compartment plug function has previously been tested in situ with good results.

The compartment plug is made up of three main parts; the fastening ring which is cast into a sawed rock slot, the collar which is welded to the fastening ring and the cap which is welded on to the collar to seal the section. A circumferential rail system is used to concentrically cut out the rock slot, for further details see Section 5.1.1. Contact grouting tubes are placed in the interfaces between rock-casting and casting-steel, respectively, these allow for Silica Sol contact grouting subsequent to welding. A key feature of the compartment plug is that the fastening ring is cast into place during drift preparations; it hence has adequate time for curing well ahead of deposition. A concrete 'bridge' allows the deposition machine to pass over the fastening ring. When the components have been deposited the 'bridge' is lifted away and only welding work remains to complete the plug at this stage, which allows for a quick installation. The collar is fitted with lead-throughs for the water filling and air evacuation procedures of DAWE. In the MPT case the collar is also fitted with lead-throughs for sensor cables. For detailed requirements and design of the compartment plug, cf. SKB (2012).
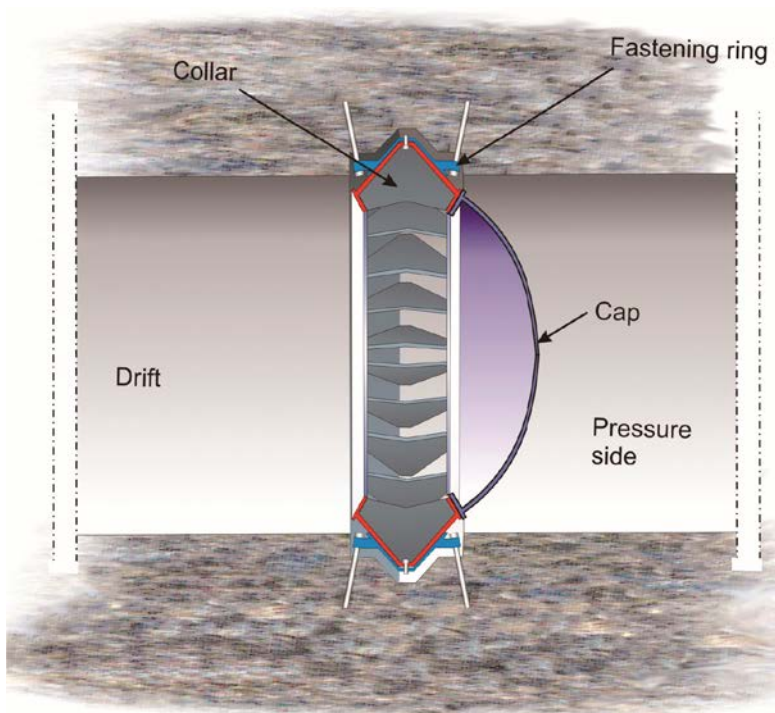
Figure 2-3. Schematic illustration of the compartment plug.

2.1.4 Transition block and pellets

For installation reasons there has to be space enough to make room for the cap inside of the collar when the collar is welded in place. In the reference design the needed length is 1.3 m and in the MPT it is 2.7 m due to cabling. The void is filled with bentonite pellets through a hole in the cap of the compartment plug; the pellet dry density requirement is $1\,000$ kg/m^3. Use of pellets thus implies loss of buffer density in this section. The distance blocks are part of the KBS-3H buffer and are associated with strict density requirements. In order to ensure their density an extra component has to be added between the pellets and the distance blocks, a transition block. The pellets and transition block make up the so-called transition zone, cf. Figure 2-4.
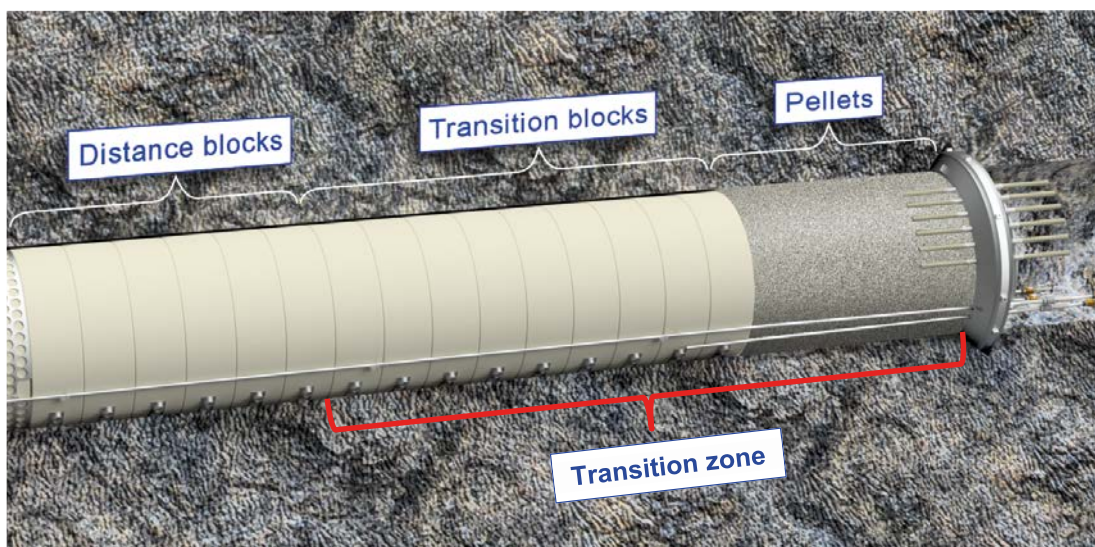
Figure 2-4. Schematic illustration of the transition zone made up of pellets and a transition block. The transition block is a four meter long composite component made up of eight segments and similarly as for the distance blocks the segments are held together by a rod system in the MPT.

2.2 Expected evolution of the MPT

A program for predictive modelling of the MPT evolution was set up during the test planning, starting with modelling of simplified small scale tests, continuing with the modelling of half scale tests (SKB 2012, p 150) and concluding with modelling of the full MPT experiment. However, the modelling faced some problems already at the small scale test stage and it was decided to cancel it. One of the main issues that could not be solved because of the lack of information about the process was the extrusion of bentonite through the perforation of the Supercontainer shell following the DAWE procedure.

In order to define and support the MPT instrumentation, a set of scoping calculations were carried out to describe the evolution of the different variables planned to be measured. Since the MPT is isothermal and does not include a heat source, the variable calculated was the liquid pressure in the bentonite (positive in saturated conditions and negative in unsaturated conditions). The hydraulic evolution in terms of hydraulic pressure in the rock was also modelled. The calculations were carried out with CODE_BRIGHT (Olivella et al. 1994, 1996).

The scoping calculations demonstrated that there would be a certain water intrusion into the buffer system during the 400 days over which the MPT was initially planned and that the swelling pressure would be related to the saturation process, although without a mechanical model it was not possible to quantify the range of the stresses expected.

The MPT was originally planned as a short-term test, with dismantling after 400 days. However, other KBS-3H studies undertaken during planning and the modelling presented above indicated that the early evolution of the buffer, following the DAWE procedure, would be even slower than what had previously been expected. For this reason, the monitoring period of the MPT will rather be based on the data actually generated from the test.

2.3 Instrumentation

The MPT is instrumented with the objective to study the behaviour of buffer- and filling components during the early part of the buffer evolution, and in addition to study the compartment plug behaviour.

The instrumentation is set up to monitor movements in the system, buffer water content, possible plug leakages, strain in the metal components, pore- and total pressure and buffer swelling pressure at the rock and plug interfaces. The development of swelling pressure acting on the rock wall is investigated e.g. to evaluate if the pressure reaches levels that could have a mitigating effect on thermally induced spalling. The development of swelling pressure exerted on the compartment plug during the operational phase (due to transition zone and distance blocks) is a question that is also addressed by the instrumentation. Another objective of the instrumentation is to increase the understanding of the relative effect and importance of three different flow paths, which are buffer, EDZ and near field rock.

Additionally, the short term influence of the Äspö water on different materials placed in the buffer is studied by the installation of metal coupons that can be examined after dismantling.

The locations of the measurement sections selected within the MPT are presented in Figure 2-5 and the type and number of sensors are presented in Table 2-1 with sensor abbreviations in Table 2-2. For further details on the instrumentation with argumentation for the different sections, cf. Pintado et al. (2016), where also the initial data generated by the instrumentation are presented.

As seen in Table 2-1 some of the sensors use a wireless system to transmit data while most are connected by wire. The use of a wireless system is novel to a KBS-3H application and there are therefore redundant wired sensors installed in places.
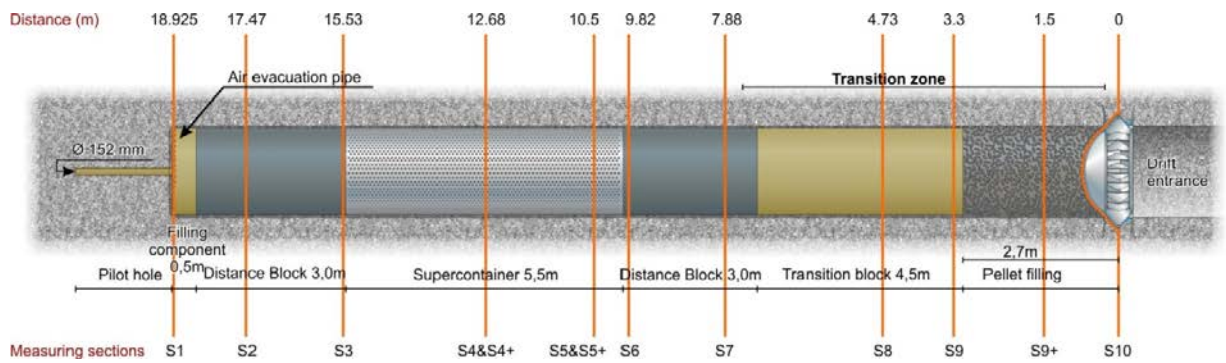
Figure 2-5. *Vertical lines show locations of measurement section.*

Table 2-1 Distribution of sensors by section showing the distribution between those that are accessed by means of conventional cables (wire) or wireless or tubings that transmit pressure.

Sensors	Sections												
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S9+	S10	Out	Tot
TP rock	5	4		2			4	4	2	6			27
TP plug											2+1		3
TP buffer				4	4	4			1				13
PP rock short	1	4					4						9
PP rock borehole									18				18
PP buffer		3+3		4	2+3		1+3				3+3		23
WC		3+3		4	2+3		3+3	4+3	3+3				34
WP		6		4	4		6	6	6				32
WF	1	2		2	2		2	2	2				13
DS				4	4								8
DB									2				2
DC												3	3
IS				2									2
IB		1					1		1+1				4
GP	1					1					1		3
SG					8							24	32
FM												1	1
Total	8	27	0	26	32	5	27	19	39	6	10	28	227
Tubings	2	4	0	0	0	1	4	0	0	0	1	0	12
Wireless	0	6	0	0	6	0	6	5	6	0	4		33
Wired	8	21	0	26	26	5	21	14	33	6	6	28	194

Table 2-2 Sensor abbreviations.

Type of sensor	Full name
TP	Total pressure
PP	Pore pressure
WC	Water content capacitive
WP	Water content psycrometric
WF	Water content volumetric
DS	Displacement of Supercontainer
DB	Displacement of bentonite
DC	Displacement of collar
IS	Inclinator for the Supercontainer
IB	Inclinator for the bentonite
GP	Gas pressure
SG	Strain gauges
FM	Flow measurement

2.4 Basic KBS-3H equipment

Equipment related to the transport and deposition of KBS-3H Supercontainers and associated buffer was developed and manufactured during 2005 by CNIM, France (Autio et al. 2008).

The equipment includes the following main components:

- Deposition machine.

- Start tube for the deposition machine with transport support.

- Transport tube for Supercontainer and distance blocks with transport support.

The development of the deposition machine was part of the research and development programme called ESDRED ("Engineering Studies and Demonstration of Repository Designs") that was funded in part by the European Commission.

Figure 2-6 illustrates the set-up of the KBS-3H equipment which was made available for the MPT at the Äspö HRL. The deposition machine uses water cushion technology to transport the Supercontainers and distance blocks. Earlier demonstrations have proven the technical feasibility of the equipment, including demonstration using concrete dummies. However, the deposition machine has faced operational problems with its control system and balancing of the deposition machine with a load and the MPT therefore included upgrading and rebuilding of the control system (Ojala and Von Numers 2015).

2.5 Constraints imposed by the experiment site

The boundary conditions associated with the KBS-3H test site at the −220 m level at Äspö are significantly different from those of the repository case and thus impose certain constraints and compromises. The ground water pressure is lower, approximately 20 bars as opposed to approximately 50 bars at repository level. The rock stress conditions are also very different from those foreseen at repository depth in Forsmark and Olkiluoto (selected repository sites in Sweden and Finland, respectively).

In addition the rock at the experimental site in Äspö is more hydraulically conductive with higher groundwater flow in fracture system adjacent to the drift. These differences have to be taken into account when evaluating the results of the MPT. Furthermore, the installation phase is more extended in time due to the comprehensive instrumentation and due to the manual work associated with the
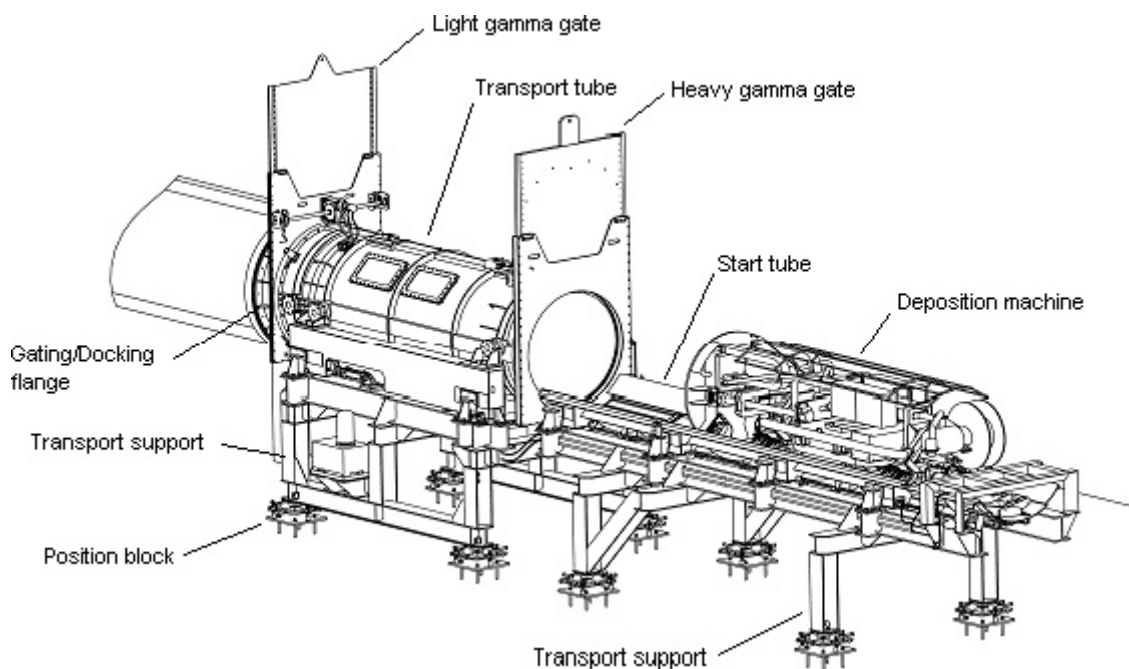
Figure 2-6. *3D-layout of deposition equipment.*

mounting of the plug (it is planned to be conducted more rapidly in a repository situation with the help of further developed techniques). This means that although the MPT only involves one Super-container, the time during which the components are exposed to the humid air of the drift is longer, about 3 weeks compared with approximately 1 week in the repository case.

The MPT experimental section is approximately 19 m compared to 150 m in the repository case, which implies that the water filling procedures of DAWE differ. Water filling is done at a level to match the water level rising inside a 150 m section, i.e. with a lower flow rate compared with the reference design.

There is no adjacent tunnel laterally away from the MPT drift. For this reason, cabling has to be run along the walls of the drift and out through the plug. Much effort has been made to limit the risk of water flow along the piping and the risk of such flow is considered to have been reduced although not fully eliminated.

The distance blocks are made up of 0.5 m long segments. Thus, 7 segments make up a 3.5 m long distance block. Each segment has one foot, and is hence unstable if not supported by a neighbouring block. This means that the outermost blocks may fall, with a potential risk for a continued domino effect on the rest of the blocks. This risk is recognised, and will be resolved for future applications once 1.0 m long blocks can be manufactured and fitted with a pair of feet, i.e. making them more stable and self-sustained. The factory manufacturing the blocks currently has a height limitation of approximately 0.5 m. The risk of potentially tilting blocks is unacceptable, both from a personnel and operational safety perspectives and for the MPT installation the project addressed this problem by stepping away from the KBS-3H reference design through installation of three lengthwise rods connecting adjacent distance block segments, for details see Section 6.1.1.

Some of the sensors used in the MPT may fail if immersed in water; this risk was also mitigated by locking the blocks together with rods.

3 Pre characterisation of the MPT test section

This chapter presents the site characterisation that was carried out prior to installation in order to define the test sections, 19 m, starting conditions prior to the MPT installation.

