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Memo on KBS-3V buffer emplacement testing

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Contents

1 INTRODUCTION

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

This report describes development of prototype machinery to demonstrate emplacement of the bentonite buffer that surrounds the spent fuel canister in a vertical deposition hole (KBS-3V concept). This has been completed as D5:4 of the LUCOEX project.

Posiva's bentonite buffer emplacement method for the bentonite blocks has been developed so that it is possible to carry out buffer emplacement at the required rate of 120 minutes per borehole. This time requirement of 120 minutes does not include the time spent installing the spent fuel canister before the 4 top-most disk-shaped blocks are installed. Placement must also attain an accuracy of +/-1 mm to the deposition hole's centreline.

The machinery developed to accomplish buffer installation 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.

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 to be transported from the manufacturing facility on the surface to the central tunnel in ONKALO (-420m) where they are loaded onto the transportation vehicle to be moved further into the deposition tunnel. Bentonite blocks are 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 to the deposition hole.

Three possible methods to cover the bentonite blocks have been investigated during the concept development 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.

2.1.1 Plastic cover

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 must be manually 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.

2.1.2 Metal cover/dome

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. The bottom plate of the transport dome has lifting points for handling in factory and in tunnel before installation. As with the plastic cover, it will be necessary to remove the cover prior to positioning and using the suction gripper to move the block into place over the deposition hole.

2.1.3 Container with gripper

In this geometry, shown in Fig. 1, the transport container also consists of a metal cover for the bentonite block but a gripper is integrated into the transport unit's lid. 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.

The container can be constructed in several ways, but the main idea is to have a canister that can be easily separated into suction gripper and container parts. Each gripper component is used only once for lifting during installation of the bentonite block it is associated with into the borehole. The grippers can be reused, but only after return to the surface and inspection in the block manufacturing facility. The cover piece has all the necessary components of a suction gripper without vacuum-generating apparatus. A gripper is equipped with connection points that allow the hoist of an installation vehicle to attach to it. This allows for very little potential for misalignment between the lifter and container. The transport container also has its own external lifting points to be used when moving the container in factory or driving tunnel.

In the process of preparing the container and block package, a bentonite block is first aligned with the container's top and then is lifted into place. Sealing of the container is achieved through use of a weak internal vacuum. This weak vacuum is maintained on the vacuum grippers during transportation, ensuring the alignment between block and gripper. Adjustable mechanical pads between the canister and the bentonite block can be used to keep the block on place during the transportation and handling in the 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 within 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 pellet storage and deposition compartments that can be constructed on top of the gripper.

The container cover piece can be extended down to lower the height of the bottom piece and to protect the block during the installation (Fig. 2). This design is useful if the lifting height becomes critical in the installation equipment. Also, an overpressure ring can be constructed inside the gripper ring to get more lifting power.

A design alternative to use of a rigid walled container could be use of an upper extension made of textile rather than metal has also been considered. This design would reduce the space needed for empty containers. It would however not eliminate the need to move empty transport containers from the deposition tunnel as there is not enough space for all the container cover pieces. As this option does not provide a material movement advantage and also provides less physical protection than the metal version, this design has not been further evaluated.

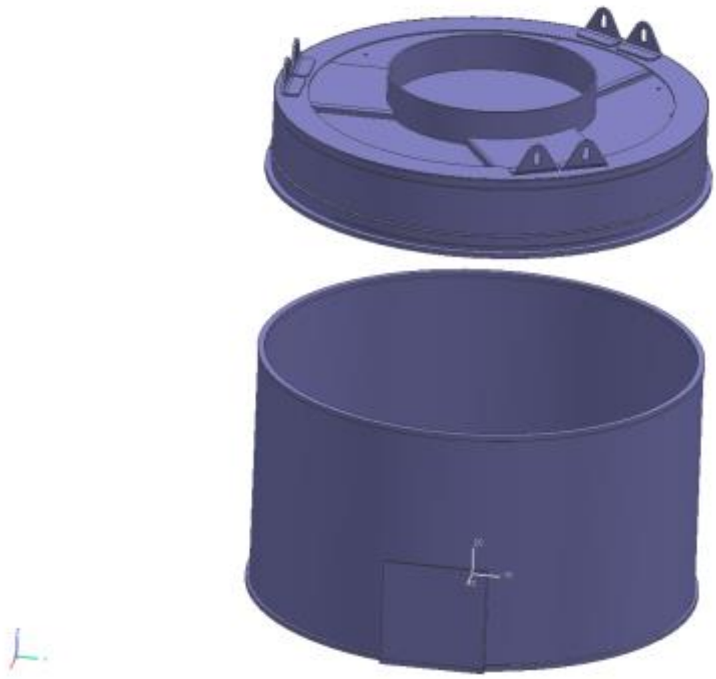


Fig. 1. *Container concept with vacuum gripper and pellet storage.*

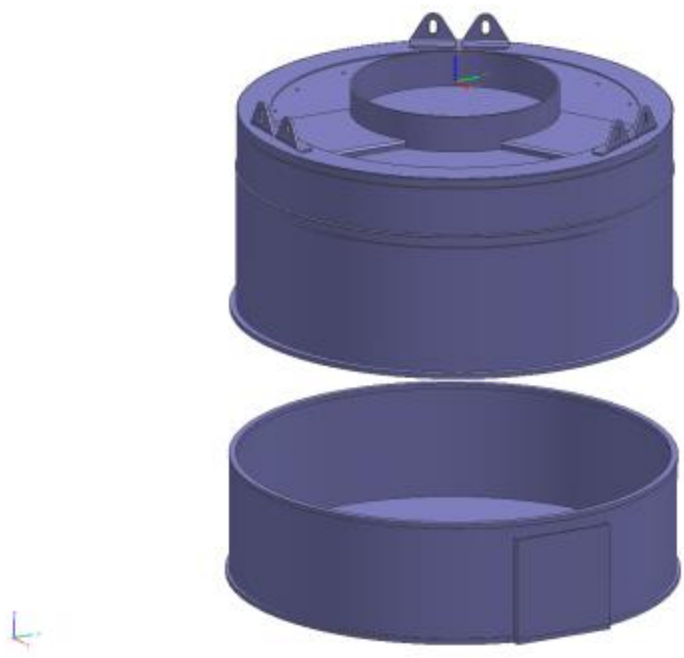


Fig. 2. *Container concept with extended cover piece.*

2.1.4 Comparing block transportation alternatives

Each of the buffer block transportation options described above in Section 2.1 has inherent advantages and disadvantages associated with them. These can be briefly summarized as follows:

Plastic-wrapped/covered blocks:
Advantages:

- Ease of handling with forklifts. Forklifts are used to move the blocks from storage to transport vehicles or from one vehicle to another.
- Forklift handling can be considered safer than handling with vacuum lifters. They can be stacked on each other and take less space compared with containers. When a process that requires moving several blocks into the deposition tunnel at a time is used, then using plastic covered blocks is the only alternative because rigid containers cannot be moved over each other in a tunnel environment due to the limited space available.

Disadvantages:

- The plastic cover has to be removed before the blocks can be loaded into the transportation vehicle. This has to be done manually which causes a safety risk.
- Used plastic covers must be stored away, which causes waste and space problems.
- Handling the pallets is an additional time and space-consuming task.
- Bare blocks must be lifted repeatedly using vacuum lifter which causes a need to realign the grippers on top of bentonite blocks with high accuracy. Lifters must also be cleaned between the lifts. Here the time consuming alignment is done in the tunnel compared to container concept where the alignment is done already in the factory under controlled conditions. This slows down the installation process.
- The plastic cover provides little or no mechanical protection to the block.

Metal cover or container over blocks:
Advantages:

- A metal cover eliminates need to manually cut away the cover.
- It gives good protection against humidity and mechanical damage during the whole transportation chain.
- The gripper is used only once underground which makes it easier and faster to align the blocks during installation compared with plastic covers.
- Worker safety is also better when there is no need to handle covers manually.
- Grippers do not need to be cleaned between blocks lifting because every block has its own gripper.
- Containers/covers can be used repeatedly.

Additionally, in the container option, by using integrated pellet storage in the gripper, the need to measure out and install the pellets as a completely separate activity in the deposition tunnel can be avoided. Thus pellet installation can be done with same lifter movement as bentonite block installation. For other concepts this use of premeasured pellet containers to make the gap filling could also be undertaken, but that would again give rise to the logistic problem of how to deal with empty pellet containers without adversely affecting operational cycle time.

Disadvantages:

- The main disadvantages of using a metal dome or container to cover the block are logistical and cycle-time related.
- Empty domes have to be stored in the main tunnel and
- There must be a vacuum lifter in the transportation vehicle to move uncovered blocks.
- The need for block alignment in the tunnel applies for the dome as for the plastic covered blocks.
- The need to move the unprotected block within the deposition tunnel constitutes a risk regarding block damage or dropping.
- Speed at which equipment can move in the deposition tunnel can also become a limiting factor for installation time.
- In the container option, the effect of an extended period of vacuum associated with the gripper on the buffer block is not yet established and is the subject of ongoing investigation.

2.1.5 Selection of preferred buffer handling approach

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

Based only 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 waste materials, but extra care would need to be taken to ensure that these materials do not get accidently transported into the deposition tunnel. It also does not however provide the same degree of physical protection to the blocks as the other options considered.

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

2.2.1 Alternative transfer vehicle concepts

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

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. 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 plays an important part in achieving the specified installation time and ensuring buffer block quality. The various vehicle concepts examined 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, equipment clearance and movement in the tunnels became issues, forcing study of possibilities of using a smaller transfer vehicle, carrying fewer blocks.

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 ultimately selected for use 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. Cycle-time calculations have also needed to be made in order to determine the total installation time for each concept.

2.2.2 Full Set Combined Vehicle (FSCV)

In this concept, a vehicle with both transfer and installation vehicles integrated into 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 before it enters the deposition tunnel. The vehicle needs to be move into the tunnel by a terminal tractor only once for each deposition hole filling; after aligning on the deposition hole the first six bentonite blocks can be installed without moving the vehicle. Driving speed therefore has minimal effect on installation time.

The disadvantages of the FSCV are that only uncovered blocks can be used, this means there is a need to align each block to the suction gripper separately at the deposition hole location. The gripper must be cleaned or at least checked after each lift to ensure adequate gripping force. Pellet filling steps during buffer installation will also need a separate filling device. This means a complicated installation process with higher quality problem risks. Measuring pellets in the installation vehicle is also difficult and time-consuming. Estimated installation time for the buffer using FSCV concept is 130 minutes, exceeding the target of 120 minutes. It also leaves no time margin for slight delays in cycling or operations.

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 prone to flexing during loading and unloading making it difficult to load blocks accurately 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.

