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Fredrik Hermansson
Peter Eriksson
Anni Fritzell

SVENSK KÄRNBRÄNSLEHANTERING AB

SWEDISH NUCLEAR FUEL
AND WASTE MANAGEMENT CO

Box 3091, SE-169 03 Solna
Phone +46 8 459 84 00
skb.se

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Fredrik Hermansson, Peter Eriksson, Anni Fritzell
Svensk Kärnbränslehantering AB

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Abstract

The bentonite buffer is an important part of the solution of storing nuclear waste according to the KBS-3 concept. The bentonite buffer surrounds the canister, which contains spent fuel, and protects the canister from shear forces and corrosion agents. In case of a breach of canister integrity, the buffer hinders transport of radionuclides by providing an environment with very low hydraulic conductivity. The buffer and the canister with spent fuel are installed in vertical deposition holes in the deposition tunnels of the final repository.

In 2020 SKB changed the design of buffer blocks from solid block layers in the shapes of discs and rings to segmented buffer block layers built up by several individual blocks. The change in design was preceded by a full-scale, in situ test with a segmented buffer (Nord et al. 2020).

In order to get a better understanding of how the buffer behaves during the installation phase with higher inflows, new full-scale tests was needed. Therefore, two new full-scale tests with segmented buffer with a inflow of 0.01 l/min and 0.1 l/min have been performed.

With the updated knowledge based on information gained from these full-scale tests it is possible to predict the upwards movement of the buffer blocks during installation. If the buffer upwards movement is too large it could hinder the backfill installation and reduce buffer density. Consequently, the model together with the data from the tests can be used to define the time available for installation of buffer and backfill for holes with different inflows and inflow locations. This information will be used for planning the installation sequence of individual deposition tunnels in the repository facility.

This report covers the execution and results from two full-scale tests with segmented buffer blocks performed during 2022 at Äspö Hard Rock Laboratory. The report presents all necessary information and data regarding the test to allow future re-examination and evaluation of the test results. The report also presents data and information from the production of components (bentonite blocks and pellets) for the tests but does not evaluate the production equipment or production process.

New knowledge on the buffer behaviour during installation was gained through these tests. For example, the larger, artificial inflow rates lead to an intrusion of water into the gap between canister and buffer – which has not been noted previously. It has also been shown that it is possible to use extruded pellets in the buffer, since the overall behaviour in full scale did not differ significantly from that of the roller compacted pellets which were used earlier. Furthermore, it is shown that it is possible to install buffer also at the maximum inflow rate to the deposition hole of 0.1 l/min.

Based on the results from the tests, times available for buffer installation at different water inflows have been estimated. As examples, the results indicate that the buffer can be left unprotected by backfill during around 60 days at the inflow 0.001 l/min, around 22 days at the inflow 0.01 l/min and 8 days at 0.1 l/min. These times are preliminary and will be refined using modelling.

Sammanfattning

Bentonitbufferten är en viktig del av lösningen för att lagra använt kärnbränsle enligt KBS-3-konceptet. Bufferten omger kapseln med använt bränsle och skyddar den från skjuvkrafter och ämnen som kan leda till korrosion. Vid ett eventuellt kapselbrott hindrar bufferten transport av radionuklider genom att skapa ett skydd runt kapseln av bentonit med mycket låg hydraulisk konduktivitet. Bufferten och kapseln med använt bränsle installeras i vertikala deponeringshål i slutförvarets deponeringstunnlar.

År 2020 ändrade SKB utformningen av buffertblock från solida blocklager i form av skivor och ringar till segmenterade buffertblockslager uppbyggda av flera enskilda block. Förändringen i utformning föregicks av ett fullskaligt in situ-försök med en segmenterad buffert (Nord et al. 2020).

För att få en bättre förståelse för hur bufferten beter sig vid vid högre vatteninflöden under installationsfasen så behövdes nya fullskaletest utföras. Därför har två fullskaletest utförts med vatteninflöden på 0,01 l/min och 0,1 l/min.

Med den uppdaterade kunskapen, baserad på information från dessa fullskaleförsök, är det möjligt att förutsäga buffertblockens rörelse uppåt under installationen. Om buffertens uppåtriktade rörelse är för stor kan det hindra återfyllningsinstallationen och sänka buffertens densitet. Den föreslagna modellen kan användas för att definiera tillgänglig tid för installation av buffert och återfyllning för hål med olika storlek och placering av inflöden. Denna information kommer att användas för planering av installationssekvensen för enskilda deponeringstunnlar i slutförvarsanläggningen.

Denna rapport beskriver utförande och resultat från två fullskaliga tester med segmenterad buffert utförda under 2022 vid Äspölaboratoriet. Rapporten presenterar all nödvändig information och data om testet för att möjliggöra framtida omprövning och utvärdering av testresultaten. Rapporten presenterar även data och information från tillverkningen av komponenter (bentonitblock och pellets) för testerna men utvärderar inte produktionsutrustningen eller produktionsprocessen.

