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Final Report LUCOEX – WP5

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Publishable Summary

The purpose of the LUCOEX Work Package 5 was the development of bentonite buffer installation techniques for KBS-3V method. In the KBS-3V repository concept, the gap between the buffer blocks and the wall of the deposition hole will be filled with bentonite pellets after the buffer block emplacement. LUCOEX Work Package 5 consisted of the development of prototype installation machines and of the demonstration of the emplacement of full-scale bentonite buffer components in the deposition holes. Quality assurance methods and problem handling procedures during installation were also developed. Installation testing was done at the ONKALO repository site in Olkiluoto, Finland, where the final disposal facility for the spent nuclear fuel will be located, approximately at the depth of -420 metres. The demonstration tunnels used to test the final disposal techniques are also located at this level in ONKALO.

For the buffer full-scale emplacement demonstration, two prototype machines, a buffer block installation machine and a transfer device, were designed and constructed. The emplacement tolerances and accuracies associated with the buffer installation were studied before selecting methods and equipment for use in the installation tests. Also the method and the tool for filling the gap between the bentonite blocks and the host rock with bentonite pellets was developed and demonstrated as part of this LUCOEX work package 5.

In the first demonstration phase, the buffer emplacement method was tested in an artificial full-scale hole at the surface level test facility in the ONKALO area. Concrete blocks of the same size and mass as buffer blocks were used instead of buffer because the bentonite blocks could not mechanically tolerate the test emplacement cycling needed. These tests showed that the concept of the buffer emplacement devices worked and the installation accuracy of buffer blocks was well within requirements. Finally in this test phase, the gap between the buffer and the test hole was filled with bentonite pellets released out of the container top. In order to fulfil the requirements, pellet quantities in separate compartments need to be adjusted for varying gap volumes around the buffer block in question.

In the second and third demonstration phase, the buffer emplacement method was tested in ONKALO tunnel using a full-scale hole. Both concrete and bentonite blocks of the full-size and mass were used. These tests also showed that the concept of the buffer emplacement devices worked in real disposal conditions and the installation accuracy of buffer blocks was well within the requirements.

In all three demonstration phases, the development work items for the future work were recorded. The most important development targets include: accuracies of the different measurements needs to be improved and optimization is required in order to achieve the desired installation times.

Quality assurance and control methods were defined, as they are needed to ensure the overall quality of buffer during the disposal process. Different measurement techniques were considered to be used for QA-purposes. Tachymeter, laser tracker, inclinometers and visual inspections were used during the demonstrations. Useful experience was gained for future development work.

This study also examined potential accidents during buffer installation. In particular, in the course of buffer emplacement, a bentonite block could fall, be damaged and damage other bentonite blocks or canister already placed in the deposition hole. This occurrence requires removal of damaged buffer block materials and pellets. In the extreme case, all the emplaced buffer blocks and the canister have to be removed from the deposition hole. In order to facilitate buffer and canister recovery in such situations, equipment was developed and tested at full-scale in field conditions. This equipment includes a bentonite fragments lifting device and a water jet-cutting device for the damaged blocks and a suction pipe to remove the remains of the bentonite blocks and pellets from the deposition hole.

Contents

1 INTRODUCTION

The report describes development of prototype machinery used to demonstrate emplacement of the bentonite buffer that surrounds the spent fuel canister, in a vertical deposition hole.

The final disposal facility to store the spent nuclear fuel will be located in Olkiluoto, approximately at the depth of -420 metres. At this level are also the demonstration tunnels used to test the final disposal techniques.

The main aim of the work is to test the feasibility of Posiva's bentonite buffer emplacement method. This emplacement method for the bentonite blocks has been developed so that it is possible to carry out buffer emplacement within the required time of 120 minutes per borehole and attain an accuracy of +/-1 mm to the deposition hole centreline. The time requirement excludes the time spent assembling the spent fuel canister before the 4 topmost disc blocks.

The machinery developed consists of a lifter device mounted on a semi-trailer format frame, a bentonite block transfer device and a modified suction gripper integrated into bentonite block transfer containers for lifting and moving bentonite blocks.

A method for filling the gap between the bentonite blocks and host rock with bentonite pellets was also developed and tested.

The quality of installation is a key aspect in making sure that the multi-barrier system functions as designed. The scope of the work in installation quality point of view is to develop sensor systems to deliver the data needed to achieve the quality assurance targets (QA). In practice this means choosing the most suitable sensor technologies. Developing the automated analysis tools associated with the buffer installation process is a vast software engineering task.

This report describes also development of methods for the management and recovery of broken buffer blocks, gap filling and other exceptional situations, from a vertical deposition hole during KBS-3V emplacement work and gap filling.

The machinery developed to remove damaged buffer components consists of a bentonite block lifter device mounted on a frame, a device for water jet cutting damaged blocks and a suction device to remove block and pellet fragments or materials from the deposition hole.

2 FEASIBILITY STUDIES

Two feasibility studies were performed; one to identify methods of handling the bentonite blocks and pellets and one to develop the prototype machinery used to transfer and emplace the bentonite blocks.

2.1 Bentonite block handling

As part of the bentonite buffer installation process the blocks are transported from the manufacturing to the central tunnel in ONKALO where they are loaded onto the transportation vehicle to be moved further into the deposition tunnel. Bentonite is easily damaged if brought into contact with water, for example water drops from the tunnel ceiling. Ambient humidity changes can also be harmful to bentonite blocks. Bentonite blocks are also easily damaged by physical impact and they should be handled with care. Therefore the blocks have to be covered and sealed from effects of the environment before moving them from the manufacturing facilities. It is favourable for bentonite if it is kept covered and shielded as far as possible, until installed into the deposition hole.
Three possible methods to cover the bentonite blocks have been investigated during the concept phase of buffer installation machinery. All methods include covering after manufacturing in the factory before moving to storage or directly to ONKALO. These methods are: wrapping in plastic, use of a metal cover, or a sealed container. All covering methods offer shielding against humidity changes and water droplets.

Wrapping in plastic is performed by first putting the block in a preformed plastic bag which is then emptied of air by a vacuum system and then sealed airtight. Blocks so prepared are moved on pallet-type bases that are suitable to be handled with a forklift. On arrival at the emplacement level, the plastic cover is removed before the block can be manipulated with a suction gripper. The uncovered blocks are then subject to humidity in tunnel environment and must be installed in deposition holes without delay.

A metal dome can be used to cover the block. In this case the bentonite block is inside a metal canister with bottom plate and a metal dome. The dome must be sealed to be airtight with bottom plate. Low vacuum could be used to hold the dome in place during transportation. Alternatively mechanical locks can be used instead of, or in combination with vacuum. To keep the block in place during transport, adjustable pads that are tightened between dome and the bentonite block can be used.

Container with gripper, shown in Fig. 1, consists of a metal cover for the bentonite block but a gripper is integrated into the transport unit. Each bentonite block is put into a separate container under controlled conditions in the factory. The container is then sealed, thereby ensuring good protection against the environment.

In the process of preparing the container and block package, bentonite blocks are first aligned with the container top and then lifted into the container. Sealing of the container is achieved through use of a weak vacuum inside the container. This weak vacuum is maintained on the vacuum grippers during transportation, ensuring the alignment between block and gripper. Mechanical pads between the canister and the bentonite block can be used to keep the block on place during the transportation and handling in factory and tunnel.

A further consideration in the planning for block placement in a borehole is that each bentonite block may have a dedicated deposition hole and location in that hole. In such a situation the amount of pellets needed to achieve the target bentonite density can be precalculated based on the pre-determined geometries of the bentonite block and borehole. Thus the amount of bentonite pellets can be premeasured in the manufacturing facility and put into a pellet storage and deposition compartment that can be constructed on top of the gripper.

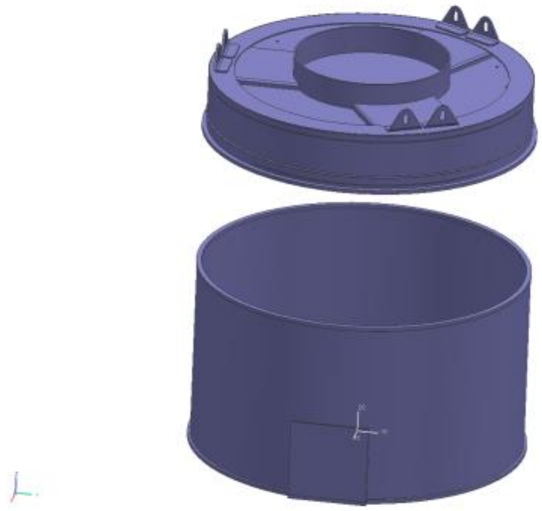

Fig. 1. *Container concept with vacuum gripper and pellet storage.*

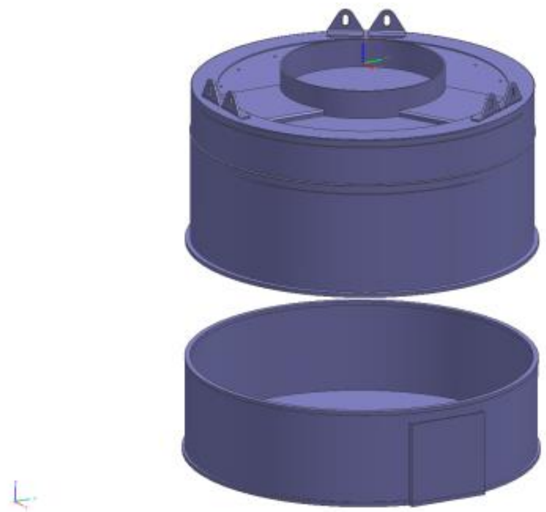

Fig. 2. *Container concept with extended cover piece.*

2.1.1 Selection of preferred buffer handling approach

Before choosing the most suitable method to cover and transport the bentonite blocks, the transportation method/sequence from the central tunnel to the deposition tunnel had to be selected.

Based on a need to minimize transportation-related activity in the deposition tunnel and an assumption that a full set of bentonite blocks are to be brought to the deposition hole at the same time, the best solution would probably be plastic wrapped bentonite blocks. This option has the smallest volume of handling-related materials.

The metal dome does not offer significant advantages over the plastic-wrapped blocks because the buffer block has to be removed from the dome in the central tunnel. This transfer location is similar to that of the plastic wrapped blocks (which could be mechanically shielded (e.g. in a boxed lorry) up until this location in the repository.

The container alternative provides best protection through the whole transportation chain until the deposition hole. The most important surface in the block, the top surface is protected all the way to the deposition hole, which is not the case with the other concepts. In this option, alignment of bentonite block and gripper is accomplished at the factory facility and high accuracy weighing and loading of pellets is also done on the ground level. Grippers and pellet storages are able to be checked before installation on the bentonite block, and in the factory there are tools, cleaning agents and sufficient space to make corrections to the gripper if needed. This significantly simplifies the quality control process and should allow for reduction of block rejection at the deposition tunnel.

Based on these considerations, it was determined that the container-type cover is the preferable choice for handling bentonite blocks before and during installation in Posiva’s KBS3-V repository.

2.2 Bentonite buffer installation equipment

In the bentonite buffer installation process the blocks are transported from the factory to the driving tunnel in ONKALO where they are loaded to the buffer installation or transfer vehicle to be moved into the deposition tunnel.

When starting concept development for the whole installation process it was assumed that the installation equipment would carry, at the same time, all the bentonite blocks needed to fill a deposition hole. With time it became obvious that there would be advantages gained with a concept consisting of separate installation and transfer vehicles.

The development of workable concepts for installation and transfer vehicles has an important part achieving the specified installation time and buffer block quality. The various vehicle concepts have inherent limitations with respect to what bentonite block handling methods can be utilized. These differences were very important in the process of assessing options and selecting suitable buffer installation equipment and logistic concepts. As equipment design options were developed, tunnel space became an issue, forcing study of possibilities of using a smaller transfer vehicle, carrying less blocks. Cycle-time calculations have also needed to be made in order to determine the total installation time for each concept.

2.2.1 Alternative transfer vehicle concepts

The main criterion in developing the transfer vehicle concept has been the need to use the machinery underground, recognizing the limited space available for its operation. Other important criteria are safety, reliability, speed, serviceability and manoeuvrability.

Five possible vehicle concepts have been developed, all of which have rubber wheeled chassis and are moved with a terminal tractor. These concepts differ in two main ways: one is using a combined transfer and installation vehicle or two different vehicles; the other is determining the amount of blocks to be transported, all at once or less - even only one–at-a-time.
The type of the vehicle has a great influence to the whole installation concept. Limited space in the tunnel means that transporting several blocks at the same time is possible only with uncovered blocks. This again defines the way in which blocks will be handled.

2.2.2 Full Set Combined Vehicle (FSCV)

In this concept, a vehicle with both transfer and installation vehicles integrated to one construction is used (Fig. 3). All bentonite blocks needed for the first installation phase (six blocks), can be moved at the same time. This vehicle has all the equipment needed for the buffer installation: suction gripper, moving lifting mechanism, pellet storage and measuring device for quality control. Only uncovered blocks can be used in this option and blocks are loaded onto the vehicle using an external loader.

The large size and heavy construction necessary for this type of placement equipment makes handling in the narrow tunnel difficult. The large frame construction makes it more flexible and also makes it difficult to load blocks into the vehicle. Stiffening the frame would make loading even more difficult. Uncovered blocks are subject to humidity in tunnel environment and must be installed in deposition holes without delay. Any device malfunction during installation would be especially harmful with this concept.

