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State-of-the-art and proof-of-concept installations for repository concepts based in crystalline rock

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ABSTRACT

Over the last five decades private and national energy programmes worldwide have been producing a variety of radioactive wastes. One of the safest ways of disposing of this waste is to bury it deep underground in purpose-built geological disposal facilities. Currently, there is no operating geological repository in Europe for high-level waste but the goal of the IGD-TP is that the first repository shall be fully operational before the year 2025. Several studies and experiments are ongoing at various potential repository sites in Europe with the goal to establish general approaches that can be adapted for any country in need of a geological repository.

The Swedish Nuclear Fuel and Waste Management Co (SKB) in Sweden and Posiva Oy in Finland are developing a method for geological disposal of high-level long-lived nuclear waste in crystalline rock, the KBS-3 method. KBS-3V (vertical) is both organizations reference design, but KBS-3H (horizontal) emplacement is also being researched as a potential alternative. Of high importance in the development is demonstrating the technical feasibility *in situ* of safe and reliable construction, manufacturing, disposal and sealing of such geological disposal facilities. Parts of these demonstrations are carried out under the framework of EurAtom/FP7 and one of these projects is the LUCOEX project where SKB is demonstrating horizontal emplacement, the Multi Purpose Test (MPT), and Posiva is demonstrating vertical buffer installation processes.

The MPT includes the key components of the horizontal design and comprises all essential steps; manufacturing of the full-scale components, their assembly, installation in the drift and monitoring of the early buffer evolution. The MPT installation was successfully performed in late 2013. By combining the components, an initial verification of the design implementation has been achieved. At the same time, integrating the components has meant the recognition of some design weaknesses and the design will be updated accordingly.

Posiva's KBS-3V buffer installation equipment that places buffer blocks with high precision in vertical deposition holes is currently being developed and will be tested during 2014 and 2015 in real underground conditions. The machine uses vacuum lifting tools for moving the buffer blocks and laser scanning technology to position both the machine and blocks. Functionality of the concept and equipment selected will be confirmed by the tests and the installation tests will provide important information about the suitability of the selected buffer dimensions and tolerances.

Keywords: LUCOEX, repository, buffer, deposition machine, deposition, Äspö, Onkalo, KBS-3V, KBS-3H.

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Introduction

During the last five decades a variety of radioactive wastes have been produced by private and national energy programmes worldwide. This includes a significant amount of high-level long-lived radioactive waste, including spent nuclear fuel, which must be isolated from humans, animals and nature for hundreds of thousands of years. One of the safest ways of disposing of this waste is to bury it deep underground in purpose-built geological disposal facilities. Currently, there is no operating geological repository in Europe for high-level waste but the vision of the IGD-TP, according to their Strategic Research Agenda (IGD-TP, 2011) is that "by 2025, the first geological disposal facilities for spent fuel, high-level waste, and other long-lived radioactive waste will be operating safely in Europe". Several studies and experiments are ongoing at various underground research laboratories (URL) and potential repository sites in Europe with the goal to establish general approaches that can be adapted for any country in need of a geological repository.

The LUCOEX project, which receives funding from Euratom/FP7 under grant agreement n°269905, has the overall objective to demonstrate the technical feasibility, *in situ*, of safe and reliable construction, component manufacturing, disposal and sealing of such geological disposal facilities through a number of proof-of-concept installations.

The proof-of-concept installations within LUCOEX are carried out at four different URL in Europe, which have been constructed for the specific purpose of developing repository technology under repository-like conditions. The proof-of-concept installations include four different geological deposition concepts of which two are optimized for crystalline rock and two for implementation in clay formations.

This paper sets out to present the current status of the LUCOEX work carried out in crystalline rock during 2011–2013. It covers the Multi-Purpose Test (MPT) at the Äspö Hard Rock Laboratory (HRL) which demonstrates that full-scale components can be installed underground, focusing on drift preparations, assembly and installation of the components, and the KBS-3V (see Section on Disposal in crystalline rock: KBS-3) emplacement tests at Onkalo focusing on the installation process for vertical disposal in crystalline rock.