Ny kunskap om buffertbeteendet under installationen erhölls genom dessa tester. Till exempel leder de större, artificiella inflödeshastigheterna till att vatten tränger in i gapet mellan kapsel och buffert vilket inte har noterats tidigare. Det har också visats att det är möjligt att använda extruderade pellets i bufferten, eftersom deras beteende i full skala inte skiljde sig nämnvärt från det hos rullkompakterade pellets som använts tidigare. Ett ytterligare resultat är att det har visats att det är möjligt att installera bufferten under det största tillåtna inflödet till ett deponeringshål, 0,1 l/min.

Baserat på resultaten från testerna har tillgängliga tider för buffertinstallation vid olika vatteninflöden uppskattats. Som exempel indikerar resultaten att bufferten kan lämnas oskyddad utan återfyllning under cirka 60 dagar vid inflödet 0,001 l/min, cirka 22 dagar vid inflödet 0,01 l/min och 8 dagar vid 0,1 l/min. Dessa tider är preliminära och kan komma att omvärderas och snävas in med hjälp av modellering.

Contents

1 Introduction

1.1 Background

The bentonite buffer is an important part of the solution of storing nuclear waste according to the KBS-3 concept. The bentonite buffer surrounds the canister with spent fuel and protects the canister from shear forces and corrosion agents. In case of a breach of canister integrity, the buffer hinders transport of radionuclides by providing an environment with very low hydraulic conductivity. The buffer and the canister with spent fuel are installed in vertical deposition holes.

In 2020 SKB changed the design of buffer blocks from solid block layers in the shapes of discs and rings to segmented buffer block layers built up by several individual blocks, see Figure 1-1. The change in design was preceded by a full-scale test with a segmented buffer, Test_Seg_N, reported in (Nord et al. 2020). This test was a repetition of a full-scale test of the previous design with solid block layers, Test_Solid_N, reported in (Luterkort et al. 2017). Both tests were performed in the CRT deposition hole at Äspö Hard Rock Laboratory with a natural water inflow of around 7–8 × 10^{-4} l/min.

To get a better knowledge on how the buffer behaves during the installation phase with higher inflows new full-scale tests were needed. Therefore, two new full-scale buffer tests with segmented buffer have been performed in the CRT-hole, Test_Seg_0.1 and Test_Seg_0.01. The tests had artificial inflows of 0.1 l/min and 0.01 l/min, respectively.

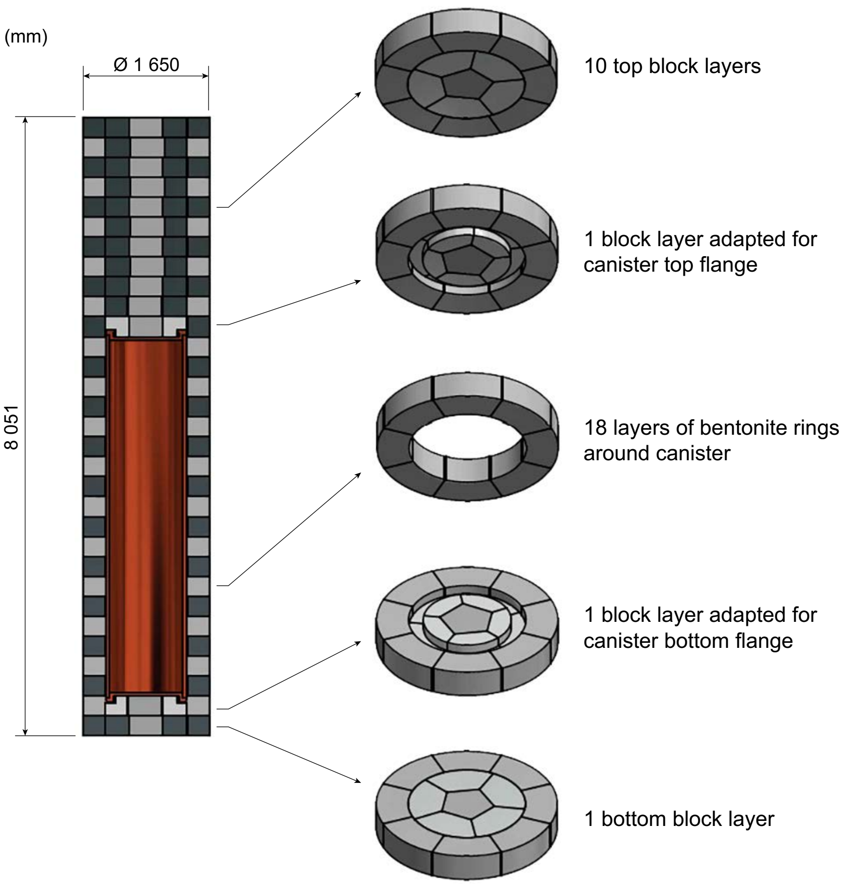


Figure 1-1. *Design of a segmented buffer.*

With the updated knowledge based on information gained from these full-scale tests it is possible to predict the upwards movement of the buffer blocks during installation. If the buffer upwards movement is too large it could hinder the backfill installation. Consequently, the data from the tests can be used to define the time available for installation of buffer and backfill for holes with different inflows and inflow locations. This information will be used for planning the installation sequence of individual deposition tunnels in the repository facility.