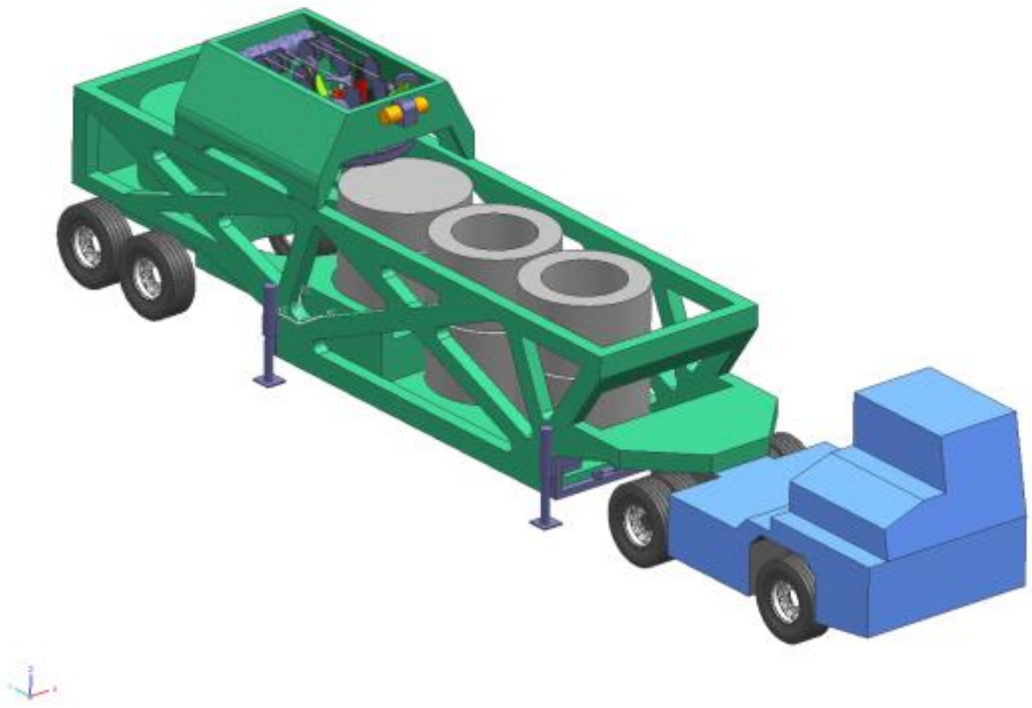


Fig. 3. *Full Set Combined Vehicle with terminal tractor.*

2.2.3 Two vehicles concepts (TVC)

The two vehicle concepts consist of an installation vehicle and a transfer vehicle. The Installation vehicle is used for the buffer block and pellet installation into the deposition hole and the transfer vehicle for moving the blocks to the installation vehicle.

Installation vehicle

An 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 the terminal tractor, an installation vehicle is aligned with the deposition hole via hydraulic supporting legs and a crane. After this is accomplished, the alignment installation vehicle is ready to start installing the bentonite blocks.

Handling the bentonite blocks is done with an electrically operated crane with hoisting ropes. The crane moves on top of the frame in the tunnel direction. The lifter is levelled and aligned with the deposition hole. The lifter is equipped with guide wheels and movable pads for accurate final positioning when a buffer block is about 2-5cm above its final position. Pads need to be constructed so that they do not interfere with the water protection rubber that might be used for a wet deposition hole. The same type of installation vehicle is used in all two vehicle concepts.

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.

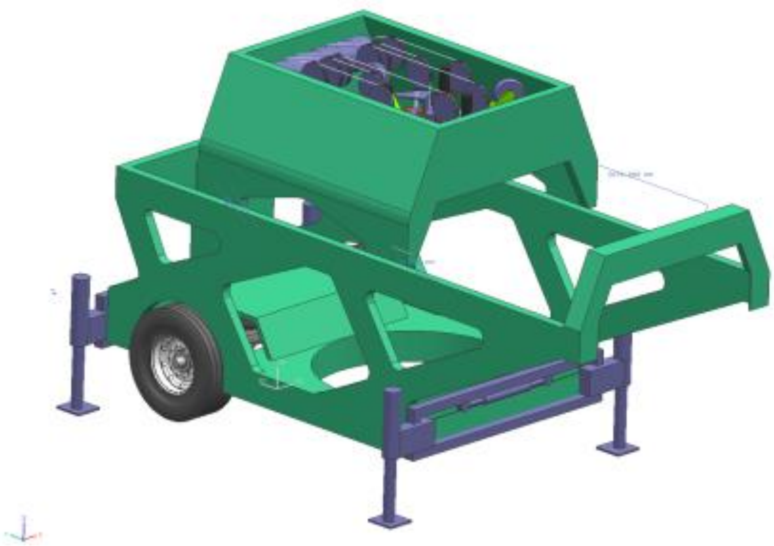


Fig. 4. *Installation vehicle concept model.*

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 same vehicle design as the six block transfer vehicle, complete with a second overhead crane on the transfer vehicle.

The simplest transfer vehicle type carries only one block in a single buffer 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 next step in transfer design evolution of the one block transfer vehicle is the one block plus platform type. The main change in design is the addition of a movable platform to store the previous gripper. This vehicle concept has two independently suspended turning wheels that can be used to level the vehicle and assist in positioning and driving in tunnel. The operational sequence can be summarized as follows:

- When the transfer vehicle approaches the installation vehicle the platform is positioned above the container in the transfer vehicle.
- When the transfer vehicle is aligned with the installation vehicle the previous gripper is lowered to the platform which then moves aside to let the lifter grab the next block container's gripper.
- The transfer vehicle then moves the latest container's lower part and the gripper (top part) to the driving tunnel where it is unloaded,
- A new block container is then loaded onto the transfer vehicle and
- The empty block containers are sent back to the surface for reloading.

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 using an installation vehicle and one block plus gripper transfer vehicle concept.

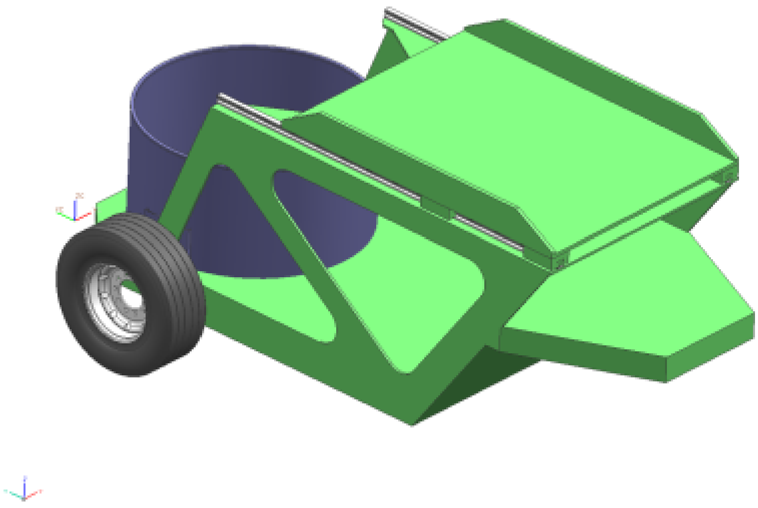


Fig. 5. *One-block-plus-gripper type transfer vehicle concept.*

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, 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 at 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.

The main disadvantages of the FSTV concept as compared with FSCV and container concepts are associated with:

- The length of the vehicle. It is long and this makes it difficult to handle in narrow tunnel space. Even with turning wheels it will be difficult to turn the vehicle from the driving tunnel into the deposition tunnel.
- The need to accurate position the blocks on the block carrier and the carrier trailer,
- The more complex block moving process that involves use of two lifters.
- Two heavy vehicles near each other have an increased risk of coming into physical contact. Even a small collision could disturb the installation process and result in a need to realign the installation vehicle.

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.

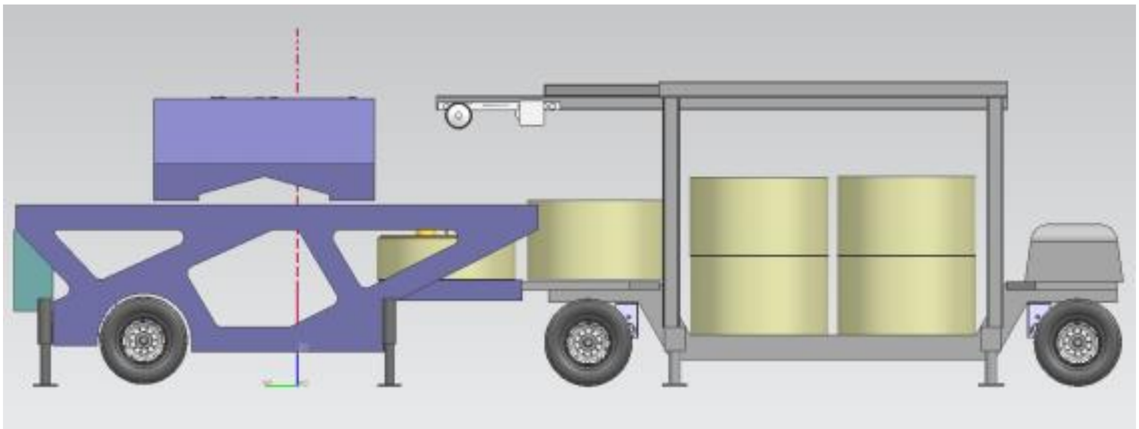


Fig. 6. *Full set transfer vehicle with installation vehicle. Concept drawing.*

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 pre.aligned 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.

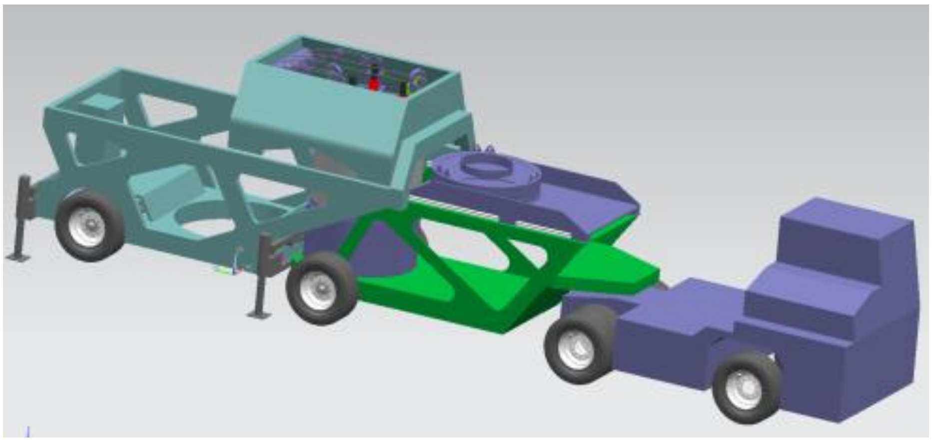


Fig. 7. *Suggested concept for installation and transfer vehicles as well as terminal tractor.*

3 DESIGN

3.1 Concept design stage

As outlined in Chapter 2, concepts of how bentonite buffer emplacement equipment might be configured have 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.