Outlook on European benefits

The partners in the LUCOEX project include four of the most developed nuclear waste management programs in Europe: ANDRA in France, NAGRA in Switzerland, Posiva in Finland and SKB in Sweden.

The LUCOEX project is integrated into these four national programs and constitutes a part of their stepwise development of their individual repository concepts. LUCOEX is in addition supporting other European countries by openly sharing the results of the project through e.g. opening the URL for visits, hosting workshops, presenting at conferences and publishing the findings. The aim of these activities is to support the less-advanced programmes in Europe.

An independent study was carried out in 2014 (Deliverable: D01:15; Wiberg, 2014) where the status of the national programmes in Europe was summarized, also including an evaluation of whether the LUCOEX results can be utilized by less-advanced programmes. The conclusions were that the countries that have made significant progress in their radioactive waste management programmes, including Spain, Slovakia, Hungary, United Kingdom, Germany, the Czech Republic, Belgium and the LUCOEX partners: Switzerland, France, Sweden and Finland are in a position where results from the LUCOEX project can be utilized in the near foreseeable future.

In addition Bulgaria, Lithuania, Poland, Romania, the Netherlands, Slovenia and Croatia may utilize the results from the LUCOEX project to obtain information on possible concepts to kick-start their waste management programmes.

Disposal in crystalline rock: KBS-3

Posiva's and SKB's plans for the final repository are based on the KBS-3 method where the spent nuclear fuel will be stored in copper canisters with a cast iron insert surrounded by a bentonite buffer hosted in granitic bedrock at a depth between 400 and 450 m. The principle behind the disposal concept is to employ multiple barriers to ensure that radionuclide release to the biosphere is within stipulated limits. The current reference design for both SKB and Posiva is that the waste canisters are positioned in vertical holes drilled in large disposal tunnels, (SKB, 2013).

An alternative design, currently being jointly researched by SKB and Posiva, is KBS-3H, where the canisters are placed horizontally by means of Supercontainers. A Supercontainer includes the canister surrounded by a bentonite buffer with an outer perforated metallic shell. The Supercontainers are placed in deposition drifts with a circular profile (~1.85 m diameter) where they are separated thermally and hydraulically with distance blocks made of bentonite. Together, the bentonite contained inside the Supercontainers and in the distance blocks constitute the release barrier called the buffer. The maximum length of the drifts is 300 m and they are divided into two compartments separated with a compartment plug. The drifts have a slight upward inclination (of about 2°), which is why water is removed from the drifts by gravity along the bottom of the deposition drift during installation. The horizontal reference design is called Drainage, Artificial Watering and air Evacuation (DAWE) and includes artificial water filling of the drifts immediately after deposition and construction of the plug at the entrance of the drift; this is made to ensure a rapid initial swelling of the system (SKB, 2012).

Multi Purpose Test (MPT)

Objectives

The MPT's main objectives are to test the system components at full scale and in combination with each other to obtain an initial verification of design implementation and components 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. This paper presents work carried out 2011–2013 relating to drift preparation, assembly and installation and does not cover the monitoring and system development.

Previous work and current experiment design

The KBS-3H project has previously excavated two deposition drifts at the –220 m level of the 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 develop a horizontal deposition machine for disposing of full-scale concrete dummy distance blocks and fully deployed concrete Supercontainers, while the 15 m drift has been used to test the compartment plug (SKB, 2012).

The MPT is a non-heated sub-system test that combines the previously tested components and also introduces bentonite blocks, a Supercontainer and a compartment plug in combination, see Fig. 1. The MPT is installed in the innermost parts of the 95 m drift according to the KBS-3H reference design DAWE.

The MPT involves five main steps; characterization of the pre-test drift conditions, assembly of the components, installation, monitoring of the system's evolution and finally dismantling and evaluation of the system.

One of the key components included is the Supercontainer. Its reference design includes a titanium shell but a steel version is used in the MPT as long-term behaviour, such as impact of the corrosion products from the shell formed on the buffer, cannot be studied in tests of this type. The Supercontainer has segmented distance blocks installed around it. The drift is sealed using a compartment plug, with its associated transition zone made up of a transition block and bentonite pellets. The transition block design is the same as the distance block design and it is used to compensate for loss of buffer density in the section filled with pellets. Further details on the KBS-3H components and design premises can be found in KBS-3H Complementary studies, 2008–2010 (SKB, 2012).