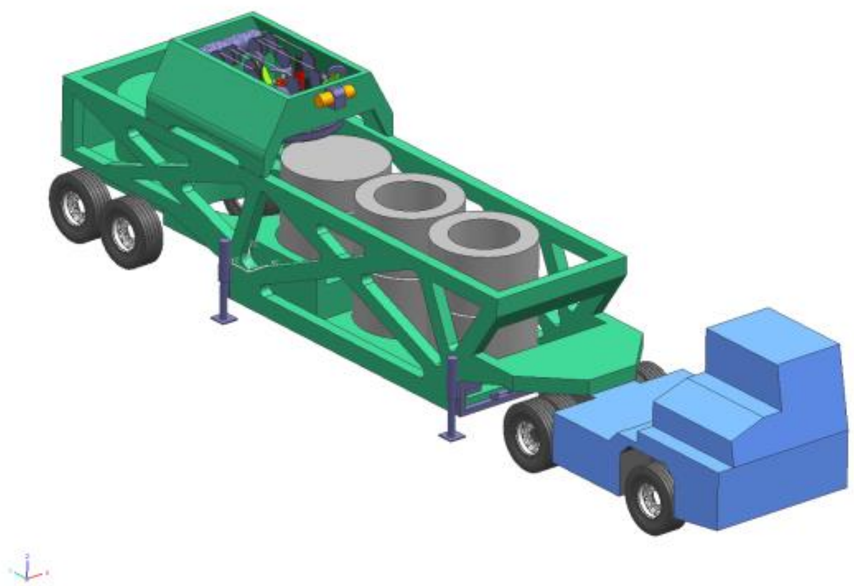

Fig. 3. *Full Set Combined Vehicle with terminal tractor.*

2.2.3 Two vehicles concepts (TVC)

Two vehicle concepts consist of an installation vehicle and a transfer vehicle. Installation vehicle is used for the buffer block and pellet installation and transfer vehicle for moving the blocks to the installation vehicle.

Installation vehicle

Installation vehicle has a frame with one axle, preferably with rubber tires and four actuated support legs to level the vehicle before and during the installation process (Fig. 4). The wheels can be made steerable to ease rough positioning over the deposition hole. The installation vehicle is brought to the deposition hole with a terminal tractor and removable fifth wheel. After rough positioning with terminal tractor, installation vehicle is aligned with the deposition hole with supporting legs and crane. After alignment installation vehicle is ready to start installing the bentonite blocks.

The details related to the lifter design differ depending on whether uncovered blocks or containers are used. When using uncovered blocks, an additional pellet storage and filler tool is needed. Also when using uncovered blocks, a platform is added to the frame for the blocks to be placed on when moved from the transfer vehicle in the full set transfer vehicle concept.

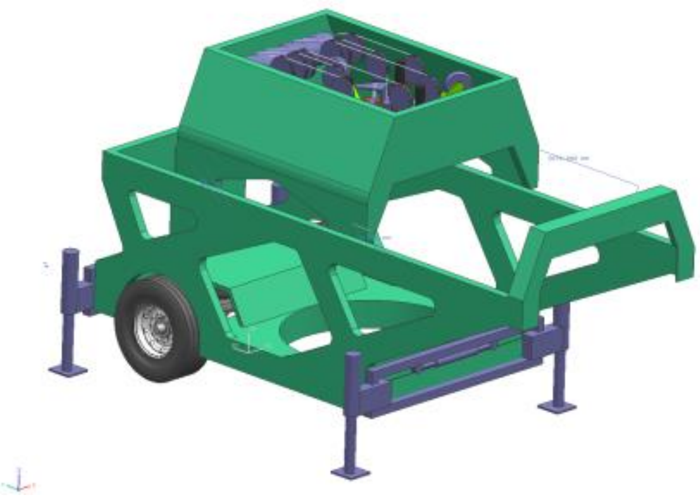

Fig. 4. *Installation vehicle concept model.*

Transfer vehicle

Bentonite blocks are transported from the driving tunnel using a separate transfer vehicle. This transfer vehicle can carry from one to six blocks at same time, depending on the specific design adopted. It should be noted that transporting more than two blocks at a time needs the six block transfer vehicle.

The simplest transfer vehicle type carries only one block in a single container (Fig. 5). Although the least complicated with respect to basic vehicle design, it does pose logistical complications as the gripper (container top piece) from the previous block has to be stored somewhere near the installation vehicle (on tunnel floor near deposition hole), when the transfer vehicle is getting the next block.

The one block transfer vehicle can be enlarged to carry two blocks. This construction provides no advantages compared with the one block plus-model, but is heavier and slower to handle. It requires additional equipment to move blocks and empty containers over each other.

The estimated installation time for the buffer is 115 minutes with installation vehicle and one block plus gripper transfer vehicle concept.

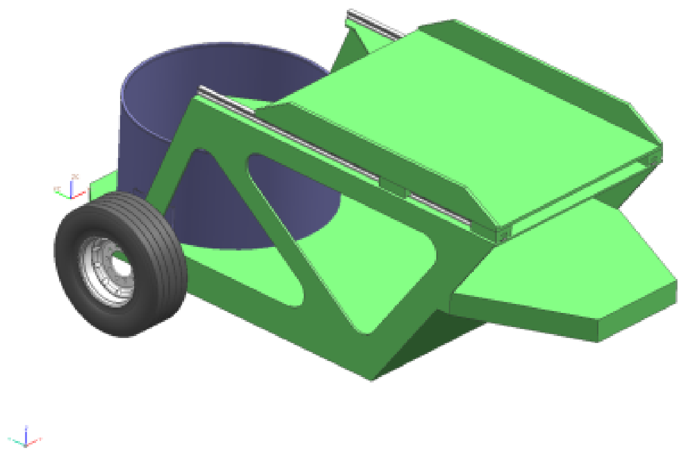

Fig. 5. *One-block-plus-gripper type transfer vehicle concept.*

Full set transfer vehicle (FSTV)

A transfer vehicle concept that can carry up to six bentonite blocks has also been studied (Fig. 6). This vehicle type must have a lifter of its own to serve the installation vehicle. Like with the FSCV concept described in Section 2.2.2, only bare blocks can be handled.

Compared with the FSCV the full set transfer vehicle is lighter and so is easier to handle in the confined underground environment. The full set vehicle needs to be driven and positioned only once to the deposition hole so the driving speed that was a factor in two vehicle concepts where smaller numbers of blocks needed to be moved and containers or lids needed to be stored has no effect on installation time. The stationary installation vehicle used in this concept can be made rigid and easier to position compared with the FSCV. The special type of lifter in the block transfer part of the system has a limited horizontal adjustability to align a block correctly for the installation vehicle. This will facilitate the transfer and registering of the blocks during the installation process.

As with the FSCV concept there is also the need to align the lifter with each block and to clean the gripper after each lift. The pellet gap filling is also complicated compared with container concepts which include the ability to complete pellet placement as part of each block installation cycle. All of these factors lead to a long installation time similar to FSCV concept.

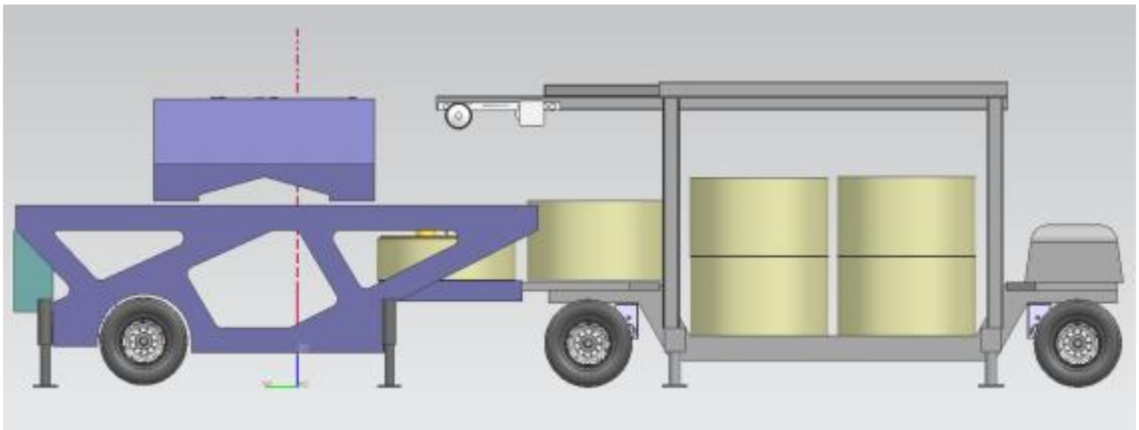

Fig. 6. *Full set transfer vehicle with installation vehicle. Concept drawing.*

2.2.4 Comparing alternatives

In comparing the concepts reliability, speed and safety are among the most important criteria.

Reliability of installation is primarily connected with the complexity of the machinery and complexity of the installation process. Concepts that enable use of blocks in containers have an advantage compared to those using bare blocks. Containerized blocks need less handling during installation because the blocks are prealigned with a gripper in the factory prior to delivery to the tunnel. Hence there is no need for alignment of the gripper on blocks in the tunnel before it can be moved into place. Blocks not provided in pre-loaded containers need repeated lifting and aligning and hence cleaning of the gripper becomes an issue since separate equipment for cleaning is needed. Pellet filling is simpler using containers that have the pellets and filling equipment integrated with the gripper. Without preloaded pellet/gripper units, the installation of the pellets will require additional filling and measurement equipment, which will slow the entire process.

With respect to operational cycle time; less work in block handling and transfer means that the installation process is faster using container blocks. Using one block transfer vehicle means travelling several times back and forth in the tunnel. This increases the number of steps in the placement process, but as the transportation is made at the same time as the installation there is only little effect on total installation time. Installation cycle time calculations show that full set combination vehicle concept has an estimated installation time of 130 minutes per borehole. In contrast the one block transfer vehicle concept is estimated to use 115 minutes to buffer in one borehole. Installation speed in the one-block transfer vehicle concept is of course very dependent on the driving speed in the deposition tunnel and logistic arrangements in driving tunnel.

Personnel safety is highly dependent on how close to the working machinery one has to go. Plastic covered blocks require the plastic to be removed manually, potentially creating a safety risk since underground staff will be moving around heavy equipment. In contrast, buffer supplied in containers and metal domes can be handled via remote control, reducing personnel risk. Remote control is used to some degree with all the concepts, particularly when installing the last buffer blocks after the canister has been installed.

A further general consideration is associated with a case where installation malfunction or other problem that needs the equipment to be removed from the deposition tunnel has occurred. In such situations, the smaller and lighter the vehicles are, the easier they are to remove so access to undertake remedial action is quicker.

Based on the considerations outlined above, a conceptual design for an installation and transfer vehicle that handles two buffer and pellet-filled containers has been developed. Fig. 7 shows how such a vehicle might be configured.

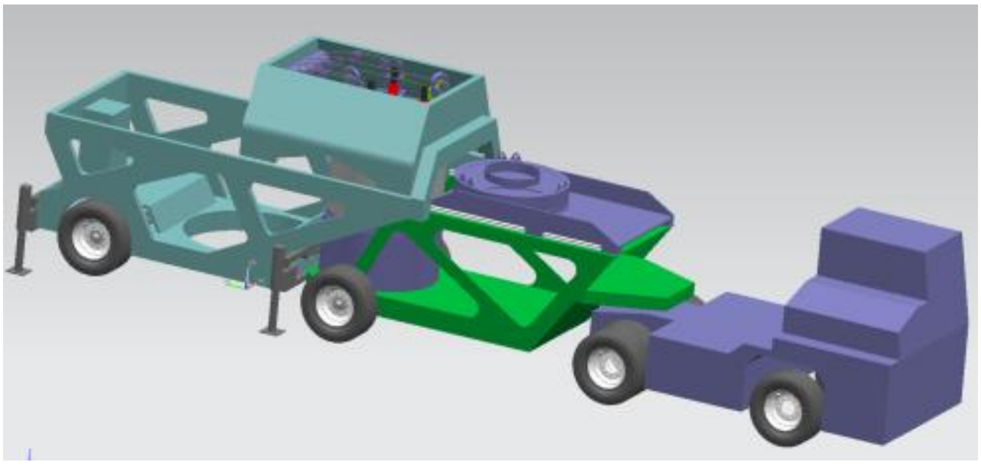

Fig. 7. *Suggested concept for installation and transfer vehicles as well as terminal tractor.*

3 DESIGN

3.1 Concept design stage

As outlined in Chapter 2, concepts of how bentonite buffer emplacement equipment might be configured has evolved from a rather simplistic 1-block at a time transfer system consisting of a beam-framed lifter system to a significantly more advanced automated device that will allow for several buffer segments to be transported in a single cycle.

In the beginning of the concept design phase, it was necessary to break down all the steps involved in bentonite buffer emplacement. From this it was possible to determine the necessary action speeds for each step. Then the actuator sizes, motor power ratings and gear ratios necessary could be calculated.

3.1.1 Sequence of activities in buffer installation

The eight basic steps associated with buffer emplacement are shown in Fig. 8.

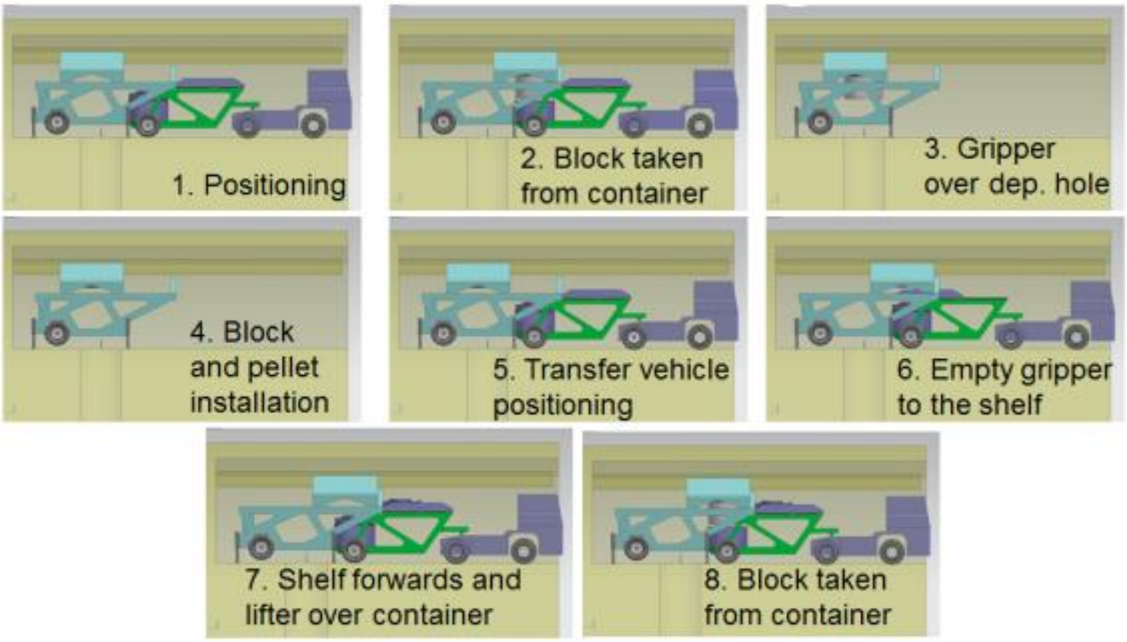

Fig. 8. *Buffer installation sequence.*

3.2 Bentonite block installation machine

3.2.1 General description

The bentonite installation machine, developed for use in Posiva's repository concept consists of a semi-trailer format frame, on top of which a lifter unit is located.