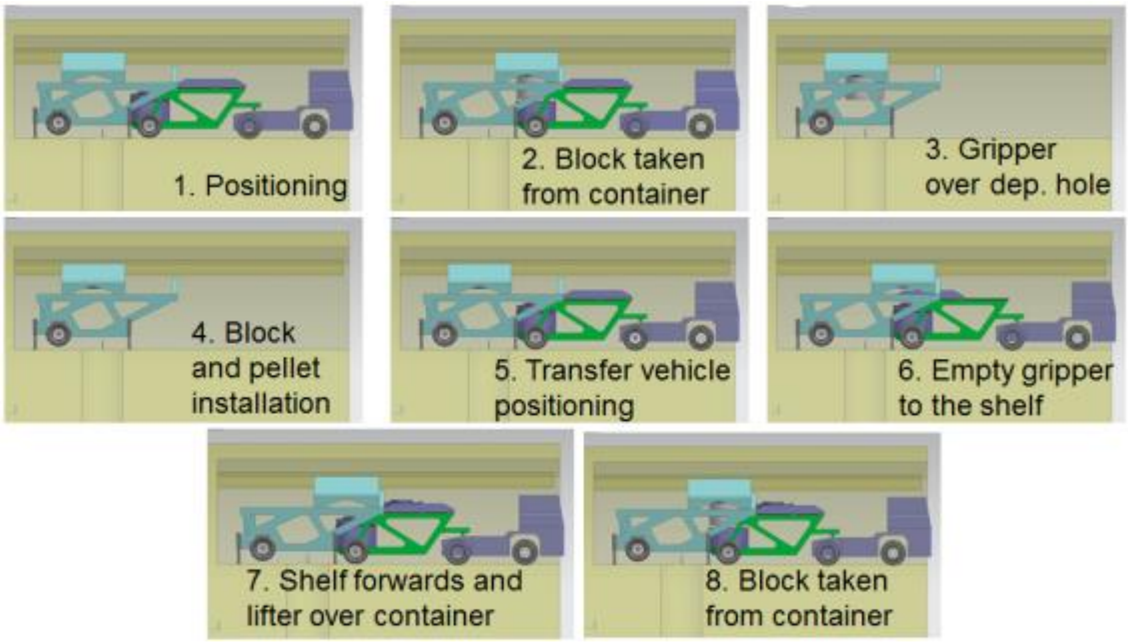


Fig. 8. *Buffer installation sequence.*

3.2 Design stage, general description

In the course of developing basic designs for the buffer installation machinery, the following software was used:

- Mechanical 3D-modelling and 2D-drafting was done using Siemens PLM Software NX.
- Structural analysis was done using the ANSYS engineering simulation program.
- Autodesk AutoCAD was used for electrical engineering and pneumatics drawings.

3.3 Bentonite installation machine (BIM)

3.3.1 General description

The bentonite installation machine (Fig. 9), 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 an 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.

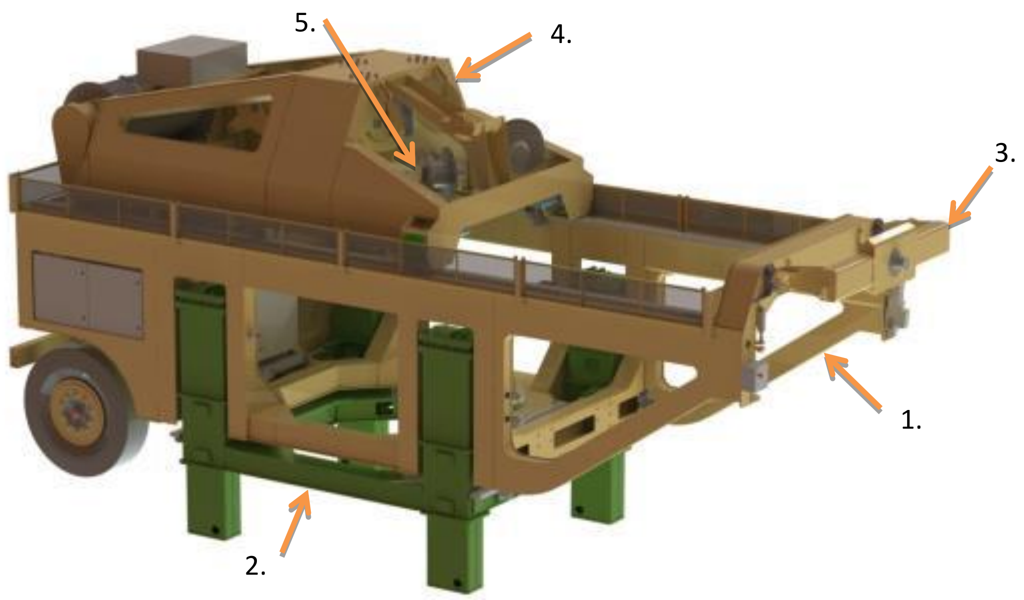


Fig. 9. *3D-model of bentonite installation machine (BIM).*

Table 1. *BIM technical specifications.*

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, CoDeSys V3	CANopen, Ethernet
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	

3.3.2 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).

Pneumatic actuation evaluation identified that the 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 operational and environmental limitations identified for the other alternatives and still retained sufficient robustness and accuracy of operation.

3.3.3 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 associated with vacuum system 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.

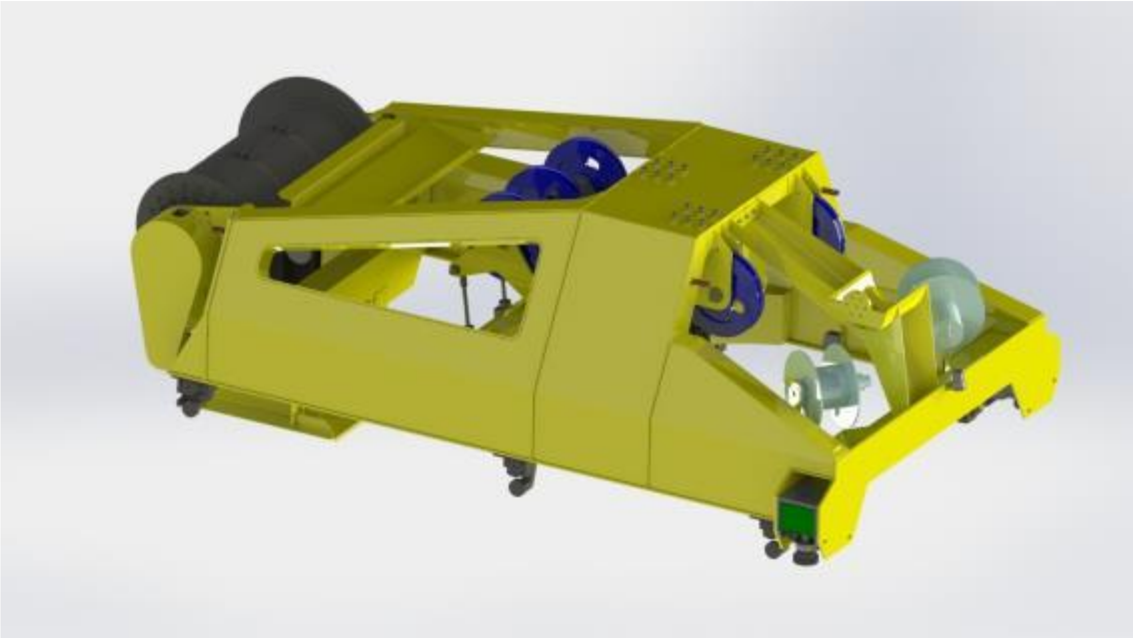


Fig. 10. *BIM lifter unit.*

Initially in the conceptual design process, all lifter components were duplicated as if the device was going to be used as a production item. These components included the steel ropes on the winch, the winch brakes, winch motors, winch gearboxes and steel rope adjustment actuators for gripper balancing. This duplication would have increased the cost and complexity of the test device without providing any significant benefit with respect to the task of field testing buffer emplacement. Therefore a decision was made to abandon duplication and continue the design work with single component sets, at least for the concept development and demonstration period. As a result, the winch drum used in the BIM is simpler and holds all steel rope on one layer, making it less prone to failure (rope entanglement etc.).

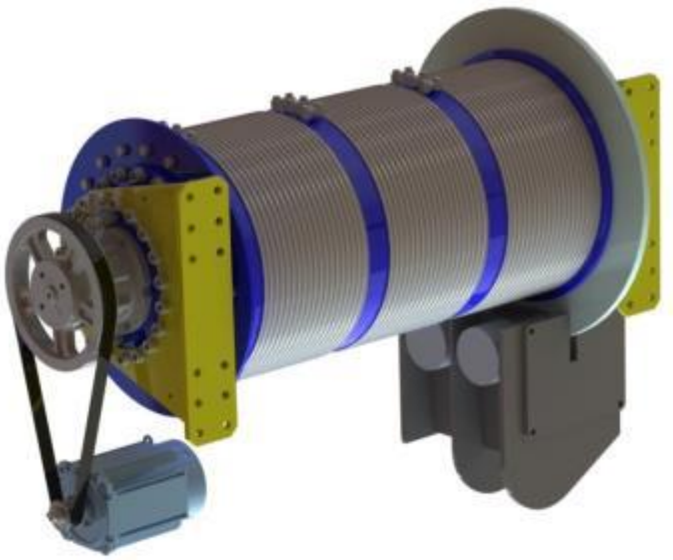


Fig. 11. *Winch assembly.*

3.3.4 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.

3.3.5 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.

The steerable axle unit is a SISU SSND-10-S front axle. The axle is rated for 10 000 kg load at 10 km/h. There are no driving brakes on the unit as movement is controlled by the terminal tractor as part of the unit positioning process. Turning of the rear wheels to allow for BIM manoeuvring within the tunnel is actuated by a single electromechanical EXLAR unit.

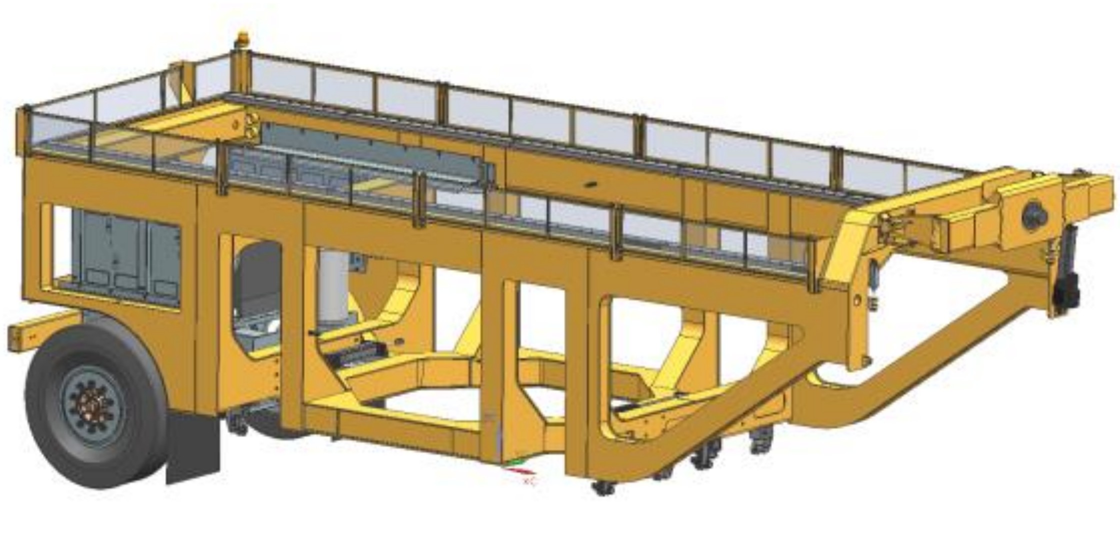


Fig. 12. *BIM main frame.*

3.3.6 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.