All tests that are used to evaluate how long installation time of buffer and backfill that is acceptable for different water inflows into the deposition hole are presented in Table 1-1.

Table 1-1. Full-scale, in situ tests of bentonite buffer used for the evaluation and conclusions in this report.

Test name	Natural inflow l/min	Artificial inflow l/min	Block layer type	Reference
Test_Solid_N	8.3×10^{-4}	-	Solid	Luterkort et al. 2017
Test_Seg_N	7.2×10^{-4}	-	Segmented	Nord et al. 2020
Test_Seg_0.01	3.7×10^{-4}	0.01	Segmented	This report
Test_Seg_0.1	3.7×10^{-4}	0.1	Segmented	This report

1.2 Purpose of the report

This report covers the execution and results from two full-scale tests with segmented buffer blocks performed during 2022 at Äspö Hard Rock Laboratory. The report presents all necessary information and data regarding the test to allow future re-examination and evaluation of the test results.

This report also presents data and information from the production of components (bentonite blocks and pellets) for the tests but does not evaluate the production equipment or production process.

A final purpose is also to present preliminary estimated times available for buffer installation at different water inflows based on the test results. In future work a THM model can be used to further back up these times and better inter- and extrapolate the time available for installation from the inflow points from the tests. The estimated times will be used as input for planning the installation process in the final repository for spent nuclear fuel.

1.3 Test objectives

The main purpose of the full-scale experiments was to learn more about different aspects of Thermal, Hydraulic and Mechanical (THM) processes during the installation phase of the buffer until it is supported by the backfill. The installation process itself is not investigated. For this reason, it is not necessary to use the planned automated buffer-installation equipment in the tests, and the test installation was done manually.

The analysed data from this experiment will be used to update, evaluate and calibrate the early-THM models and to get a better understanding of the THM processes. Data will also be used to estimate available times for buffer installation, see Section 1.2.

The highest inflow of the two, 0.1 l/min is the highest allowed inflow to a deposition hole in the repository for spent nuclear fuel. The test with this inflow also serves the purpose of testing the maximum allowed inflow to investigate the buffer behaviour in this situation, which has not been done previously.

A third purpose is to test the performance of extruded pellets as buffer pellets. Earlier investigations (Lundgren and Johannesson 2020) has indicated that it is possible to use extruded pellets but it has not been demonstrated in a full scale in situ test before.

2 Production of blocks and pellets

This chapter describes the results and the experience of designing and manufacturing of segmented bentonite blocks used in the full-scale test.

2.1 Block design

The design work for segmented block layers is presented in Nord et al. (2020). The results are summarised in this section. Figures 2-1 and 2-2 show the resulting design.

Type I$_1$: Outer block around the canister. These blocks have a higher density than the rest of the blocks. This is further explained in Section 2.2.1.

Type I$_2$: Outer block placed together with type II$_1$ or II$_2$ and a type III to make an entire block layer.

Type II$_1$: Inner ring.

Type II$_2$: Inner ring with a machined groove for the canister flange, illustrated in Figure 2-2. These blocks are placed together with block types I$_2$ and III to create the layers against bottom and top of the canister.

Type III: Centre block.