3.1 Geological mapping

Prior to excavating the 95 m drift a pilot hole was drilled and characterised in 2003. After excavation, the drifts were mapped with focus on rock types, fracturing and groundwater inflows. Details about this characterisation are presented by Bäckblom et al. (2005). Since the drift wall had been geologically mapped the updated characterisation for the purpose of the MPT focused on inflow points.

The main rock type in the inner part of the MPT drift, between 75.0–94.5 m (drift end −19.5 m) is Äspö diorite (91% of the rock surface) with Ävrö granodiorite constituting approximately 9% of the mapped drift wall surface. Minor occurrences of fine-grained granite and gabbroic-dioritoide also occur. Water occurs only in minor quantities from a few fractures which are concentrated in two areas within the MPT section. The first is between 80.0–83.0 m (drift end – (14.5 m to 11.5 m)) where 5 fractures showed the lowest observed leakage (with the lowest observed leakage defined as occasional drops, minor seepage or patch of moisture). The second area is between approximately 86.0–92.5 m (drift end – (8.5 m to 2.0 m)), where there are 10 fractures and 2 fracture zones that showed the lowest appearance of leakage (as defined earlier), while one fracture at approximately 90.5 m (drift end –4.0 m) showed a little more leakage (defined as drops, seepage or wet surface) this fracture has a 1.8 m trace length.

3.2 Inflow measurements

The leakage into the 95 metre drift has been monitored since it was excavated in 2005. Initially the flow was approximately 12 l/min but by 2007 it had naturally reduced to approximately 5 l/min. In 2007–2008 the five observed occurrences showing the highest inflows were post-grouted with Silica Sol using the so called Mega Packer. Post grouting reduced the drift inflow to approximately 0.4 litres/min (Eriksson and Lindström 2008). By 2011 the inflow had naturally decreased to approximately 0.25 litres/min.

In order to obtain a good view of the inflow conditions in the MPT section, a set of wooden weirs were installed, Figure 3-1. The weirs were placed where the rock conditions allowed so, but they matched up quite well with the components positions. Detailed inflow data are presented in Table 3-1

Summarising the data in litres per day gives the approximations below:

- Full MPT section two months prior to installation   ~32 l/day
  - Supercontainer section in 2012   ~19 l/day
  - Inner distance block section in 2012   ~8 l/day
  - Outer distance block, transition block and pellets 2012   ~3 l/day

It can be noted that the inflow in the MPT section is well below the 0.1 l/min which is the current KBS-3H design premise stipulated for a Supercontainer section.

Figure 3-1. *Wooden weir used to section off and measure the distribution of groundwater inflow in the MPT section.*

Table 3-1 Inflow conditions in the MPT drift during 2011–2013, possible outliers (weir disturbance) are marked in red. Measurements were limited in 2013 due to development work on the deposition machine.

Date	Drift end-4,07 m (l/min)	Drift end-9,07 m (l/min)	Drift end-11,17 m (l/min)	Drift end-17,87 m (l/min)	Drift end-19,27 m (l/min)	Drift end-34,47 m (l/min)	Drift end-94,47 m (l/min)*	Date	Drift end-18,47 m (l/min)
2011-09-20	0,0060	0,0140		0,0240		0,1480	0,2200		
2011-09-21	0,0060	0,0230	0,0290	0,0220		0,1460	0,2200		
2011-09-22	0,0065	0,0215	0,0215	0,0225		0,1470	0,2100		
2011-10-06	0,0062	0,0182	0,0212	0,0217		0,1560	0,2100	2013-08-23	0,0228
2011-10-20	0,0058	0,0200	0,0202	0,0215		0,1500	0,2130	2013-08-26	0,0220
2011-11-08	0,0060	0,0200	0,0205	0,0205		0,1540	0,1980	2013-09-09	0,0216
2011-11-21	0,0055	0,0195	0,0205	0,0210		0,1360	0,1930	2013-09-10	0,0236
2011-12-06	0,0060	0,0194	0,0197	0,0205		0,1330	0,1930	2013-09-12	0,0230
2012-01-10	0,0060	0,0195	0,0195	0,0205		0,1350	0,1930	2013-09-16	0,0232
2012-05-22	0,0056	0,0190	0,0190	0,0205		0,1700		2013-09-18	0,0224
2012-06-07	0,0053	0,0186	0,0190	0,0193		0,1330	0,1830	2013-09-19	0,0224
2012-06-28	0,0056	0,0190	0,0190	0,0198	0,0202	0,1330	0,1900	2013-09-23	0,0224
2012-07-18	0,0055	0,0190	0,0190	0,0200	0,0260	0,1300	0,1830	2013-09-25	0,0200
2012-09-27	0,0050	0,0162			0,0162	0,1280		2013-09-30	0,0280
2012-10-17	0,0050	0,0180	0,0180	0,0180	0,0200	0,1260	0,1800	2013-10-04	0,0228

* There is a natrual tendency for lower inflows over time.

3.3 Laser scanning and photography

Laser scanning and photography was carried out using a Leica scanner P20 with a Nikon 800 E system camera. The work was done subsequent to excavation of the sensor holes, cable notches and fastening ring but before the main piping was cast in place, cf. Figure 3-2. Together with coordinates of where the notches are cast, the scanning allows for calculations of voids added to the nominal drift volume due to the various piping. This information can be used when assessing buffer densities after dismantling of the experiment. Figure 3-2 illustrates the scanning data.
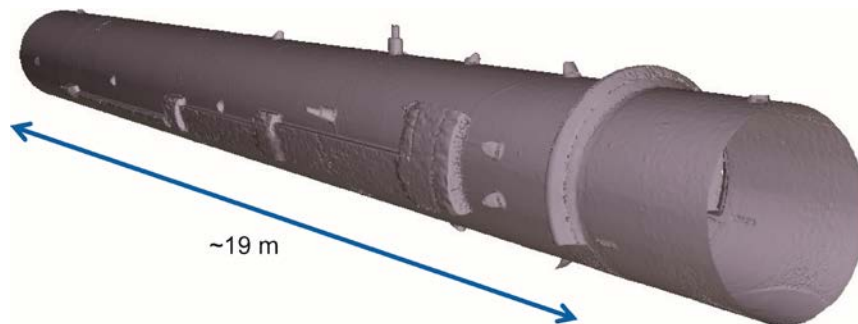
Figure 3-2. *Model composed of laser scanning data of the MPT section. Sensor holes as well as notches for cabling are visible. The plug position is visible to the right of the image and its bottom part is temporarily filled with concrete to allow the deposition machine to drive over it.*

4 Manufacturing of the compartment plug

This chapter presents the MPT compartment plug material selection in brief, including manufacturing and MPT-specific modifications made to the reference design.

4.1 Materials selection

The original plan for the MPT was to use a steel compartment plug. However, in 2011 it was decided, for long term safety reasons, that the metal components in KBS-3H should be made using titanium as reference material (SKB 2012). For this reason an evaluation of what material to use in the MPT was made, steel or titanium. The evaluation concluded that a change to titanium would limit the number of potential manufacturers compared with using steel and would in addition increase the cost for the MPT. It also concluded that the uncertainties when using metallic materials, such as titanium, in general are relatively small and it was therefore deemed that demonstration of a titanium plug could be done later, in conjunction with a possible future KBS-3H system test.

4.2 Manufacturing and design modifications

The same manufacturer that had done the previous compartment plug installation (SKB 2012) provided the best option and was awarded the contract which included both manufacturing of the steel structure as well as its installation in the drift.

For manufacturing reasons the cap, Figure 2-3, had to be made in 30 mm steel and machined down to its required thickness of 16 mm, the required shape could not be pressed directly. Rather than doing this it was decided that the cap would be used, 30 mm thick, i.e. skipping the machining. In its original design the compartment plug can handle the water pressure (~5 MPa at repository level) and a low initial swelling pressure from the buffer but it only has a function until the drift plug, which is sturdier, effectively seals off the drift and upholds the full pressure exerted by the ground water and the buffer swelling. At the −220 m level at Äspö the water pressure will be maximum 2.2 MPa so the MPT compartment plug can actually withstand both water- and swelling pressure in case the MPT was prolonged for a longer period. The 30 mm thick cap should give even bigger margins.

Figure 4-1 illustrates the compartment plug in conjunction with the Factory Acceptance Test (FAT).
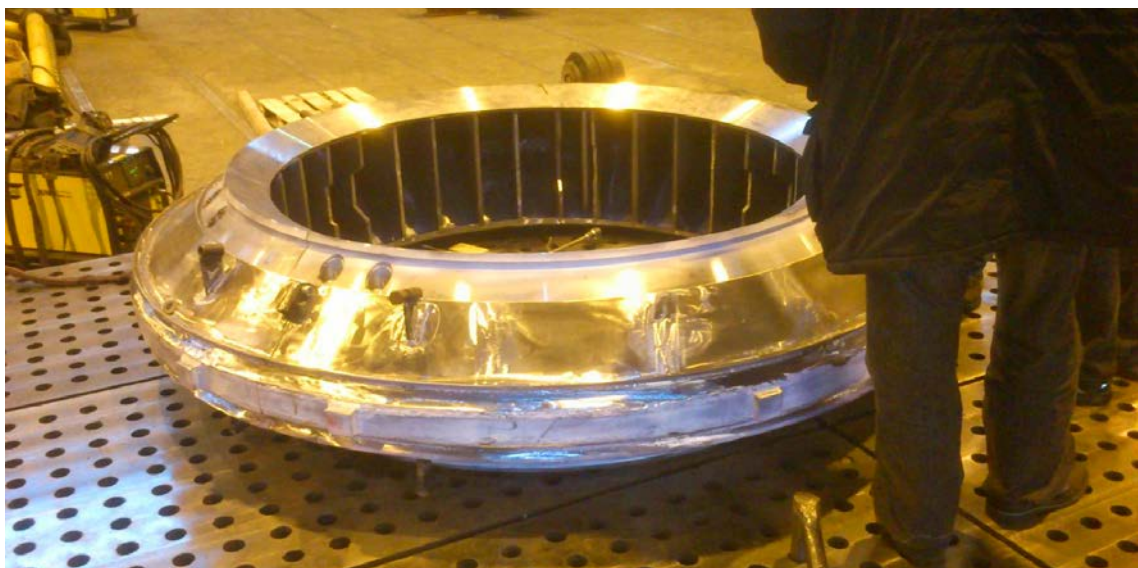
Figure 4-1. Test assembly of the compartment plug fastening ring and collar during the FAT.

5 Drift preparations

This chapter presents the preparations made in the drift for the compartment plug including sawing of a plug slot and casting of the fastening ring, activities which all are part of the KBS-3H reference design. It also details MPT-specific preparations including sawing for and installation of cable piping as well as the drilling and installation of rock sensors.

5.1 Plug preparations

The plug is installed in two main steps of which the first, the fastening ring installation, is done during the drift preparation stage and the second, including the collar and cap, cf. Figure 2-3, is done after deposition.

5.1.1 Sawing of the plug slot

The plug requires a position in high quality rock without fractures. An extra control of the rock quality at the designated position of the plug was made by geologists prior to sawing.

A circular saw, mounted on a circumferential rail is used to cut out a slot for the compartment plug, cf. Figure 5-1. It total 14 parallel cuts were made, with approximately 45 mm between each cut and extending to a depth of 283 mm which allows for an effective depth of approximately 263 mm when the slabs of rock are broken loose. The rock is broken manually using wedges, starting at the highest point, with rigid precautions taken to ensure worker's safety. The fastening ring has 12 positioning bolts around the periphery of the slot for which 12 cored holes (Ø 80 mm) were drilled radially to a depth of 180 mm prior to the sawing. Figure 5-2 illustrates the cutting pattern and visualises two of the cored holes. The drilling step can most likely be excluded in the future by making the two outermost parallel cuts slightly deeper using a hand held saw at the corresponding positions, thus enabling sufficient space for the fastening ring's positioning bolts.

Figure 5-1. *Rail and saw installed inside the drift. The reference ring towards which the rail is pulled in 45 mm steps can be seen to the left in the picture.*
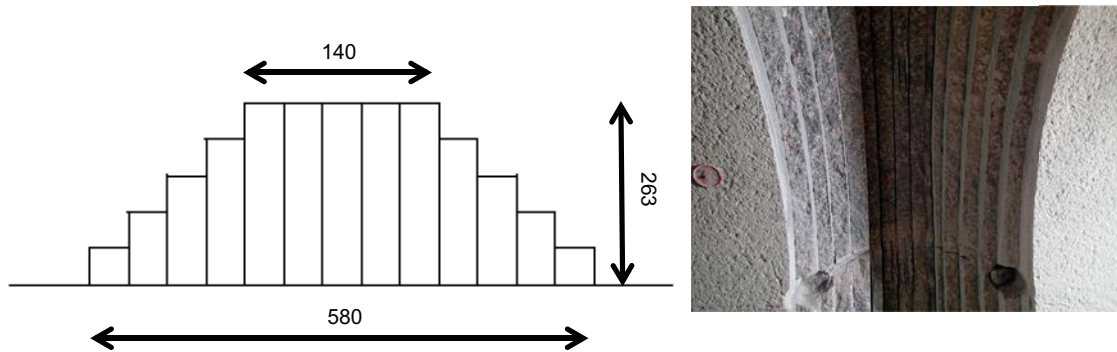
Figure 5-2. *To the left an outlining of the plug slot seen perpendicular to the drift axis and to the right a picture of the slot with the rock broken off. The remains of two of the core holes for the fastening rings positioning bolts can be seen at the bottom of the picture, flanking the slot.*

5.1.2 Installation of the fastening ring

As a first step a contact grouting tube was nailed down firmly to the bottom of the rock slot, cf. Figure 5-3, positioned on the pressure/upstream side of the plug. It allows for contact grouting in the rock-casting interface using Silica Sol grout once the entire plug has been installed.

The fastening ring is manufactured in four pieces. It was transported into the drift using a hand truck and hand operated winches were used to position the components. Figure 5-3 displays the installation work. Once assembled and welded the fastening ring's position was fine-tuned geodetically using its positioning bolts ensuring it to be centralized and orthogonal to the axis of the slightly inclined drift. High accuracy in its positioning is essential for the deposition machine which passes through the fastening ring.

Figure 5-3. *Installation of the fastening ring, the contact grouting tube in the rock-casting interface can be seen to the right in the picture.*

Once the fastening ring was positioned, a second contact grouting tube was threaded around the fastening ring and tightened as much as possible against the steel, fastened in places, with silicone. This tube allows for contact grouting at the steel-casting interface once the rest of the plug has been welded in place. This tube is of high importance since welding implies a risk that the steel might separate from the casting due to shape changes/material shrinkage. Positioning this tube proved difficult and the project will assess if the contact grouting function could be integrated into the fastening ring itself using internal channels (lead-throughs) and some type of geotextile.

The bentonite can be affected by high pH leachate from the concrete. For this reason SKB and Posiva have been developing low pH concretes recipes for plugs (Vogt et al. 2009), however, these mixes have not been tested for full scale KBS-3H compartment plugs. Given that the plug is more or less essential for the possibility to study the buffer behaviour after installation, the project decided not to take any risks with un-proven recipes and a conventional cement-based concrete was used to cast the plug. Figure 5-4 displays the mould-work for the casting. Several valves were introduced into the form to allow stepwise pumping and de-airing in order to control the rising level of concrete in the mould. The concrete was initially pumped into the lowest point and as the concrete reached higher levels the point of application for the pumping point was moved higher and the pumping was finalised when the concrete reached the level of the air evacuation pipe located in the highest point of the slot. In total 400 litres of concrete was used.

Once the wooden framework had been removed, a bridge, for the deposition machine was cast inside the lower part of the fastening ring. Plastic sheets were placed between the steel and casting and the bridge was fitted with lifting loops to allow for easy removal after deposition of the components. A future improvement would be to design a steel bridge that could be reused in multiple drifts.

5.1.3 Plug cap preparations

Multiple sensors were placed on the inside of the plug cap. However, the current KBS-3H design requires that the cap is positioned on the floor in front of the plug, Figure 9-11, while the collar is being installed; this would imply crushed sensors so the MPT-cap was fitted with a steel structure on which it could lean during installation. The sensors were instead installed protected by the steel structure and lead-troughs were drilled through the cap for their cables.

Figure 5-4. *Form-work for the casting of the fastening ring.*

5.2 Rock sensors and cabling

5.2.1 Sawing of the cable notches

Since no tunnel is located nearby the MPT drift, and excavation of a parallel tunnel was outside the project scope, all cables had to be taken along the drift sides and out through the plug. Cabling is also constrained by the fact that there is limited annular space between the components and the drift wall (42.5 mm). For this reason all cabling had to be placed outside the drift periphery, i.e. cable notches had to be cut in the rock. The cutouts are small close to the drift end and expand stepwise in size towards the plug as more and more cables are added to the bundle. In the pellets section the cutouts are further widened to form a cable storage where all cables had to be placed during component installation but before the plug was installed. Both sides of the drift have cutouts for sensor cables; the laser scanning in Figure 3-2 illustrates the cutouts on the left side of the drift.

A standard concrete cutting saw was fitted with a peripheral drift-shaped anchor that allowed parallel cutting in a similar manner as for the compartment plug, cf. Figure 5-5. A depth of 100 mm was required nominally for the cable piping so slightly deeper cuts were made. At the connection points the depth was expanded to 150 mm to allow more work space, a similar arrangement was done also in the cable storages.