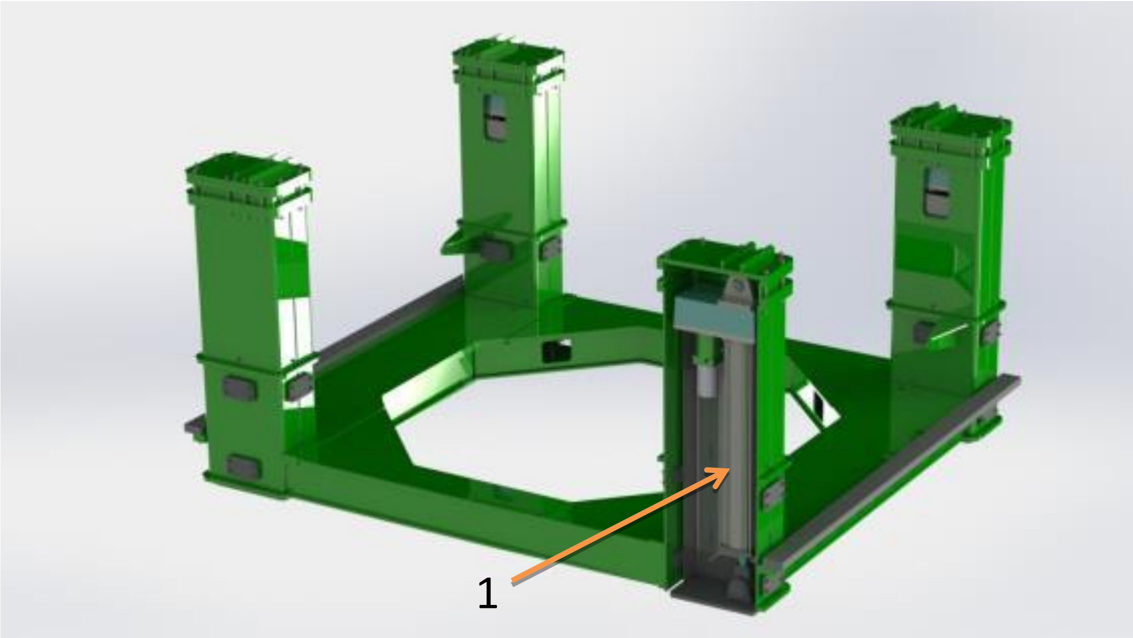


Fig. 13. *Support leg subframe assembly.*

3.3.7 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

3.3.8 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 a 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*

The mechanical gripper unit in the prototype BIM was designed with three guide wheels to prevent block or gripper collision with deposition borehole walls. Each wheel unit is paired with an electromechanically actuated centring pad for accurate horizontal adjustment of the load position. During testing of the prototype BIM, the centering of the gripper unit in the hole proved difficult because the pads caused radial movement while extending and retracting. For a production machine, replacing solid rubber pads with horizontal wheels is suggested.

As discussed previously, in the container concept pellet storage is integrated into the container top and pellets are unloaded by lifting the outer skirt of container top. The gripper unit has three pneumatically actuated levers that engage with the container skirt and control its opening and closing.

3.4 Bentonite 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 facilitate its positioning near BIM and to limit the steering effort while driving in the 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.

Before the bentonite block is lifted off, the BTD is levelled by two hydraulic support legs at the rear corners and terminal tractor's fifth wheel. At the same time, the axle subframe is lifted hydraulically so that the wheels are not in contact with the tunnel floor, thus eliminating any effect from deformation of the rubber tyres with operation of the BTD or BIM.

As shown in Fig. 15, the transfer device in the prototype BTD carries one block in a container. This device has a longitudinally moving platform to store the previous container top. When the transfer device approaches the installation machine the platform is positioned above the container in the transfer device. When the transfer device is aligned with the installation machine the previous container top is lowered to the platform which then moves aside to let the lifter grab the next block container's top. The transfer device then removes the container's lower part and the suction gripper (container top part) to the driving tunnel and takes a new block container back to the tunnel.

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

3.5 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.

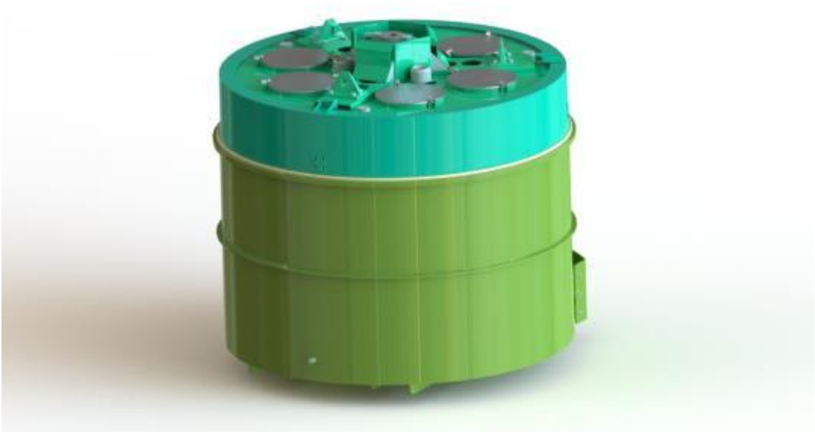


Fig. 16. *3D model of bentonite container.*

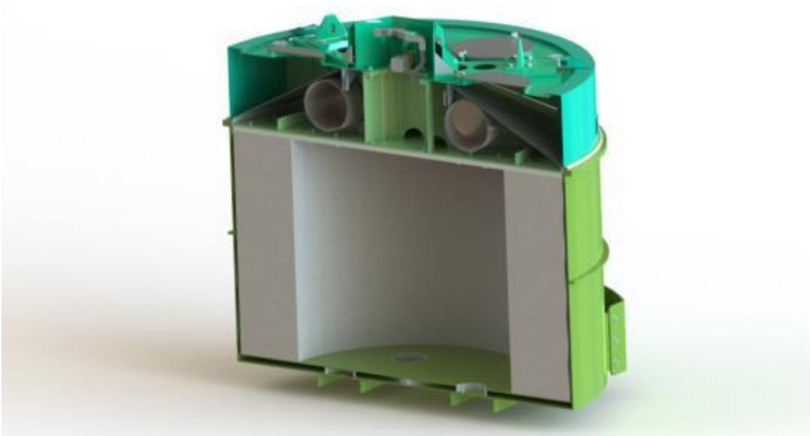


Fig. 17. *Split view of the bentonite container with a ring block. Picture shows the later variation of container top.*

Initially two complete containers were manufactured, one for 960 mm high ring block and another for 500 mm high solid block. The taller container can be used for 800 mm blocks during the demonstrations by adding spacers to its bottom. Likewise the shorter container can be used for trials using a 400 mm high solid block.

One container top was finished and factory tested. After the tests some alterations were made for the second container top as follows:

- Integrated vacuum reservoirs were abandoned in favour of more rigid toroid section reservoirs.
- Vacuum suction surface was made of a single plate with only six suction areas (three suction circuits). Suction surface in first container top consists of 27 separate plates.
- Slight alterations to manufacturing dimensions and tolerances for better pellet compartment functionality.

The first container top was also upgraded so that the only major difference between them remained the suction surface. Both container tops are interchangeable.

3.5.1 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. Adoption of the concept of utilizing steel containers to hold and deliver the buffer and pellets into the borehole necessitated a re-design of the suction gripper.

The vacuum needed to operate the gripper is generated via three ejector pumps located on the mechanical gripper. The mechanical gripper is permanently attached to the lifting ropes in BIM lifter unit. The suction gripper which locates in top part of the container is classified as a non-fixed load lifting attachment according to euro norm SFS-EN 13155 Cranes. Safety. Non-fixed load lifting attachments.

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	

3.5.2 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 used to stepwise fill the remaining volume between the blocks and the walls of the deposition hole. The amount of pellets loaded into each compartment is determined by calculating the gap between block and wall of the deposition hole. Calculation is based on laser scanned model of the hole and bentonite buffer size and location.

3.5.3 Pellet drop test

The selected method of pellet filling involves an integrated cylindrical pellet compartment at the top of the bentonite block container (Fig. 18). This pellet compartment bottom is shaped as a truncated cone and is divided into six equal sectors. This will enable filling the annular gap with the correct amount of pellets and to compensate for possible variations in the dimension of the gap between bentonite blocks and host rock.

Before detailed design of the pellet compartment was completed, a series of tests were conducted to determine the best bottom surface inclination for unassisted dropping of pellets. To do this, a test device (Fig. 19) was fabricated to simulate the pellet compartment. It consists of a mild steel sheet metal frame, an adjustable steel bottom plate and a vertically sliding gate for pellet release.

In the simulator, the bottom plate inclination can be adjusted between 5 and 45 degrees in 5 degree intervals using fixed holes in frame plates. Additional adjustment is made by shimming the front (low) edge of the bottom plate. The top of the device is open to enable pellet filling and the sliding gate is opened manually to release the pellets.

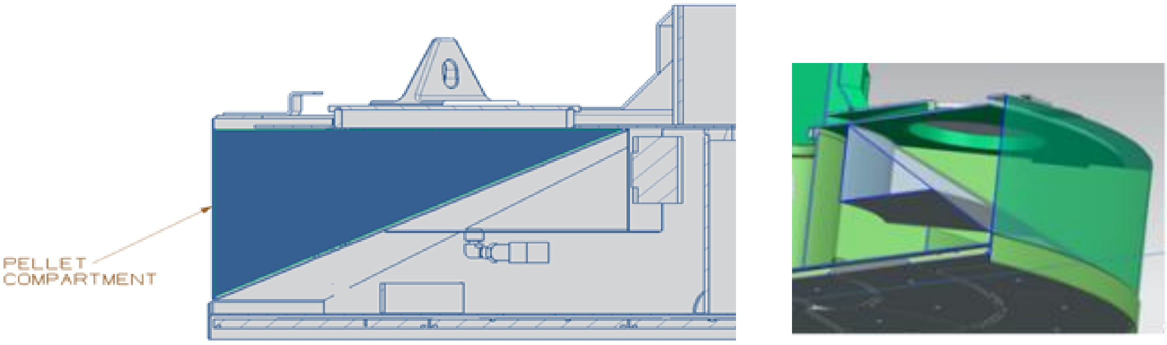


Fig. 18. Pellet compartment in container top

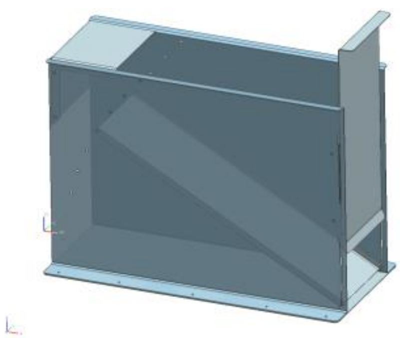


Fig. 19. Pellet drop test device

Three types of bentonite pellets were tested before the design of the pellet compartment component was finalized:

- cylindrical & 8, lenght 12- 25 mm
- square pillow-shape 12x12 mm, 5.5 mm thick
- round pillow-shape d 12 mm x 5.5 mm thick

After conduct of a series of trials where the angle of the bottom plate was varied, it was determined that an inclination of 25 degrees allowed all pellet types to freely discharge by gravity. In order to provide a slightly more conservative design, an additional 2 degrees was added to the angle of the bottom plate to produce a total inclination of 27 degrees. Drop tests were repeated multiple times and there were no pellets remaining on bottom plate at any time. Based on these tests, a 27 degree inclination was selected for use in the actual pellet compartment's bottom surface.

3.5.4 Robotic connector between sensors and power actuators

The vacuum sensors and optional pellet vibrators require electrical feed-throughs between mechanical gripper and container top. A robotic connector (Fig. 20) was developed and employed for this task, enabling automated connection of signals and power.
The initial design of this connector was found to have some issues related with its use. These modifications to the robotic connector were all of a design and operation improvement nature and did not reflect any basic problem with the concept and its operation. They consisted of the following:

- Firstly, due to the nature of the welded steel construction of the gripper and the container top, the connector was between these components was found to be prone to misalignment causing a connection failure. After the first factory acceptance tests it was deemed necessary to use a more robust connection for a production level machine.
- The second item observed was that continuous monitoring of container vacuum circuits was unnecessary and a design change was made to move these sensors to the mechanical gripper side.
- The third item was the need to change the vacuum break valves to direct actuated magnetic valves, eliminating the need for pilot pressure feed-throughs from mechanical gripper to container top.

On completion of these modifications to the robotic connector, it was found to be suitable for use.