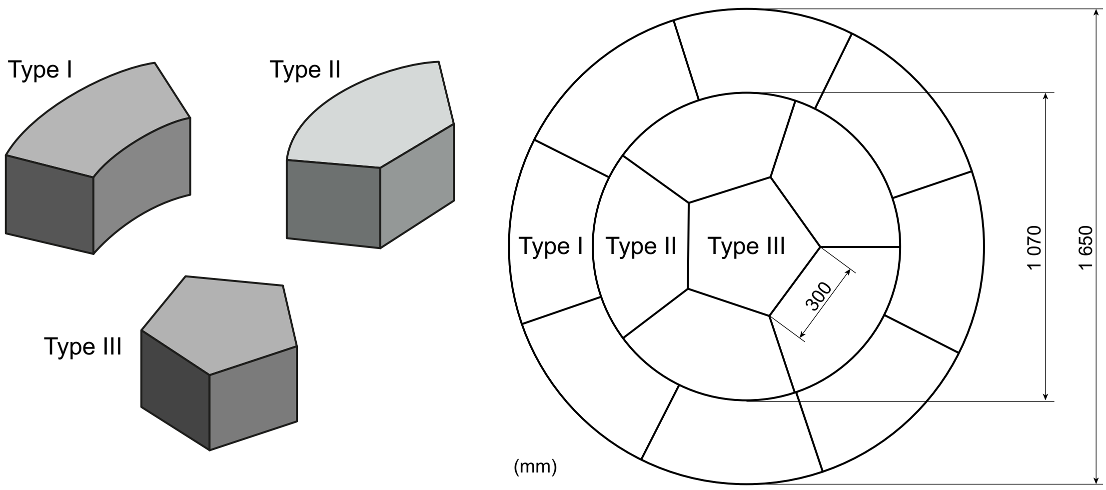


Figure 2-1. *Type I Outer block, Type II Inner block and Type III Centre block.*

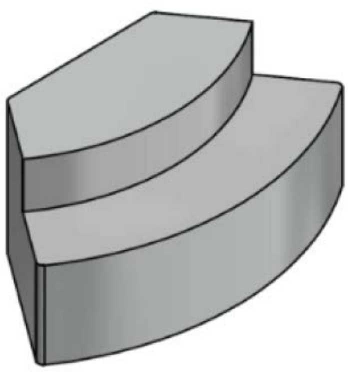


Figure 2-2. *Machined slot for canister in a type II$_1$ block to get a type II$_2$ block.*

In order to carry out the full-scale tests presented in this report, blocks according to this design has been produced using uniaxial compaction, with the following exceptions:

- The centre blocks were not produced as a single pressed block. Instead, the centre block was made by cutting out two block halves from blocks of type I with a band saw, see Section 4.1.
- Blocks of type II_2 were not used, instead a groove for the canister flange was produced by seam drilling directly in the deposition hole during installation, see Section 4.1.

2.2 Material, density and water content

The blocks were made of a bentonite with the commercial name BARA-KADE 1002. This is a natural sodium-dominated bentonite from Wyoming in the United States. All bentonite was first delivered to Äspö, where it was characterised (BARA-KADE 1002 has been characterised earlier at SKB, see Svensson et al. (2019) and conditioned. The bentonite was mixed with water to achieve a water content of approximately 17 %, before it was sent to the company Höganäs Borgestad AB for the block manufacturing.

In the design process, the block dry density was chosen so that the overall buffer dry density shall correspond to a swelling pressure meeting the required span of 3–10 MPa. The block density is based on small-scale compaction experiments and conducted swelling pressure measurements on the material. For full description of conducted tests, see Kronberg et al. (2020).

In order to get as small density differences as possible in the buffer after saturation, the blocks in the ring sections around the canister were compacted to a higher density compared to the blocks placed above and below the canister.

When installing segmented blocks, the number of gaps has been estimated to be 0.8 % of the buffer volume. To simplify and setting a conservative estimation for this test, 1 % is used in the design. To compensate for the gaps in a conservative way, the dry density of the segmented blocks is increased by 1 %. The target dry density of the different blocks used in this test is presented in Table 2-1. However, for the purposes of the full-scale tests presented in this report the requirement on the achieved density is not considered to be a crucial aspect. More important in this test is to have stricter requirements on dimensions than on dry density. The block tolerances are presented in Section 2.3.

It was decided to use a water content of 17 % based on experiences from MX-80 bentonite which is similar to BARA-KADE 1002.

Table 2-1. Recommended dry density of segmented blocks.

Block type	Water content (%)	Dry density (kg/m^3)
I_1 Ring blocks around the canister	17	1785
II_1 Inner ring blocks	17	1750
I_2 Outer ring above and below the canister	17	1750

2.3 Block tolerances

To achieve a buffer that is possible to install the height is important in the quality control. The height tolerance is wider than what is planned for the reference design since the production line for this test is not optimised and a wider tolerance is acceptable for the purpose of the test. For usage in the real repository also the weight together with the dimensions of the blocks will be important to achieve the dry density required for safety after closure. However, for this test, the weight is less of a priority.

Table 2-2. Tolerances used in block manufacturing.

Block type	Target value	Tolerance
Block type I_1		
Block height (mm)	250	± 1.5
Dry density (kg/m^3)	1785	± 50
Weight (kg)	79.52	± 2.23
Block type I_2		
Block height (mm)	250	± 1.5
Dry density (kg/m^3)	1750	± 50
Weight (kg)	77.96	± 2.23
Block type II_1		
Block height (mm)	250	± 1.5
Dry density (kg/m^3)	1750	± 50
Weight (kg)	73.92	± 2.11

2.4 Production of blocks

A total of 709 blocks were manufactured according to specifications during a total of 18 days in March and April 2022 at the company Höganäs Borgestad AB. The average production rate was about eight blocks per hour, including preparations and post-press activities such as regular cleaning of the mould. However, the actual compaction time for one block was around two minutes.