There are five primary components to this machine:

- The frame (1): is equipped with two wheels on a single steerable axle.
- The support leg subframe (2): The machine is levelled using four support legs moved by electromechanical actuators. It can be moved transversely (Y-direction) allowing the positioning of the machine directly on top of the deposition hole. The subframe is attached to main frame via two linear guides and moved by two electromechanical actuators.
- The pulling beam (3): This contains a king pin connection that is lifted to enable the bentonite transfer device (BTD) to pick up empty container top.
- The lifter unit (4): The lifter is movable on a pair of linear guides (X-direction) and actuated by two electric motors driving gear wheels against tooth racks. A winch with three steel ropes is providing movement (Z-direction) to a mechanical gripper to raise and lower the container top with bentonite blocks and pellets.
- The gripper (5): It has three electromechanical actuators that enable accurate radial positioning of the bentonite block during the last 100 mm downwards travel. The gripper attaches to the container top via three pneumatically actuated lock pins. The container top has a vacuum lifting surface against the top surface of bentonite block.

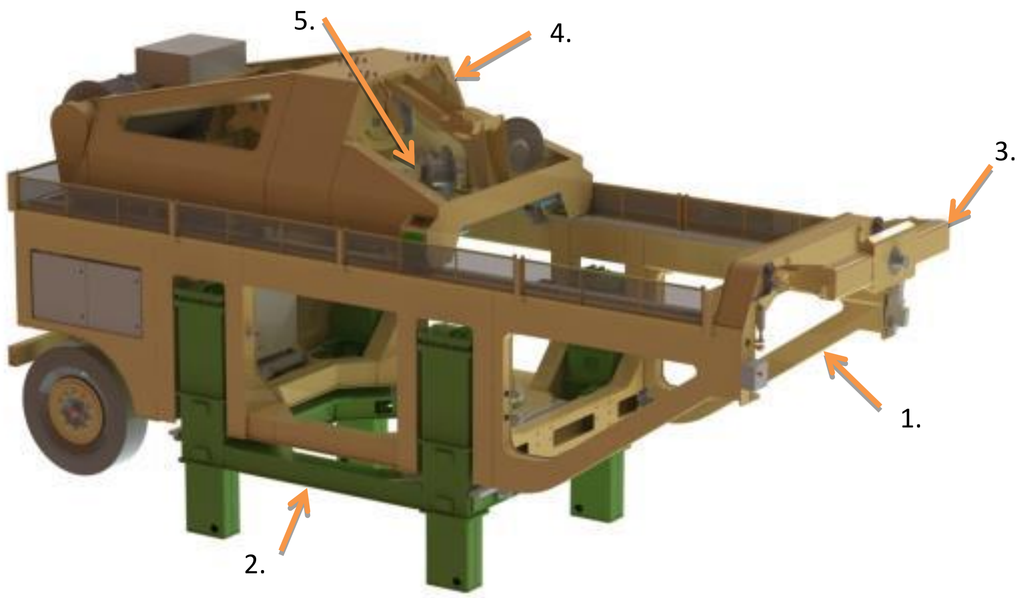

Fig. 9. *3D-model of bentonite installation machine (BIM).*

Table 1. *BIM technical specification.*

Mass	20000 kg	
Length	7710 mm	
Width	2590 mm	
Height	3750 mm	
Power	Electrical P=30 kW	
Electrical feed	3x400 VAC, 63 A, 50 Hz (TN-S)	connection to tunnel network
Batteries	200Ah/24VDC	control unit, lights and steering of rear axle
Control unit	Crosscontrol CCpilot XM,	CANopen, Ethernet

	CoDeSys V3	
Operators	1 person	
Transfer speed	<5 km/h	
Buffer emplacement time	120 min/deposition hole	
Buffer emplacement accuracy	±1 mm	measured from deposition hole vertical centre line
Gripper carrying capacity	5000 kg	
Gripper X-movement	2650 mm	
Gripper Y- movement	225 mm	
Gripper Z- movement	12000 mm	
Ground clearance	280 mm	

3.2.2 Actuation options

At the beginning of the BIM design process, the movements of the BIM were intended to be hydraulically actuated. However, hydraulic oil used in this type of equipment creates a contamination hazard for bentonite blocks and the deposition hole. For this reason, there was a need for an alternative actuation method to be identified and developed. Options identified were water hydraulics, pneumatic and electromechanical actuators. Water hydraulics was studied and found to be technically possible. As most components would need to be customized for water, the cost would have been impractically high (5 to 7 times the cost of oil hydraulics).

Pneumatics actuation evaluation identified that air flow and volume required to run the system would have been a technical challenge, requiring a lot of space within the machine frame for hoses, compressor and air storage.
Accuracy of such a system's operation would have been compromised due to compressible nature of air. The size of the actuators needed to deliver the required forces would have been very big.

Electromechanical actuation was the third option and it avoided most of the limitations identified for the other alternatives and still retained sufficient robustness and accuracy of operation.

3.2.3 Lifter unit

The lifter unit frame is a welded steel plate construction onto which the winch, mechanical gripper and other lifting equipment are attached (Fig. 10). It also carries the laser scanner, pneumatic hose and electrical cable reels. The lifter unit moves longitudinally on linear guide racks on BIM main frame unit (Fig. 9) and is powered by two electrical motors via gearboxes and pinion wheels.

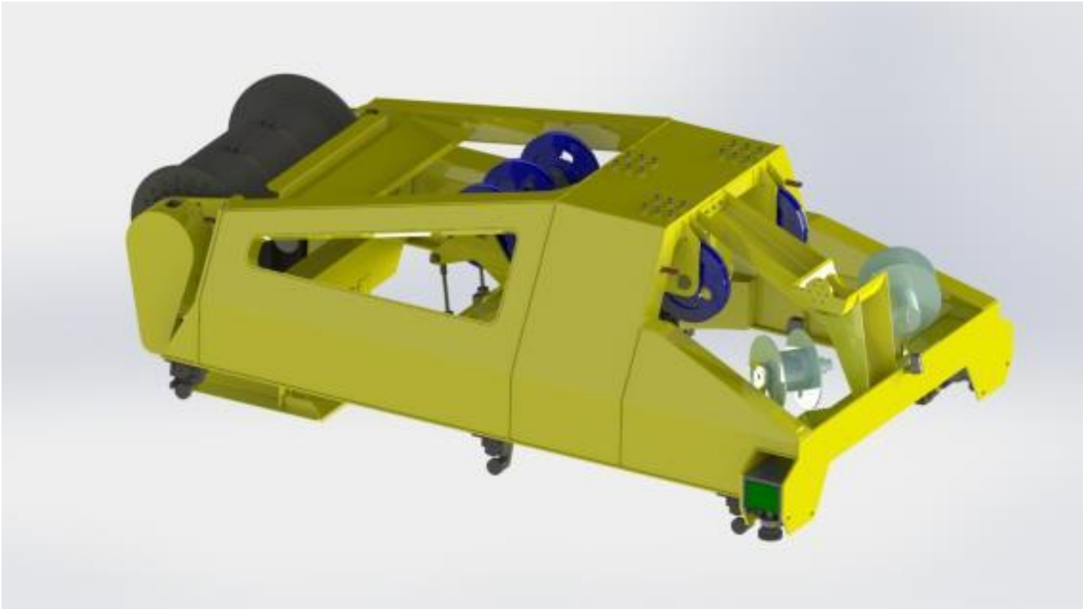

Fig. 10. *BIM lifter unit.*

3.2.4 Winch brake and gearbox system

The winch brake and gearbox system are critical in terms of ensuring safe and controlled movement of the buffer blocks. The winch brake used in the BIM design is an electrically activated and manually disengaged Dellner EFP 2x100 disc brake. The brake activates when an electric solenoid is de-energized (e.g. electrical power failure). The tangential braking power is 120000 N.

The gearbox selected for the winch system will determine the smoothness and speed(s) at which buffer blocks can be handled (raised/lowered). During the selection process for the winch gearbox type needed, consideration was given to helical gear unit, worm gear unit, a Posiplan unit and a planetary gear unit. As the planetary gear unit offered the required reduction ratio and torque capacity in a compact enough space, it was the choice for further design.

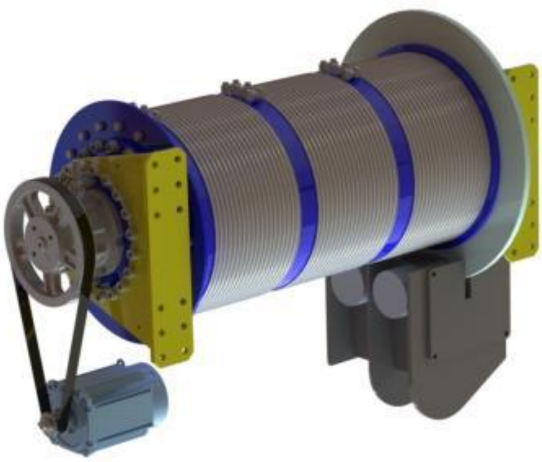

Fig. 11. *Winch assembly.*

3.2.5 BIM main frame

The BIM main frame unit (Fig 12) is a welded steel plate construction, onto which the steerable rear axle, linear guides for lifter unit and support legs, the pulling beam, pneumatics system and electrical system are attached. It has a pair of longitudinal linear guides for the lifter unit and a pair of transverse linear guides for the support leg subframe.

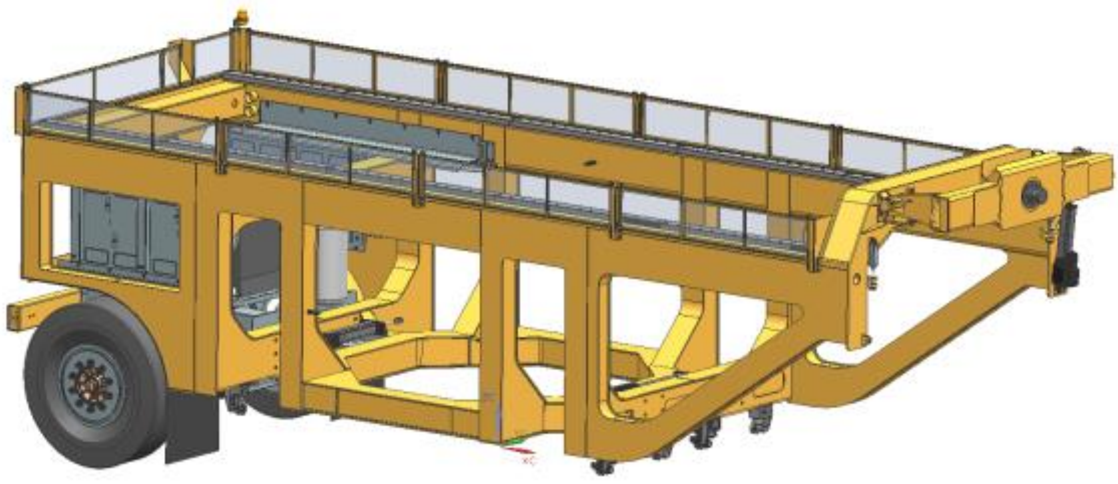

Fig. 12. *BIM main frame.*

3.2.6 Support leg subframe unit

The support leg subframe assembly of the BIM is a welded steel plate construction with four independently actuated legs (Fig. 13). The subframe can be moved on linear guide units to enable limited lateral positioning changes of the machine. Each support leg has one servo driven Exlar FT-60 electromechanical actuator (1) rated at 90.8 kN thrust force and 600 mm nominal travel. Actual travel is limited to 550 mm.

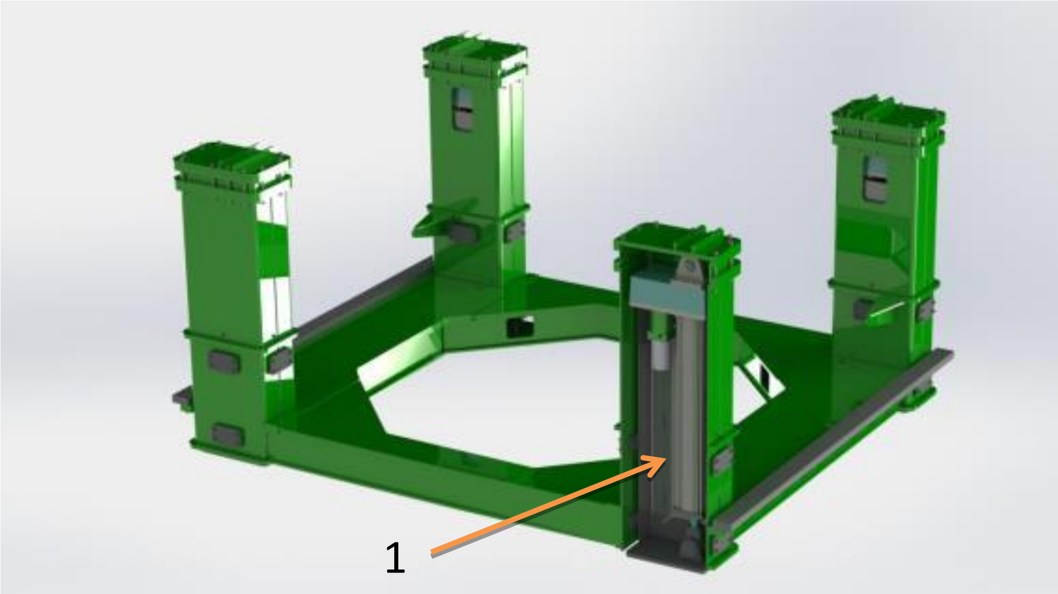

Fig. 13. *Support leg subframe assembly.*

3.2.7 Pneumatic system

While the design selected for the BIM does not use water or air actuators, there is still a need for a vacuum system to operate several of the peripheral components. The BIM therefore has an independent pneumatic system to deliver compressed air for vacuum generation, pulling beam lock cylinders, gripper lock cylinders and the container pellet release system.