The outlining of the cutouts were marked out geodetically on the drift wall. The sawing procedure worked out as intended. The entrepreneur made an accidental extra cut at the uppermost position to the right. This extra cut is well defined in the laser scanning data and will not affect subsequent evaluation of the test.

Figure 5-5. *Saw fitted on rails with anchoring's that allow for cutting of parallel cuts along the drift sides. Slices of rock were later broken of starting at the highest point and continuing downward.*

5.2.2 Drilling for rock sensors

Sensors for measuring total- and pore pressure were installed on the rock walls inside the test section, these required holes to be drilled. Table 2-1 and Figure 2-5 lists and illustrates which sensors are placed in which sections, for drawings and further details, cf. Pintado et al. (2016). The total pressure sensors (Geokon 4820 "Jackout Cell"), required a concentric shelf approximately half way down the hole so it was drilled in two steps starting with a 310 mm deep Ø100 mm followed by a 160 mm deep Ø180 mm core hole. The pore pressure sensors (KELLER series 23) are smaller and required a 160 mm deep Ø20 mm hole. Each hole position was marked geodetically on the drift wall prior to drilling.

Where needed, a shallow cut was made by a saw from the sensor position to its closest cable notch, this was necessary for example to protect the sensor cables along the floor from being crushed by the deposition machine.

To allow for an increased understanding of the hydraulic boundary conditions around the drift, three 10 m long Ø76 mm cored boreholes were drilled radially from the drift in a location approximately between the pellets section and the transition block, cf. Figure 1-3. Figure 5-6 illustrates how the drilling was carried out and also visualises the cable notches discussed in Section 5.2.1. Checking for groundwater inflow was done during drilling and quantified.

The boreholes, named KA1620A01 (inclined 30°, in a coordinate system where 0° is to the right and 180° is to the left), KA1619A03 (150°) and KA1619A04 (270°, i.e. in the floor), respectively, were later instrumented with packer systems and hydraulically characterised, see Section 5.2.4 for details.

The cores were photographed and tentatively mapped for rock types and fracture frequency. The dominant rock type seen in the boreholes is Äspö diorite with minor occurrences of fine-grained granite. In the overview mapping the broken fractures of the cores were all interpreted as possibly open fractures (containing fracture fillings). The total numbers of fractures in the boreholes are: KA1619A03 = 7 fractures, KA1620A01 = 13 fractures and borehole KA1619A04 = 5 fractures.

Figure 5-6. Core drilling of 10 m long boreholes inside the MPT test section. The picture also visualises the cable notches. Note that the Supercontainer vaguely seen at the end of the drift is the concrete dummy used during deposition machine testing; it was removed prior to the main MPT installation.

5.2.3 Installation of rock sensors

The total pressure sensors were fitted with two steel rods that were fitted to the shelf inside the hole, see Section 5.2.2, these rods were used to centre the sensor, cf. Figure 5-7. The grout inlet and air evacuation was placed depending on the orientation of sensor relative to the drift (on the floor, side or top of the drift), always with the air evacuation located in the highest and grout inlet in the lowest point. A wooden frame was used to seal around the pipes and Emaco Nanocrete R4 Fluid used to cast the sensor.

The pore pressure sensors were installed by gluing a plastic casing in the hole using WÜRTH nr. 089322612. The sensor was subsequently placed in the casing and sealed with an O-ring after which the outer part of the hole was filled with the same glue.

5.2.4 Packer installation and pre characterisation of the 10 m core holes

To allow for hydraulic characterisation and subsequent monitoring over time during the MPT a hydraulic packer system was installed in each of the three cored boreholes, each hole with 6 test sections instrumented for measurement of pressure. The geological mapping of the drill cores was used to select three 'dry' sections in each hole while the remaining 3 sections were placed in-between these, being either 'dry' or with inflow. Figure 5-8 illustrates the packer system during a test assembly in the workshop.

Figure 5-7. *Total pressure sensor position in their holes prior to casting. The picture, which is taken at the drift end, also illustrates the shallow cutouts in which the sensor cable pipes were placed (red spray on the wall).*
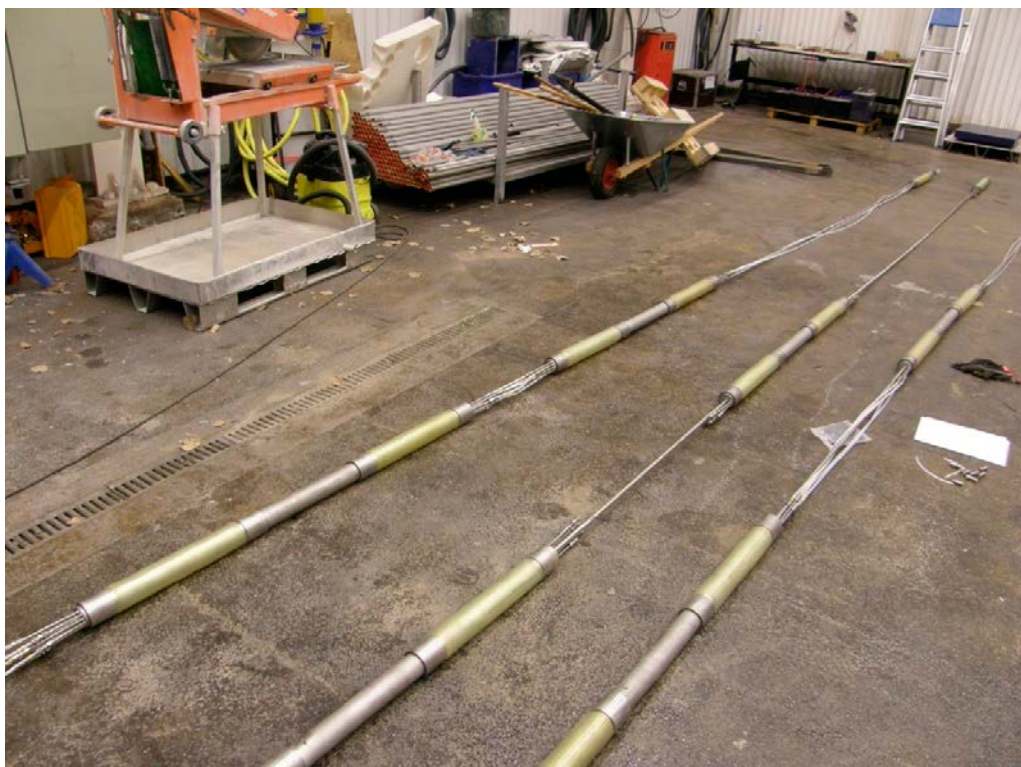
Figure 5-8. *Test assembly of the packer system in the workshop.*

In situ measurements were carried out in two steps; first as full length borehole outflow and secondly as selective section-wise outflow and pressure-build-up measurements. The section-wise measurements comprised the following test sequence:

- Outflow stabilization, 30 min.
- Flow measurement, 1–2 min.
- Pressure-build-up, 30 min.

Borehole KA1620A01 (up, to the right) had five 'dry' sections and one flowing section: 0.059 l/min, 1 146 kPa (between 5.44–9.45 m).

Borehole KA1619A03 (up to the left) had three 'dry' sections and three leaking sections; one leaking 0.015 l/min, 1 183 kPa (between 5.26–9.17 m), one leaking 0.0265 l/min, 1 182 kPa (between 3.29–3.96 m) and one leaking 0.00057 l/min, 1 174 kPa (between 0.83–1.99 m).

Borehole KA1619A04 did not yield any measurable outflow and was therefore not measured section wise.

The groundwater pressure which was measured slightly below 12 bars illustrates that the conditions around the drift is drained to some extent, a fully developed groundwater pressure at the −220 m level, drawdown of the Äspö HRL neglected, would be in the order of 22 bars.

In hindsight the positioning of these cored boreholes, inside the MPT test section where they are not accessible after installation is not really a good solution. This was something that was missed even with extensive expert review of the instrumentation plan. A failing pipe, connector or packer could open up the core holes and allow their natural inflow (in the order of 0.1 l/min in the three holes) to influence the MPT buffer in a manner that to some extent is artificial compared to the natural inflow into the MPT section. One such incident did occur only a few days after the MPT installation, when the gas pipe pressurising the water in the packers failed, effectively deflating the hydraulic packers in the boreholes. This problem was noted quite quickly and could be resolved outside the plug, but

there are other types of problems that would be even worse if they were they to occur. Extra measures with additional valves have been taken and the system is operating properly one year after installation and should be able to operate properly for very long periods (5 years function of the packers are guaranteed by the manufacturer but SKB has had similar system operating in access of 15 years).

5.2.5   Installation of cable piping

Flow paths established along cable bundles constitute a well-known risk when installing sensors in bentonite buffer. In the MPT this is a real risk given the constraint that there was no neighbouring tunnel, and all cables thus had to be brought along the drift sides and out through the plug. In an effort to minimise this risk a strategy utilising a few larger pipes as lead-throughs for the smaller once was employed. A stainless steel 'hedgehog' connector where the small pipes were lead through and brazed was developed. As an extra precaution the pressure side of the connector was also glued with epoxy. The connectors were fitted to larger pipes that were placed inside the cable notches along the drift sides, cf. Figure 5-9 and 5-10. Inside the larger pipes, tecalan tubes were used for each smaller lead-through. A string was prepared inside each pipe as can be seen in Figure 5-9, this was later used to pull through the cable once the bentonite component in question had been placed in the drift.

In order to minimise the voids and channelling in the cable notches, low pH concrete was cast around the larger pipes. However, rather than casting along the full extent, smaller openings were left uncast along the larger pipes to allow for the bentonite to swell in and around them, see Figure 5-10. This was done to minimise the risk of leakages behind the casting along the drift sides. The openings are well documented allowing for calculations on how much extra volume the cable notches add to the system.

All larger pipes ended in the cable storage, Figure 5-10, where tecalan tubing and cables were stored during installation. Once the plug was subsequently built these tecalan tubes with cables inside were taken through large flexible stainless steel pipes and out through the plug.

Overall, the solutions employed during installation were deemed to reduce the risk of leakages along cables and inside the cable notches. The employed solutions also allowed for all cables inside the MPT to be protected by stainless steel piping all the way from the sensors and out through the plug. The only exception to this was a test of a novel set of strain gauges mounted on the Supercontainer shell; these had to be protected by tecalan tubing from the Supercontainer to the larger pipes inside the walls.

Much of the solutions presented in this chapter were developed for the MPT specifically. All key steps worked out as planned, although there are optimisations to be made if a similar system is to be employed again, see Section 9.4.

Figure 5-9. *'Hedgehog' connectors at the Supercontainer position, in this case three 'hedgehogs' due to the numerous sensors inside the Supercontainer. The pipe passing by at the bottom carries the sensor cables from the innermost distance block. The small pipe in a loop and already connected is from one of the rock-sensors.*

Figure 5-10. *The MPT drift prepared for installation, note the partial low-pH casting around the larger pipes. Also visible is the cable storages where tubes and cables are placed during installation.*

6 Equipment, assembly facility and block preparations

This chapter presents MPT-specific equipment which introduce alterations compared with the KBS-3H reference design, but were necessary to employ to ensure workman's and operational safety and to enable sensor installations. It also presents the assembly facility, machines and equipment used as well as preparations made to the blocks prior to the actual assembly work.

6.1 Test specific equipment, modifications to the reference design

6.1.1 Lengthwise rods

As stated in Section 2.5, the 0.5 m blocks with one foot were unstable and may tilt; this was found unacceptable both from an operational and workman's safety perspective, additionally some of the sensors used in the MPT may fail if immersed in water. To mitigate the tilting risk a segmented stainless steel rod-system was designed which allowed the block segments to be locked together tightly.

It worked by drilling three Ø 40 mm cores at 0°, 135° and 225° at positions 450 mm from the block centre, countersinking the holes to Ø 80 mm to a depth of 16 mm for connecting and aligning nuts, Figure 6-1.

The bentonite cores produced by drilling were placed in airtight bags, the air was drawn out by vacuum and the bags welded together. These cores, three from each distance- and transition block segment provide samples of the actually installed MPT blocks which could be studied at a later stage.

At assembly the distance block segments were lowered one by one on top of each other, with each alignment to the previous block guided by the three aligning nuts. Once a block was placed three new rod segments were connected by the connecting nuts and thus three continuous steel rods were installed inside the distance block. The voids around the rods were filled with bentonite powder with a water content of 21%, corresponding to the water content of the blocks.

The rods were left inside the component after installation and were thus a deviation from the KBS-3H reference design. However, being made of stainless steel they are not expected to have any major implication for the relatively short term MPT.
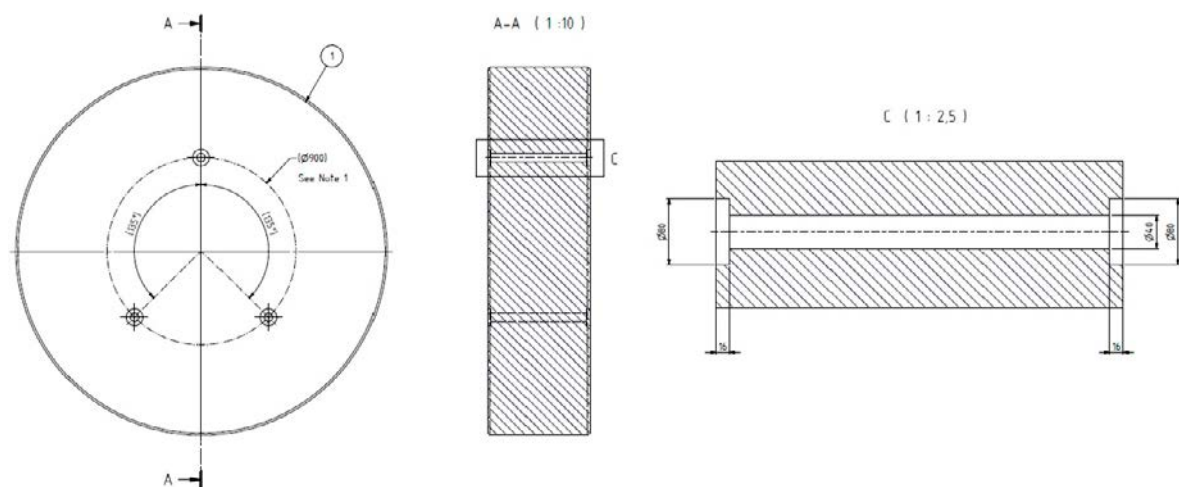
Figure 6-1. Top view of the distance block (left), side views (right).

6.1.2 Cable blocks

Since the distance blocks are installed inside the drift as fully assembled composite components (3.5–4.0 m long) the sensors have to be fitted inside the composite already in the assembly hall. This is the same also for the Supercontainer. In addition, all sensor cabling have to be kept within the component periphery since there is only a 42.5 mm annular gap between the component and the drift wall during installation. This is quite different from SKB's and Posiva's earlier experiences in KBS-3V, where sensors are installed once the blocks were placed in their final locations in a deposition hole.

In order to address this issue a hollow metal block was designed, later called a cable block. It is basically two metal plates with the same diameter as the distance blocks, 1 765 mm, with several supports between them but with a hollow space that allows for storage of cables during deposition, cf. Figure 6-2. It is 240 mm long and fitted with holes that allow it to be temporarily connected to the segmented rod system (Section 6.1.1), thus enabling a stiff connection to the components. Its bottom plate can be dismantled, allowing for access to the cables once in the drift, and it has wheels that allow it to be rolled out from the drift after the cables have been connected to the drift's piping system, see Section 5.2.5.

For the distance blocks the cable pipes were placed in small milled groves along the block surface and extending to the cable block, thus ensuring that everything was kept inside the component periphery.

For the Supercontainer the pipes were instead drawn inwards towards the canister and downwards in milled grooves on the inside of the bentonite rings, and finally out through a core drilled hole in the bottom Supercontainer block into the cable block.

Since the cable blocks are removed after component installation they do not impose a permanent change once installed. However, the components are somewhat "front heavy" since they are longer including the cable block. This affects the balance of the deposition machine, especially for the Supercontainer.
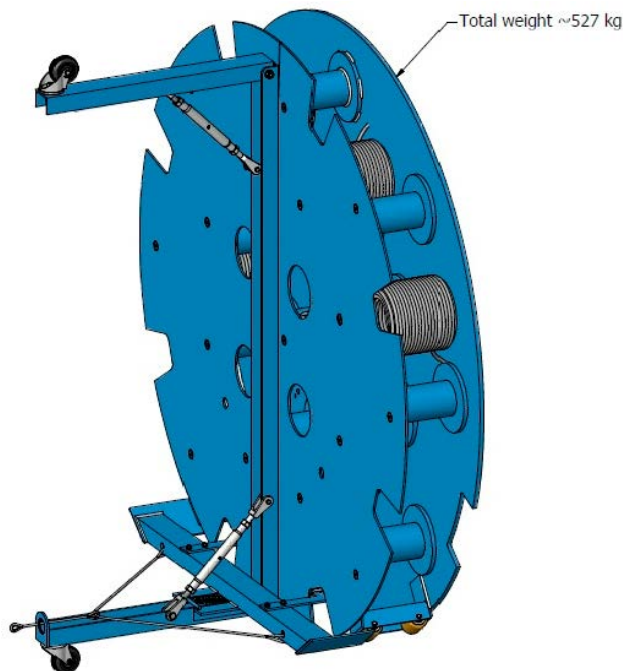
Figure 6-2. *Cable block developed for the MPT. The Supercontainer, distance- and transition blocks are assembled on the cable block and it allows for storing cables inside the component pheriphery during installation in the drift, cf. Figure 9-6. The wheel assembly seen to the left is connected once in the drift so that the cable block can be removed.*

6.1.3 Stacking plates

The Supercontainer is assembled on its heavy gamma gate, Figure 2-6. To allow for a fast installation all components were planned to be assembled and ready in storage above ground once the main MPT installation was initiated. For this reason, simpler plates, similar to large steel pallets were designed for the distance- and transition blocks. They were made with the hole profile corresponding to the transport tube such that they could be lifted. They also provide one side of the axial load securing when they are transported horizontally down to the test site. The plates are only used for handling, thus, this design change is mainly an operational and personal safety issue.