Multiple sensors are installed to monitor pressure (swelling and pore), moisture, temperature, displacements and water leakages through the plug. After test termination, dismantling of the various components will provide post mortem data on buffer homogenization. The duration of the test will be determined depending on the evolution of the test itself.

Buffer manufacturing

SKB and Posiva have extensive experience in manufacturing of full scale blocks for KBS-3V, (Johannesson, 2002). However, KBS-3H has a slightly larger diameter of blocks and a new mould had to be manufactured. The requirements and the blocks that were manufactured for the test are listed in Table 1. Wyoming MX80 bentonite was used and a thorough material analysis programme was carried out prior to onset of compaction using the uniaxial method. The montmorillonite content was measured at 90% which is at the high end of the stipulated 75–90% requirement.

Limitations introduced by the facility for compaction resulted in the maximum height of the

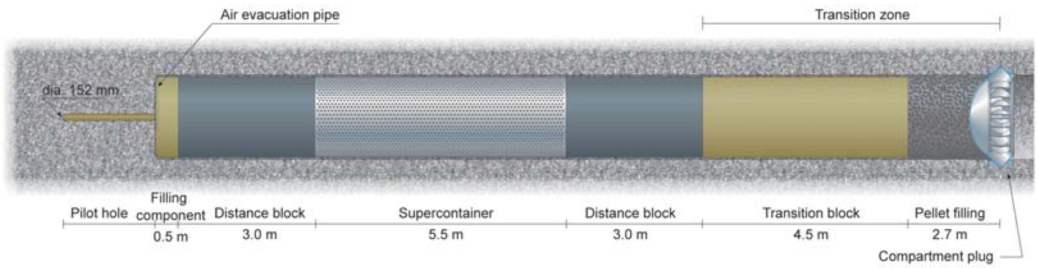

FIG. 1. Schematic illustration of the MPT layout. It includes a Supercontainer flanked by bentonite distance blocks on both sides and a compartment plug with its accompanying transition zone made up of a section filled with bentonite pellets and a bentonite transition block.

blocks being 500 mm instead of the 1211 mm stipulated in the design of the Supercontainer rings.

All the blocks were manufactured according to the pre-set requirements. A few of the blocks had a water content immediately below the requirement with densities immediately above requirement. The main reason for this was that there was no possibility to make an extensive test series before making the blocks for the test. However, the deviations were so small that it was deemed unlikely to affect the evaluation of the test. It was also deemed that there should be no problems in manufacturing blocks according to the requirements if a more extensive test series is run in the future and compaction parameters are optimized. Pellets for the test were manufactured using an extrusion technique. Further details on material analyses, compaction and results can be found in the working report on the MPT buffer (Johannesson, 2014).

Deposition machine

The KBS-3H deposition machine which was originally developed during the ESDRED project (www.esdred.info) uses water cushion technology to transport the components inside the deposition drift. Testing prior to the MPT had identified some issues with the machine with components having a tendency to tilt inside the drift. Extensive upgrades to both soft- and hardware were carried out as part of the MPT to enable improved automation and higher reliability for the deposition cycles. A key step in this development was to instrument the machine with additional sensors to measure its tendency to tilt and install a logging system whereby the previously somewhat undefined problems could be investigated and addressed. The control method for deposition could then be enhanced by developing all interacting functions step by step. Further details on the deposition machine work can be seen in the working report on the upgrades to the deposition machine (Ojala and Von Numers, 2014)

Drift preparation

Characterization of the test section (length = 19 m) hosting the MPT components was undertaken by means of small weirs to locate the main areas of

TABLE 1. Requirements and number of blocks manufactured for the MPT.