The pressing moulds used for the block production were manufactured for the test Test_Seg_N in 2019. The design and manufacturing of the moulds is presented in Nord et al. (2020).

The press used was a 1 600 metric ton SACMI press, illustrated in Figure 2-3.

The segmented blocks were handled by an industrial robot (see Figure 2-3). The robot grabs the block with a vacuum tool from the press and places it on a scale to check the weight of each block. After the weight control the robot stacks the block on a Euro-pallet (EU standard size).

Each pallet house 6 blocks that are stacked in two layers separated with Styrofoam as protection. The block stack was then sealed with two layers of a transparent plastic film, illustrated in Figure 2-4.

Figure 2-3. The industrial robot grabbing a finished block from the SACMI press.

Figure 2-4. Pallet with 6 blocks separated with Styrofoam and the transparent plastic film.

2.5 Quality control

2.5.1 Hydraulic pressure and filling height

To achieve the right density of the blocks, the weight and height of the blocks must be within the given tolerances described in Section 2.3. At Höganäs Borgestad AB this was achieved by test compaction at the beginning of the production where production parameters, such as compaction pressure and filling height, were adjusted to give acceptable results. By comparing these data with the actual weight and height of the final products the press could be tuned in for each block type. When these parameters were stable, production began.

During production the filling height, hydraulic pressure and height of each block were monitored and recorded manually. Hydraulic pressure and filling height are displayed in Table 2-3.

2.5.2 Block weight

After compaction an industrial robot placed the block on the scale, where a person manually recorded the value before the robot placed the block on a Euro-pallet. The average block weights are shown in Table 2-3.

2.5.3 Block height

The final height was recorded for each block during the compaction of the blocks by the press control system. As an extra measurement of the produced blocks the heights of a selection of blocks were also measured manually by a digital calliper. The average block heights are displayed in Table 2-3.

Table 2-3. Quality control during manufacturing.

	Type I_1	Type I_2	Type II
Number of blocks produced	342	229	138
Block height, specified value (mm)	**250 ± 1.5**	**250 ± 1.5**	**250 ± 1.5**
Average measured by press (mm)	250.0	250.0	250.0
Standard deviation, block height measured in press (mm)	0.3	0.2	0.4
Average height measured with calliper (mm)	250.1	249.9	250.0
Standard deviation, block height measured with calliper (mm)	0.5	0.8	0.6
Block, specified weight (kg)	**79.52 ± 2.23**	**77.96 ± 2.23**	**73.92 ± 2.11**
Average, measured during production (kg)	79.14	77.48	72.63
Standard deviation, block weight (kg)	0.51	0.79	0.52
Dry density, specified value (kg/m^3)	**1 785 ± 50**	**1 750 ± 50**	**1 750 ± 50**
Average, calculated from production data (kg/m^3)	1 771	1 735	1 721
Standard deviation, dry density (kg/m3)	10	25	11
Compaction pressure (average in MPa)	39	30	26.5
Compaction pressure, standard deviation (MPa)	3.9	3.4	1.6
Filling height in mould (average in mm)	410	404	395
Standard deviation (filling height in mm)	3	5	4
Number of checked blocks with calliper (%)	10	12	31

2.6 Conclusions from the block production

The blocks were of overall high quality, and were well within the specified requirements presented in Section 2.3.

As the blocks were compacted, three main deviations were noted. Firstly, the block properties varied during adjustment of the press. It was difficult to set the right parameters for the press at the beginning of production which for a while resulted in large variations in the weight and height of the blocks.

Secondly, all the blocks manufactured for this study had horizontal hairline cracks which were located in the lower half of the block, perpendicular to the direction of compaction, see Figure 2-5. The cracks are thought to be shallow and seem not to affect the mechanical properties of the blocks.

The last deviation concerns material sticking to the pressing moulds. The bentonite blocks tended to stick to the bottom of the mould. Over time the material started to form small "cakes" that created imprints in the shape of pits in the blocks. This meant that the press had to be stopped so that the moulds could be cleaned. The problem seemed to increase when a higher compaction pressure was used. At the beginning there was a thin film of bentonite formed on the bottom of the form, this gradually evolved into a larger aggregation in a corner of the form. The corners were the most susceptible to form this cake as illustrated in Figure 2-6.

This problem has been observed in previous projects when compacting blocks with bentonite materials, see for example Nord et al. (2020). The deviations was not further investigated but will be addressed when optimising the production line for the real repository.

Figure 2-5. *Euro-pallet with blocks. Small horizontal cracks can be seen on the lower half of the blocks.*

Figure 2-6. *Bottom mould plate with material build-up.*

2.7 Production of pellets

The pellets used for the filling of the outer slot between the buffer blocks and the wall of the deposition hole was manufactured at the Äspö HRL test facility. The bentonite used for the production of the pellets is the same as for the production of the buffer blocks i.e. BARA-KADE 1002.