The pneumatic system installed in the prototype BIM consists of a Gardner Denver compressor, a Hiross air dryer, piping, valves and accessories.

Table 2. *Pneumatic system specification.*

Peak flow	360 l/min
Operating pressure	7 bar
Pressure reservoir capacity	2 units of 200 l each
Condensate water tank capacity	30 l

3.2.8 Mechanical gripper unit

The original lifter (Saari et al. 2010) used in testing vacuum lifting of large concrete blocks (simulating bentonite buffer blocks) was equipped with a rotary vane vacuum pump. As the temperature range in Onkalo demonstration tunnel was given as +5…+12 °C, and the operational ambient temperature lower limit for such rotary vane pump is +12 °C it was necessary to find a pump type suitable for underground environment. The solution identified was use of a set of three ejector pumps rated to temperatures as low as -10 °C (Fig. 14).

The mechanical gripper unit is suspended from the lifter unit by three steel ropes, each individually adjustable via electromechanical actuator for accurate levelling of the gripper and its load. The gripper also has a robotic connector in the centre for electrical and pneumatics feedthrough to the container.

Fig. 14. *Mechanical gripper unit*

3.3 Bentonite block transfer device

The bentonite transfer device (BTD) shown in Fig. 15, is a trailer moved by a terminal tractor unit. It is equipped with a single steering axle to ease the positioning near BIM and to limit the steering effort while driving in demonstration tunnel. The BTD is steered manually by the terminal tractor operator. The operator has a direct view to BTD, assisted by live feed from video cameras on BTD. The BTD gets both its hydraulic power and 24V electric power (for controls) from the terminal tractor. All BTD movements are actuated by hydraulic cylinders controlled by proportional valves.

As shown in Fig. 15, the transfer device in the prototype BTD can carry one block in a container. This device has a longitudinally moving platform to store the previous container top.

Fig. 15. *3D-model of bentonite transfer device.*

Table 3. **BTD technical specification.**

Mass	4600 kg	
Length	6960 mm	
Width	2790 mm	
Height	2500 mm	
Power	Hydraulic P_{min}=200 bar	From tractor unit
Electrical feed	24 VDC, 2x10 A	From tractor unit
Control unit	Crosscontrol CCpilot XM, CoDeSys V3	CANopen, Ethernet
Operators	1 person	
Transfer speed	<5 km/h	
Maximum load	6000 kg total	Top shelf: empty container top 440kg
Maximum lateral inclination	20 %	
Ground clearance	0…500 mm	hydraulic adjustment

3.4 Bentonite block container

Resulting from the bentonite handling feasibility study, a steel container was designed for bentonite blocks (Fig. 16 and Fig. 17). The primary roles of this container are to protect the block from humidity, contamination and possible impacts during transportation.

A container consists of:

- Cylindrical, bottom vessel built using mild steel and
- A top with integrated suction gripping surface and pellet compartments.

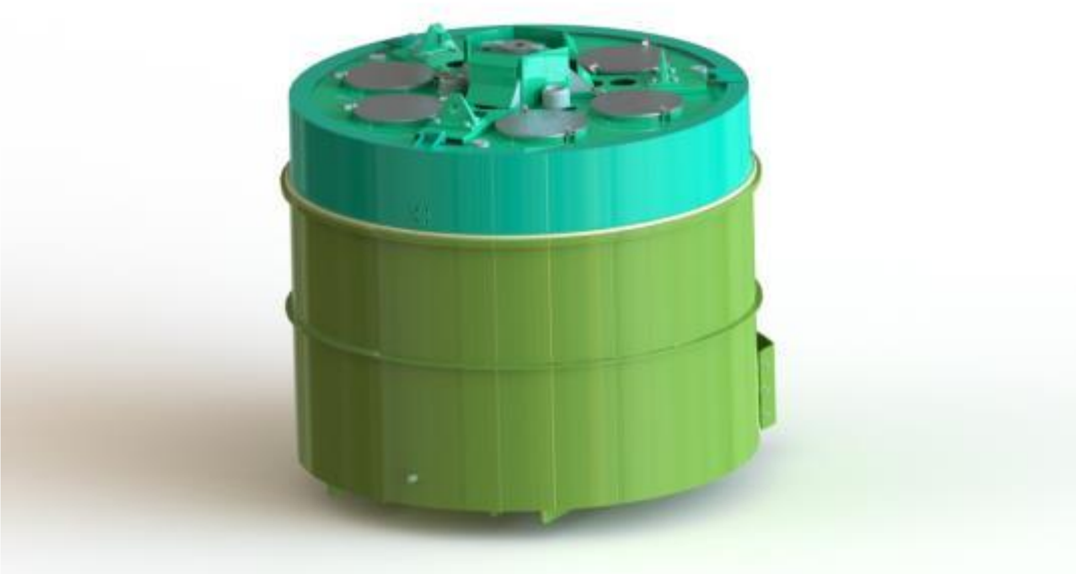

Fig. 16. *3D model of bentonite container.*

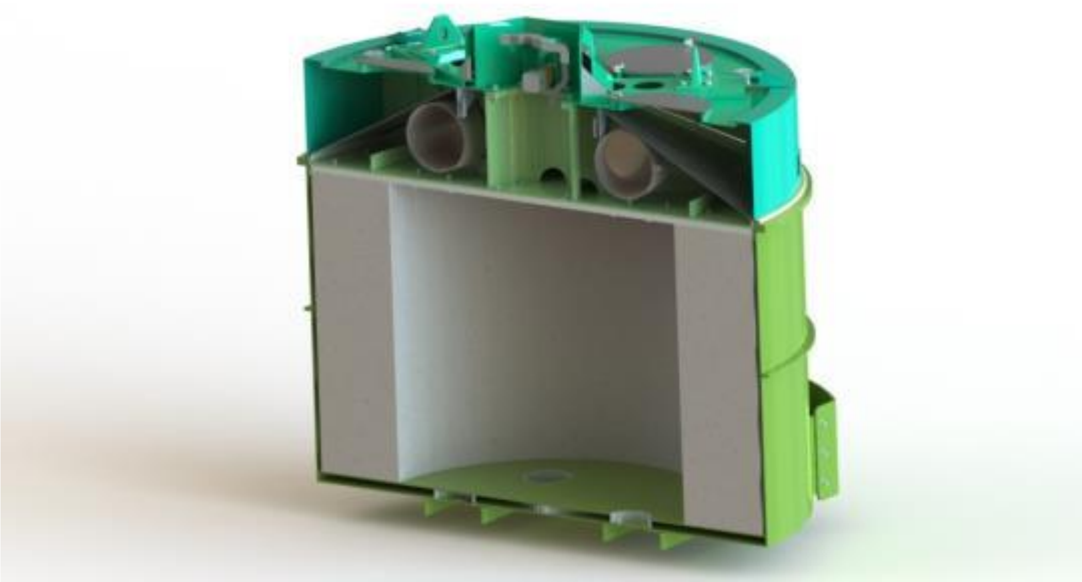

Fig. 17. *Split view of the bentonite container with a ring block. Picture shows the later variation of container top.*

3.4.1 Re-designed suction gripper

The initial design for a suction gripper was for a single unit consisting of a steel structure with vacuum pump and suction surfaces. Current design divides the functionality between bentonite block container and bentonite installation machine.

Vacuum generation comes from three ejector pumps located on the mechanical gripper. The mechanical gripper is permanently attached to the lifting ropes in BIM lifter unit. The top part of the container is classified as a non-fixed load lifting attachment according to SFS-EN 13155.

The top part of current container serves three functions:

- covers and seals the bentonite block within the container
- provides a vacuum gripping surface to lift the bentonite block
- contains bentonite pellets for gap filling

Table 4. *Technical specification for container top/suction gripper.*

Lifting capacity	3900 kg nominal	4875 kg test lift weight (125%)
Vacuum generation	3x Piab P6040 Xi	
Vacuum level	95% of full vacuum	
Minimum vacuum level	40% of full vacuum	n=2
Air consumption	110 Nl/min	
Pellet capacity	250 litres	6 compartments
Vacuum reservoir displacement	68,4 litres	6 reservoirs 11,4 litres each
Number of suction circuits	3	

3.4.2 Pellet compartments

There are six pellet compartments inside the container top. Each compartment contains a pre-measured amount of bentonite pellets, so that after each bentonite block is in place, the pellets can be filled into the remaining volume. The amount of pellets loaded into each compartment is determined by calculating the gap between block and deposition hole wall. Calculation is based on laser scanned model of the hole and bentonite buffer size and location.

3.5 Control and automation systems

The control system of the installation equipment consists of two independent subsystems, one for the Buffer Installation Machine (BIM) and other for the Bentonite Transfer Device (BTD). Both are based on a PC-based controller with CoDeSys V3 programming environment.

Although not expected to be a normal operating practice, the BIM control system comprises of both direct manual operations and automatic operations initiated by the operator. Fig. 18 and Fig. 19 show the control unit associated with the BIM. When the BIM is travelling along the tunnel, it is possible for the tractor operator to steer the BIM rear axle from the tractor cabin.

The BIM is normally expected to be operated from a remote operating station in order to maximize worker safety by minimizing physical interaction of personnel with large equipment. All BIM functions can be controlled from this position utilizing sensor data (as shown in Fig. 20) and video feed from cameras. How this is accomplished via an automation program is shown in Fig. 21.

All the movements of the BIM are accomplished by use of electromechanical actuators. The support legs, winch drum and lifter X-movement are controlled via servo drives located inside electric cabinets. Electromechanical linear actuators with integrated servo drives are used for rear axle steering, frame Y-movement, winch rope adjusters, pulling beam lifting and gripper fine positioning. All adjustable movements in BIM are equipped with absolute sensors so as to ensure that no limits regarding positioning are exceeded.