6.2 Assembly facility

The transport length, and thus transport time, should be short to minimise the effects on the components, both mechanical as well as those due to exposure to improper air humidity. Also, the assemblies are done vertically which requires a high building. Ideally the assembly facility should have a traverse crane for controlled lifts. In the case of the MPT a near-by facility with a traverse crane was not available and the facility previously used to assemble concrete Supercontainer dummies was used. The lack of a traverse crane implied that all hoists had to be done either with a wheel loader or a small crane.

6.3 Machines and equipment

6.3.1 Heavy transport vehicle

SKB has a heavy transport vehicle, 'MODE', intended for transports in an access ramp, which was used for transporting the components inside of the transport tube as seen in Figure 7-5. Securing of the load was done by designing some smaller fittings to connect between MODE and the cradle of the transport tube.

6.3.2 Mobile crane

A 160 ton mobile crane was used for lifting the components inside the transport tube.

6.3.3 Fork lift

A 25 ton fork lift was used to move the distance- and transition blocks out from the assembly facility.

6.3.4 Wheel loader and Maeda crane

For the lower lifts a wheel loader was used to e.g. move the vacuum tool and blocks while the higher lifts were done using a Maeda crane which was small enough to fit inside the assembly facility and has high enough strength and accuracy to manoeuvre the blocks into the Supercontainer, even with the limited head room available.

6.3.5 Transport containers

Airtight transport containers previously developed for the Prototype repository experiment were used for transporting blocks from the buffer manufacturing factory in Ystad, Sweden, to the machining factory in Finland and further on to Äspö HRL for storage and assembly.

There were not enough transport containers available to cover all the MPT blocks. However, rather than manufacturing additional containers they were complemented with wooden pallets and airtight plastic protection in storage. All transports were done with the containers.

6.3.6 Vacuum tools

A standard, vacuum tool with three circular suction segments that allowed for lifting of both rings and solid blocks was purchased and used during the assembly. In addition an older tool with multiple smaller vacuum cups was serving as backup.

6.4 Fitting feet to the blocks

The distance block feet were designed like a thin metal strap with two metal cylinders making up the standing area in each end, seen in Figure 7-4. A smaller drilling machine was attached to a fixture placed on each block segment to align the holes. When the drilling was completed the threads were cut by hand.

The feet were attached with two 150 mm long M-30 bolts. They were tightened with 50 Nm torque. A lashing strap was used to hold the feet tight to the block while the bolts were tightened.

6.5 Dimensional controls of the blocks during assembly

The blocks were machined in a factory in Finland (Johannesson 2014), during machining their dimensions were measured and with a few exceptions the requirements were fulfilled. The inner diameter of the rings was only slightly machined, in some instances parts of the mould lubricant remained on the inner surface; this was later removed using sandpaper during assembly. The reason for the inner diameter of the rings being large is that the blocks expand after compaction and the moulds inner diameter should ideally have been somewhat smaller to allow for greater margins, i.e. a few more millimetres to machine away. In order to get a second control, measurement were taken during the assembly. The axial height was measured at 0°, 90°, 180° and 270° and the diameter was measured at two positions, between 0°–180° and at 90°–270°. The dimensional measurements were taken with a slide caliper. Each block was also weighed by lifting.

The slide caliper accuracy can be questioned in relation to the ±1 mm requirement. This was not sorted out during the MPT work, but is something that needs to be improved for later buffer manufacturing. Laser scanning measurements or improved control at milling are possible options.

7 Pre-test of distance block

The KBS-3H project had prior to MPT never worked with full scale bentonite components, only concrete dummies had been assembled and tested in the drift. Early project risk assessments had identified this as one of the main uncertainties and a pre-test was incorporated early in the planning. All procedures were included in the pre-test; i.e buffer manufacturing, machining and handling, component assembly with dummy sensors, transportation and test transportation in the drift.

This chapter covers the pre-test. It presents details of the assembly, component handling, transportation and deposition. For details on material studies, mixing, block compaction and machining, cf. Johannesson (2014).

7.1 Lifting problems and solutions

The pre-test was initiated in February 2013, and it quickly proved that the original intention to protect the blocks with plastic foil while drilling and preparing them for assembly would be inadequate. The relative humidity (RH) and temperature was logged and due to the winter season, the RH was between 15–25 % at the time and the distance blocks started to develop surface cracks within an hour in conjunction with drilling. Some of the blocks also had cracks already when the transport containers were opened, indicating that the containers were not air tight. Although the surface cracks were quite small initially they were still too large and prevented the use of the vacuum hoist tools and therefore halted the work.

The delivered distance block had a water content of 21 %. In order to define at which RH to best handle the blocks a test was carried out. The corresponding powder from which the blocks were made was placed inside a plastic bag, and the RH was measured once equilibrated. The powder equilibrated at a RH of approximately 86 %.

In order to check that the cracking indeed was due to drying some rough but indicative tests were carried out by drilling sampling holes (producing axial and radial cores) in a cracked block. Subsequent determination of water content profiles indicated lower water content a couple of centimetres into the blocks, providing verification that the damage was due to drying.

Several actions were taken in order to address the cracking problems; all transport containers were fitted with new rubber seals, plastic bags with aluminium foil and more rigid wooden pallets were purchased (the MPT includes more blocks than there were transport containers available). Plastic bags the size of the full scale components were also purchased. However, the installation of an industrial humidifier in the assembly facility was the solution to the problem. It allowed for a controlled environment during assembly, i.e. a RH of 86 % in the air during the assembly of the distance blocks.

Introduction of a controlled environment simplified the work considerably, cracking ceased and blocks that had previously been cracked could be lifted after a while as their cracks began to self-heal, Figure 7-1.

Blocks that showed cracks with the magnitude presented in Figure 7-1 were not used in the pre-test since the 'self-healing' and closure of cracks is most likely only cosmetic and the block is indeed mechanically weakened. Such mechanical weakness may compromise the block integrity during deposition. However, due to limitations in number of blocks available, some blocks that had small surface cracks were used in the pre-test.

In order to have a backup solution if hoisting would remain problematic, a mechanical lifting tool was developed. It was designed to either make use of the three holes already drilled for the lengthwise rods (Section 6.1.1) or for three new holes to be drilled in case of Supercontainer rings. The only adaptation needed to the already available holes was that a small cone-shaped expansion had to be drilled inside each hole to allow for expansion of three grippers of the mechanical liftingtool. Correspondingly in case of the Supercontainer rings the cone shaped expansions would be made in each of the three lifting holes.

At this stage of development the implications of having a Supercontainer design with blocks of two different water contents, rings of 11 % and blocks of 17 %, was added to the risk list, see further details in Section 8.3.4.

Figure 7-1. *To the left, one of the worst drying cracks noted on the distance blocks, several centimetres long and in the order of 1 mm wide. To the right a picture of the same area once the block had been stored for some days in a RH corresponding to its equilibrium state, the closing of the crack is apparent.*

7.2 Assembly

Once the block cracking issue was under control the distance block preparations, i.e. drilling for lengthwise rods, dimensional measurements and installation of feet followed by the assembly was rather straight forward.

The cable block was placed on the stacking plate after which the bentonite block's were placed in position one by one, cf. Figure 7-2, with the lengthwise rods being connected stepwise.

Six dummy sensors were installed on two of the distance block segments. Three dummies were of dimension, Ø 55 mm and 23 mm high, similar to the total pressure cells to be used and three dummies were of dimension, Ø 12 mm and 87 mm long, similar to the water content sensors to be used.

Figure 7-2. *A Distance block segment being placed using a wheel loader and a vacuum tool in the controlled environment of the assembly facility. The distance block feet can be partially seen to the left on the stack of blocks.*

The milling for the sensors was done with tight tolerances and the sensors were squeezed in place. The friction between the sensors and the bentonite made the sensors stay in place. Bentonite powder with a water content corresponding to the blocks was pressed into remaining voids around the sensors.

The sensor pipes were milled into the top surface of the distance block segment, then gently bent over the edge and milled into the surface all the way down to the cable block where the final part of the pipe and the cable roll was placed.

After the assembly was completed the distance block was stored in the same controlled environment as it had been assembled. As an extra precaution a component size plastic bag was thread over it, awaiting its deposition.

7.3 Transports

The deposition test was initiated by removing the plastic protection and moving the test assembled distance block outside the assembly facility by means of a fork lift, cf. Figure 7-3.

The next step was to thread the transport tube over the test distance block, cf. Figure 7-4. This procedure was done by use of a mobile crane and had to be done very gently such that the tube did not hit the feet. Having a perfectly levelled ground proved extremely important, this was finally achieved by the use of gravel. However, for the actual MPT installation, a perfectly aligned steel surface will be prepared and levelled prior to the start of the work to make it more efficient.

Another issue was the alignment of the bolts between the transport tube and stacking plate. During the assembly the cable block had been centred on the stacking plate, this now proved to be an error in relation to the hole profile of the stacking plate and transport tube. It should have been placed off-centre to compensate for the feet. This issue was eventually sorted out by drilling new holes in the stacking plate, however, for the actual MPT, the cable block position will be adjusted in order to compensate for the hole profiles and feet.

Figure 7-3. *Test distance block being moved out from the assembly facility. The red arrow marks the cable block placed on the stacking plate.*

Once the transport tube was secured to the stacking plate it could be lifted by the mobile crane and placed in its transport cradle, cf. Figure 7-4.

When the transport tube was in place on its transport cradle, the heavy transport vehicle, MODE, was driven in underneath and the whole package secured to MODE, cf. Figure 7-5. In addition the test distance block was secured inside the transport tube by means of adjustable posts with wooden protection at the bentonite surface and beams locked to the transport tube. The beams which were part of the original equipment had never been tested before and did not fit as intended which caused further delay as new ones were manufactured, and made available for. For the actual MPT, the new once were thus available.

Figure 7-4. The transport tube is being lowered over the distance block (left). The feet placed on each distance block segment are clearly visible (red arrow) and two cable pipes milled into the block surface can be seen to the right of the component (blue arrow). The transport tube is being lowered on to its transport cradle (right).

Figure 7-5. Transport tube secured to MODE transport vehicle being ready for transport down to the deposition drift at −220 m.

7.4 Alignment of the deposition equipment

The transportation down to the −220 m level worked out as planned and the securing straps, posts, wooden supports and beams were removed after which the transport tube could be placed in front of the drift on its floor supports. The starting tube with the deposition machine, cf. Figure 7-6, was then moved into position behind the transport tube and placed on its floor supports. This procedure had been done many times before, and all the moves, and electric and mechanic connections worked properly. Figure 7-7 illustrates all equipment in position prior to deposition.

Figure 7-6. Starting tube with the deposition machine being moved into position by MODE.

Figure 7-7. Starting- and transport tube aligned in front of the drift, being ready for deposition. The test distance block is inside the transport tube with only the bottom of the cable block visible.

7.5 Test deposition

Concrete dummy distance blocks had been successfully deposited earlier (Ojala and Von Numers 2015), so machine control issues mainly involved a verification of previously developed functionality. The main issue of interest was thus the stability and durability of the bentonite components and whether the dummy sensors and pipes would remain in place. The effect of splashing from the deposition machine's water cushion system on a bentonite component was also a major question. Mechanical design changes in order to avoid accidental water splashing had been suggested but not implemented during the MPT due to other more prioritised upgrades.

The test deposition cycles worked as intended. Figure 7-8 illustrates the distance block passing in to the drift. Minor deformation was noted on the feet but they showed no signs of coming loose and the bentonite around the feet looked sound, both during the work and when a foot was removed and inspected afterwards.

A few small flakes of bentonite were found on the drift floor but are assumed to be from the milled out slots for the sensor pipes.

Splashing wetted the block on both sides of the lifting pallet, but no immediate damage was noted when visually inspected.

Overall, the test distance blocks integrity was not compromised during the test even though it was kept in the drift for approximately a week. For further details, cf. Ojala and Von Numers (2015).

After test deposition the procedure for removing the cable block when inside the drift was also tested and was verified to work as intended.

Once all steps had been tested the test distance block was moved into the transport tube and the procedures reversed, leaving the test distance block inside the assembly facility. Figure 7-9 shows the block in the assembly facility after the test. The effects of splashing are quite evident and the bottom block is starting to fall apart severely at this stage. For the MPT this was not deemed critical, however, the splashing issue need to be resolved in future development work to avoid the blocks being sprayed with water during deposition. In a worst case, pieces could fall lose inside the drift with risk for clogging the water drainage underneath the components with the added risk that larger bentonite pieces could fall onto the air evacuation pipe with possible ensuing problems associated with pipe removal.

Figure 7-8. Distance block driven in to the drift from the transport tube. The tight fit between the component and drift wall when it is lifted can be seen in the top part of the picture.

Figure 7-9. *Test distance block back in the assembly facility, the effects of splashing is evident.*

7.6　Experiences for the MPT installation

Having tested all the procedures from bentonite powder to an instrumented distance block, placed inside the deposition drift at the −220 m level proved crucial for the actual MPT installation. Several issues were identified that could have compromised the actual MPT installation. The major issue identified being the insufficiency in using plastic protection during assembly, i.e. the absolute need for a controlled environment inside the assembly facility to avoid development of cracks in the blocks. Other aspects, like the cable blocks being stacked off centre from the centre line on the stacking plates and use of improper beams would also have slowed down the installation considerably.

The mechanical tool for lifting will also prove valuable when some of the actual MPT blocks had small surface cracks already when taken out of their transport containers.

Having actual time estimates for all steps also allowed for a detailed scheduling of the MPT installation. It was concluded that a fully instrumented component can be moved from the assembly facility to its final location in the drift during one day with the night available for connecting sensors. The same should be valid for the Supercontainer; however, its extensive numbers of sensors have to be taken into account when setting the schedule.

8 MPT component assembly

This chapter describes the assembly of the MPT components; the Supercontainer, two distance blocks and one transition block. Key experiences from the pre-test, cf. Chapter 7, were implemented and the assembly work was carried out in a similar manner for the three block components. For the most part the Supercontainer assembly follows the same outline with the introduction of the Super-container shell and canister being the main differences. All work was carried out in the assembly facility with a controlled environment employed.

8.1 Preparation of blocks

The distance- and transition block segments were all prepared for insertion of axial rods as described in Section 6.1.1. Their dimensions were measured as described in Section 6.5 and holes for the feet were prepared as described in Section 6.4. However, in order to fit inside the transport containers the feet could not be fitted already at this stage. The feet were instead fitted later, once the full composite component had been assembled. For details on the block dimensions and weights, as built, cf. Section 9.14.

8.2 Distance- and transition block assembly

In the basic MPT design, cf. Figure 1-3, the distance blocks are each 3 m long and the transition block is 4.5 m long. There is also the 0.5 m filling component which is shaped as the drift end. For practical reasons the inner distance block was assembled together with the innermost filling component, with a total length of approximately 3.5 m. The outer distance block and the transition block, totalling 7.5 m, were divided in one 3.5 m long and one 4 m long composite segments, i.e. one segment of the transition block is assembled together with the outer distance block. This is a step away from the reference design, however, all segments are made up of the same material and quality and the order in which they are installed will not affect the outcome of the test. It should also be noted that there are ongoing discussions as to whether the segments should be installed in metre long segments with a fork lift type machine rather than with the deposition machine, see Section 11.1 for further details. Figure 8-1 illustrates the three composite components with their sensor sections. For corresponding sensor sections when installed in the drift, see Figure 2-5.

Figure 8-1. *The MPT block components; to the left the inner distance block including the inner filling component, in the middle the outer distance block together with one segment from the transition block and to the right the remaining transition block segments making up the final component.*

The assembly was carried out as described in Section 7.2, in this case with the cable blocks stacked off centre from the centre line to allow for proper connection between the stacking plates and the transport tube.

Once a segment that should be instrumented had been stacked, a template corresponding to that specific section was placed on the block and the sensor positions marked. Holes of various dimensions were drilled for circular sensors, cf. Figure 8-2, and milled to host square sensors and transmitters. Channels were milled for the corresponding cable pipes. Figure 8-3 illustrates the sensors once placed and Figure 8-4 visualises the component from the side with the pipes milled into its surface and down to the cable block.