Block type	No. of blocks	Water content (%)	Dry density (kg/m^3)	Outer diameter (mm)	Height (mm)	Inner diameter (mm)
Distance block	21	21 ± 1	1712 ± 20	1765 ± 1	485 ± 1	
Supercontainer ring	10	11 ± 1	1885 ± 20	1740 ± 1	485 ± 1	1058 ± 1
Supercontainer block	2	17 ± 1	1753 ± 20	1740 ± 1	350 ± 1	
Drift end block	1	21 ± 1	1712 ± 20	1765 ± 1	485 ± 1	

inflow. The leakage was measured as 33 l/day with the bulk of the inflow in the innermost part where the Supercontainer and the inner distance block were later positioned. The test section was also geologically mapped with focus on leakage points. Laser scanning was carried out.

The plug notch was excavated using a circular rail enabling parallel cuts which produce rock slices that were later broken loose. Further details on the sawing technique are given in KBS-3H Complementary studies, 2008–2010 (SKB, 2012). The part of the plug called the fastening ring was placed and casted in the notch. As the fastening ring is already cast in place during the drift preparations it allows for a quick plug installation that only required welding. The location of the drift did not allow for sensor cables to pass as is usual, via the drift wall to a nearby parallel tunnel. Instead all the cabling had to be taken out through the plug. Cut-outs were made on both sides of the drift and piping was installed. To minimize loss of buffer density the cut-outs were largely cast with low-pH concrete. Openings were left for the bentonite to swell into and around the pipes to minimize the risk for flow paths between concrete and rock. The instrumented drift prepared for installation is illustrated in Fig. 2. On the top and sides the pressure sensors installed in the rock can be seen. There are also pore pressure sensors in the rock.

Component assembly

Full scale components made up of bentonite had not previously been assembled or deposited by the KBS-3H project prior to the MPT. For this reason the strategy was to undertake a pre-test of assembly procedures, transports and deposition using a bentonite distance block. This proved highly valuable because the strategy of assembly using plastic protection proved to be inadequate and equipment for controlling the relative humidity inside the assembly hall had to be installed to avoid cracking of the blocks. A mechanical tool for lifting the blocks was also developed in the event that the vacuum lifting tool failed to work because of the development of small surface cracks. The need for a minor redesign of the distance block feet on which the blocks stand in order to allow for lifting with the deposition machine and drainage underneath was also identified, some sharp metal edges were softened and the height of the feet slightly increased.

During assembly one pair of feet was installed centralized on each 485 mm wide distance block 'slice'. Several of these slices formed the distance block and, this meant that they were unstable when placed horizontally. For this reason three rods were placed axially inside the full length of the distance block. These rods also kept the block 'slices' tightly together which limited the risk for water flooding the sensors in conjunction with onset of the DAWE procedure.

Holes for the sensors were drilled or carved out at the ends of the bentonite blocks according to the instrumentation plan. All cabling was protected inside steel pipes to minimize the risk for damage when the clay started to swell.

All piping and cabling had to be kept within the periphery of the bentonite component as there is only a 42.5 mm annular gap between the rock and the components. Therefore, a cable block made of metal was placed at the bottom of each component that allowed for protection of the cabling during deposition (Fig. 3). The cable block was removed after deposition. As the relative humidity in the

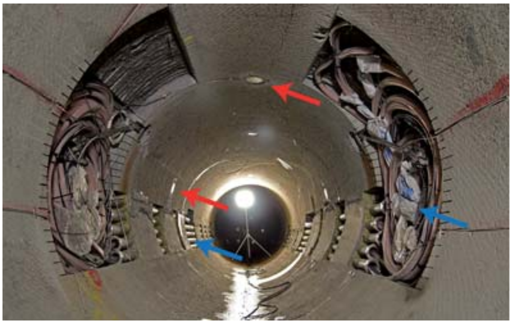

FIG. 2. The drift prepared for installation. The plugs fastening ring is casted in place approximately at the position of the camera. Some total pressure sensors are marked with red arrows and cable piping with blue arrows.

FIG. 3. A fully assembled distance block, the cable block can be seen at the bottom of the component (marked with a red arrow).

assembly hall was optimized for the blocks there was no further surface cracking and the blocks could be lifted using the vacuum tool.