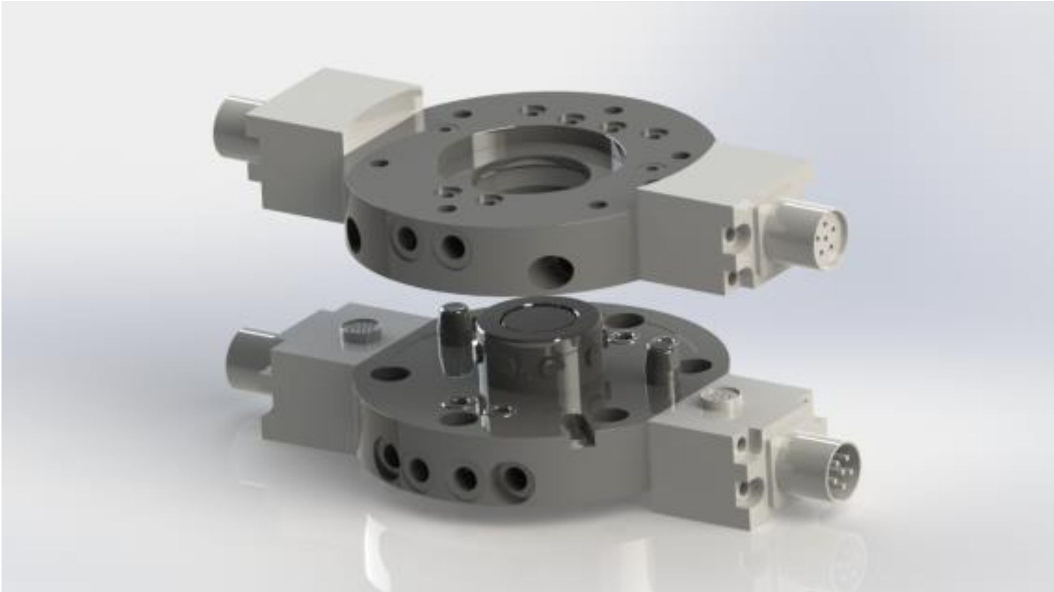


Fig. 20. *Robotic connector used for electrical power, signal and compressed air. Top part is attached to mechanical gripper and bottom part to container top.*

3.5.5 Suction surface on block lifter

The development of a suction system for use in holding the lifter head in place during block loading, unloading and installation underwent two main design iterations, as shown in Fig. 21.

The first container top (Fig. 21-left side), was manufactured with a suction surface design consisting of 27 separate aluminium suction plates, similar to the original suction lifter tested in 2010. These were intended to provide a well – distributed series of lifting areas to provide good reliability should some local areas on the upper surface fail to hold under suction.

For the second container top design (Fig. 21 right side), the suction surface was re-designed to have only six separate suction areas on one-piece aluminium plate. The result of this redesign was a substantial reduction in the number of fabricated parts, vacuum hoses and fittings. This reduced the complexity of the construction, operation and hence component cost. The results of trials using a lifter of this design were successful.

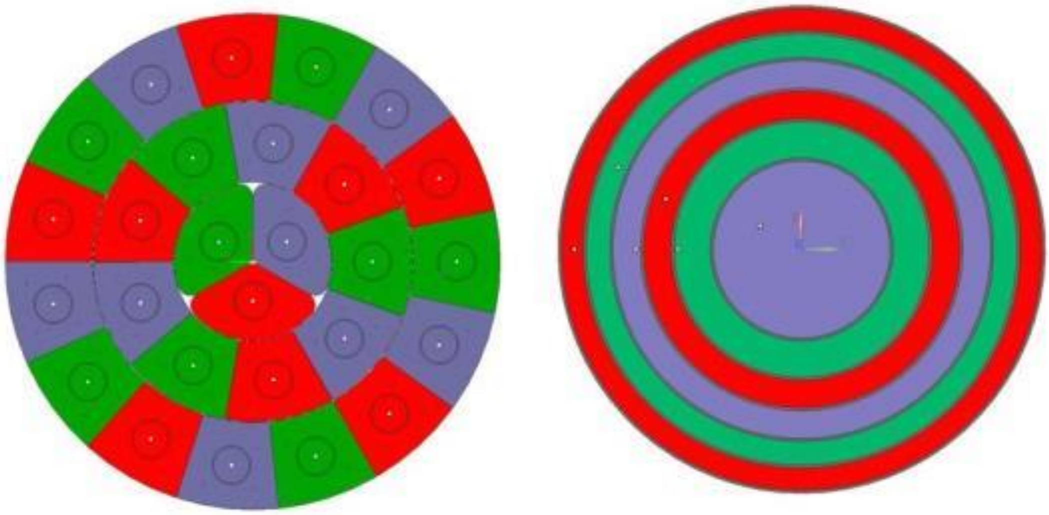


Fig. 21. *The 3-circuit division of the original (left) and new (right) suction gripping surfaces. Each colour corresponds to one independent suction circuit.*

3.6 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 needed in normal operating practice, the BIM control system comprises of both direct manual operations and automatic operations initiated by the operator. Fig. 22 and Fig. 23 show the control unit is 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. 24) and video feed from cameras. How this is accomplished via an automation program is shown in Fig. 25.
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 the BIM are equipped with absolute sensors so as to ensure that no limits regarding positioning are exceeded.

The key electronic and software-related components associated with the BIM and BTD are as follows:

- The positioning system for BIM and buffer blocks is based on a laser tracker and laser reference targets inside the demonstration tunnel.
- The laser tracker used is an API Omnitrac2.The field buses associated with the control system used in the BIM and BTD are CAN and Ethernet.
- In order to accommodate attachment of the lifter to the buffer block, a centring algorithm was developed for mechanical gripper.

When located at the demonstration hole, the BIM gets its power from demonstration tunnel 400 V electrical network. For transfer along the tunnel to and from the demonstration hole, the BIM has two batteries powering the rear axle steering, lights and control system. A different power supply network will be necessary during actual placement operations but this is not considered to be a significant issue since the operational areas of the repository will need to have a robust power supply.

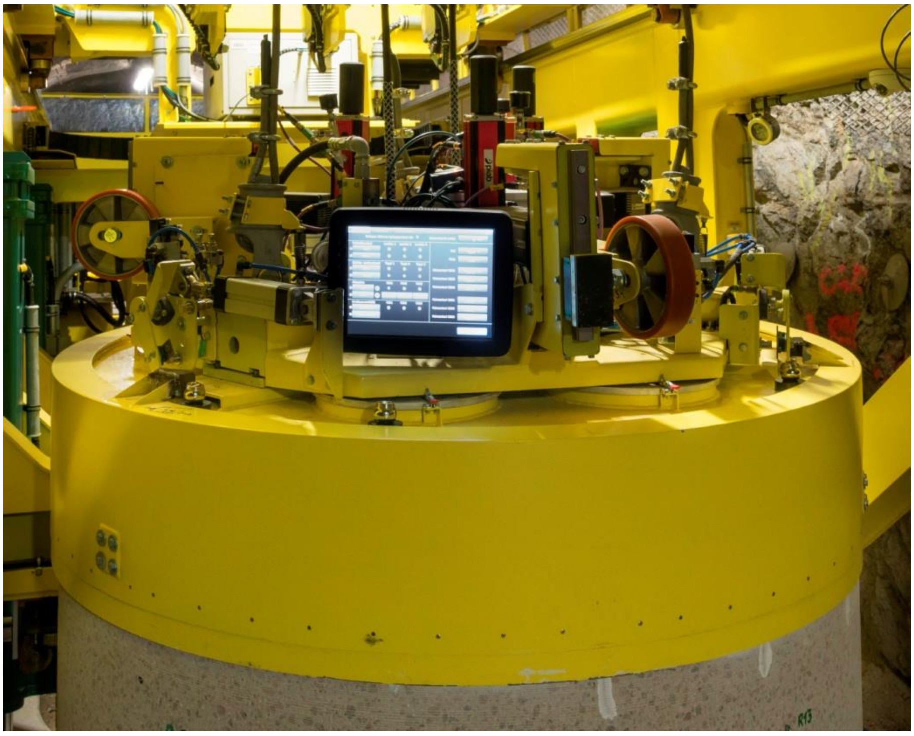
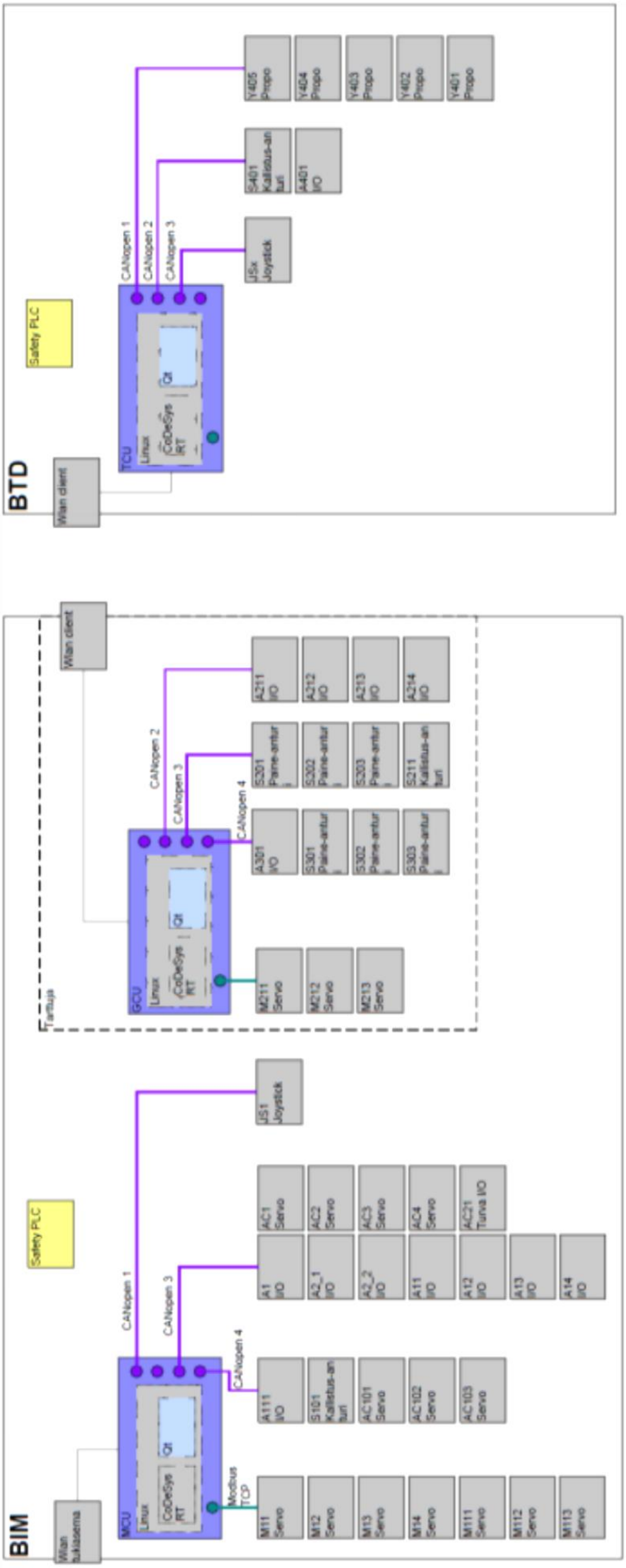


Fig. 22. *Gripper control unit computer on BIM mechanical gripper*

Fig. 23. *BIM main control unit*

Fig. 24. *Remote control view of BIM main control unit and gripper control unit*



1. **Fig. 25.** *Automation program layout for BIM and BTD*

3.6.1 Safety features

As noted previously, safety of the staff associated with the BIM and BTD is the primary concern during all phases of repository activity. There is additionally the need to protect the machinery from unexpected conditions or to rapidly shut it down should mechanical problems or control issues be detected. The BIM is therefore equipped with manual emergency stop switches and a key switch to disengage all actuator movements. The BTD has its emergency stop switch located inside tractor cabinet.