Figure 8-2. Drilling for placing sensors in section 7, one of the wireless transmitters and its sensors has already been placed, to the right.

Figure 8-3. Sensors in place and ready for filling of bentonite powder around and on top of them. The hole in the upper part of the picture is one of the holes for the segmented lengthwise rods.

Figure 8-4. Lower part of one of the composite components, with the cable piping milled into and running along its periphery to the cable block. The pipes and cable rolls were later secured inside the cable block.

When the composite components were assembled they were each protected by a large plastic bag.

The assembly overall worked out as intended, but a few blocks showing surface cracks had to be used while there were limitations in the number of blocks available, some of which were lifted with the mechanical tool due to problems in applying the vacuum hoist tool. In one case the surface cracks led to a bigger problem, the top block on the transition block composite component was placed but it started to develop fractures quite rapidly, eventually so bad that the work area around it had to be closed off due to the risk of pieces coming loose and falling 4 metres to the floor down below. The block had to be removed and replaced by a new block. Although the block that failed did not look visually worse than some of the other blocks used it was still deemed probable that its failure was due to cracks developed due to drying during storage. The replacement block worked fine, as did the top blocks of the other two composite components.

8.3 Supercontainer assembly

Two concrete dummy Supercontainers have previously been assembled in the same assembly facility and the old foundation and support structure was still available. The earlier assemblies were done by first placing the bottom plate, then the bottom block followed by the canister after which the concrete blocks were threaded around the canister. Once all blocks were in place the carbon steel Supercontainer shell was threaded around the blocks. One of the experiences from these assemblies was that the bottom plate could not be properly welded to the shell due to the gamma gate blocking access and a suggestion for improving the procedure was to lower blocks provided with chamfers into the shell instead. In addition, for the MPT, the buffer vacuum tools would not allow the blocks to be treaded around the canister. The improved strategy was implemented in the MPT.

Figure 8-5 illustrates the assembly sequence for the Supercontainer including its four instrumented sections. The carbon steel shell previously used in one of the concrete dummies was reused for the MPT. The shell was stiffened by welding 10 reinforcing plates around it.
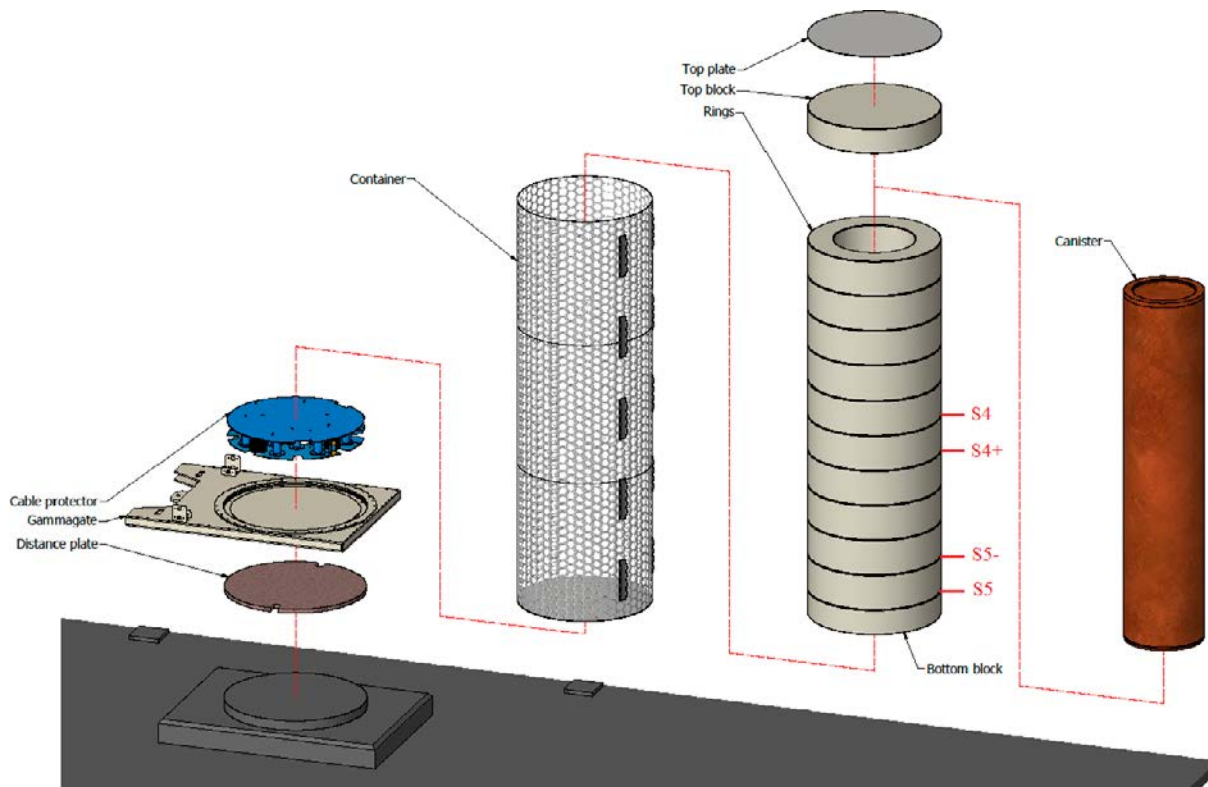
Figure 8-5. *Assembly sequence for the Supercontainer with its four instrumented sections marked.*

8.3.1 Bottom block, rings and sensors

All block dimensions were measured as described in Section 6.5. For details on the block dimensions and weights (as built) cf. Section 9.14. Table 2-1 and Figure 2-5 lists and illustrates which sensors are placed in which sections, for drawings and further details, cf. Pintado et al. (2016).

The bottom block was prepared by drilling sensor holes and two 76 mm diagonal holes that allowed for cable pipes to be drawn from the interior, close to the canister, and out to the cable block. These holes in effect short-circuit the possibility to lift the block with the vacuum tool and consequently three extra holes were drilled to allow for hoisting using the mechanical lifting tool. The block was then lowered into the shell. This procedure worked out satisfactorily although the block touched the shell almost all the way down. However; thanks to a small angle milled on to the block edges the shell didn't cut into the block and it held together with only one small piece falling off, which could later be placed once the block was in its final position. Hitting the shell as much as in this case is not acceptable, however, much of the problem is deemed to be caused by having to use a small mobile crane standing on the side of the Supercontainer rather than an ordinary overhang crane which provides much better control. In addition, a new shell would be straighter than a reused one.

Once the block was in place the sensors were installed in a similar manner as for the distance blocks, cf. Figure 8-6, but in this case bentonite powder with a water content of 17 %, corresponding to the block, was used to fill around them.

The rings were then lowered one by one and sensors installed to their respective blocks, in this case with bentonite powder with 11 % water content, corresponding to the rings water content. The cable pipes were milled into and drawn along the inside of the rings, as seen in Figure 8-7. Once nine rings were placed, the distance between that ring and the top of the shell was measured. The height of the 10th ring was then machined tailored before it was placed to ensure a correct total height of the buffer blocks inside the shell.

Figure 8-6. *The bottom block inside the Supercontainer with all cabling through diagonal holes and into the cable block. For the Supercontainer the wireless transmitter that can be seen to the left had an antenna extending outside of the shell to avoid any Faraday's cage effects.*
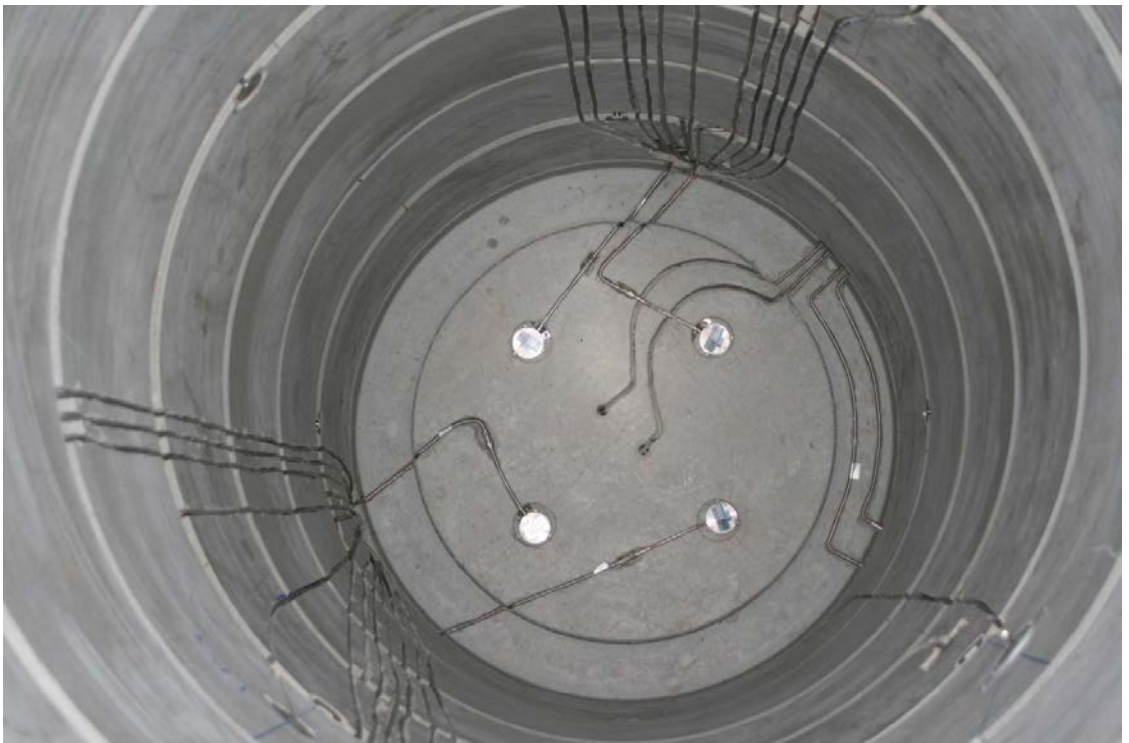
Figure 8-7. *Interior of bentonite rings inside the Supercontainer shell with sensors placed and associated cable pipes.*

In addition to the sensors, 12 metal coupons were installed between buffer rings inside the Super-container: two of each Cu-OFE, Cu-ETP, carbon steel S235, carbon steel S355, titanium grade 3 and stainless steel AISI 316 were installed. One additional sample of each type was stored as a reference sample. All coupons were well characterized (weight and dimensions), and would allow for material studies after dismantling, although it would be necessary to make a more in depth assessment of how the MPT conditions (electrical currents and no heat etc.) might affect them.

8.3.2 Canister

One of the canisters previously used in the concrete dummies was re-used for the MPT. Given that the MPT, which is non-heated, has no specific objectives in relation to the canister it was simply cleaned and scanned to define its basic outer 3D outline. Copper corrosion is extensively studied within KBS-3V and it is deemed that this phenomenon is much better studied in test setups devoid of cables and electric currents or in a controlled laboratory environment rather than in this type of in situ test setup.

Figure 8-8 illustrates the lowering of the canister into the Supercontainer by use of a mobile crane. The canister was installed as planned.

8.3.3 Top block and top plate

The top block is machined to fit the canister's flange, i.e. it has a flat surface with an elevated centre machined onto it. This block is thus the only block which has to be turned upside down before placing it inside the Supercontainer. A strategy for turning it by placing it between two stacking plates and roll over the whole package gently on the floor was used. This attempt failed and the block cracked into three large pieces. In order not to delay the MPT installation it was decided to use and place the three broken pieces by use of the mechanical tool rather than waiting for a new block to be machined in Finland. Figure 8-9 illustrates the three block pieces when in place inside the Supercontainer. This procedure clearly needs improvement; first of all, the block cannot lean on its elevated centre so it has

Figure 8-8. Canister being lowered into the Supercontainer. The stiffening plates for straightening the shell can be seen on its outer periphery.

to be placed in a specially designed transport container where the block's weight is evenly distributed on its entire surface. In the case of the MPT, wooden distances were used, these were probably not even enough and the block broke by its own weight. Secondly, the rolling over of the block can probably be done much gentler by designing and using a rotating cradle which locks the block around its periphery by metal straps. It can be noted that such a turning device would also be needed if it is found necessary to machine the bottom side of every blocks in order to fully meet requirements.

Because of the adaptation of the last ring the height of the buffer inside the shell allowed the top plate to be placed and welded as intended. This procedure is also part of the KBS-3H reference design and solutions for a quick measurement and machining of a block will have to be developed for a future assembly facility.

8.3.4 Controlled environment and water content of the blocks in the Supercontainer

The Supercontainer has been designed with blocks of two different water contents; solid blocks with $11 \pm 1\%$ and rings with $17 \pm 1\%$. This means that the RH in the air in the assembly facility cannot be optimised for both block types, which equilibrates at approximately RH 50 % and 86 %, respectively. In the case of the MPT a RH in between the two stated equilibrium was selected, which worked out reasonably well, although some flaking was noted on the rings. This is an obvious design problem, which can only be addressed by harmonising the water contents in the solid blocks and rings. The KBS-3H project will add this design aspect into the current project phase.

Figure 8-9. *Top block placed inside the Supercontainer. The three pieces could be lifted individually by the mechanical lifting tool and positioned with tight fit, like a jigsaw puzzle. Machining of the height of the final ring ensured a total buffer height corresponding well with the height of the shell.*

9 MPT Installation

This chapter presents the installation of the MPT. It covers all aspects of the installation starting with the pilot hole filling and ending with test start and initiation of the DAWE procedure. At start of installation, all components were assembled and ready for installation, for assembly details cf. Chapter 8. For more in depth description and data on the deposition machine's functionality during the MPT installation, cf. Ojala and Von Numers (2015).

9.1 Installation schedule

For KBS-3H, an efficient installation is a key part of the design. A preliminary assessment is that the components and the plug that make up a compartment have to be installed within 10 days to ensure that the buffer remains intact when the DAWE procedure is initiated.

With the MPT being strongly focused on the handling and installation of the full scale components it was decided to carry out the installation as fast as possible. At the same time, the test involve in the order of 200 sensors that need to be taken into account. Figure 9-1 presents the as built schedule. It is one day longer than planned at onset, mainly due to the pulling and connecting of cables taking longer time than expected. Originally the schedule had some slack during cable pulling and the data acquisition system (DAS) connection; however, this time was eventually needed in order to keep to the schedule.

Activity	November																	December						
	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	1	2	3	4	5	6	7
Filling components pilot holes	▓																							
Inner distance block and cables	▓																							
Supercontainer and cables		▓	▓	▓																				
Outer distance block and cables					▓																			
Transition block						▓																		
Cables and sensors on last block								▓	▓															
Plug and cables									▓	▓	▓	▓	▓	▓	▓									
Pellets filling																▓								
Connecting the DAS																		▓	▓	▓	▓	▓		
Contact grouting plug																							▓	
DAWE																								▓

Figure 9-1. *The MPT installation schedule, basically one bentonite component per day, with connection of cables during the nights and with the Supercontainer installation requiring three days due to its many sensors. A week required for installing the plug with cables and a week for connecting the DAS.*

9.2 Air evacuation pipe

During one of the final test runs with the deposition machine prior to the MPT installation, a dummy air evacuation pipe was fitted in its planned location down to the left on the drift wall and the machine driven up against it. This test identified that the machine shield actually would hit the pipe, followed by parts of the machine also hitting it. In order to solve this problem, a cutout was sawed into the shield so that it would pass the pipe. The next part of the machine that hit the pipe could however not be removed without major mechanical changes. For this reason the segmented pipe was introduced and mounted piece by piece during the MPT installation, instead of the full pipe length in one step as in the reference design. This allowed deposition work to be carried out as intended without hitting the pipe.

At the drift end the pipe leading up to the highest point, Figure 1-4, of the drift was fitted as planned and its valve connected to the segmented main pipe going out. The valve is in place to ensure that water cannot flow backwards through the pipe during pipe removal.

If a second generation deposition machine was to be developed, design work would have to take into account the air evacuation pipe. For the current deposition machine the mechanical changes would be unjustified so if it is to be used for another full-scale demonstration this issue would have to be resolved in a manner similar to that employed in the MPT, with segmented pipes, installed piece by piece.

9.3 Pilot hole

Bentonite cores with diameters corresponding to the remainder of the main pilot hole (270 mm) and the 76 mm characterisation hole, had been drilled from a distance block, i.e. water content 21 %. The pilot hole filling pieces were cut in lengths so that when all were placed their outer surface corresponded to the remaining front at the end of the drift front level. The pieces were introduced manually, cf. Figure 9-2. For details on dimensions and weights, cf. Section 9.14.

Figure 9-2. *Bentonite filling components placed in the remainder of the main pilot hole, centre of picture, and in the 76 mm characterisation hole seen at the bottom of the picture. Also seen are three of the drift front total pressure sensor with their piping sawed into the rock and by their side a small distance placed to ensure that the first distance block would not crush them.*

9.4 Inner Distance block

Installation of the inner distance block was started by a final inspection of the component at the assembly facility, cf. Figure 9-3. It was ensured that the pipes and cables were satisfactorily secured inside the cable block and on the component periphery, thin straps where placed where needed. The torque on the feet bolts was checked and the bentonite was checked for surface cracks. After inspection the component was cleared for installation. For details on dimensions and weights cf. Section 9.14.