Fig. 18. *BIM main control unit*

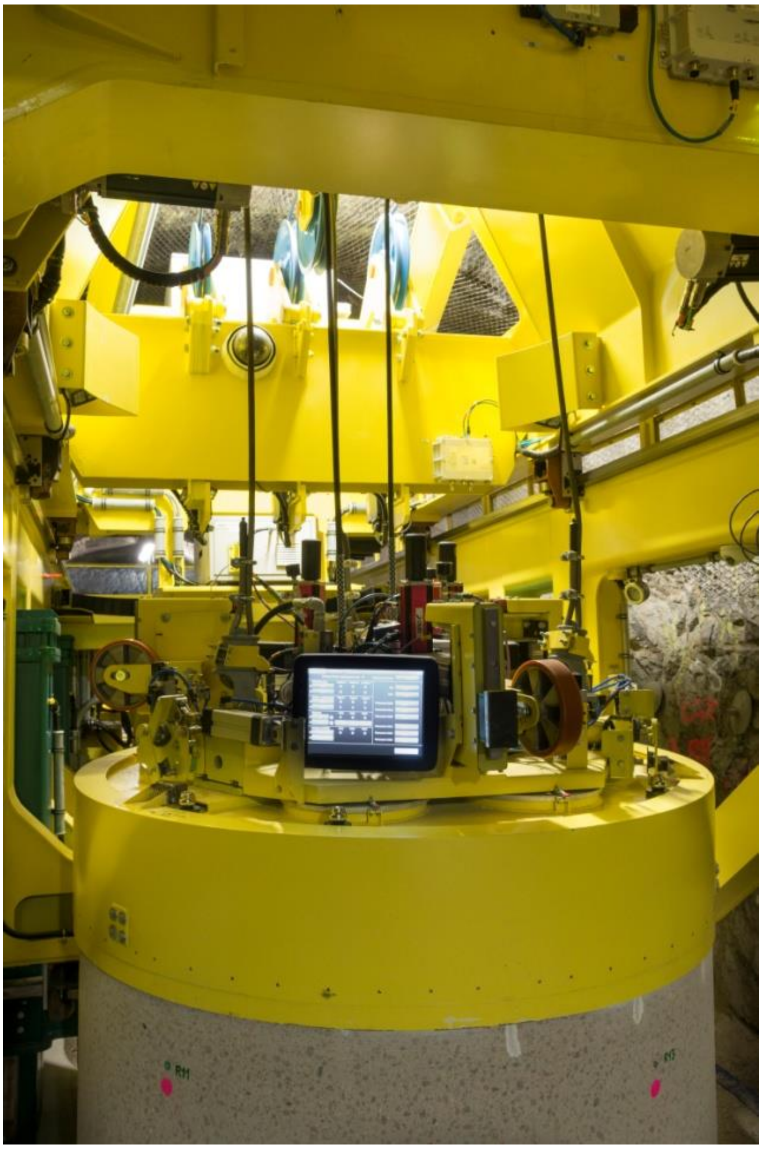

Fig. 19. *Gripper control unit computer on BIM mechanical gripper*

Fig. 20. *Remote control view of BIM main control unit and gripper control unit*

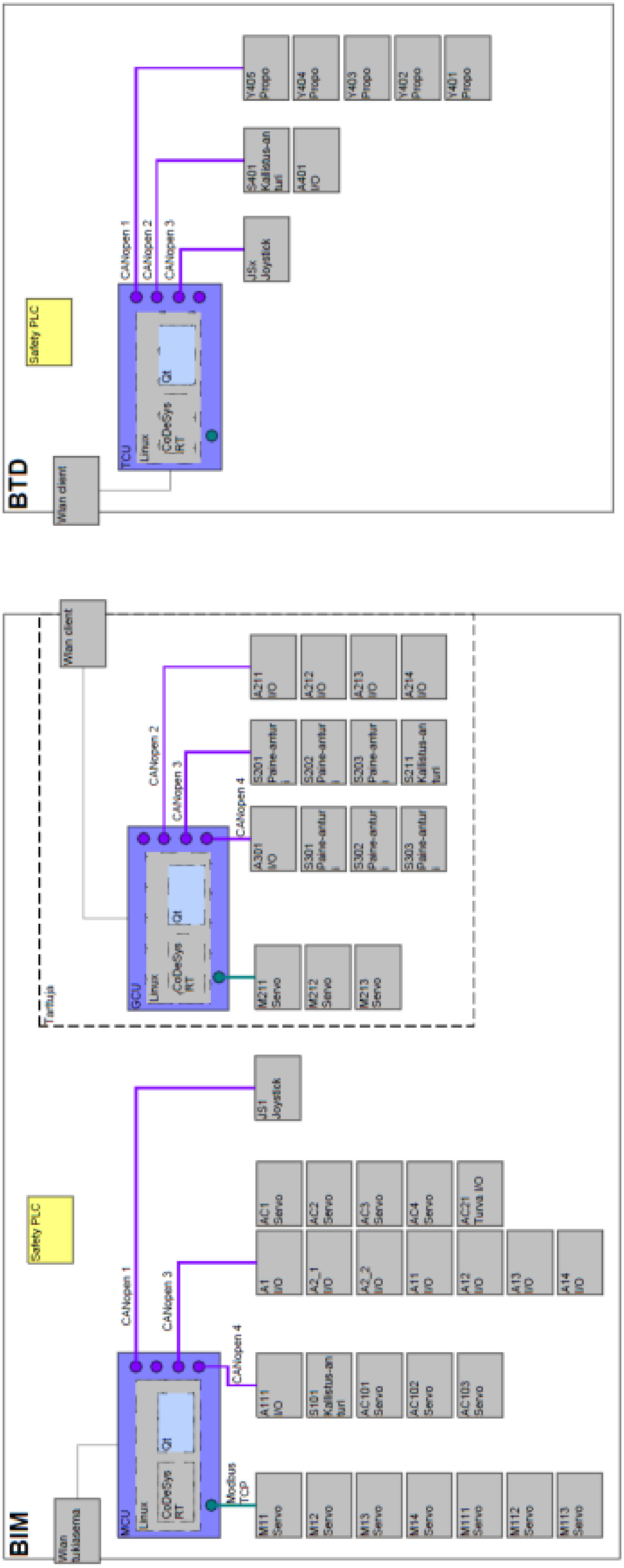

Fig. 21. *Automation program layout for BIM and BTD*

4 MANUFACTURING

Manufacturing of the prototype equipment developed conceptually for use as BIM and BTD began in the summer of 2012 (BIM) and in the spring 2013 (BTD).

4.1 Bentonite block installation machine

The bentonite installation machine was manufactured by Konepaja Laaksonen Oy in Turku, Finland. This machine was a completely novel design and required very stringent construction specifications to be followed. The result was a slower than planned construction and delivery delay past the originally anticipated date. The machine was however completed and delivered to Posiva Oy for use in installation trials on the surface at Olkiluoto and underground in Onkalo.

All electrical installations were made by Elmont Oy, from Lahti, Finland in Konepaja Laaksonen Oy premises.

4.2 Bentonite transfer device

The bentonite installation machine was manufactured by Lehtosen Konepaja Ltd. in Kokemäki, Finland. As with the BIM, this component was a new design and required specialized manufacturing expertise. It was completed within the specified time-frame and used in surface and subsurface trials once linked to the BIM.

4.3 Bentonite block transfer container

The bentonite block transfer container manufacturing was split between Konepaja Laaksonen Oy and Lehtosen Konepaja Ltd.

The container tops are closely related to BIM lifting system and therefore require that they be built in close consultation. As a result the tops and BIM were both manufactured at Konepaja Laaksonen Oy.

The lower, container bottom vessels to be carried by BTD were constructed by Lehtosen Konepaja Ltd. The container base is of welded sheet metal construction, which made creation of a relatively lightweight but dimensionally accurate unit challenging. While not simple, the lower component represents a more basic mechanical construction that still must be mated to the lids.

5 TESTING AND DEMONSTRATIONS

Test plans associated with the BIM and BTD were made in order to accomplish the following:

- Completion of factory acceptance tests (FAT) for bentonite installation machine and bentonite transfer device
- Testing the machinery functions and buffer installation using a concrete simulation of buffer rings and disks at ground level (Demonstration Phase 1)
- Testing the installation of concrete buffer in ONKALO demonstration tunnel (Demonstration Phase 2)
- Demonstration of the installation of bentonite buffer in ONKALO demonstration tunnel (Demonstration Phase 3)

5.1 Factory Acceptance Tests (FAT) for BIM and BTD

FAT for BIM was started on 11.6.2013. All machine movements and functions were tested. Some minor issues were identified and after correction the BIM was released from the factory to Posiva on 7.10.2013. Of particular importance was confirming operation of the container top suction lifter, which was tested with a 4875 kg weight and found to be functioning as expected.

FAT for BTD was performed on 4.7.2013. There were issues with steering hydraulics, which required a modification before the BTD could be used for demonstration tests.

5.2 Testing machinery functions

First test phase (Demonstration Phase 1) was evaluating the construction and design of the devices. Accuracy of movements and positioning were tested extensively to ensure successful emplacement tests. These tests took place in the surface level test and development facility in Posiva’s Onkalo area.

The machinery functions were tested and the automation development continued during this time.

Fig. 22. *Bentonite installation machine at surface level test facility.*

5.3 Emplacement demonstrations in surface facility

The purpose of these tests was to demonstrate that a full-sized borehole volume could be successfully installed using concrete blocks of the same size and mass as buffer rings and disks within two hours' time, to a lateral accuracy of +/-1 mm.

5.3.1 Execution

Surface level testing started in September 2014.

First buffer installation test was started on 18.2.2015. Fig. 22, Fig. 23 and Fig. 24 show how the blocks were moved in the course of the test.

The measure of block to container top concentricity was a key goal in the placement trials. This was measured by an external tachymeter so that the position of the block could be measured from the laser targets on top surface of the container top.

As outlined previously in this document, the buffer installation process is a complex activity that needs to be carefully sequenced. Additionally for the purposes of these trials, there is a need to be able to accurately determine what the degree of as-placed positioning accuracy can be accomplished well as identifying what improvements could be made before underground trials occur or real buffer components are used.

The buffer installation sequence was defined as follows:

1. Terminal tractor operator moves the BIM to a 10 metre distance from test hole. Timing is started. Terminal tractor operator connects BIM to tunnel electrical feed and moves the combination the remaining 10 metre distance onto the test hole.

2. The operator positions and levels the BIM from the remote operation station. BIM shall be positioned so that the installation aperture on support leg subframe is +-100 mm from test hole centre line. The BIM shall be backed as close as possible to the transverse centre line of the hole. Maximum correction with BIM lateral shifting is 200 mm and so initial positioning is important. The BIM must be aligned with the tunnel centreline so that the BTD can be accurately driven to load transfer area and both BIM and BTD can be aligned correctly. The sideways shifting is done by moving the support leg subframe onto test hole centre line while the terminal tractor is connected. Support legs are lowered into contact with the floor so that they support the BIM weight. The terminal tractor is then disconnected from BIM. Terminal tractor is driven away and BIM frame is moved into a centred position, aligning the lifter unit with test hole centre.

3. Once the BIM is standing on its support legs, the terminal tractor moves to fetch the first bentonite container.

4. BIM is raised as high as possible within the range of its feet and the pre-defined tunnel height specification and levelled to its final stance. If BIM is not sufficiently raised, there is a risk of BTD wheels touching the BIM frame, disturbing the positioning. The BIM's pulling beam is then raised to full up position so that the BTD can fit into the load transfer area.

5. Terminal tractor operator fetches the BTD and container loaded with a block and pellets. The terminal tractor operator moves the BTD into BIM load transfer area. The maximum acceptable transverse deviation between BIM and BTD centre lines is +/- 170 mm. The BTD must be reversed accurately and as parallel as possible to BIM centre line, taking into consideration any deviation between BIM and tunnel centre lines.

6. BTD is positioned to BIM load transfer area and levelled by two support leg cylinders and the fifth wheel. The wheel subframe is lifted up at the same time so that the full weight of BTD is on support legs and fifth wheel. The BTD wheels must not carry its weight during unloading, as the weight shift causes the tyres to flex, disturbing the positioning and levelling.

7. BIM operator moves the gripper into load transfer area and grips the container top. Vacuum suction system starts and creates a vacuum level of 60…90 % between container top suction surface and the block. After gripping, the BIM operator lifts the gripper with the attached container top and block up to clear the vessel's lower container and moves them onto test hole centre line. Maximum loaded gripper ascent speed is set at 4 m/min. Maximum gripper horizontal speed while loaded is 8.3 m/min. The bottom vessel of the container remains on BTD.

8. Block is lowered so that it passes the laser sensors installed on the support leg subframe installation aperture. Sensors measure the centring of the block and

container top. Maximum loaded gripper descent speed is 6.7 m/min.

9. BIM operator lowers the block further to the test hole and the mechanical gripper support wheels keep the gripper centred so that the block does not hit the wall of the borehole. When the block is 50 mm above the final installation level, the centring pads on gripper are brought into contact with the walls and the gripper with block is centred to its final horizontal position.

10. After the final centring, the block is lowered fully and the pads are retracted. The positioning is verified using the laser tracker; if there is any deviation the pads are again extended to hole wall, the block lifted slightly and repositioned.

11. When the block is resting at the bottom, BIM operator releases the pellets to fill the volume between the block and hole wall.

12. After the pellets are installed the suction vacuum is broken. When the pressure between suction surface and block reaches ambient level, the mechanical gripper and container top may be lifter up. Maximum unloaded gripper ascent speed is 7 m/min.

13. BIM operator lifts the container top out of the test hole and moves it onto BTD top shelf. The terminal tractor operator has moved the shelf to its back position into BIM load transfer area.

14. BIM operator releases the container top from gripper. The mechanical gripper is carefully lifted up so that the robotic connector and gripper eyelets are free. BIM operator moves the gripper back, out of the BIM load transfer area.

15. BTD top shelf is moved to full forward position.

16. BTD wheels are lowered so that wheel subframe is horizontal and support leg cylinders are retracted.

17. Terminal tractor operator moves the BTD and empty container away from BIM and fetches the next loaded container.

18. The steps above are repeated starting from step 3 for bottom, ring and top blocks until the buffer is complete. When installing the ring blocks, the two inner suction circuits in container top must be closed (manual operated valves in container top). The container top is prepared before it is moved over the ring block.

19. If spent fuel canister installation is to be tested as well in the installation trial, the buffer installation is interrupted after the last ring block is installed and the BIM is moved away from the demo tunnel. Testing continues after the canister installation test is finished. In an actual canister installation the same operational sequence would also be necessary.

    a. BIM gripper shall be lifted to top position so that the support wheels prevent it from swinging during transfer. Gripper contains delicate components that may get damaged if the gripper hits the lifter unit frame.

b. BIM lifter unit is moved to full forward position.

c. BIM pulling beam is lowered and locked with pneumatically operated pins.

d. BIM support leg subframe is moved to its centre position.

e. Terminal tractor operator connects the tractor fifth wheel to BIM king pin.

f. BIM support legs are raised fully to ensure proper ground clearance.

g. Terminal tractor operator moves the BIM 10 metres from the test hole and disconnects the electrical feed.

h. The test will continue by repeating from step 1.

20. As the last step the BIM is connected to terminal tractor (see steps 19a…f), and moved 10 m away from test hole.

Fig. 23. *Gripper and concrete block lowered into test hole.*

Fig. 24. *Gripper and concrete block lowered into test hole.*

5.3.2 Test results

Tests initially showed that the installation accuracy of the bottom block was well within requirement of 1 mm from test hole centreline. The bottom block centre line was 0.28 mm from test hole centre line, measured using the laser tracker installed in BIM.

Laser scan measurement of the spent fuel canister space within the buffer showed results that deviated from what was measured by a laser tracker during the installation. The deviations measured and listed in Fig. 25 ranged from 1.78 to 4.03 mm whereas the as-installed deviation ranged from 0.13 to 0.90 mm.