The BIM also has built-in provision for linking into external area control system to provide for automated shut down should anyone be in the vicinity of the operating equipment.

The safety features for buffer installation machinery is designed in accordance with euro norm SFS-EN ISO 13849 class 1.

Before the introduction the safety and risk analysis for both the BIM and BTD was performed by Posiva's safety experts consultants. A few changes had to be done.

3.6.2 Linking the control systems

As the BIM and the BTD are designed to operate together they need to have a co-ordinated control system. To accomplish this there is a wireless Ethernet connection between BIM and BTD. This connection is designed to transfer the video signals from BIM cameras to the tractor cabin and also for use when steering the rear axle of BIM during its movement along a demonstration tunnel.

The tractor used to relocate the BTD is linked to it through physical connectors. There are connectors for coupling the tractor hydraulics into BTD and linking the BTD to its control unit located inside the tractor cabin.

Connection between BTD and its remote control is established via wireless Ethernet or through cables utilizing CANopen and Ethernet protocols.

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 installation machine (BIM)

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 a delivery delay past the originally anticipated date. The machine was however completed and delivered to Posiva Oy in time for its 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 (BTD)

The bentonite installation machine was manufactured by Lehtosen Konepaja Oy 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 Oy.

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 Oy. 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 also tested and the automation development continued during Demonstration Phase 1.

5.3 Emplacement demonstrations in surface facility

The purpose of the surface facility 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. This installation was also required to be accomplished within two hours' time, to a lateral accuracy of +/-1 mm.

5.3.1 Execution

Surface level testing using simulated buffer blocks started in September 2014. On completion of these intial trials, the first buffer installation test was started on 18.2.2015. Fig. 26, Fig. 27 and Fig. 28 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.

Fig. 26. *Bentonite installation machine at surface level test facility.*

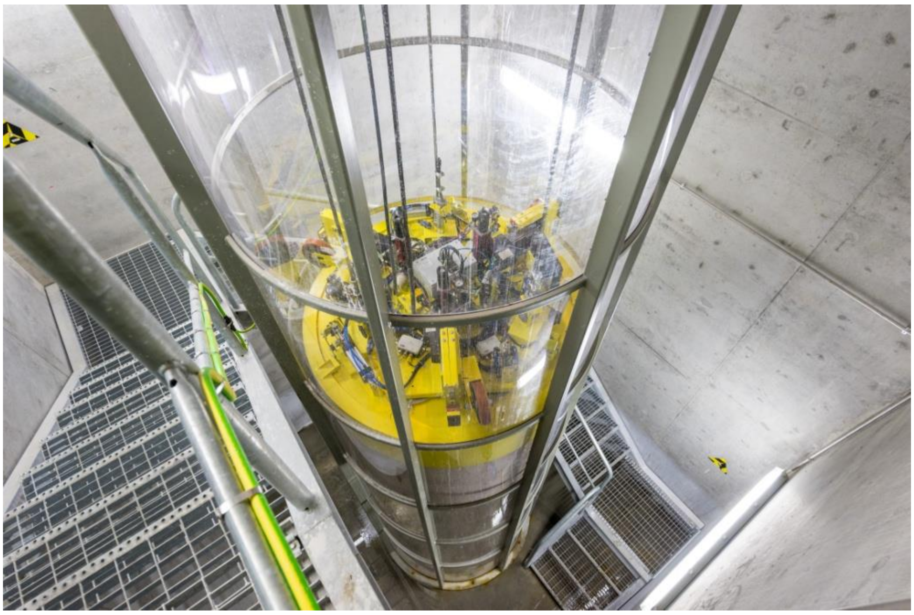


Fig. 27. *Gripper and concrete block lowered into test hole, seen from above.*

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 degree of as-placed positioning accuracy can be accomplished, as well as identifying what improvements could be made before underground trials occurred or real buffer components are used.

The buffer installation sequence requires careful pre-planning . The sequence followed in these trials are as follows:

1. Terminal tractor operator moves the BIM to a 10 metre distance from test hole at which time activity timing is started. The terminal tractor operator first connects BIM to tunnel electrical feed and then moves the BIM-tractor unit the remaining 10 metre distance to the test hole.

2. The operator positions and levels the BIM from the remote operation station. 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. BIM is therefore positioned so that the installation aperture on support leg subframe is +/-100 mm from test hole centre line. The BIM is also backed as close as possible to the transverse centre line of the hole. Initial positioning of the support legs is accomplished by lowering them into contact with the floor so that they support the BIM weight. The sideways shifting is then done by moving the support leg subframe onto test hole centre line while the terminal tractor is connected. Maximum correction with BIM lateral shifting is 200 mm and so initial positioning is important. Once BIM positioning is accomplished and its weight is fully supported by the legs, the terminal tractor is disconnected and is is driven away. At this time the 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 the 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 to 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 the BTD.

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

10. After the final centring, the block is lowered fully to contact the surface below it 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 and centering is confirmed, 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 released. When the pressure between suction surface and block reaches ambient level, the mechanical gripper and container top may be retracted back up the hole. 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 previously moved the shelf to its back position into BIM load transfer area.

14. The container top is lowered onto the shelf and the BIM operator releases it from the gripper. The mechanical gripper is carefully raised 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. The Gripper contains delicate components that may be damaged if it 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.

As noted previously, this entire sequence of activities are specified to be completed within 120 minutes if the installation schedule for actual repository operations are to be met.

Fig. 28. *Gripper and concrete block lowered into test hole.*

5.3.2 Technical issues in surface trials and adjustments made

Prior to the start of installation testing, the concrete blocks to be used to simulate the buffer components were prepared and positioned for use. They were brought to the BIM on a pallet by a fork lift; the BTD was not used at this time. The results of the installation test were not affected by this, as the installation time is determined by the BIM operations and not the block transfer operation. A number of non-conformances were identified prior to and during the conduct of the surface trials. These and the manner in which they were remedied are as follows:

1. It was determined just prior to conduct of the first surface trials that the ring-shaped concrete blocks to be used for testing did not meet the dimensional tolerances of the bentonite blocks e.g. they had a too large diameter centre hole. Although not an exact size match, they were close enough to actual buffer blocks that they could still be used for demonstration tests without compromising the results.

2. One of the five ring-shaped concrete blocks scheduled for use in the trials was found to be defective and was therefore left out of buffer installation. The accuracy of the spent fuel canister space within the ring blocks was thus measured for the four ring blocks only. Later in the testing program, the defective block was fixed and tested for use in subsequent underground installation trials.

3. Flexing of the test holes' acrylic wall caused problems; the wall would yield up to 10 mm from contact by the centring pads. It was still possible to centre the block, even though the procedure used to achieve centring would not be representative of the actual emplacement in rock-walled deposition hole. In an effort to remediate this, the test hole was modified to include steel stiffeners at places where the centring pads would touch the wall.

4. The test hole bottom did not initially meet the specification set for its levelness. A deviation of 3 mm was measured, which could cause the blocks to shift when lowered onto a previously installed block or when centring pads were released. This was corrected during testing by levelling the bottom using filler material.

5. There were two occasions during the installation where the WLAN connection between BIM main control unit and gripper control unit was lost. The cause for connection loss was not found. Connection loss prevents the operation of BIM and is still a major operational concern.

5.3.3 Discussion of surface test results

Tests initially showed that the installation accuracy of the bottom block was well within requirement of 1mm 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 installationFig. 29). The deviations measured and listed in Fig. 29 ranged from 1.78 to 4.03 mm whereas the as-installed deviations measured 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 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. 29.*Position of the inner cylinder of 4 concrete ring bottom centre points in test hole.*

The installation time required to complete the buffer during surface trials exceeded the 2 hour requirement; The 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 therefore set at 4 hours 12 minutes.

Factors affecting this timing were:

1. The block location measurements made during the placement trials consumed a lot of time as they had to be made manually. The laser tracker was not integrated into the automation system. It had difficulties in locating the target reflectors on the container top, even when they were in plain sight. The location readings from the laser tracker had to be fed into the control system manually before the container top position could be corrected. This issue will need to be dealt with in future modifications to the emplacement machine since manual measurement and positioning will not be a viable option in a deposition tunnel. Once dealt

with the speed of the installation process should see a substantial improvement but if enough to bring the process into compliance with the target is not known.

2. The centring of the container top using the gripper actuator pads was also slow, and had to be repeated multiple times for each block. A possible but unconfirmed reason for this was an actuator jamming, causing the control current to rise too soon and stopping the actuator movement early. This step in the installation process also needs to be further evaluated.

3. Pellet filling of the gap between the buffer and test hole wall was performed once. 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.

4. The pellet filling evenness was very sensitive to the location of pellets inside the container top pellet reservoirs; if they were just poured into container top pellet compartments, pellets would end up on top of the installed block (
5. Fig. 30). The pellets have to be filled in reservoirs carefully and quantities need to be adjusted for the varying gap around the blocks. Even then, some waviness of pellet fill top surface will be present.

Fig. 30. *Pellet fill: uneven distribution.*

5.4 Emplacement of buffer in ONKALO demonstration tunnel

On completion of the surface trials and the actions identified as being necessary to improve placement accuracy, speed and efficiency, 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. Fig. 31 shows the BIM at the location of the deposition hole location (background) . The remote operation control was located near the entrance of the demonstration tunnel (Fig. 31 foreground).

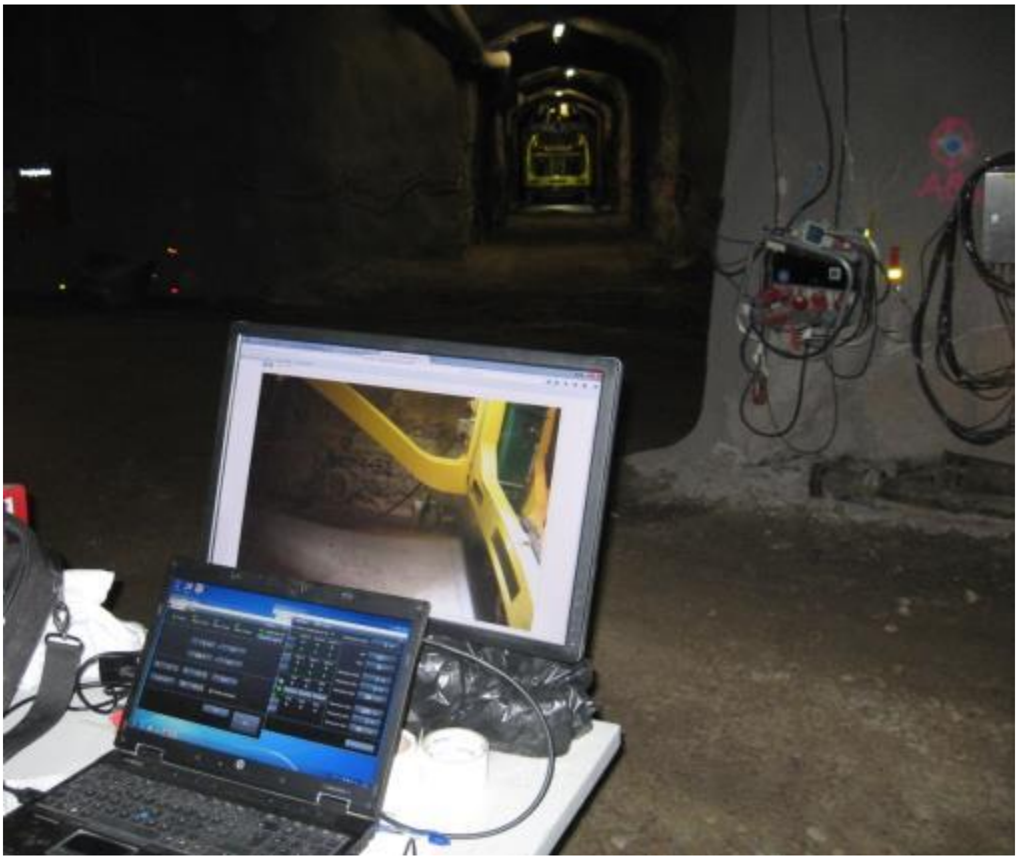


Fig. 31. *Remote operation area and BIM in ONKALO demonstration tunnel. BIM in top centre of picture.*

5.4.2 Demonstration Phase 2

Demonstration Phase 2 started with installation of a concrete block that simulated the buffer. The simulated buffer block assembly consisted of 11 massive concrete segments. In order of their installation they were: a 500 mm high solid block, then five ring blocks, each 960 mm high, followed by one solid 400 mm high block, two solid 800 mm high blocks and finally, one solid block 500 mm high.