Similar procedures were used for the Supercontainer assembly but no rods were needed because the blocks are placed inside the Supercontainer shell. Temporary 'stiffeners' were used on the outside of the shell to ensure straightness during assembly. During the Supercontainer assembly it was recognized that the current design with end blocks and rings having different water contents is unsuitable because the relative humidity inside the assembly hall cannot be optimized for two different types of blocks simultaneously. This has prompted a redesign of the buffer blocks for the Supercontainer, with the aim of harmonizing the water content of the blocks.

Installation

The MPT installation was carried out from November 14th through to December 7th of 2013. The components were transported down the Äspö HRL access tunnel one by one to the –220 m level inside a transport tube. The transport tube was placed outside the drift after which the starting tube with the deposition machine was placed behind it. The deposition machine then runs through the transport tube picking up the component and automatically drives the component to its position inside the drift. Overall the various depositions worked well and the automated sequence managed most of the control with some manual fine-tuning at the end. Good contact was achieved between the components and only 4 mm differed between the four components total length measured at assembly and the overall length of the deposited components, this is assumed to be within the measurement tolerances.

When all the components had been deposited the compartment plug was installed. Technical details on the compartment plug can be found in KBS-3H Complementary studies, 2008–2010 (SKB, 2012). Figure 4 illustrates the compartment plug installation which was undertaken in three main steps; first the collar, which is made up of four steel segments, was welded to the previously installed fastening ring. All cables and piping were then led through the collar and finally the cap was lifted and welded in place. The plug installation was followed by installation of pellets through the pellet filling hole in the plug. Even though the plug had been inspected by a certified company two holes were noted in the weld (pellet dust was seen escaping through a pore) and they had to be re-welded, see continued discussion below. Filling with pellets was followed by contact grouting via two sets of tubes; between the steel and casting and between the casting and rock. Contact grouting was carried out using silica sol grout.

Once this was completed all the sensors were connected to the data acquisition system (DAS) and checked then monitoring was initiated. The final step of the installation was the DAWE procedure where water was supplied through the pipes at the bottom of the plug and air evacuated with a long pipe at the top of the drift front. The KBS-3H reference design stipulates that the removal of the pipe is initiated when the water level reaches the highest point and water starts to flow from the air evacuation pipe. However, in this case a slight overpressure was applied onto the section which allowed functional checks of some of the sensors employed in the test. Additional leakages were noted in the plug welds which had to be re-welded. This leakage has prompted a change of design of the plug which will allow for easier access to welding and inspection of the welds prior to water filling. Another update will be the addition of a drainage pipe at the bottom of the plug; this is needed to avoid water filling up inside the collar during the installation phase before the cap is welded in place and pellets are installed.

Status of monitoring

The test is currently being monitored (October 2014). Initially it was planned that pre-modelling would enable the definition of an appropriate test duration. However, the modelling encountered problems, mainly with conceptualization of the extrusion of bentonite through the perforated Supercontainer shell. As a result of this a date for dismantling will be based mainly on measurements from the actual test and the desired dismantling conditions.

KBS-3V buffer installation

Objective

This effort aims at developing the necessary machinery and quality control programme including problem handling for the manufacturing and installation of buffer components in order to create a stable proof of concept for the KBS-3V repository concept.

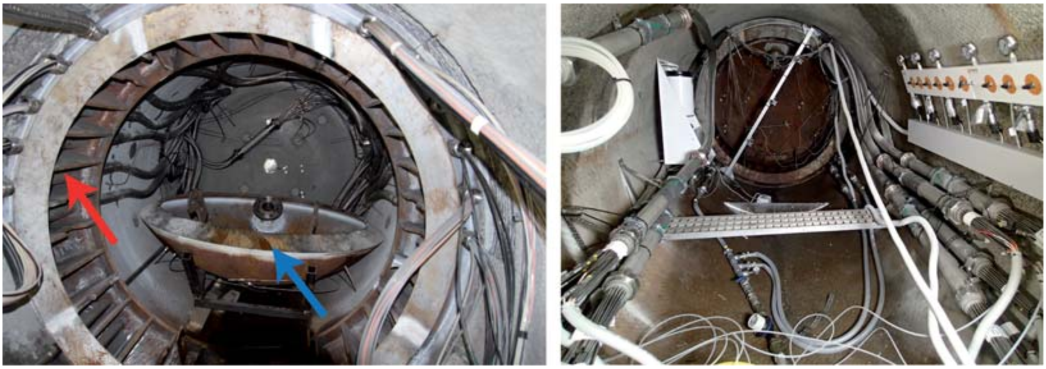

FIG. 4. Left: Installation of the plug, the collar is installed (red arrow) while the cap (blue arrow) is on the floor prepared to be lifted and welded in position. Right: the outside of the test section with the plug in position and all the cabling connected.