The transport and alignment of the deposition equipment was carried out in the same way as described in Sections 7.3 through 7.4. Once the distance block was in place outside the drift, a final inspection of the drift was carried out to ensure that nothing was left inside or that anything protruded inside the drift periphery.

The deposition was then initiated by use of the automated deposition sequence. The automatic sequence worked well all the way until the final lift. For the last lift the component needs to be extended over the lifting pallet of the machine in order to reach the drift end wall by the end of the stroke. Due to the large overhang in the front the lifting was slow causing dragging of the distance block feet against the drift bottom.

The friction between the feet and the drift required additional pushing force and the increase in actuator current was so large that the control system incorrectly assumed that the component had reached contact with the drift end wall. The last deposition stroke was therefore ended too early and had to be extended manually.

When carried out manually, a loud thump echoed in the drift as the component made contact with the drift end. The deposition machine was then reversed to the entrance of the drift.

Figure 9-3. *Final inspection of the component prior to installation.*

Cable work was initiated by the nightshift, cf. Figure 9-4. It worked basically as intended, however, if similar installations are to be carried out again there are some optimisations that can be recommended;

- A larger sawed out notch in the position where the connections were made, Figure 5-9, would have simplified the looping of pipes which is needed, also moving the main connection pipes, cf. Figure 5-9, further back towards the plug would have simplified access and looping of pipes.

- The main pipes in the rock wall were prepared with mainly 6 mm pipes and a few ¼" and 8 mm pipes. Ideally they should all have been of a large diameter, in the order of 8 mm, as it was the pulling of cables through the pipe system that required much longer time than planned. The cables introducing problems were minutely larger than the manufacturer had specified, but in the long pipes and tubes this still proved to be a big problem. Some of the cables showed such tight fit that a few of the pulling strings broke, however, several spare pipes were available and used. In a few cases the plastic protection on the cable had to be peeled off. It should not affect the sensor function, but was very time-consuming. An 8 mm pipe would be stiffer; however, if a smaller pipe (1/4" as in the MPT) would be used on the bentonite component (with the cable pulled in the factory) an expanding connector could then be used to connect it to a larger (8 mm) pipe on the 'hedgehog'. This would imply larger tecalan tubes inside the main wall pipes and the cable storage inside the drift would also have to be increased in size.

- A system for marking the cables with colour codes would have been preferable in order to avoid the tags that were used in the MPT. They could be removed in one end and placed back onto the cable in the other end without problem, however, at a later stage when taken through the plug they were already somewhat loose and unfortunately a few were lost at that stage. Most of them could later be traced and identified based on their main pipe, but that took a lot of time and a handful also remained uncertain.

Once all cables had been pulled and placed back in the cable storage, Figure 5-10, the cable block was rolled out of the drift.

When the cable block was removed a large crack was noted on the distance block, c.f Figure 9-5. Its origin is not fully understood. It was located on the bottom surface of the block which is the under most block during assembly 4 and during the final inspection prior to installation. There were no notes taken that it was present at that stage. Being so large and extending all the way to the periphery it should have been noted but it cannot be excluded that there might have existed a smaller crack underneath the block during assembly that had not developed fully all the way to the block periphery. For details on the various issues faced with surface cracking during the pre-test, see Section 7.1.

Figure 9-4. One of the sides of the inner distance blocks with all cables connected and the cable block removed.

Figure 9-5. Crack on the inner distance block which was noted when the cable block was removed.

The block evidently endured the stepwise lifting and lowering during the deposition sequence in the order of 60 times so the crack could not be all that deep. If it was very deep, pieces of the block would have come loose. The integrity of the distance blocks is of highest importance and if such a large piece had come loose it could have caused a jamming of the machine.

This type of cracking was not experienced for the second distance block nor for the transition block. However, it is something that has to be avoided in the KBS-3H design. Future studies, with more extensive test series will have to verify that the distance blocks maintain their integrity during deposition. An option could be to develop a transport vehicle for distance blocks without water cushions, more like a fork lift, see Section 11.1.

9.5 Supercontainer

Installation of the Supercontainer was commenced with a final inspection at the assembly facility. It was ensured that all pipes and cables were safely secured inside the cable block. After inspection the Supercontainer was cleared for installation. For details on buffer dimensions and weights, cf. Section 9.14.

The transport and alignment of the deposition equipment was carried out in the same way as described in Sections 7.3 through 7.4 with the main difference being that the Supercontainer could not be moved by the heavy truck. Instead it was lifted out through the roof of the assembly facility using a mobile crane.

Once the Supercontainer was in place outside the drift, a final inspection was again carried out to ensure that nothing was left inside the drift or that any object protruded inside the drift periphery.

The deposition was then initiated using the automated deposition sequence. It worked well all the way to the final stage, at which the sensors did not identify the distance block in front of it. A manual override had to be carried out. Full cushion pressure also had to be applied and longer lifting time allowed on the deposition machine since the Supercontainer was front heavy due to the added length of the cable block. With the use of manual control a smooth contact was established with the distance block in front of the Supercontainer.

Figure 9-6 shows the cable block in the situation when its bottom plates have been removed. Pulling the cables of the Supercontainer lasted a weekend with similar issues as described for the inner distance block in Section 9.4.

Figure 9-7 shows the Supercontainer once the cable block had been removed and all cables pulled.

Figure 9-6. Pulling of cables from the Supercontainer to the main piping in the drift walls and to the cable storage, cf. Figure 5-10.

Figure 9-7. Supercontainer positioned in the drift with all its cables pulled. The tight fit between the Supercontainer and drift wall is clearly visible. A small paper has been placed down to the left of the Supercontainer to ensure that the deposition machine will detect the Supercontanier during deposition of the next component.

9.6 Outer Distance block

Installation of the composite outer distance block followed the same procedure as for the inner one, cf. Section 9.4. It was also cleared for deposition immediately prior to starting the installation work. For details on dimensions and weights cf. Section 9.14.

In this case the automated deposition sequence of the deposition machine worked as intended and the component was deposited automatically establishing good contact with the Supercontainer.

Figure 9-8 shows the outer distance block once the cable block had been removed and all cables pulled.

9.7 Transition block

Installation of the composite transition block followed the same procedure as for the inner and outer composite distance blocks, Section 9.4 and 9.6. It was also cleared for deposition prior to starting the work. For details on dimensions and weights view Section 9.14.

The length of the composite transition block did not match the pairwise coupling of the deposition machine's cushions and therefore either one cushion row too many or one too few had to be deactivated. This resulted in longitudinal balancing problems with the front end lifting either too much or too little. Especially activating cushions outside the load twisted the free part of the lifting pallet strongly to either side causing excessive balancing problems.

After manual selection of cushions an automatic deposition sequence could be used and the deposition machine's control system balanced the weight.

This time the machine did not detect the previous component in the drift and could therefore not carry out the end sequence for driving the components into good contact. The machine was stopped, reversed somewhat and restarted to activate the automatic end sequence. A good contact was this way established between the composite transition block and the outer distance block.

For future development the cushion problem can be eliminated by removing the coupling between cushions and using independent cushion control instead.

Figure 9-9 shows the outer distance block once the cable block had been removed and all cables pulled.

Figure 9-8. Outer distance block deposited.

Figure 9-9. *Transition block deposited and protected by plastic film awaiting installation of the plug. Note that the cable storages (left and right flanking walls) are now filled with all the cables from the various components.*

9.7.1 Tight deposition results

An increase in the machine's axial pushing power was measured in the final stage of deposition for all the components, indicating good mutual contact. This was further verified by comparing the total length of the components, known by measurement of the transition block's position and knowing the drift end position. This value could then be compared to the added extent of the 4 components as measured in the assembly facility. A deviation of 4 mm was established which was deemed to be within the measurement tolerances. Hence, it was concluded that tight deposition of components is possible with the current equipment.

9.8 Plug installation

9.8.1 Collar installation

With the fastening ring already cast in place, cf. Section 5.1.2, plug installation is simply a welding activity. Work was started by removing the concrete bridge for the deposition machine in the lower part of the fastening ring. The surfaces of fastening ring were subsequently cleaned while the plug cap and four collar segments were pulled into the drift using a small hand-tuck. The cap was placed upstream the position of the plug, leaning on its sensor protecting steel structure, cf. Section 5.1.3.

The collar segments were placed starting with the lower and ending with the smallest top segment, cf. Figure 9-10. The segments were welded to the fastening ring, and the welds inspected by an inspection company and approved accordingly. This inspection was however proved wrong at a later stage when during filling the pellets dust was seen coming out of a pore in the weld. The leaky points were identified to be the contact surfaces between segments. This is an area which is both difficult to weld and to inspect. The difficulties had been identified already when building a plug back in 2009–2010, (SKB 2012). However, that plug eventually turned out to be water-tight, and a future automated welding procedure was expected to solve the issue. The MPT design was thus the same as that previously employed and again, it was manually welded.

Figure 9-10. Three of the collar segments placed with only the fourth smaller top segment remaining. The plug cap, leaning on its steel support can be seen between the collar and the transition block.

This reoccurring issue will now be tackled by a redesign of the plug to allow for both easier welding and inspection. Another issue noted during the MPT will be addressed at the same time, namely the fact that water starts to collect inside the collar once it is welded in place. If the flows are high, water could potentially reach the transition block prior to pellets filling, which is to be avoided. A drainage pipe will be included in the new collar design.

In the case of the MPT, the welding company was re-commissioned after pellets filling to re-weld the leaky points from the outside the plug. Welding from the "wrong side", once the cap is installed, is even more difficult, and the leakage problems would eventually reoccur during the DAWE proce- dure, cf. Section 9.12.

9.8.2   Cable lead-troughs and piping

The collar was designed with six lead-troughs on each side. Twelve flexible steel pipes were connected between the collar and the main pipe systems on the drift wall, cf. Figure 9-11. Cables and tecalan tubing was drawn inside the flexible steel pipes. In a second step, the cables were also drawing through flexible steel pipes on the outside of the plug as well.

As mentioned in Section 9.4, a couple of the sensor labels came loose at this stage. Losing labels is a major issue, basically, if several of the same type come loose, it will be unclear where those sensors are actually located in the test. As mentioned previously, almost all sensors which had lost their labels could be clarified by knowing which main pipe corresponded to which bentonite component.

Another issue that was faced was that an early error in the design calculation implied that there were a few pipes from the packer system in sensor section 9 that would not have a lead-through. However, this was resolved by placing an extra main pipe connector at this stage. This solution was possible since one of the main pipes from the Supercontainer had been purposely left idle (more lead-troughs had been prepared than was actually needed at the Supercontainer position).

Once all cables had been pulled, the water filling and air evacuation pipe was drawn through and connected to the plug. The air evacuation pipe extending all the way to the highest point in the drift, Figure 1-4, while the water filling pipes pass just underneath the transition block, i.e. just beyond the pellets filling section.

Figure 9-11. *The flexible pipes between the collar and the main wall pipes can be seen attached on the drift wall between the collar and the transition block.*

9.8.3 Cap installation

The final step of the plug installation is the raising and welding of the cap. It was raised using chain pulleys and the procedure worked as intended, cf. Figure 9-12. If similar work is done again it would be preferable if the plug sensor lead-troughs through the cap were placed higher up on the cap. As it was, they now ended up in the lower half and were unnecessarily close to being bent while the cap was being raised.

When the cap was in position it was secured and welded. The welds were inspected by an inspection company and approved.

Figure 9-12. *Raising of the cap by use of chain pulleys.*

9.9 Pellets filling

A pellets filling was done during the plug installation in 2009–2010 (SKB 2012), but that was a 15 m long drift. In the MPT case, the plug is located around 75 m inside the drift. The pellets blower which is a standard dry shotcrete equipment was placed immediately outside the drift and the company blowing the pellets had earlier tested an 80 m long hose to estimate the required airflow. In order to avoid dust along the entire drift and for acceptable working conditions, air and dust had to be sucked out at the same rate as air was blown in, done with a T-connector at the pellets filling hole in the plug. To achieve adequate suction at almost 100 m distance a high pressure sewage truck was used. Figure 9-13 illustrates the setup of equipment and Figure 9-14 illustrates how the T-connection with it's in and outlet was connected to the pellets filling hole of the plug. The equipment setup worked as intended without dust being an issue and as presented in Section 9.8, a accidental pore in the weld was actually identified by dust that escaped through it.

During the pellets filling, samples were taken from each pellets big-bag and an endoscope camera was used to check inside the plug so that the filling was proceeding as intended. Work was stopped when the camera confirmed that the entire void behind the plug was filled. A final filling of the top cavity was done manually in conjunction with mounting of the closing flange. For details on the total weight of pellets installed, cf. Section 9.14.

Figure 9-13. *Pellets blower (red arrow) placed immediately outside the drift with pellets being filled. In the background, to the left, is the sewage truck used to suck out air and dust from the compartment.*

Figure 9-14. *T-connector connected to the pellets filling hole in the plug.*

9.10 Connecting and initiating the sensors and Data Acquisition System (DAS)

Each cable was designed to come out through the plug collar inside a tecalan tube. Outside the plug, the cables could basically have been directly connected to the cabinets. However, in order to allow for sealing of possible leakages through the pipes, 'hedgehog' connectors were placed on the outside of the plug as well, cf. Figure 9-15. This means that if a leakage was to occur through a pipe, the connection between the tecalan tube and the 'hedgehog' could be disconnected and that pipe in the 'hedgehog' glued tight around its cable, possibly allowing for continued function of the sensor as opposed to just cutting the cable and sealing the tecalan tube.

The DAS computer was installed inside a control container outside the drift with a few main Ethernet cables going in to the plug location where the connection cabinets with data logging units were installed on the drift walls, cf. Figure 9-16. Most of the cables were connected to the cabinets as planned but some cables had to be extended to reach the cabinets, which for practical reasons had to be placed further away than originally planned. This should not affect the data collection; however, it took quite a long time to resolve and should be avoided if a similar system is used again. The methodology with the cable blocks, Section 6.1.2, which is now tested in situ actually allows for quite large cable bundles, so a couple of extra metres of cable should not be a problem.

The packers in sensor section 9, c.f Section 5.2.4, were pressurised and the sections de-aired before connecting them to the pressure panels. The leakage weir of the plug, strain gauges and LVDT- sensors were installed and connected and the rock pore pressure sensors purged from air before connection.

All sensors were subsequently inspected and checked according to a Site Acceptance Test (SAT) procedure. Data collection was initiated on December 4th, 2013.

The KBS-3H installation procedure only allows for geodetic surveying of the rock sensors in the drift, while the final location of the bentonite sensors which are installed in the assembly facility cannot be surveyed once installed in the drift. Instead the Supercontainer and distance/transition block positions in the drift together with the drawings were used to attribute each sensor with its respective as built (x,y,z)-coordinates. For further details on the sensor configuration, cf. Pintado et al. (2016)

Figure 9-15. Flexible piping and outer 'hedgehogs' with the cabling inside. The picture was taken during the DAWE procedure.

Figure 9-16. Connection cabinets placed on the drift wall immediately outside the plug.

9.11　Contact grouting with silica sol

Contact grouting tubes were placed during the fastening ring installation, cf. Section 5.1.2. Two tubes were installed at the interfaces rock-casting and casting-steel, respectively. Similar to the pellets blowing activity this had previously been carried out for a plug in 2009–2010, but again, at a limited depth in the drift of 15 m compared with the approximate 75 m in case of the MPT.

In order to avoid large batches of silica sol being pumped from outside the drift (> 75 m), small pressure vessels were moved into the drift and used for the contact grouting. A small mixer was used for mixing and nitrogen gas was used for pressurising.

A contact grouting strategy starting with water loss measurements was implemented. Water was pumped in from the pressure vessels at 5 bars. The established flow rates were 1.0 L/min for the rock-casting interface and 1.4 L/min for the casting-steel interface, respectively. For these flow rates the design stipulated a 36 min curing time and a minimum batch size of 40 litres of silica sol for these water loss measurement results.

Contact grouting was eventually carried out simultaneously for both grouting tubes and for 45 min at 5 bars. A total volume of 1.6 litres of silica sol was injected at the casting-steel interface and 7.0 litres at the rock-casting interface, cf. Figure 9-17. The grouting at the casting-steel interface worked as intended, attaining close to full gelling at 45 min. However, the mixing had not worked properly in the rock-casting vessel and the silica sol did not gel as intended, although, the grout take slowed down to a full stop during the 45 min. Visual inspection of the plug during grouting indicated some minor flows of silica sol coming out at 9 o'clock and at 4 o'clock, indicating that the contact grouting was working as intended with grout filling up leakage points around the periphery of the plug.

Figure 9-17. Contact grouting in the blue tubes, corresponding to the casting-steel interface. The silica sol seen down to the right is from flushing prior to starting the grouting. The silica sol leaking out at 9 and 4 o'clock was much less.

The overall function of the contact grouting will be assessed as the test is monitored and possible leakages measured. It should however be noted that during the DAWE procedure, cf. Section 9.12, when a slight water overpressure was applied to the sealed MPT-section, no leakages were noted at the interfaces. These observations suggest a successful contact grouting.

As mentioned in Section 5.1.2, a future optimisation would be to integrate the grouting tube with the metal structure for contact grouting at the casting-metal interface, thereby possibly avoiding the technically difficult positioning and checking of the grouting tube.