Only the first block was brought to the BIM using the BTD and fully-loaded container. The cameras on BTD were not functional and so reversing near the 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. As a result, the rest of the concrete blocks were brought to the BIM on pallets using a wheel loader equipped with lifting forks. The installation timing 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 (an issue identified in the surface trials also (section 5.3.2)). 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. Demonstration Phase 3 (full-scale installation of an actual buffer block assembly)

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. 32). Fig. 33 through Fig. 36 are photos showing the BIM and the subsequent block installations in the test borehole. There was no stepwise pellet filling process performed as part of this trial since this buffer installation was also to be used for a pellet fill test, where all the pellets were released into the buffer to rock wall gap at once.

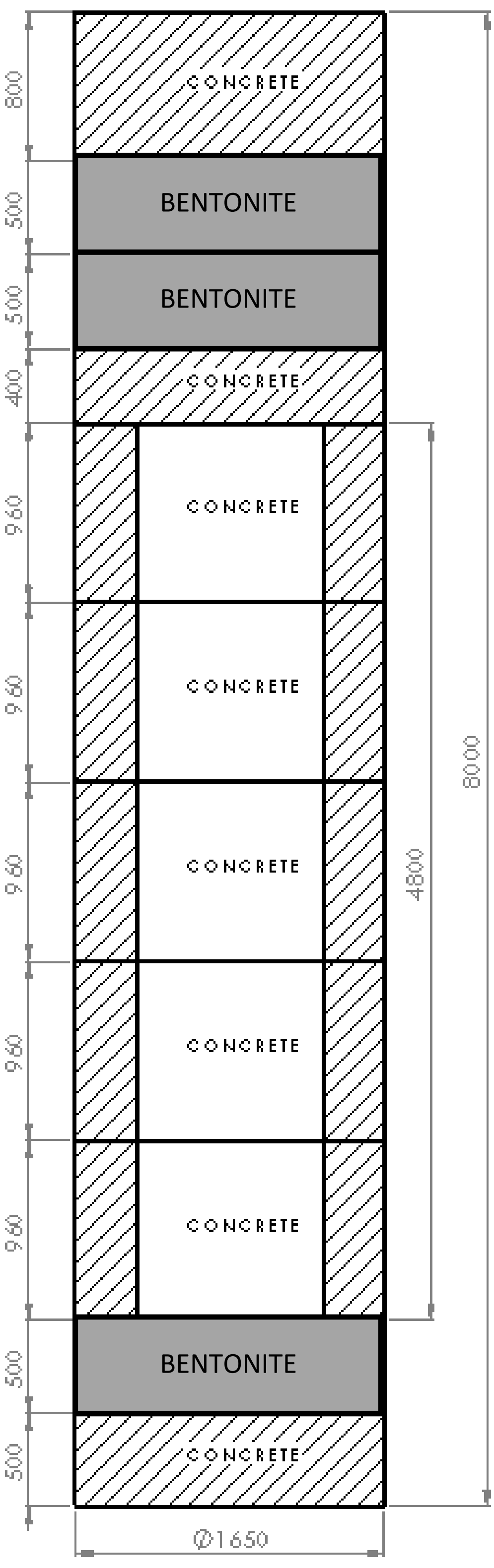


Fig. 32. *Buffer consisting of bentonite and concrete blocks*

Fig. 33. *Bentonite installation machine in ONKALO Demonstration Tunnel 1.*

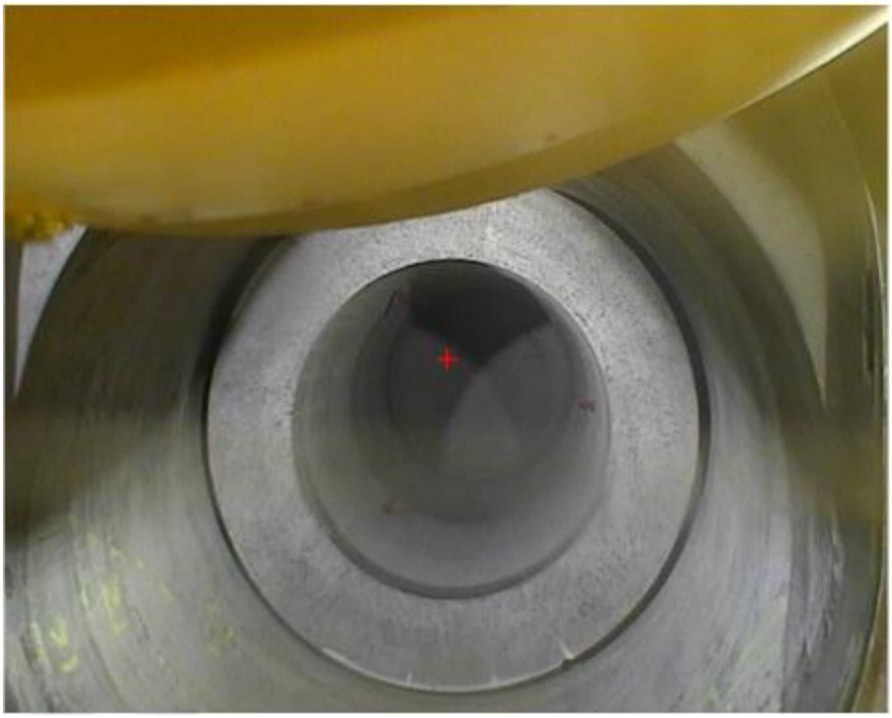


Fig. 34. *Buffer with ring blocks installed, seen by BIM dome camera.*

Fig. 35. *Installing the top solid blocks, seen by BIM dome camera.*

Fig. 36. *All buffer blocks in test hole, seen by BIM dome camera.*

5.4.3 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 assembly, 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 5.3.3, results that deviated from these measurements. In the case of Demonstration Test 2 the deviation ranged from 2.2 to 8.8 mm from test hole centre line (

Fig. 37).

The possible sources for the deviation are again the same as for Phase 1 test, listed in section 5.3.3.

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. 32, 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. 37. Position of the inner cylinder of 5 concrete rings in test hole EH8.

6 SUMMARY

6.1 Dimensional accuracy of installed buffer

The equipment developed showed that it is possible to locate 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.

6.2 Installation time for buffer

During the demonstrations the targeted buffer installation time of 120 minutes was not reached. This was mainly caused by issues related to the performance of 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.

6.3 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 more substantial recommendations are described below with regards to each of the major system components.

6.3.1 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 use of WLAN between control units could be eliminated, as the connection problems caused several malfunctions. 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.

6.3.2 Suction gripper

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.

6.3.3 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.

7 ACKNOWLEDGEMENT

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8 REFERENCES

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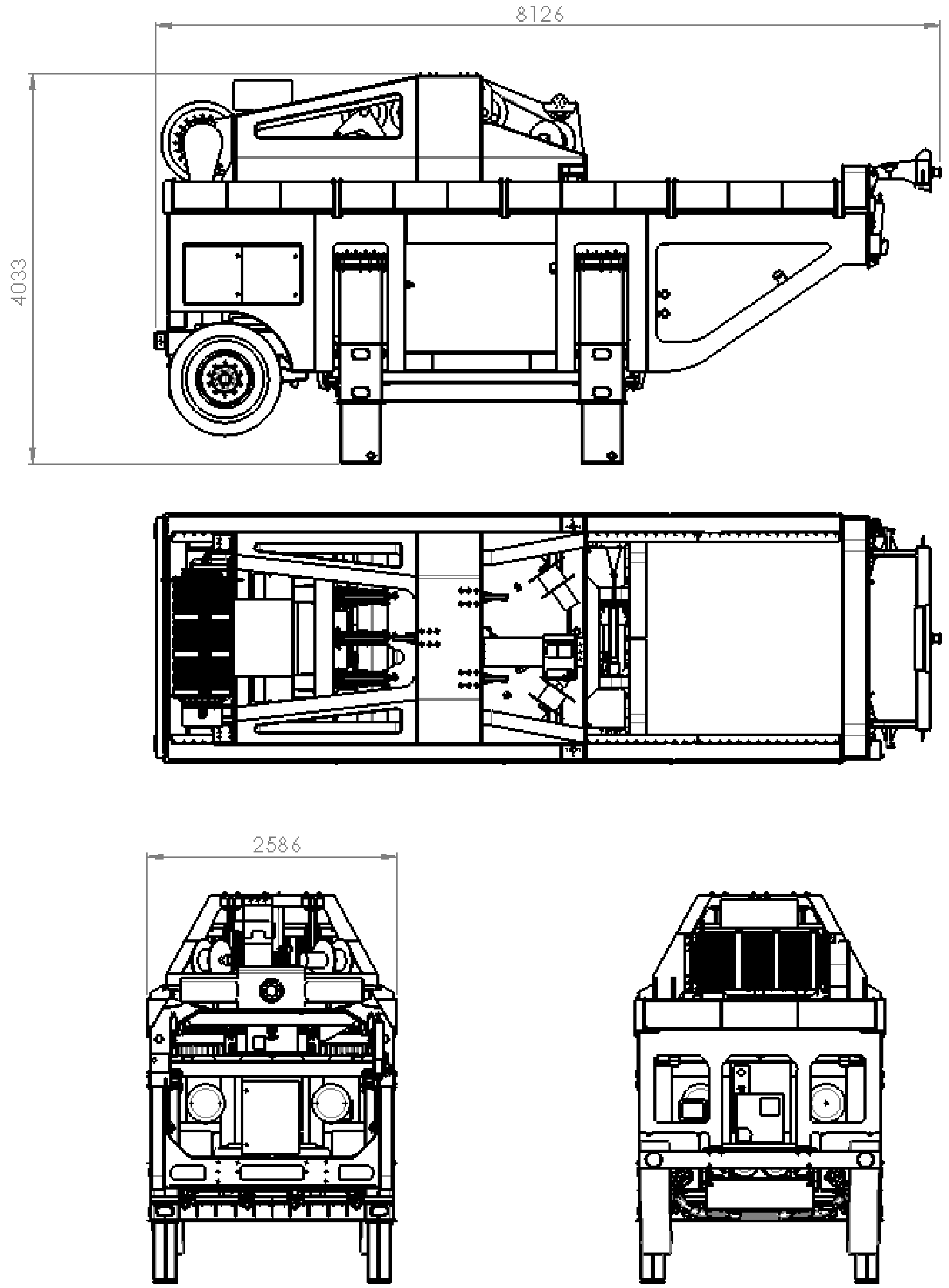
9 APPENDICES