There were at least five possible sources for the differences in these two sets of measurements:

- Error in measuring the location of buffer block during installation
- Error in measuring location of canister space relative to test hole centre line
- Error in measuring the geometry of individual blocks (outer vs. inner surface)
- Uneven surface of the concrete blocks
- Horizontal movement of the blocks in relation to the container top during installation

Points to Objects Relationship Rengaslohko 1 to CL (Reported in Loppusijoitusreiän mittaus::HalliFrameHzAtBottom)										
Name	Object			Point			Delta			
	X1	Y1	Z1	X2	Y2	Z2	dX	dY	dZ	Mag
Rengaslohkojen mittaus reiassa::Lohko1Cardinal Points::Center	0.00	0.00	1008.48	3.05	2.10	1008.48	3.05	2.10	0.00	3.70
Rengaslohkojen mittaus reiassa::Lohko1Cardinal Points::Bottom	-0.00	0.00	541.43	2.99	1.75	541.43	2.99	1.75	0.00	3.47
Rengaslohkojen mittaus reiassa::Lohko1Cardinal Points::Top	-0.00	0.00	1475.53	3.11	2.45	1475.53	3.11	2.45	0.00	3.95

Points to Objects Relationship Rengaslohko 2 to CL (Reported in Loppusijoitusreiän mittaus::HalliFrameHzAtBottom)										
Name	Object			Point			Delta			
	X1	Y1	Z1	X2	Y2	Z2	dX	dY	dZ	Mag
Rengaslohkojen mittaus reiassa::Lohko2Cardinal Points::Center	0.00	0.00	1966.29	3.13	1.74	1966.29	3.13	1.74	0.00	3.58
Rengaslohkojen mittaus reiassa::Lohko2Cardinal Points::Bottom	-0.00	0.00	1497.82	3.63	1.75	1497.82	3.63	1.75	0.00	4.03
Rengaslohkojen mittaus reiassa::Lohko2Cardinal Points::Top	-0.00	0.00	2434.76	2.64	1.72	2434.76	2.64	1.72	0.00	3.15

Points to Objects Relationship Rengaslohko 3 to CL (Reported in Loppusijoitusreiän mittaus::HalliFrameHzAtBottom)										
Name	Object			Point			Delta			
	X1	Y1	Z1	X2	Y2	Z2	dX	dY	dZ	Mag
Rengaslohkojen mittaus reiassa::Lohko3Cardinal Points::Center	0.00	0.00	2921.43	-0.90	0.36	2921.43	-0.90	0.36	0.00	0.97
Rengaslohkojen mittaus reiassa::Lohko3Cardinal Points::Bottom	-0.00	0.00	2452.93	-1.35	1.16	2452.93	-1.35	1.16	0.00	1.78
Rengaslohkojen mittaus reiassa::Lohko3Cardinal Points::Top	0.00	0.00	3389.94	-0.44	-0.44	3389.94	-0.44	-0.44	0.00	0.62

Points to Objects Relationship Rengaslohko 4 to CL (Reported in Loppusijoitusreiän mittaus::HalliFrameHzAtBottom)										
Name	Object			Point			Delta			
	X1	Y1	Z1	X2	Y2	Z2	dX	dY	dZ	Mag
Rengaslohkojen mittaus reiassa::Lohko4Cardinal Points::Center	0.00	0.00	3882.07	-1.23	0.91	3882.07	-1.23	0.91	0.00	1.54
Rengaslohkojen mittaus reiassa::Lohko4Cardinal Points::Bottom	-0.00	0.00	3410.69	-1.86	0.68	3410.69	-1.86	0.68	0.00	1.98
Rengaslohkojen mittaus reiassa::Lohko4Cardinal Points::Top	0.00	0.00	4353.45	-0.60	1.15	4353.45	-0.60	1.15	0.00	1.30

Fig. 25.*Position of the inner cylinder of concrete ring bottom centre points in test hole.*

The installation time required to complete the buffer during surface trials exceeded the 2 hour requirement; shortest installation time achieved was 3 hours 53 minutes and this was for an installation that was still short of one ring block. Estimated time for a complete buffer installation was 4 hours 12 minutes.

Pellet filling of the gap between the buffer and test hole wall was tested. As per the planned method, after each block was in place in test hole, the pellets loaded inside the container top were released into the gap between buffer and test hole wall (Fig. 26).

Fig. 26. *Releasing of pellet into the gap between buffer and test hole wall*

5.4 Emplacement of buffer in ONKALO demonstration tunnel

On completion of the surface trials, work was moved underground to test operations in an environment more representative of a deposition tunnel. The BIM and BTD were moved into ONKALO Demonstration Tunnel 1 on 26.2.2015.

Conduct of Demonstration Phase 2 with concrete blocks started on 11.3.2015.

5.4.1 Execution

Test area was at ONKALO Demonstration Tunnel 1. The remote operation control was located near the entrance of the demonstration tunnel (Fig. 27).

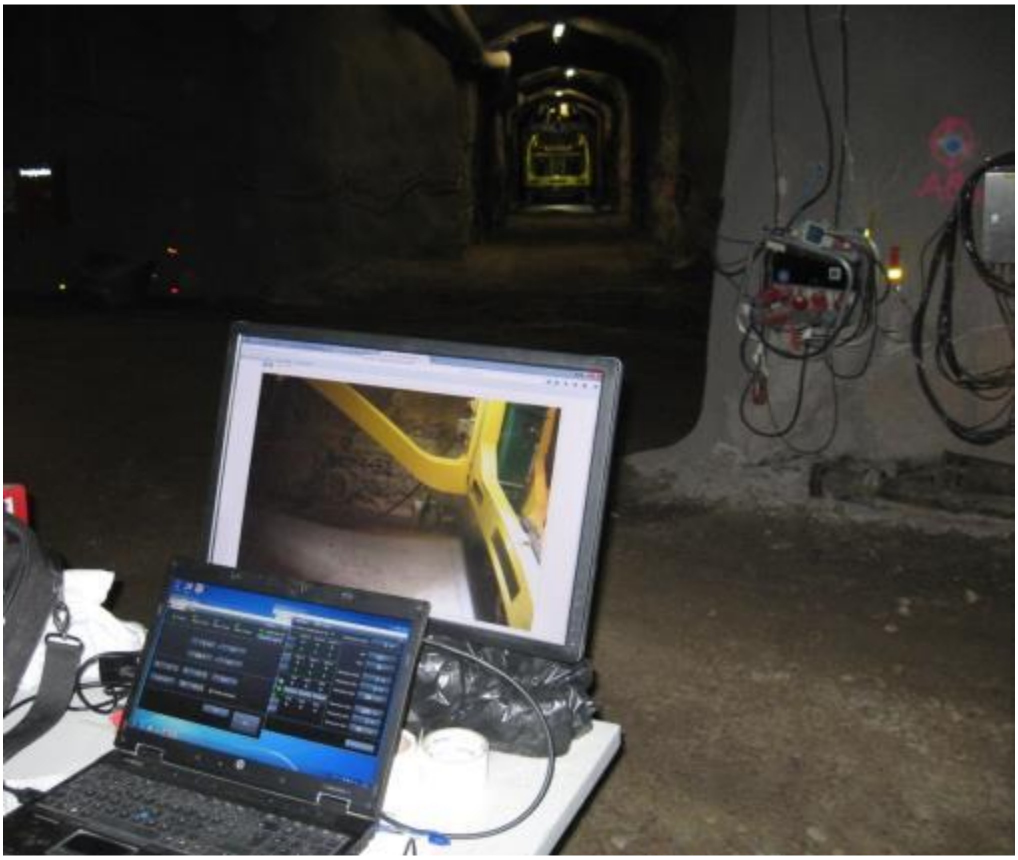

Fig. 27. *Remote operation area and BIM in ONKALO demonstration tunnel. BIM in top centre of picture.*

Demonstration Phase 2

Demonstration Phase 2 started with installation of a concrete block that simulated the buffer. The simulated buffer consisted of 10 massive concrete segments. In order of their installation they were: a 500 mm high solid block, then five ring blocks, each 960 mm high (Fig. 33), followed by one solid 400 mm high block, two solid 800 mm high blocks and finally, one solid block 500 mm high.

The first block was brought to BIM using the BTD and full container. The cameras on BTD were not functional and so reversing near BIM was challenging. As only two containers were manufactured, and re-using them in demonstration area would have been time-consuming and risked damage to blocks or equipment the rest of the concrete blocks were brought to BIM on pallets using a wheel loader equipped with lifting forks. The results of the test were not affected by this movement technique, as the installation time is determined by the BIM operations and not the block transfer along the tunnel.

Testing was slowed down substantially by repeating problems with wireless communication between control devices. Connection was lost 13 times during this test, either between the BIM main control unit and gripper control unit, or between BIM control units and the external computer used for remote control. In addition the external remote control computers were affected by electromagnetic disturbances during the underground testing, rendering them to non-bootable. These computers were replaced by ones with better EMC protection, but this did delay the testing program. Source of the disturbances was not confirmed during the testing.

On completion of the installation test, the concrete buffer was disassembled by lifting the blocks from the test hole with BIM onto pallets carried by the wheel loader (Fig. 28).

Fig. 28 Carrying of ring blocks in Onkalo by the wheel loader.

Demonstration Phase 3

Phase 3 could not be completed to plan, due to lack of full set of bentonite blocks. Instead, a buffer assembly consisting of a mix of concrete blocks and bentonite blocks was installed (Fig. 29). Unlike the reference plan buffer consisted of eleven blocks. Fig. 30 through Fig. 33 are photos showing the BIM and the subsequent block installations in the test borehole.

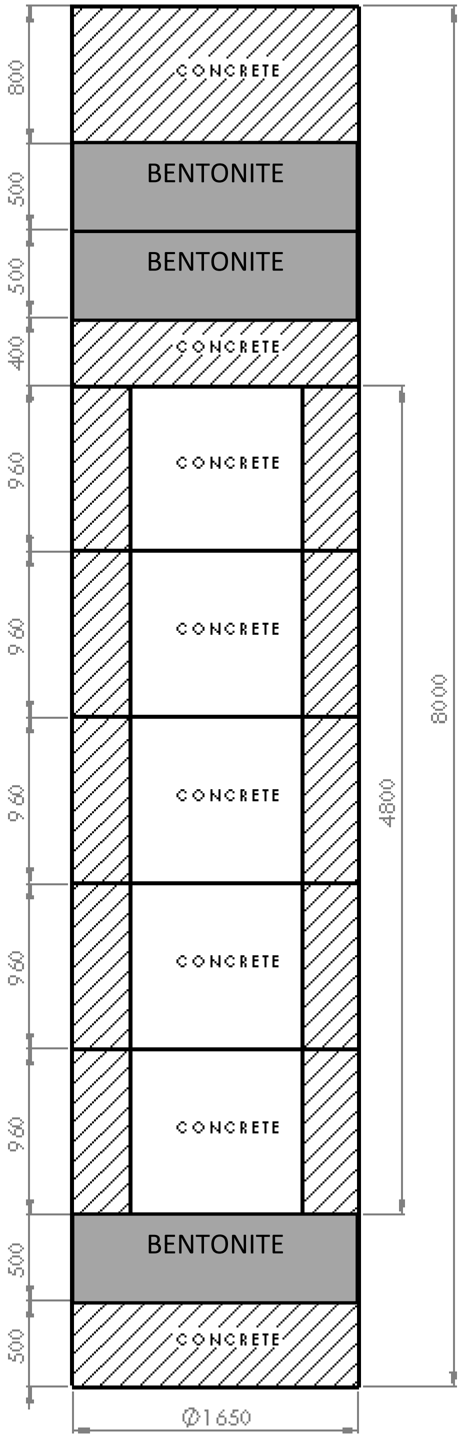

Fig. 29. Buffer consisting of bentonite and concrete blocks

Fig. 30. *Bentonite installation machine in ONKALO demonstration tunnel 1.*

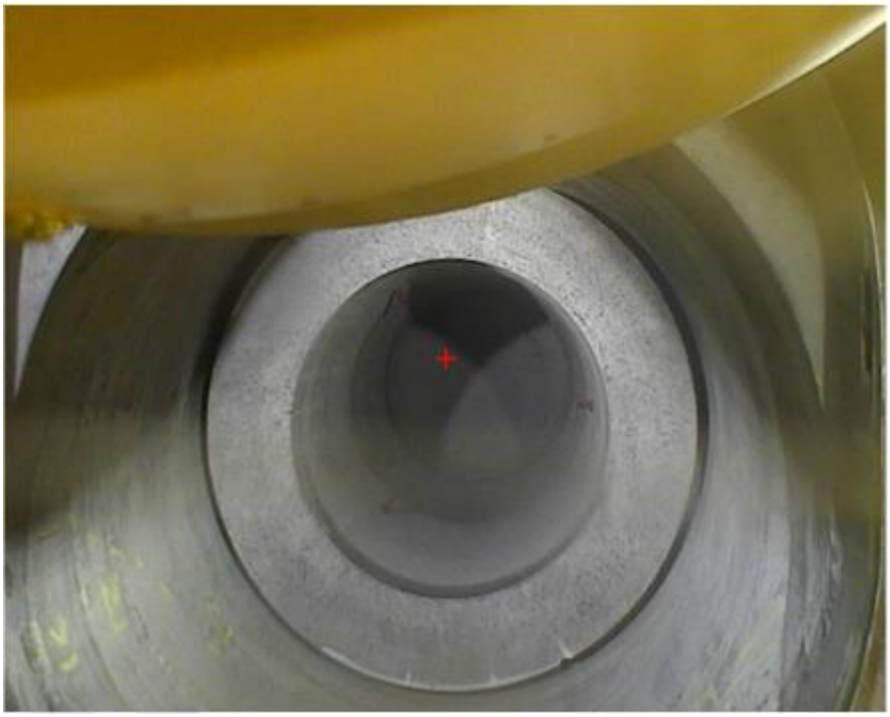

Fig. 31. *Buffer with ring blocks installed, seen by BIM dome camera.*

Fig. 32. *Installing the top solid blocks, seen by BIM dome camera.*

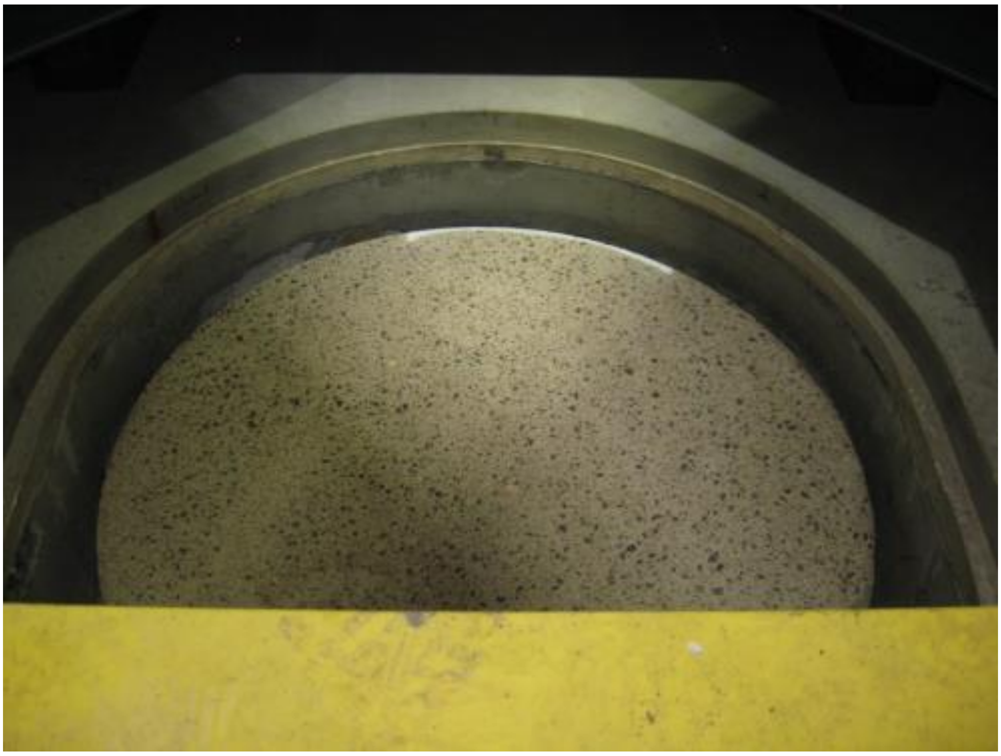

Fig. 33. *All buffer blocks in test hole, seen by BIM dome camera.*

5.4.2 Discussion of test results

Measurements during the installation demonstrations showed that the installation accuracy was within specified requirements. The bottom block centre line deviation from test hole centre line was measured to be 0.36 mm for full concrete buffer and 0.94 mm for the mixed concrete and bentonite block buffer, measured using the laser tracker installed in BIM.