Irrespective of whether contact grouting is carried out with a pump or with a pressure vessel, the equipment should be customized to ensure easy transport into the drift.It should also be equipped for automated mixing of the grout. A second option would be pumping from outside the drift; however, with distances in the order 150 m, as in the KBS-3H reference design, long hoses and unnecessary large volumes of grout would be needed.

9.12 Water filling of the MPT

The water filling and air evacuation of the MPT was carried out on the 7th of December 2013 with data logging in process since the 4th of December. Hoses were connected to the three water filling pipes as seen in Figure 9-15, fresh water, which corresponds to the KBS-3H reference design, from the fire-extinguishing system was used, and the flowrate was set for 15.5 L/min, where Figure 9-18 illustrates the filling procedure. The flow rate had been calculated to achieve a total filling time of 8.4 hours, corresponding to the KBS-3H reference design for a 150 m section, i.e. considerably reduced in the MPT case. The remaining void space in the MPT test section had been calculated to be approximately 7.8 m^3. However, water came out through the air evacuation pipe already when 5.5 m^3 of water had been pumped in. At this stage the air evacuation pipe was closed with the flow allowed to continue as the pressure slowly started to increase. Eventually, an additional 1.4 m^3 was added over 50 minutes resulting in a total volume of 6.9 m^3 at a maximum pressure of 4 bars. The reason for the quick filling can be found in the pellets section which clearly did not fill up fully with water as long as no overpressure was applied.
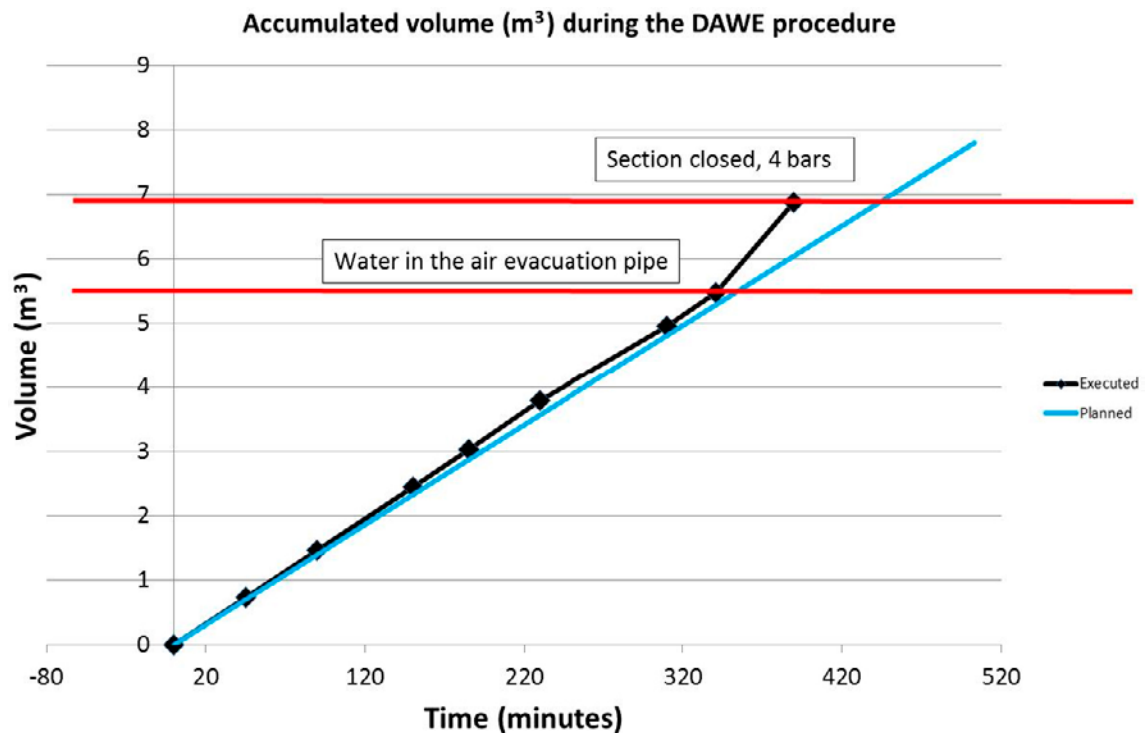
Figure 9-18. *MPT water filling procedure. The actual flow rate was 17.6 l/min on average and the filling was stopped at 6876 litres after 6 hours and 30 minutes.*

During the final 50 minutes an increasingly hissing sound was heard and eventually found to be emanating from a hole in the plug. At 4 bars there was a large leakage of water, cf. Figure 9-19. Attempts were made to seal it with cloth and wood, however, it naturally decreased when the pressure reduced and was eventually very small. The volume that leaked out was not possible to quantify, however, it filled up the measurement weir and there was a continued leakage over the weir for some time, so the leaked volume may be in the order of a hundred litres. The point of leakage was eventually re-welded in mid-January. Re-welding did not entail a direct increase in pressure in the MPT section, however, some weeks later a marked pressure increase was noted in the pellets section which is highly likely due to the fixed leak.

An added positive effect by pressurising the full MPT section for a few minutes was that the rock sensors could be checked and verified to function as intended.

Once the water filling was finalised the air evacuation pipe was pulled out using a manually operated winch, this worked out as intended but a mechanical pulling device should be used for quicker action. Figure 9-20 illustrates the air evacuation pipe once pulled out; bentonite can be seen in its valve end part.

After the air evacuation pipe, two of the three water filling pipes were pulled out from the plug. One of the pipes was left to allow for the possibility for pumping in additional water in case the plug would continue to leak.

Overall the water filling and venting procedure worked out as planned and there were no indications that the pipes would get stuck which would be a large problem for the KBS-3H design. The valve at the inner end of the pipe which stops water from flowing out of the pipe during pipe removal also worked as intended.
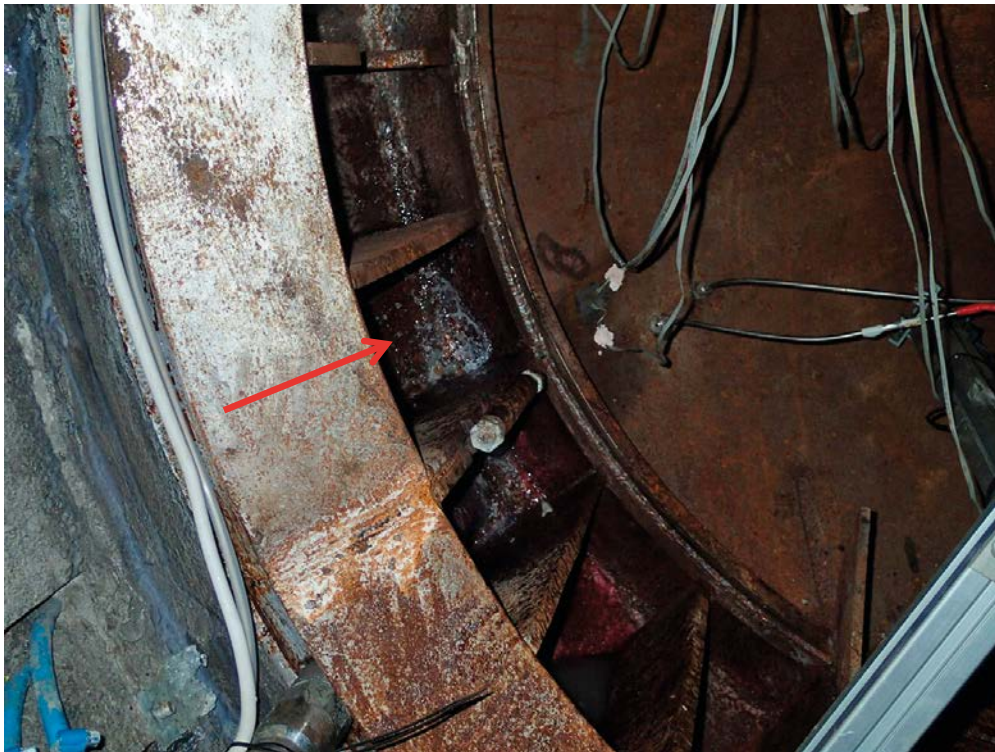
Figure 9-19. Water leakage in the plug at the end of the DAWE procedure. Leakage point is marked with a red arrow.

Figure 9-20. The air evacuation pipe has just been pulled out and the first water filling pipe is connected with a wire to be pulled out. Bentonite can be seen stuck to the valve part of the air evacuation pipe (red arrow).

9.13 Assessment of relative speed of installation

Compared to the reference design where about 4 components are expected to be placed each 24 hours the corresponding MPT work was carried out at about a quarter of that speed. On the other hand, without the cabling, two components would have been managed in 24 hours during the MPT which would equal half the speed expected in a repository situation. At this stage of KBS-3H development this outcome is deemed acceptable. In a repository case the transport and starting tube handling would be managed by self-propelled vehicles, connections between the deposition machine and the control room would be wireless and the alignment of the vehicles with the drift would be automated. The deposition sequence could also be optimised with the transport tube being reloaded with a new component during deposition of the preceding component.

Concerning the plug, it is expected to be installed during one day in the repository situation, but it took a week in the MPT. Approximately half of the MPT time is due to management of sensor cabling, and the work was done without a night shift so the MPT plug installation is in the order of twice the time when it comes to actual working hours. This is also deemed acceptable in the current stage of development since the work was mainly done manually in the MPT and there is lots of time to be gained by automating the transportation of the plug parts, their placement and welding.

In the MPT, one day each was allotted for the pellets filling and post grouting of the plug. These activities would have to be speeded up considerably to 3 and 4 hours respectively. These kind of speeds would require on-site customized equipment's, but should be feasible.

Water filling is pretty straight forward and takes the time decided. Pipe removal would have to be speeded up by an automated pulling system rather than retaining the more manual performance employed in the MPT.

9.14 Installation data

This section summarises the main installation data for the MPT. Concerning instrumentation with 'as built' drawings, cf. Pintado et al. (2016).

9.14.1 Bentonite components

Table 9-1 gives the data for the bentonite component, 'as built' in the MPT.

In total 81.3 tons of bentonite was installed in the MPT. Most of the requirements on the components were fulfilled but there are a few outliners and further improvement of the quality control will be required when continuing development. Larger production series will allow for fine-tuning of parameters which will also help considerably in fulfilling all requirements.

8047 kg of pellets was installed. A rough estimate is that the void is 7.3 m^3 (2.7 m length and 1.85 m diameter). This would give a dry density of 940 kg/m^3.

For later evaluation an improved calculation can be made for the pellets section using the exact position of the composite transition block, the geometry of the compartment plug cap and the scanning data in order to take into account the cable storage cutout. Also, the densities for the full MPT can be calculated in a similar manner.

9.14.2 Water filling of the MPT

The water filling of the MPT required 6876 litres. However, there was a leakage in the plug and it is estimated that in the order of a hundred litres leaked out.

9.14.3 Inflows prior to installation

The inflow into the MPT section was measured repeatedly to approximately 32 litres/day two months prior to the MPT installation.

Repeted measurements in 2012 gave approximate leakages:

*   Supercontainer section   ~19 l/day
*   Inner distance block section   ~8 l/day
*   Outer distance block, transition block and pellets   ~3 l/day

Note that the measurement weirs could not be placed exactly in relation to extents of the different composite components due to the local geological conditions (e.g. fracturing). However, the presented numbers are considered fair estimates.

9.14.4 Compartment plug concrete

The recipe and mixing order of the concrete used to cast the fastening ring is given in Table 9-2. The recipe was scaled to 50 litre batches during casting.

In total, eight 50 litre batches were mixed and a total of 400 litres of concrete was used.

Table 9-1 Data on the 'as built' MPT components. Red cells mark where the requirement has been exceeded to some extent.

Component	Block position starting at the drift front	Block ID	water content (%)	wc requirement (%)	Dry density (kg/m³)	Dry density requirement (kg/m³)	Weight machined (kg)	Length (avg of four positions) (mm)	Length requirement (mm)	Diameter (avg of two orientations) (mm)	Diameter requirement (mm)
Distance block (inner)	1	KBS313C11	20,6	21±1	1721	1712±20	2405	no meas	485±1	no meas	1765±1
	2	KBS313C10	20,7	21±1	1721	1712±20	2476	486,0	485±1	1765,4	1765±1
	3	KBS313C28	19,9	21±1	1721	1712±20	2471	485,0	485±1	1765,0	1765±1
	4	KBS313C20	20,9	21±1	1715	1712±20	2472	485,2	485±1	1764,8	1765±1
	5	KBS313C21	20,4	21±1	1715	1712±20	2450	485,4	485±1	1764,5	1765±1
	6	KBS313C8	21,1	21±1	1700	1712±20	2472	486,1	485±1	1765,4	1765±1
	7	KBS313C25	19,8	21±1	1723	1712±20	2462	486,4	485±1	1764,6	1765±1
Supercontainer	8	KBS313C1	17,8	17±1	1756	1753±20	1722	350,0	350±1	1740,3	1740 +1−2
	9	KBS313R12	11,0	11±1	1902	1885±20	1217	386,0	optimised (386)	1740,0/*	1740+1−2/1058±1
	10	KBS313R6	11,2	11±1	1904	1885±20	1533	485,0	485±1	1739,5/*	1740+1−2/1058±1
	11	KBS313R7	11,1	11±1	1894	1885±20	1528	485,2	485±1	1740,2/*	1740+1−2/1058±1
	12	KBS313R2	10,9	11±1	1903	1885±20	1542	485,4	485±1	1740,4/*	1740+1−2/1058±1
	13	KBS313R11	11,0	11±1	1897	1885±20	1542	485,4	485±1	1740,9/*	1740+1−2/1058±1
	14	KBS313R1	11,0	11±1	1879	1885±20	1526	486,3	485±1	1740,0/*	1740+1−2/1058±1
	15	KBS313R3	10,8	11±1	1901	1885±20	1540	484,5	485±1	1740,1/*	1740+1−2/1058±1
	16	KBS313R9	11,0	11±1	1898	1885±20	1540	485,4	485±1	1743,5/*	1740+1−2/1058±1
	17	KBS313R5	11,1	11±1	1898	1885±20	1535	485,3	485±1	1743,3/*	1740+1−2/1058±1
	18	KBS313R4	10,8	11±1	1895	1885±20	1547	485,6	485±1	1740,5/*	1740+1−2/1058±1
	19	KBS313C2	17,3	17±1	1764	1753±20	2040**	428,2	428±1	1740,0	1740 +1−2
Distance block (outer)	20	KBS313C6	20,6	21±1	1724	1712±20	2456	485,7	485±1	1765,0	1765±1
	21	KBS313C23	20,4	21±1	1709	1712±20	2471	484,5	485±1	1764,2	1765±1
	22	KBS313C19	20,2	21±1	1724	1712±20	2473	486,5	485±1	1765,1	1765±1
	23	KBS313C18	20,2	21±1	1724	1712±20	2476	485,6	485±1	1764,0	1765±1
	24	KBS313C14	19,5	21±1	1744	1712±20	2473	485,0	485±1	1764,9	1765±1
	25	KBS313C26	20,4	21±1	1711	1712±20	2470	486,5	485±1	1765,1	1765±1
	26	KBS313C15	19,9	21±1	1738	1712±20	2471	485,5	485±1	1764,9	1765±1

Component	Block position starting at the drift front	Block ID	water content (%)	wc requirement (%)	Dry density (kg/m³)	Dry density requirement (kg/m³)	Weight machined (kg)	Length (avg of four positions) (mm)	Length requirement (mm)	Diameter (avg of two orientations) (mm)	Diameter requirement (mm)
Transition block	27	KBS313C9	21,4	21±1	1705	1712±20	2482	486,2	485±1	1765,7	1765±1
	28	KBS313C17	19,3	21±1	1738	1712±20	2472	485,3	485±1	1764,6	1765±1
	29	KBS313C13	20,8	21±1	1721	1712±20	2476	485,0	485±1	1765,0	1765±1
	30	KBS313C24	20,5	21±1	1702	1712±20	2469	485,0	485±1	1764,3	1765±1
	31	KBS313C16	20,7	21±1	1725	1712±20	2476	485,0	485±1	1764,5	1765±1
	32	KBS313C27	20,4	21±1	1710	1712±20	2473	485,0	485±1	1764,7	1765±1
	33	KBS313C12	20,6	21±1	1724	1712±20	2469	485,3	485±1	1765,0	1765±1
	34	KBS313C7	20,9	21±1	1715	1712±20	2479	486,1	485±1	1765,3	1765±1
Pellets			18,4		940***	1 000	8 047				
Pilot hole (270)			~21	21±1			51	440	optimised (440)		
			~21	21±1			56	485	optimised (485)		
Pilot hole (76)			~21	21±1			14	1 940	optimised (1940)		
						Total installed bentonite weight:	81 275				

*not measured during assembly, very close to 1 058 at compaction.
** 2 056 kg prior to drilling for sensor cabling.
*** based on a simplified calculation of the pellets void.

Table 9-2 Recipe and mixing order for the casting of the fastening ring.