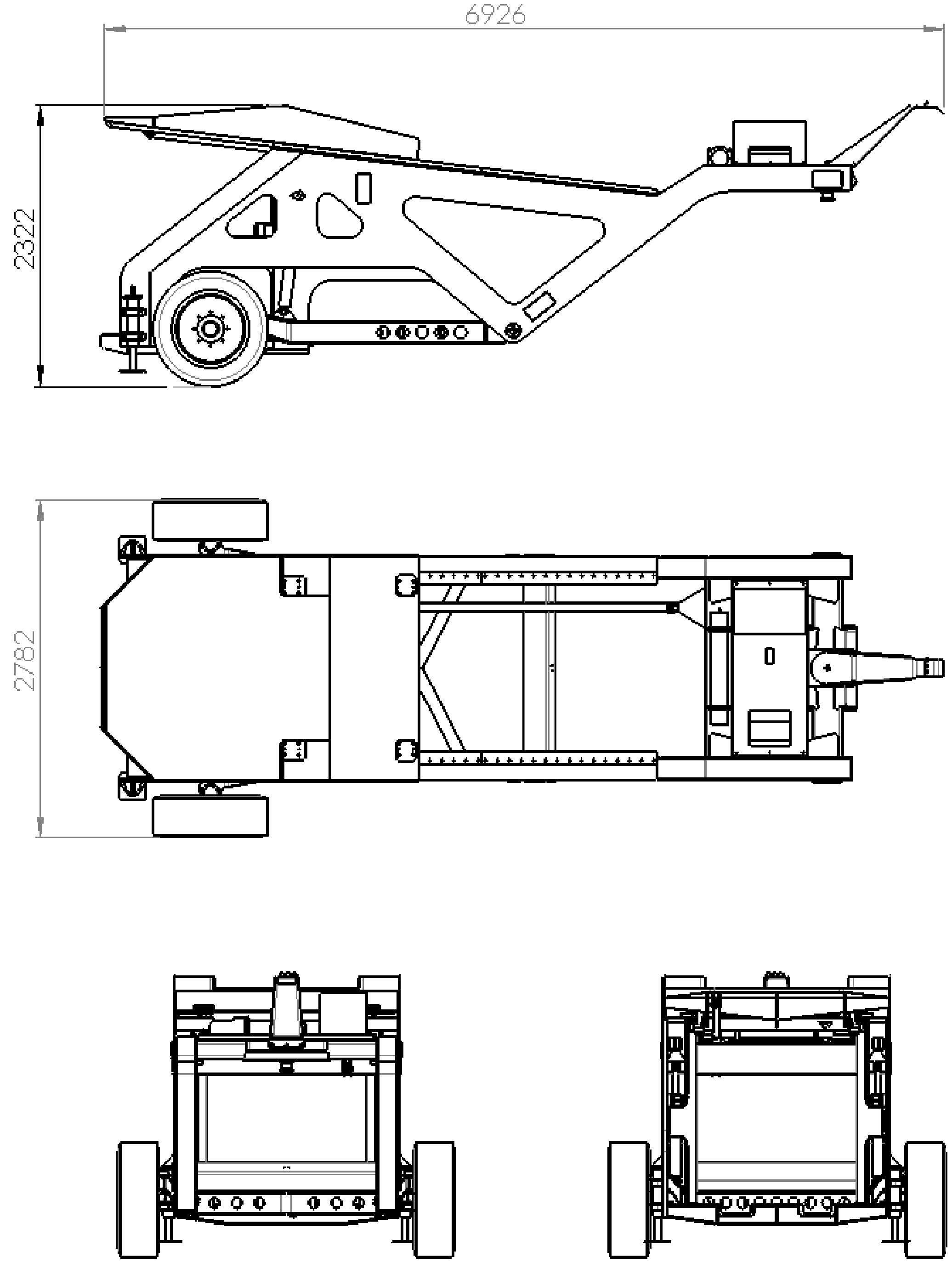
Appendix 1. Dimensional drawing of the bentonite installation device
Appendix 2. Dimensional drawing of the bentonite transfer device
Appendix 3. Dimensional drawing of the bentonite container
Appendix 4. Demonstration phase 1 tests
Appendix 5. Demonstration phase 2 and 3 tests

Appendix 1.



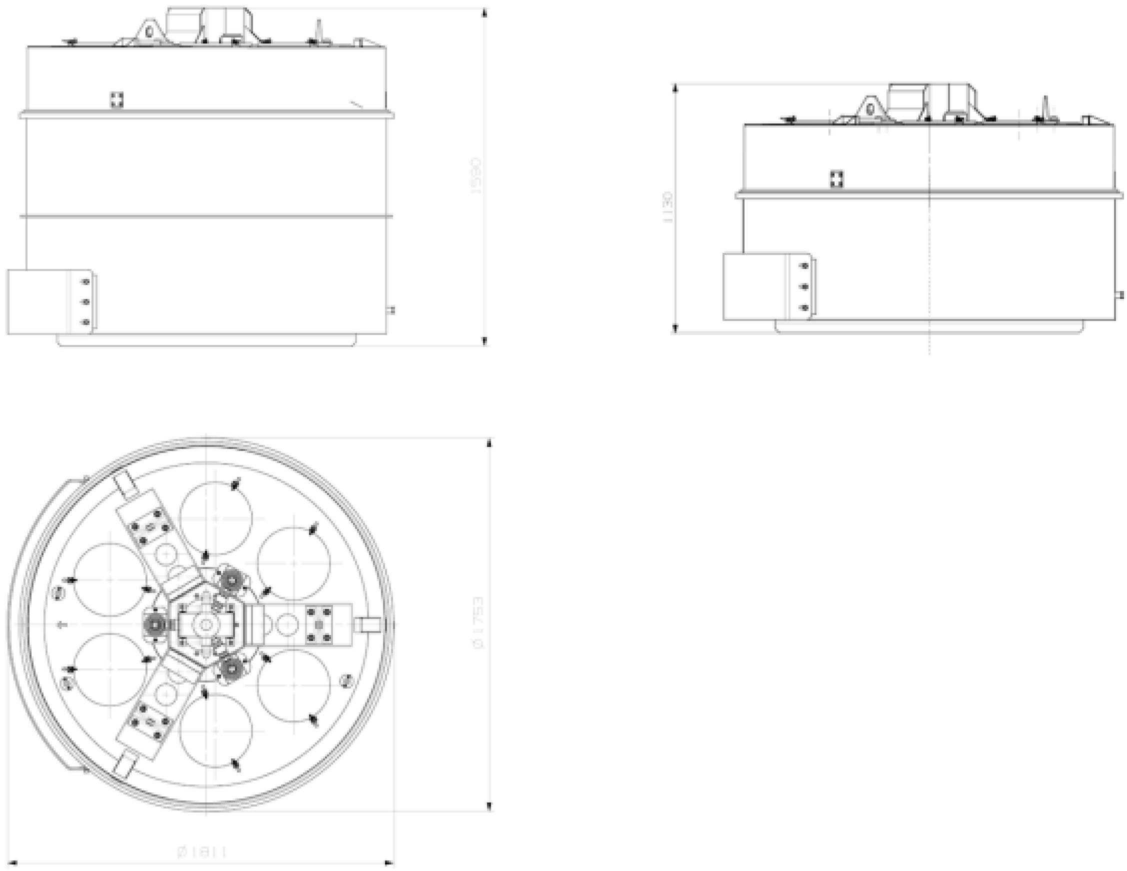
Dimensional drawing of the bentonite installation device

Appendix 2.



Dimensional drawing of the bentonite transfer device

Appendix 3.



Dimensional drawing of the bentonite container

Appendix 4.

LUCOEX, Buffer installation machine and bentonite transfer device	
Test phases	
Demonstration phase 1 (Ground level tests)	
Rivi	Testattavat toiminnot
1000	**BIM moving and positioning onto test hole**
1001	Axle steering and steering angles
1002	Ease and logicality of steering, functionality of centring
1003	Adequacy of camera visual range for reversing and positioning of BIM
1004	Accuracy of moving BIM onto test hole
1005	Support leg subframe, transverse (Y) direction positioning to test hole
1006	Descent of support legs, level sensor readings
1007	Detaching the fifth wheel and moving the terminal tractor away
1008	BIM stability on support legs
2000	**BIM initial measurements and high accuracy positioning onto test hole**
2001	Levelling of BIM frame
2002	Positioning the BIM frame onto test hole
2003	Positioning the lifter unit and gripper onto the test hole
2004	Descent of empty container top to test hole bottom, checking the gap between top and hole wall
2005	Fine positioning of the container top using linear actuators, visibility of laser targets
3000	**BTD transfer, loading and levelling**
3001	Axle steering and steering angles
3002	Loading the bentonite container onto BTD
3003	BTD Ease and logicality of steering while loaded, reversing/driving forward
3004	Levelling the BTD frame with support leg cylinders while loaded
3005	BTD unladen top shelf movements
3006	BTD top shelf movements, with container top
3007	Reversing the BTD between BIM front frame
4000	**Lifting a block off BTD (or similar platform) and positional measurements**
4001	Block position measurement from laser tracker targets and centring of mechanical gripper to block
4002	Descent of gripper onto container top, locking, checking the vacuum level
4003	Lifting a block (1cm), vacuum level during lifting
4004	Block descent, gripper to container top interlock
4005	Positioning the lifter unit and gripper onto test hole, loaded with a block
5000	**Block descent and installation**
5001	Defining the block center point relative to container top using laser sensors in BIM support leg
5002	Block descent to fine positioning level
5003	Levelling of block using rope adjustment actuators
5004	Driving fine positioning pads to hole wall and fine positioning of the block
5005	Descent of block to installation level, final checks before block release
5006	Moving container top onto BTD top shelf using BIM lifter
6000	**Pellet tests**
6001	Opening the pellet ring on an empty container top
6002	Installation of pellets after a block is installed into test hole

Appendix 5.

LUCOEX, Buffer installation machine and bentonite transfer device	
Test phases	
Demonstration phases 2 and 3 (Tests in Onkalo demo tunnel)	
Rivi	Testattavat toiminnot
1000	**BIM moving and positioning onto test hole**
1003	Adequacy of camera visual range for reversing and positioning of BIM
1004	Accuracy of moving BIM onto test hole
1007	Detaching the fifth wheel and moving the terminal tractor away
3000	**BTD transfer, loading and levelling**
3007	Reversing the BTD between BIM front frame
4000	**Lifting a block off BTD (or similar platform) and positional measurements**
4002	Descent of gripper onto container top, locking, checking the vacuum level
4005	Positioning the lifter unit and gripper onto test hole, loaded with a block
5000	**Block descent and installation**
5002	Block descent to fine positioning level
5003	Levelling of block using rope adjustment actuators
5004	Driving fine positioning pads to hole wall and fine positioning of the block
5005	Descent of block to installation level, final checks before block release
5006	Moving container top onto BTD top shelf using BIM lifter
6000	**Pellet tests**
6002	Installation of pellets after a block is installed into test hole
7000	**Full installation cycle of the bentonite buffer**
7001	Full installation cycle of the bentonite buffer
8000	**Removal of buffer**
8001	Removal of pellets
8002	Removal of blocks

10