Subsequent laser scan measurement of the spent fuel canister space within the mixed buffer showed, as they did in the surface tests presented in Section 5.3.2, results that deviated from these measurements. In the case of Demonstration Test 2 the deviation ranged from 2.1 to 8.8 mm from test hole centre line.

The possible sources for the deviation are again the same as for Test Phase 1.

As with the Demonstration Test Phase 1, installation time exceeded the 2 hour requirement; installation time was 3 hours 19 minutes. As can be seen in Fig. 29, due to the unavailability of a full set of clay buffer blocks, Demonstration Test Phase 3 contained one additional block compared to reference buffer. Estimated time for an installation that meets the geometric requirements of a reference buffer installation was 3 hours 10 minutes. As noted before, this time does not include the canister installation activities and activities associated with it.

Points to Objects Relationship R5 Points to EH8-Vertical CL (Reported in Nominals::EH8-HZ-Frame)										
Name	Object			Point			Delta			
	X1 (mm)	Y1 (mm)	Z1 (mm)	X2 (mm)	Y2 (mm)	Z2 (mm)	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
Cylinder-End	0.00	0.00	5772.21	6.39	-5.47	5772.21	6.39	-5.47	0.00	8.41
Cylinder-Center	0.00	0.00	5320.03	6.76	-5.32	5320.03	6.76	-5.32	0.00	8.60
Cylinder-Begin	0.00	0.00	4867.86	7.13	-5.17	4867.86	7.13	-5.17	0.00	8.80

Points to Objects Relationship R4 Points to EH8-Vertical CL (Reported in Nominals::EH8-HZ-Frame)										
Name	Object			Point			Delta			
	X1 (mm)	Y1 (mm)	Z1 (mm)	X2 (mm)	Y2 (mm)	Z2 (mm)	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
Cylinder-End	0.00	0.00	4815.31	-2.52	-0.82	4815.31	-2.52	-0.82	0.00	2.65
Cylinder-Center	0.00	0.00	4359.30	-2.36	-0.52	4359.30	-2.36	-0.52	0.00	2.42
Cylinder-Begin	0.00	0.00	3903.30	-2.20	-0.22	3903.30	-2.20	-0.22	0.00	2.21

Points to Objects Relationship R3 Points to EH8-Vertical CL (Reported in Nominals::EH8-HZ-Frame)										
Name	Object			Point			Delta			
	X1 (mm)	Y1 (mm)	Z1 (mm)	X2 (mm)	Y2 (mm)	Z2 (mm)	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
Cylinder-End	0.00	0.00	3855.46	-4.33	-1.88	3855.46	-4.33	-1.88	0.00	4.72
Cylinder-Center	0.00	0.00	3399.79	-4.16	-1.67	3399.79	-4.16	-1.67	0.00	4.49
Cylinder-Begin	0.00	0.00	2944.12	-3.99	-1.47	2944.12	-3.99	-1.47	0.00	4.25

Points to Objects Relationship R2 Points to EH8-Vertical CL (Reported in Nominals::EH8-HZ-Frame)										
Name	Object			Point			Delta			
	X1 (mm)	Y1 (mm)	Z1 (mm)	X2 (mm)	Y2 (mm)	Z2 (mm)	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
Cylinder-End	0.00	0.00	2889.16	-4.61	-1.11	2889.16	-4.61	-1.11	0.00	4.74
Cylinder-Center	0.00	0.00	2448.67	-4.42	-0.98	2448.67	-4.42	-0.98	0.00	4.53
Cylinder-Begin	0.00	0.00	2008.18	-4.24	-0.84	2008.18	-4.24	-0.84	0.00	4.32

Points to Objects Relationship R1 Points to EH8-Vertical CL (Reported in Nominals::EH8-HZ-Frame)										
Name	Object			Point			Delta			
	X1 (mm)	Y1 (mm)	Z1 (mm)	X2 (mm)	Y2 (mm)	Z2 (mm)	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
Cylinder-End	0.00	0.00	1942.96	-4.63	-1.00	1942.96	-4.63	-1.00	0.00	4.74
Cylinder-Center	0.00	0.00	1480.10	-4.26	-1.12	1480.10	-4.26	-1.12	0.00	4.40
Cylinder-Begin	0.00	0.00	1017.24	-3.89	-1.23	1017.24	-3.89	-1.23	0.00	4.08

Fig. 34. Position of the inner cylinder of 5 concrete rings in test hole EH8.

6 Quality Assurance During Buffer Emplacement

The quality of installation is a key aspect in making sure that the multi-barrier system functions as designed. The scope of the work defined for LUCOEX is to develop sensor systems to deliver the data needed to achieve the quality assurance targets (QA). In practice this means choosing the most suitable sensor technologies, designing the needed Buffer Installation Machine (BIM) / transfer vehicle mounted support mechanics and electronics and provide the data produced from these activities for use in QA-related software. Developing the automated analysis tools associated with the buffer installation process is a vast software engineering task. Off-the-shelf analysis programs may be used in the initial assessment process but they might not allow for conduct of a fully automated QA process.

6.1 The Scope of quality assurance

Technologies and methods are analysed and compared in respect to the general requirements and parameters (such as reliability, costs, complexity, time usage, suitability for underground environment etc.) and in respect of the requirements of each individual QA target. As a result a recommended approach is given for each QA target.

This study is limited in that it is based on communication with the instrument supplier candidates, interviews, web researches and experiences of the author but not on tests accomplished in real application environment with real materials and full scale dimensions. This means that some final technology decisions are delayed until actual full scale application environment is available.

A primary guideline for the development of the QA process is avoiding slowing down the buffer installation process lowering any instrumentation down to the deposit hole with a separate winch should be avoided.

The QA targets defined for development of quality control equipment are as follows:

- a) The integrity of the buffer blocks during the process
- b) The final position of the buffer structure
- c) The accurate position of individual block in the final buffer assembly
- d) The compactness of the joint between the blocks and between the pellets and the host rock
- e) The width of the gap between assembled block and the host rock
- f) The inclination of the assembled buffer and each block

Based on the discussions at the initiation of this work, targets b), c) and f) were combined into one target. This new target covers the whole installation accuracy of the bentonite buffer and the blocks it consists of. In addition, the compactness of the joint between the blocks (originally part of the target d) also falls within this new target. This new target is called "The quality of the position of the assembled buffer and the bentonite blocks the buffer consists of" (It is referred to as target QA:2).

For revised listing of QA targets are as follows:

- QA1: The integrity of the buffer blocks during the process.
- QA2: The quality of the position of the assembled buffer and the bentonite blocks the buffer consists of.
- QA3: The width of the gap between assembled block and the host rock.

- QA4: The compactness of the joint between the pellets and the host rock.

6.2 QA1: The integrity of the Buffer Blocks during the Process

The goal of this QA target is to ensure that a bentonite block will end up as one piece in its target position in the deposition hole. A fracture in a bentonite block may decrease the strength of the block so that it breaks into pieces under its own weight or because of the movements undertaken as part of normal BIM handling of the block.

According to studies undertaken on large buffer blocks, fractures capable of endangering a block will be visible on the outer surface of the block. Because of this it is enough to inspect only the outer, side surface of the block as shown in the Fig. 1. The minimum crack width that needs to be found during inspection is 0.2 to 0.4 mm. Measurements have to be done without physical contact and without any alteration to the surface of the block (such as powders or moisturized air) as these could compromise the blocks integrity. Surface area to be inspected varies between 4.98 m2 and 2.1 m2 depending on the block type being inspected. The circumference of the blocks is 5183mm and so scanners must be able to examine this length of surface.

However, some additional investigations and especially bench-top and field tests are still needed to be able to finalize the technology selection for fracture detection in buffer blocks. The conduct of additional testing and evaluation is not a risk to the schedule for technological application as all the presented sensor technologies require similar supporting mechanical and electronic equipment.

6.3 QA2: The quality of the position of the assembled buffer and the bentonite blocks the buffer consists of.

Alignment of the individual blocks in respect other blocks and the verticality of the whole buffer structure are critical parameters for ensuring the canister clearance requirements are met. This is the motivation for tracking, preferably preventing the possible tilting of the assembly and measuring how close to the target XY-coordinate each block is installed. Because there is practically no vertical asymmetry in a bentonite block (the height of one block is the same no matter where it’s measured) the only source for tilting is a foreign object on the surface to which the next block will be lowered (touch point for now on), or an initially non-level foundation. This is the reasoning for checking that the touch point between the blocks is clean.

It should also be noted that even if all the individual blocks are aligned precisely with respect one-another but the whole buffer assembly is not correctly positioned in the XY-plane, the gap between the host rock and the block can deviate unacceptably from the installation specifications. This may create problems during filling the gap with premeasured amounts of pellets.

Because the laser tracker will probably be used as BIM’s 3D-coordinate measuring instrument, using it also to provide horizontal angle information for the lowered block comes almost at zero additional cost and effort. The disadvantage to this method is that the measurement is not direct but assumes that block’s angle can be derived from transport container’s angle.

Using a state of the art inclinometer doesn't provide any advantages compared to the laser tracker. Inclinometer also does not measure a block's angle directly and it doesn't provide better accuracy than other approaches.

A laser-based distance measurement unit mounted on the rotating fixture on BIM's frame produces accurate and directly measured angle information. It requires some additional mechanics and support electronics but those will probably be needed anyways for the QA_3 and QA_4.

The recommended approach is to combine the data that the existing laser tracker already provides with the direct measurement with one laser distance meter mounted on the rotating fixture.

6.4 Ensuring that block's touch point is clean enough to prevent the tilting

The buffer structure should be vertically aligned to allow successful canister installation and pellet filling. Checking that the touch point surface is free of foreign items is relevant because they are the most probable reason for tilting. The most probable cause for loss of horizontal alignment is a bentonite pellet from the gap fill between the host rock and buffer blocks accidently falling onto the installed block.

The maximum observation distance from monitoring sensor to surface is 12 meters (when installing the first bentonite block).

It is quite clear that machine vision is the most viable of the two approaches considered unless the inspection time is relaxed to 4-6 minutes per block. To be able to operate at varying measuring distances without losing resolution, a motorised zoom lens is required. Particle observation accuracy can probably be boosted by adding a structured laser illumination to highlight the deviations in surface. The same machine vision system could be possibly used also for other QA tasks such as the gap measurement (between the host rock and buffer) and analysing the pellet formation created in gap filling.

6.5 Ensuring that the whole buffer and each block are placed within ±1mm tolerance to the planned XY coordinate.

There are three basic approaches available to accomplish measurement of the X-Y placement tolerance:

1. Laser tracker.
2. Machine vision.
3. Laser scanner.

It should be noted that the target accuracy in block placement of ±1mm can only be reached by the laser tracker. Other methods such as machine vision may be used as a support measurement but none of them is able to give information other than that the installation is totally out of the desired position.

The recommended approach is to rely on the accuracy of the laser tracker, monitor its accuracy and minimize the risk of block movement within the container. Machine vision can be used as a supportive method as it is able to identify major changes to block location.

6.6 QA3: The width of the gap between assembled block and the host rock.

The accuracy target for the gap width measurement between the assembled blocks and the host rock is 5mm. It should be noted that the surface of the host rock is not smooth while it might have horizontal roughness of 10mm as the result of the diamond drilling process. This will make accurate placement of the blocks a challenge since radially measured distances will vary with depth in the deposition hole.

By measuring the gap between the host rock and just assembled block during the buffer installation process and then comparing this to the pre-installation measurements, it is possible to ensure that the installation process is going as planned.

Machine vision is the most promising candidate for tackling the gap measurement challenge.

6.7 QA4: The compactness of the joint between the pellets and the host rock.

The surface created when the gap between the host rock and bentonite block is filled with bentonite pellets needs to be measured to ensure that the minimum density of the bentonite buffer is reached.

As with the block location activities within the deposition hole, the pellet filling activity is planned prior to the actual buffer installation using the actual 3D model of the hole generated at the time of its excavation. This allows use of premeasured amounts of pellets which can be dosed into the compartments of the above the container holding the buffer block so that the variation in the gap width (due to hole drilling tolerances) can be compensated for. Pellets are released after each block has been lowered to correct XY-coordinate but prior to the block's release (or before the container has been moved from the release position).

The target in terms of evaluating the volume of and consistency of pellet fill within the annular gap is to reach the elevation measurement accuracy of approximately one pellet thickness in formation inspection.

There are two candidates for use in achieving the desired measurements, laser scanning and machine vision. Both have been presented earlier in this document in respect of accuracy, measurement times, costs etc. The measurement distance is also the same as in QA3: The width of the gap between assembled block and the host rock.), but the measurements become harder to make as each block is installed since the outer edge of a block shadows the gap to an increasing degree the closer the block is to the sensor. In practise this means that the sensor should move to a viewpoint above the gap so that there is always line of sight to the gap. The same mechanics that can be used in direct pitch and roll measurement of the assembled block with a laser distance meter, could also be used to provide exact distance information for the pellet fill.