Component:	Amount:
Ballast moist content	5%
Construction cement	320 kg
Water	107.9 l
Sika Evo 26	1 kg
Sika Control 40	6.4 kg
Sika Intraplast	2.8 kg
Stone powder	410.3 kg
Total batch size	*400 l*

Mix order:	Mix time:
Dry materials	2 min
Water, shrink reducer and half of the fluidifying additive	2 min
The remaining fluidifyer	Minimum 2 min

10 Conclusions

The performance of the MPT is part of the stepwise development and demonstration of the KBS-3H design and it has been preceded by a number of full scale in situ demonstrations at the Äspö HRL:

- The excavation of a KBS-3H drifts at the −200 m level (Bäckblom et al. 2005).
- The development and testing of a deposition machine with concrete dummies (Autio et al. 2008).
- Mega Packer post grouting (Eriksson and Lindström 2008).
- Pipe removal tests (Autio et al. 2008).
- Compartment plug tests (SKB 2012).

The MPT integrates earlier development work with the objective of obtaining an initial verification of the KBS-3H design implementation and the components mutual function when combined.

The MPT was also set up with the aim of gaining further experience from working in full scale at ambient in situ conditions, thus allowing for the recognition of potential implementation issues associated with the DAWE design.

10.1 Experiences from the MPT

It is concluded that the MPT has demonstrated the potential of the KBS-3H design, the inherent strength of a slimmed system working with pre-assembled components. The key KBS-3H components have been tested in mutual combination and the DAWE procedure has been carried out basically as intended. The actual function of the components will have to be assessed from sensor data and an eventual dismantling of the test. Initial data from the MPT is presented in Pintado et al. (2016).

Several implementation issues in need of further development have also been identified by the test, in particular the need to harmonise the water contents of the blocks inside the Supercontainer. The previous design with bentonite blocks of two different water contents (11% and 17 %) does not allow for fixating a relative humidity level in the assembly hall and subsequent storage that matches the water content of the blocks. The challenges faced with cracking blocks during the MPT also illustrate the importance of establishing controlled environments during all steps when handling bentonite components. Based on the MPT experiences, the KBS-3H design will now be updated with use of Supercontainer blocks with common water content.

The MPT also highlights the need for improved geometrical measurements of components in order to ensure that the requirements are actually fulfilled. The slide caliper used should be replaced and improved methods established, possibly using laser scanning or simply approving the blocks at milling which is done with very high accuracy. A method for turning blocks upside down also needs to be developed, both in order to allow for placing the top block in the Supercontainer, but also to allow for machining of opposing sides of a bentonite block, when required in order to fulfil geometrical requirements.

Another implementation issue that was highlighted is the practical difficulties involved in welding the compartment plug (also being relevant for the drift plug which has a similar design). Similarly identified was the need for a drainage pipe at the lowermost part of the plug collar, Figure 2-3, so naturally inflowing water can be drained prior to pellets filling. Difficulties in placing a contact grouting tube at the steel-casting interface highlighted the possibility of integrating the grouting tube in the plug design itself, in order to allow for improved contact grouting. These experiences will all be brought to the drawing board and the KBS-3H plugs will be updated accordingly. When updating the plug designs a re-usable 'bridge' for the deposition machine to pass over the fastening ring will also be considered as opposed to the simpler single use concrete 'bridge' employed in the MPT.

With respect to the KBS-3H deposition machine the MPT has demonstrated that a controlled and automated deposition sequence with good contact between components is possible already with the current deposition machine, although it is identified that the current prototype is not fully compatible with the use of an air evacuation pipe, a finding to be addressed in future development work.

The issue of splashing of water onto bentonite components during transportation and deposition, which has been identified already in earlier development work, has to be addressed before doing any further full scale bentonite component installation. Splashing does not however appear to destroy or deteriorate the components immediately; however, since this problem can be solved by mechanical upgrades it should be incorporated in subsequent development work.

In addition to the implementation issues presented above the KBS-3H project has gained a lot of experiences for future installations. Methodologies are now available for both assembly and installation of components including advanced sensor systems, cf. Chapter 11.

11 Future work and recommendations

A decision on whether to continue the KBS-3H development work will be taken in coming years. No practical concerns suggesting a closure of the development work was identified during the MPT. However, the results of the MPT will be flanked by results of the Safety assessments related to and application of KBS-3H. This chapter discusses and suggests possible future demonstrations bearing the MPT experiences in mind. Possible design optimisations are also discussed, mainly from an engineering perspective, i.e. before any continued assessment they would have to be judged in relation to the results of the Safety Assessment.

11.1 General

In the outlining of verifying tests for the KBS-3H development the MPT would be followed by an integration test, again including all key components but with multiple and heated canisters. Since titanium has been selected as the reference material for the KBS-3H components (SKB 2012), it should ideally be the metal used.

Prior to such a test there are several questions to decide upon, two key once being:

- Should the current deposition machine be used or should a second generation prototype be developed.

- Should the block components be placed by the deposition machine or should a smaller fork lift type of equipment be developed.

The deposition machine development within the MPT concluded that the developed composite control method would allow for further conceptual testing (Ojala and Von Numers 2015). Several of the suggested improvements would, however, favour the development of a new machine.

A 3 m long distance block weighs close to 15 000 kg, whereas a 1 m segment would weigh in the order of 5 000 kg. A weight of 5 000 kg should be possible to handle with a fork lift type machine inside the drift. Disadvantages with that type of solution would be the need to use another machine and to have multiple cycles with the smaller type of bentonite segment. On the other hand a fork lift should be much quicker than the deposition machine. Operational reliability and safety could possibly be easier to ensure with a fork lift type machine, the blocks would not have to withstand the lifting and lowering of the deposition machine's water cushion system and the exposure to splashing would be removed for the distance and transition blocks. Reversed operation (retrieval) in case of an error is possibly easier with the fork lift system.

For future demonstrations the distance- and transition block deposition can be done by the deposition machine. However, as long as the length of the block segments is limited to 0.5 m they will not be (self sustainable) stable in themselves and lengthwise connections and anchoring will be required, i.e. a step away from the reference design. The same situation would apply for use of fork lift type equipment. One meter segments would require a new press and a new mould or development within the field of isostatic compaction.

When comparing KBS-3H with KBS-3V from a demonstration perspective, both designs have run repetitive testing of concrete buffer and canister installation. Both designs have also performed installations with bentonite components, with KBS-3V having done more extensive testing. However, one of the major differences is that the step from use of concrete dummies to bentonite buffer is greater for KBS-3H than for KBS-3V given the added complexity introduced by the feet, which add an entirely different type of mechanical strain imposed on the bentonite blocks. In the MPT, test transportation of one distance block and installation of three composite components was carried out successfully; however, a quite significant fracture was noted on the innermost distance block and the reliability of the this procedure has to be further verified during the continuing development work.

If the next development step is a larger KBS-3H integration test, it should preferably include a pre-test to ensure reliability in the function of the feet. Such tests are by definition highly restricted in time, since the blocks will naturally weaken due to the unfavourable relative humidity of the air of the drift.

A larger integration test would involve use of heaters which introduces quite a large difference in relation to conditions experienced during the MPT. Heaters have generally been switched on when everything is safely installed in the test setups. Running the tests in such a manner artificially removes the complexities added by management of the hot canisters affecting the bentonite already during installation. KBS-3H assembles Supercontainers and stores them prior to installation. This constitutes a potentially important design issue which should be assessed in more detail prior to initiating an integration test. Similar research is done in KBS-3V, however, KBS-3H differs quite a lot and separate studies will need to be done, possibly including a full scale pre-test of the Supercontainer assembly and storage.

A step from using construction steel to titanium should, at installation, mainly imply a difference in welding, due to the inert gas required for titanium. Based on previous experiences the plug will be re-designed with easier access for welding and inspection. These are changes that could possibly be tested for the first time in an integration test. However, the plug is critical for achieving tests objectives and the success of its installation must not be in question. Therefore, a proper assessment of the differences will hence be required prior to making the decision.

11.2 Integration test with multiple heated canisters

The MPT can to some extent be regarded as a dress rehearsal for a full system test of the KBS-3H reference design. It included the development of several technical solutions that are planned to be fully implemented in a more comprehensive integration test.

Due to the MPT's novel set up and to some extent due to imposed time constraints, the technical solutions, such as the cable block, for handing of sensors and cables had to be developed in parallel to and partly subsequent to developing the instrumentation plan. For a future test, the technical solutions are readily available and can be incorporated in the instrumentation design from the start. With the possibilities and constraints well defined from the onset there should be neither major issues with pipe or cable lengths nor with lost cable labels.

11.2.1 Buffer manufacturing and machining

Buffer manufacturing can be done in a similar way as for the MPT. However, it would be recommended to start storing large quantities of bentonite in order to obtain more evenly distributed water content in the material. This would probably also sort out effects of the small variations in water content generated by the current mixing equipment.

If a press for one meter blocks will become available a new mould would have to be manufactured, if to be used for an integration test. The moulds take quite a long time to manufacture which also need to be taken into account.

A further recommendation would be to move the machining of the blocks to a locality closer to where they should be applied, compared with the MPT where the machining was done in Finland. Ideally it could be done close to the test facility and with a controlled environment. Storage of the blocks should ideally also be done in a controlled environment. However, transport containers similar to those used in the MPT would be needed for the transport between the factory for buffer pressing, machining and assembly. If these facilities are located close to each other, time and money can be saved.

Quantification of the geometry and dimensions of the bentonite blocks also needs to be improved.

11.2.2 Assembly

Future assembly of the Supercontainer and distance blocks could be done in the same way as for the MPT, underscoring the high importance of the use of a controlled environment. A strong recommendation also is to use an assembly facility with an overhead crane for more controlled lifts. Using a traverse crane would also speed up the assembly process considerably and both operational and personal safety measures would be easier to implement.

One meter long blocks will possibly not be available for a first KBS-3H integration test, but the lengthwise rods developed for the MPT distance blocks could be used again. The procedure would also be the same if a fork lift solution is developed.

A special storage container would have to be designed for the Supercontiner top block, as well as a device for turning it upside down.

11.2.3 Deposition machine

One of the major decisions prior to an integration test is whether to use the current machine, basically as deployed in the MPT. Additional mechanical modifications may, for example, include an upgrade to avoid splashing. The alternative being to develop a second generation machine.

If the old machine is used the stepwise placing of the air evacuation pipe would have to be implemented as performed in the MPT since the deposition machine would hit the pipe otherwise.

11.2.4 Cabling in the drift

In the MPT a method to pull cables along the side of the drift with a reduced risk for axial flow along the cables was developed as presented in Section 5.2.5. The eventual success of this strategy will have to be assessed after dismantling, but it is deemed to constitute a significant improvement compared to having cable or pipe bundles along the side of the drift.

The strategy applied in the MPT could be implemented in a system test as well. However, in order to fully exclude the risk of introducing artificial flow along the drift axis, a neighbouring tunnel to which cabling can be pulled would be preferable. A neighbouring tunnel would also mean that the cable storages of the MPT would not be needed and cable connection could start as soon as the component was in place and the cables pulled, rather than as in the MPT where it had to wait until after the plug was installed. This would actually allow for a continuous deposition work and two components could probably be installed per 24 hours with the current deposition equipment. Connection of cables could be done in parallel.

The slim 'hedgehog' type connector can be used again, although with approximately 8 mm connections to allow for easier pulling of cables. Also the 'hedgehogs' should be moved somewhat further back towards the plug and the rock cutout at their location should be larger than employed in the MPT to allow for easier looping and connection of pipes.

11.2.5 Other topics

Plug installation with improved possibilities for welding and inspection could be done in a way similar as for the MPT, now taking inert gas requirements for titanium welding into account. The same goes for pellets filling as well as water filling and air evacuation; they could be done similar to the MPT. Contact grouting could be done with pressure vessels again, but with an improved means of mixing the silica sol.

Regarding sensors, their functionality in the MPT will have to be assessed prior to selection and use of similar sensors again.

In the MPT three packer systems were installed in a cross-section located well inside the MPT test section, with their pressurisation controlled from outside the plug. In hindsight this is not an optimum solution given that all piping cannot be accessed. In the event a pipe inside the section would fail it could add water to the section that would be from the borehole rather than just the natural inflow

through the fracture system. The system used in the MPT failed on the outside of the plug at one time, and new valve procedure has been put in place from then on to safeguard the function of the packer system. However, a preferred choice would be to have holes for measuring the boundary conditions that do not go into the drift itself, but are rather drilled form tunnels close by.

11.3 Potential design optimisations

The MPT work has not identified any major additional technical issues, and the KBS-3H design currently seems fully possible to implement. At the same time, doing all steps in full scale highlights both design strengths and technical solutions that require additional verification. One of these topics is the question as to whether to develop a fork lift system for distance blocks or further verify the block integrity during deposition by additional testing with the current deposition machine.

Another design that clearly works, but, could be further optimised is the air evacuation system. It could possibly be removed, although it would imply large changes to the drift setup and hence the safety assessment. A solution could be double tunnels with drifts reamed between them. This was discussed prior to the development of the KBS-3H Basic Design. However, for the Basic Design (Autio et al. 2008), the benefits were not considered sufficiently large, but the recently selected DAWE reference design brings forth further advantages and the question may possibly require renewed attention.

In principle, a 340 m core hole would be drilled between two tunnels, a reamer head would be connected at one end and the drift would be reamed to 300 m. Before component installation, air evacuation and water filling pipes would be taken through the remaining pilot hole (40 m) through a small titanium plug. The entire 300 m drift could then potentially be installed with components, effectively saving one compartment plug.

Advantages that could emerge from this solution would be:

- Traditional reaming with easier muck handling rather than push reaming.

- One compartment plug less for each drift.

- Water filling and air evacuation could be done from the end of the drift, i.e. the larger drift plug would not require air- and water filling pipes.

- More time for installation would likely be available since the main risk with a failing block is that it locks the air evacuation pipe inside the drift and this would no longer be an issue which would allow more time. A failing bentonite block would only be a problem if it fell on the drift floor and was eroded considerably.

- The heat effect from the canister could potentially be reduced since cracking and a failing bentonite block would only be a problem as described above.

- Many of the points listed above imply large cost savings.

Disadvantage could be:

- Future risks for circulating water-flow in the repository due to the drift being 'open' in both ends. This would have to be assessed for long term safety reasons.

- The backward tunnel, located slightly higher than the main tunnel, would have to excavated and backfilled which would add costs.

- Additional safety assessment work means increased costs.

Figure 11-1 illustrates how the drifts would look and Figure 11-2 zooms in on the end of one drift.

Figure 11-1. *Schematic illustration of a double tunnel system, drifts are reamed between two tunnels, rock 'cover' is left in the end and only the pilot hole has to be plugged at that side.*
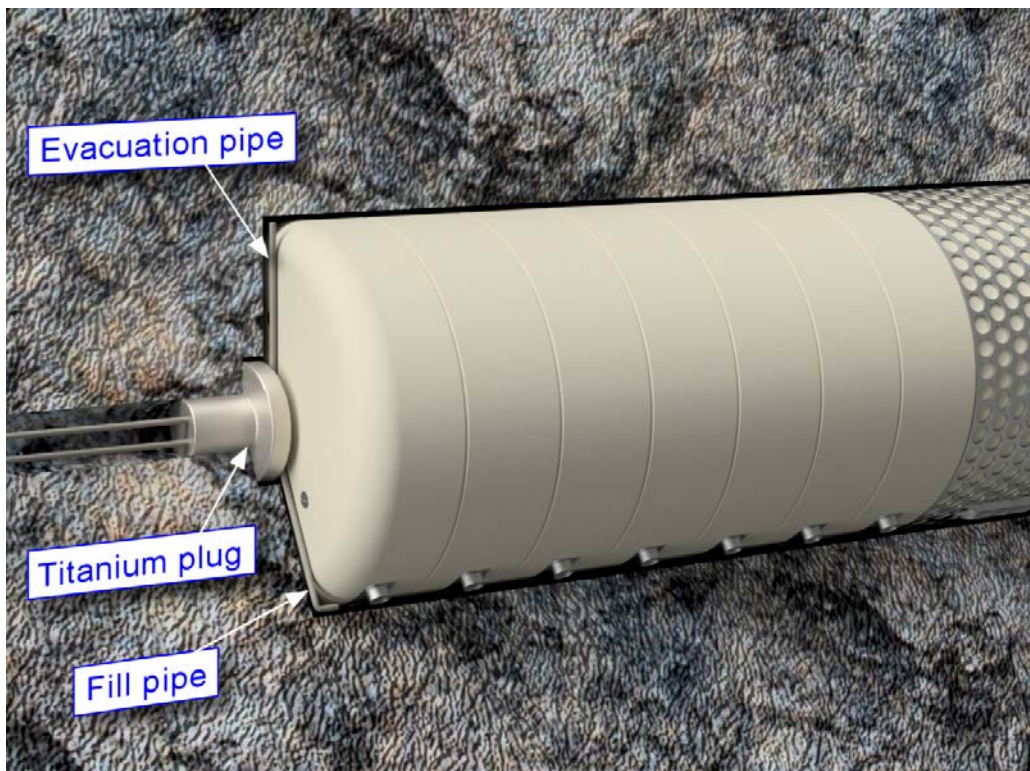
Figure 11-2. *Drift front in a 300 m long drift, the innermost distance block will swell and lock the titanium pilot hole plug (champagne cork plug) against a flat machined surface, thus, it will not move even when the concrete used to tighten it is dissolved after hundreds of years. The remaining parts of the pilot hole could be filled with bentonite blocks after the pipes have been removed, not illustrated here.*

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