The pellet type chosen for the full-scale test was extruded pellets since one of the test purposes was to investigate the performance of extruded pellets used in the buffer.

Before the pellet production started the bentonite was mixed with water to achieve a water content of approximately 17 %.

The pellet production line in the multi-purpose testing facility at Äspö is a standard setup which consists of a material container, a control unit, the extrusion unit, a belt transporter unit and a shaker table, see Figure 2-7. The extrusion unit is shown in more detail in Figure 2-8.

In the extrusion unit the raw material is passed through an extruder matrix with a certain pressure. To be able to get the material compacted the extruder matrix is designed with a chamfered edge which is slightly larger than the extrusion hole. This design together with the friction in the holes of the extruder matrix gives a compaction of the material while it is passing through the extruder matrix. For this project the diameter of the holes in the extruder matrix was 6 mm. A rotating blade with height adjustment is assuring the pellets get the right length.

Figure 2-7. *The setup for the production line. 1) Material container, 2) Control unit, 3) Extrusion unit, 4) Belt transporter unit, 5) Shaker table.*

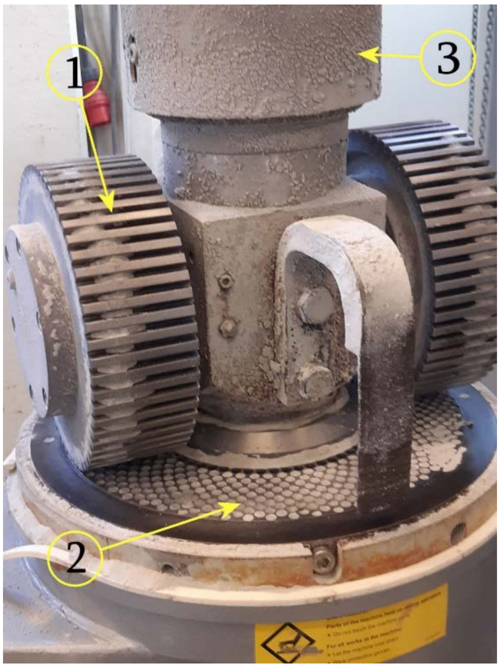


Figure 2-8. *The extrusion unit: 1) roller, 2) extruder matrix, 3) hydraulic ram.*

In total around 6 300 kg of extruded pellets were manufactured for the full-scale tests. The pellet quality was tested according to the SKB method description for pellet quality control and the results after production (Sandén 2020). The results of the quality control are presented in Table 2-4.

Table 2-4. Results from quality control after pellet production.

Type of pellet (extruded)	Water content	Density filling		Density single pellet		Macropores	Durability index
		Bulk density	Dry density	Bulk density n = 5	Dry density n = 5		n = 3
BARA-KADE 2022_17.0 %	16.5 %	1 154 kg/m³	991 kg/m³	2 148 kg/m³	1 844 kg/m³	46.3 %	93 %

2.8 Conclusions from pellet production

Extrusion of pellets and their quality control are activities that are part of normal operation at Äspö. The production went as planned and pellets of good quality were produced.

3 Test design, instrumentation and basic equipment

3.1 General test design

Two different full-scale tests with a segmented buffer have been performed at Äspö Hard Rock Laboratory in the deposition hole DD0092G01, often called the CRT-hole.

The operation phase for the first test was planned for 14 days with an artificial water inflow of 0.1 l/min and the second test for 30 days with an artificial water inflow of 0.01 l/min.

Furthermore, the test was carried out with a pellet-filled outer gap (extruded pellets) and a heated canister with a thermal power corresponding to the power expected from a canister with spent nuclear fuel, about 1 700 W.

As buffer material, both for the blocks and the pellets, a Wyoming bentonite with the trade name BARA-KADE 1002 was used, see also Section 2.2.

Below the most important differences between the buffer design for the repository at the time of writing this report, see Figure 1-1, and the design used in this test, see Figure 3-1, are listed:

- The test hole at Äspö is 8 624 mm deep while the buffer design is 8 051 mm high. To fill up the extra space but still have room to measure any uplift two extra layers were installed, making it a total of 20 ring layers (reference design 18 rings plus one adapted layer for canister flange) and 11 full block layers above the canister (reference design 10 full block layers).
- The average diameter of the selected deposition hole is 1 762 m while the reference design nominal diameter of 1 750 mm. This causes the pellet-filled outer gap to be nominally 6 mm wider than the reference design.
- The test deposition hole lacks the chamfer in the upper part.
- The canister has an extra lid on the top of the canister that protects the heater cables. This means that the canister in the experiment is about 150 mm higher than the reference design. This also means that the buffer blocks around the canister are correspondingly 150 mm higher to match the height of the canister.
- The bottom plate is made of copper in the reference design but stainless steel was used for the test.