The main activities include the development of the installation technique for vertical bentonite buffer including the design, manufacturing and testing of the machinery; the tools and methods for quality control of the buffer; and the necessary tools for problem handling in case of unexpected problems during the buffer installation.

The final part of the work package involves the demonstration of a complete bentonite buffer installation at the Onkalo underground testing facility at Olkiluoto, Finland.

Installation machinery

The buffer blocks and pellets used in the KBS-3V installation are transported from the interim storage to the buffer installation machine installed over the disposal hole shielded inside special transportation containers. The transportation container assembly includes a bottom part and a top part. The bottom part is an air-tight container in which the single buffer block is placed. The top part is a cover which includes the gripping surface of the vacuum lifting system. The buffer installation machine connects to the upper part of the transportation container enabling employment of vacuum lifting trough the container top.

The transportation of the transportation container from the deposition tunnel entrance through the deposition tunnel to the disposal hole is handled using the Buffer Transportation Device (BTD). The BTD transports the containers one by one and carries the empty containers back to the central tunnel. The BTD is remotely controlled and moved by a terminal tractor. The bentonite buffer is installed in the deposition holes by a remotely controlled Buffer Installation Machine (BIM). During its operation the BIM is transported to the deposition hole by a terminal tractor that first roughly positions the BIM on the deposition hole. More accurate positioning is then carried out by the BIM itself using a laser tracker and focus points attached to the deposition tunnel.

When positioned, the BIM lowers its legs, raises its frame and carefully positions the buffer perpendicular to the tunnel with the internal crane centred immediately above the deposition hole. The accurate longitudinal positioning is made by the crane of the BIM during the installation of blocks.

All the functions of the BIM are carried out using electric power. No hydraulics are required.

KBS-3V tests in Onkalo, general

Installation of the bentonite buffer blocks in the Onkalo disposal facility is challenging because of bentonite swelling. During the transportation the buffer blocks need to be well shielded against exposure to water and moisture. An added requirement is that installation of blocks in the disposal hole must be done rapidly. Another challenge is the tight tolerances applicable to the installation of the buffer blocks. Installation will be carried out with the aid of laser guiding equipment.

Buffer installation concept design

Within the LUCOEX project Posiva's vertical installation concept has been subject to careful review. New ideas have been introduced into the transportation and installation concepts and associated designs.