A laser scanner is an excellent option for use in measuring 3D formations. The only disadvantage to its use is that measuring, data transfer and analysing consumes several minutes is problematic in applications that require response time(s) of a few minutes at maximum. Because of this, the Machine vision (photogrammetry) method is also recommended for consideration in accomplishing this QA task. It is not the ideal solution for 3D mapping but is accurate enough and the same instrument could also be used to other QA tasks such as gap width measurement and touch point cleaning – inspection.

6.8 Summary of Quality Assurance tools

Based on the studies outlined above, all QA targets QA1-4 are feasible and the probability of successful implementation is high. As a result of these evaluations and considerations, the estimated sensor cost of the BIM has been decreased by using less expensive sensor technologies and using the same sensor in more one QA task. The probability of meeting the development schedule for the BIM and its operation was also improved by choosing technologies that will require only moderate engineering effort to complete.

The QA targets and their briefs are listed below:

- QA1: The integrity of the buffer blocks during the process.

  The motivation behind the target is to get the buffer blocks into place in the deposition hole safely. To be able to do this, each block has to be inspected in prior of moving it above the deposition hole.

  -> According the results from estimations, video inspection is sufficient to accomplish this task. The block will be inspected by cameras when it has been lifted out from transportation container, before lowering to the deposition hole.

- QA2: The quality of the position of the assembled buffer and the bentonite blocks the buffer consists of.

  The motivation for the QA2 is to ensure that there is enough clearance for the canister's installation and also for the filling of the gap between the buffer and host rock. This means that each bentonite block and the whole buffer construction have to be installed at the planned XY-coordinates and maintain levelness. The following subtasks can be derived from the target:

  - Measuring the tilt angles (pitch and roll) of each installed block,
  - Reducing the risk of tilting by inspecting that the surface where the block is lowered is free from particles, and
  - Measuring the XY position of each installed block

  -> Use of a Laser tracker and inclinometers are suitable for precise installation. According to the estimations made, camera inspection is sufficient to check that installation area is free from particles.

- QA3: The width of the gap between assembled block and the host rock.

  The width of the gap between the host rock and block is an important dimension because the gap will be filled with premeasured amount of pellets. Filling is done in stages, one filling increment per each lowered block. The bentonite pellets are dosed based on the 3D model of the hole. By measuring the gap between the host rock and just assembled block during the buffer installation process we can increase the certainty that the gap filling with pellets goes as planned.

-> To ensure gap width, inspection using the machine vision cameras is the recommended solution.

- QA4: The compactness of the joint between the pellets and the host rock.

  The gap between the host rock and the bentonite blocks is filled with bentonite pellets as described in QA3. The density of the filling has to reach the minimum level to guarantee that the buffer works as planned. This is the reasoning to measure the surface formation created in the filling.

  -> The use of a camera viewing method is the recommended solution for this task.

7 PROBLEM HANDLING OF BUFFER COMPONENTS EMPLACEMENT

As error handling in buffer installation can be understood as relatively wide problem from water filled hole to oil leaking from deposition tunnel backfilling machinery, some limitations to project scope were made as part of LUCOEX WP5 LOT3 problem handling work description. Further limitations to LOT3 were made during the technical feasibility study phase and while completing the work in LOT2 and LOT1.

Some speculative conceptual problem descriptions and technical demands could led to very complex problem handling equipment with high price and high technological risk regarding achieving them. As a result, the demands regarding problem resolution were reviewed and reduced to those that could be reasonably encountered at some point during placement activities. From this revised listing, means to achieve a technically robust design to handle potential undesirable conditions that could perform the task of ensuring long term safety in deposition tunnels have been developed. The state of buffer (and canister) installation present when the need to undertake remedial action can be broken down into those prior to canister installation and those encountered after a canister has been installed. In both situations those items that it should be possible to remove from the deposition hole are:

- Irregularly shaped bentonite clods
- Gravel like small bentonite pieces
- Bentonite pellets
- Bentonite dust
- Slurry from bentonite (bentonite/water mix)
- Small rocks
- Rubber moisture protection shield and pieces of it
- Complete bentonite blocks
- Broken bentonite blocks
- Machine parts, nuts, bolts, pins
- Contaminated blocks (radiologically and non-radiologically)
- Water

7.1 Problem handling before canister installation

If installation of buffer blocks fails before canister has been installed, the fastest, most accurate and fail safe solution is to use a human operator in the hole for cleaning. Some equipment will be needed to break the bentonite blocks and to lift block pieces and pellets from the deposition hole. Suggested tools are a heavy hammer drill and vacuum cleaner (industrial cleaning lorry).

The use of screws or anchors on bentonite is questionable based on the tests performed. Three anchor types were chosen for ground level testing, based on the results from pull and shear tests made in Tampere University of Technology during June and July, 2013, where five types of anchors were used. With all anchor types it was very easy to crack the bentonite during anchor installation. The anchor test in ONKALO was performed on 19.5.2015. Based on these tests, the feasibility of using the anchors to remove broken bentonite block parts seems to be limited to specific cases, where the bentonite still retains its strength near manufacturing values. If there has been exposure to humidity or severe shocks, there is a very high chance that this method is not suitable.

It is expected that a human worker can clean up the fragments from the broken bentonite block so that lifting surface of the first complete bentonite block remains unharmed. This enables complete buffer dismantling with a vacuum lifter in minimum time. This would also be the case where a complete ring block had fallen onto previously installed blocks.

Damaged blocks that are still mostly intact and have a sufficient top surface area can be removed using a suction lifter. When installed with adapter plate to the bentonite installation machine (BIM) gripper Posiva's existing vacuum lifter has been shown to be able to be used for 800mm high bentonite block removal from a deposition hole. Broken ring segment removal will probably not be possible with standard lifting and moving procedure as space between the BIM's legs and the gripper is limited.
With a vacuum lifter the following items can be removed from the deposition hole:

- Complete bentonite blocks
- Broken bentonite blocks
- Contaminated blocks

7.2 Problem handling after canister installation

Problem handling after canister installation has two additional challenges compared to what is needed for situations where material removal is needed before canister installation. First, the work has to be performed remotely because of the radiation field from the canister. Secondly, extra care has to be taken not to damage the installed capsule. With regards to the recovery process, there is also a need to ensure that ongoing careful radiological monitoring of materials removed from the deposition hole (bentonite, water) to ensure that the canister is intact and not releasing any contamination. In a situation where the canister were compromised methodologies would need to be put into place to minimize the volume of impacted material generated, ensure it is not spread elsewhere in the repository and that worker safety is maintained at all times. Consideration of this condition is beyond the scope of the current study, it is assumed that the canister is sound at the time of its recovery.

Several methods of handling broken or damaged blocks in a deposition hole where a canister has been installed were considered and evaluated. Those options considered most viable were discussed in WP5 reports 5.08 and one, hydrodemolition was selected for field testing.

7.3 Hydrodemolition

Hydrodemolition was a method selected for testing removal of bentonite from deposition hole. A hydrodemolition machine breaks the bentonite into small pieces using a very high water pressure (water jet) and has an attached vacuum suction pipe to remove bentonite fragments and water. It can be used in all problem solving cases involving bentonite removal from deposition hole; manually before capsule is installed, or by remote control after capsule installation.

A hydrodemolition machine was designed with a combined suction pipe and 3000 bar water pressure hose lines and then used to test the concept (Fig. 35 to Fig. 37). The concept was tested using a simplified arrangement, without the remote control option, to verify its viability for use in a deposition hole. Tests were successfully performed on ground level in December, 2014 and in ONKALO demonstration tunnel in May, 2015. The mist from the high pressure water was far less than expected based on the ground level test and the splashes of bentonite sludge remained almost fully inside the test deposition hole. This is a positive result in that it would not adversely affect other nearby boreholes during its operation. Based on the test in ONKALO, the removal time for one disc block is approximately one hour, hence complete excavation of a full borehole should be able to be accomplished in an eight-hour day

During the ground level test, the water jet was intentionally directed onto a dummy copper canister lid for several minutes. It caused some polishing on the copper and it was possible to feel a slight edge with finger where the jet had been active for a prolonged period. For production use it would be relatively easy to design different pressure and suction nozzle variations for operation on bentonite buffer between capsule and host rock. Mechanically limiting the water jet direction to avoid contact with the copper capsule, thereby avoiding damage would be simple.

Fig. 35. *Top of copper canister subjected to extended direct contact with water jet, showing polishing.*

The major drawback using hydrodemolition is that the whole buffer and the canister need to be removed and reinstalled. Due to introduction of water into the deposition hole, it is not possible to design a hydrodemolition system that would leave underlying bentonite usable.

Fig. 35. *Hydrodemolition device, ground level test.*

Fig. 36. *Hydrodemolition device on excavator during test in ONKALO.*

Fig. 37. *Bentonite block during test in ONKALO.*

Removal of small particles or stray items from upper surface of bentonite blocks

The testing of buffer installation has also revealed that even a small particle on a bentonite block's top surface will disrupt the installation of the next block.

Removing large bentonite fragments accurately enough to allow for subsequent block installation(s) could prove to be very time consuming, if practical at all and further work is needed to develop proven remedial approaches.

For incidents involving other materials entering the deposition hole (small rock, nuts, bolts etc.), a simple vacuum suction can remove almost all particles in centimetre size range. Use of a simple magnet could be used to pick up metallic objects. Larger items would need a remote operated device, similar to a commercial concrete demolition machine, although consideration would need to be given to the robustness needed for such a machine before it would become more practical to go to a fully dismantling step.

8 FINDINGS

8.1 Buffer installation

8.1.1 Dimensional accuracy of installed buffer

The equipment developed showed that it is capable of locating an individual block within accuracy of 1 mm of its target location, provided that the position measurement data is correct.
However, the completed buffer positional measurement accuracy appears to remain outside the tolerance expected. This inconsistency is a topic that will need to be addressed in subsequent studies and improvements to the equipment.

8.1.2 Installation time for buffer

During the demonstrations the expected buffer installation time of 120 minutes was not reached. This was mainly caused by issues related to the unfinished status of the positional laser tracker measurement system and the slow process of centring the block in the test hole by mechanical gripper actuators. A substantial improvement in these activities will be necessary in order to reduce installation time by the approximately 50% needed to meet specifications.

8.1.3 Proposals for further development

Several development ideas surfaced during the tests and demonstrations. Most of these were for improving some relatively minor details on the machinery, but some major improvement suggestions were made as well. These are described below with regards to each of the major system components.

Buffer Installation Machine BIM

Moving the bentonite installation machine with a terminal tractor in demonstration area was challenging. Therefore it was proposed that the production scale machine should be self-propelled.

The control system should be redesigned so that the WLAN disturbances between control units could be eliminated. This will require consideration of how to install hardwire connections that can be kept safe from accidental damage during tunnel operations.

The laser tracker should be integrated into the automation system and should have proper scripting for automated target search. There should be further research into the cause of the deviations in position measurements of the buffer blocks.

Container top

Positioning of buffer block to the container top should be redesigned so that precision of buffer installation would be better.

It was suggested that a revision to the pellet installation process be considered. If the pellet installation could be successfully done at one go, instead of stepwise per block installed, the gripper should be simplified. The pellet compartments could be eliminated and whole construction made more compact and dimensionally accurate.

Buffer Transportation Device BTD

The BTD as currently designed proved to be quite awkward to load, unload and move in an underground environment. It should be changed to provide a more easily controlled machine, possibly a wheeled loader. Inclusion of some additional equipment for carrying empty container tops and allow for remote control would be useful for production use.

8.2 Buffer installaltion quality

Based on the studies all QA targets QA1-4 are feasible and the probability of successful implementation is high. As a result of these evaluations and considerations, the estimated sensor cost of the BIM has been decreased by using less expensive sensor technologies and using the same sensor in more one QA task. The probability of meeting the development schedule for the BIM and its operation was also improved by choosing technologies that will require only moderate engineering effort to complete.

8.3 Problem handling

8.3.1 Problem handling before canister installation

If installation of buffer blocks fails before canister has been installed, the fastest, most accurate and simplest solution is to use a human operator in the hole for cleaning. Some equipment will be needed to break the bentonite blocks and to lift block pieces and pellets from the deposition hole. Suggested tools are a heavy hammer drill and vacuum cleaner (industrial cleaning truck).

The use of screws or anchors on bentonite is questionable based on the tests performed.

A human worker can clean the broken bentonite block so that lifting surface of the first complete bentonite block remains unharmed. This enables complete buffer dismantling with vacuum lifter in minimum time also in case of complete ring block has fallen on top of previously installed blocks.

Damaged blocks that are still mainly in one piece and have a sufficient top surface area could be removed using a suction lifter. Posiva's existing vacuum lifter can be used for 800mm high bentonite block removal from deposition hole, when installed with adapter plate to the bentonite installation machine (BIM) gripper. Ring segment removal will probably not be possible with standard lifting and moving procedure as space between legs and gripper is limited.

With a vacuum lifter the following items can be removed from the deposition hole in error situations:

- Complete bentonite blocks

- Broken bentonite blocks
- Contaminated blocks

8.3.2 Problem handling after canister installation

Hydrodemolition is a plausible method for removing bentonite from deposition hole. It can be used in all problem solving cases involving bentonite removal from deposition hole.

It can be utilized manually before the canister is installed, or by remote control after canister installation, provided that the canister is not physically compromised.

For production use it would be relatively easy to design different pressure and suction nozzle variations for operation on bentonite buffer between capsule and host rock. Mechanically limiting the water jet direction to avoid copper canister damage would not be technically challenging.

The major drawback using hydrodemolition is that the whole buffer and the canister need to be removed and reinstalled. Due to introduction of water into the deposition hole, it is not possible to design a hydrodemolition system that would leave underlying bentonite usable. The testing of buffer installation has revealed that even a small particle on bentonite block top surface can disrupt the installation of the next block. Removing bentonite parts accurately enough with other methods studied would be very time consuming, if practical at all.

For incidents involving other materials entering the deposition hole, a simple vacuum suction can remove almost all particles in centimetre size range. If the foreign material in the borehole is ferrous (e.g. stray bolt or fitting from machines), and not in close proximity to the canister then a small suspended magnet could be used to lift and remove it. Larger items would need a remote operated gripper device of similar concept to the BROKK demolition machine.

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