3.2 Marking and coordinate system for installed blocks, sensors and sampling

For the positions of the various instruments to be traceable in the buffer a marking system for segmented blocks has been used for this test, illustrated in Figure 3-1. The full bentonite layers below and above the canister are referred to as C-blocks. Block layers around the canister (ring segments) are referred to as R-blocks. For example: first layer that was installed in the bottom of the deposition hole was C1. The individual blocks of layer C1 are marked as in Figure 3-1 (right).

A coordinate system for the deposition hole has been developed at Äspö and used in many full-scale tests during the years (for example all tests in this buffer test series; Test_Solid_N, Test_Seg_N, Test_Seg_0.1, Test_Seg_0.01). The layout and the coordinate system are also used when placing the outer blocks and determining positions for the different samples taken from the buffer. The inner- and centre blocks are placed in random directions but always so that gaps between different block layers were avoided. Each position in the buffer can be determined by three coordinates as illustrated in Figure 3-2:

1. r-coordinates determine the horizontal distance from the centre of the deposition hole.
2. z-coordinates determine at what height from the bottom of the deposition hole the position is located.
3. α-coordinates determine the angle from the horizontal direction A (0° = end of the tunnel).

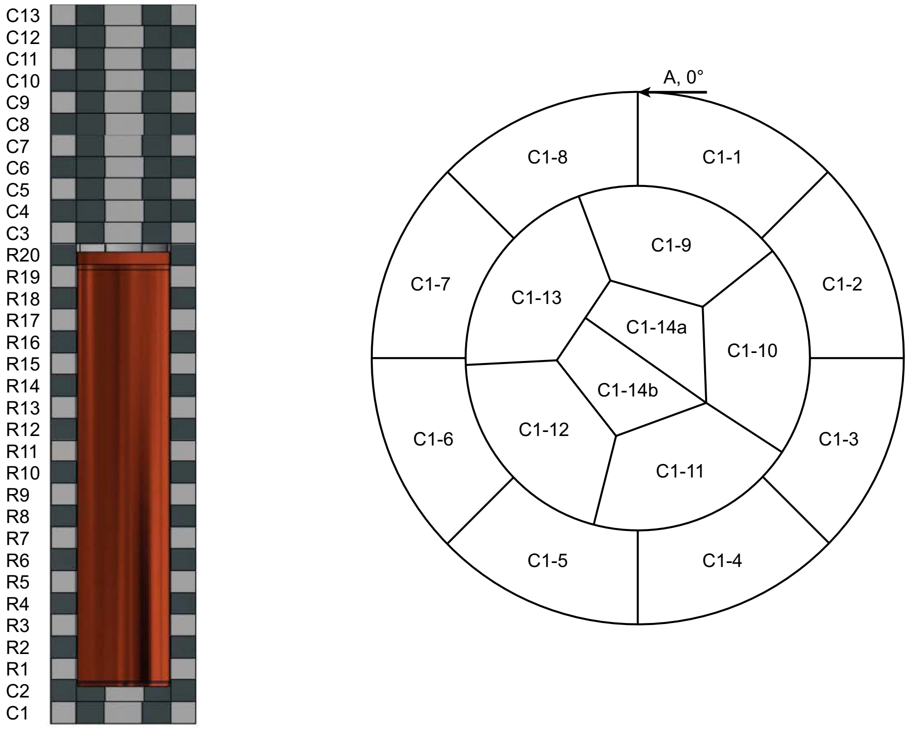


Figure 3-1. *Example of numbering of induvidual blocks in one block layer, in this case block layer C1.*

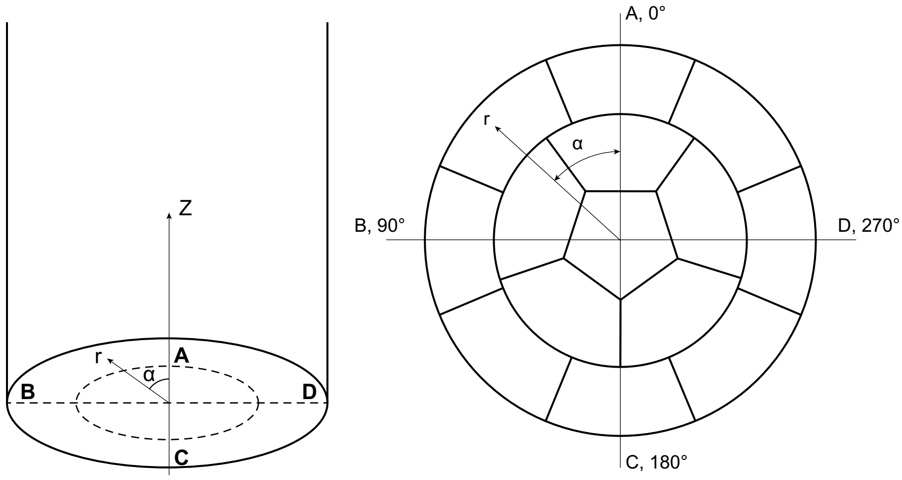


Figure 3-2. *Coordinate system used when describing the positions of the installed sensors or samples. A, 0 degrees are pointing towards the end of the tunnel and C, 180 degrees towards the tunnel mouth.*