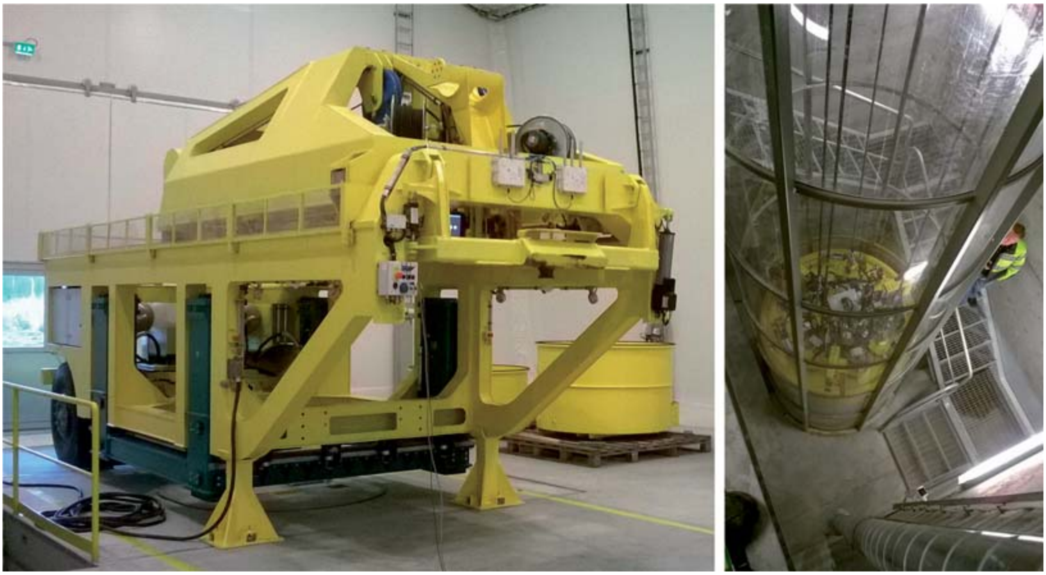

FIG. 5. Left image: the buffer installation machine in the test hall during the lifting test. Testing is done with a concrete block. Right image: the vertical deposition hole, a concrete test block is being lowered to the bottom.

Installation tests

Testing will consist of three phases: Testing in the test hall at the Onkalo site with concrete blocks, testing in the Onkalo demonstration tunnel with concrete blocks and testing in the Onkalo demonstration tunnel with bentonite blocks.

Tests in the test hall

Installation tests in the test hall started at the beginning of April 2014. The BIM in the test hall is shown in Fig. 5. A final preparation of automation and adjusting of machine functions is carried out in that phase. In the test hall, it is possible to perform the whole installation process. In the floor of the hall there is a full-scale artificial disposal hole with a transparent wall. Monitoring of the installation is easy and safe.

Tests in the Onkalo demonstration tunnel

After tests in the test hall, the buffer installation tests will continue in a demonstration tunnel in Onkalo. The installation is mainly planned to be carried out with concrete blocks. Some bentonite blocks should be available, in which case the testing will also be undertaken with a mixture of bentonite and concrete blocks. Monitoring of the testing in the Onkalo demonstration tunnel is difficult because access to the demonstration tunnel is denied because of safety considerations. Therefore the steering of the installation machine will be performed by remote control via a wireless local area network.

Testing of problem-handling tools

The accidental dropping of a buffer block is one of the problems which can occur during the installation. The handling of this problem is divided in to two cases, before and after canister installation. Before canister installation it is possible to use a crane and gripping devices which are suitable for bentonite block lifting. After canister installation the problem of handling is more difficult. In that case a water-jet cutting system will be tested. Tests will be undertaken in the Onkalo site and in the Onkalo demonstration tunnel.

Quality control and verification

During the installation process the quality of the buffer block and positioning are inspected with cameras and measuring equipment. The aim is to use as simple methods as possible, however the accuracy requirements are so demanding that designers have been forced to use electronic equipment. The results of the verification must be traceable.

Concluding remarks

For the KBS-3H concept the MPT has firmly demonstrated the ability to manufacture full-scale components, their assembly at ambient *in situ* conditions and the undertaking of a logistically complicated *in situ* installation according to the reference DAWE design. Monitoring and subsequent dismantling will provide important information on the early development of the buffer components.

By combining the key components, an initial verification of the design implementation has been achieved. At the same time, integrating the components has meant the identification of design weaknesses and the design will be updated accordingly, e.g. the water content in the Supercontainer buffer and the identified need of additional drainage in the plug collar during the installation phase.

Posiva's KBS-3V buffer installation equipment is currently being developed and will be tested during late 2014 and 2015 in realistic underground conditions. The installation machine uses technology that has not been used before for this purpose. The functionality of the concept and equipment selected will be confirmed by the tests.

Despite the safe installation methods selected, problems during the installation are possible. Experiences regarding testing of problem-handling tools are the starting point for the design of tools needed in the final disposal work. Buffer installation tests provide important information about the suitability of the selected buffer dimensions and tolerances. After the installation of bentonite rings, there needs to be enough space for installation of a copper canister in the deposition hole.

These demonstrations are key activities in the stepwise development of European repository concepts. The project partners will, based on the collective experiences gained, update the detailed design of their respective concepts. Other European nations will have the possibility of building on this work that has been carried out to jump-start their own programmes.

Acknowledgements

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