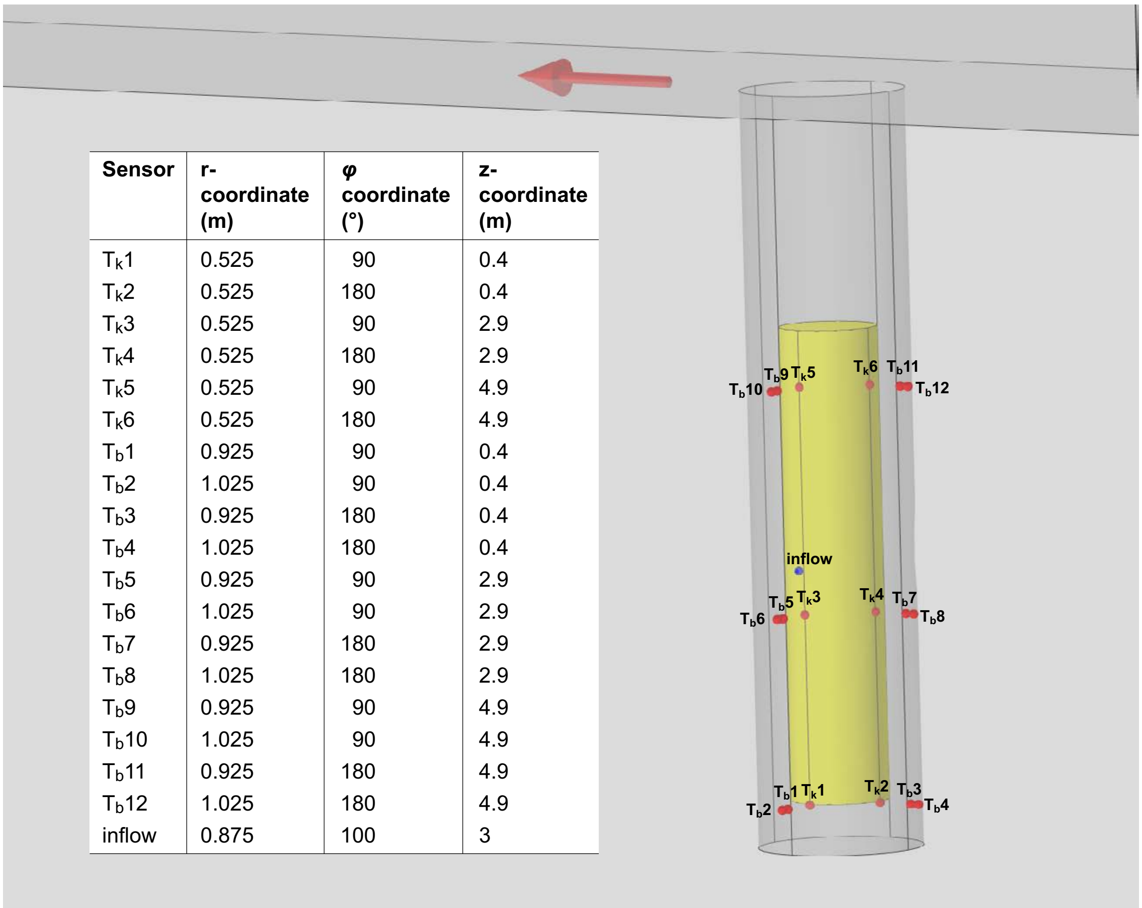
3.3 Instrumentation and monitoring

18 temperature sensors and 2 humidity-sensors (RH-sensors) were installed in the buffer, on the canister surface and in the surrounding rock, see Figure 3-3.

The cables for both the RH sensors and the heaters are routed through the buffer blocks and along the outside of the buffer stack. The RH sensors were placed in block C3 which is closest to the top of the canister. They were placed between in the joint between the outer and inner blocks at 90 and 180 degrees. The placement of the sensors was chosen to try to catch if vapour was transported by convection in the slot between the blocks.

The machining of the buffer blocks required for the installation of sensors and cables as well as cables from the heaters in the canister was done when the buffer blocks were in place in the deposition hole. This was done to minimize the risk of dropping a block when handling them.

Measurements of the vertical position of the top buffer blocks were monitored during the test operation by measuring the position of each each block in the top layer block through openings in the protective lid for the test, see Figure 3-4 for the measurement points, MP:s. These measurements were given by comparing the difference in vertical position between a reference point in the tunnel wall next to the test and the position of the top surface of installed blocks, using a levelling instrument and a measuring rod.



Sensor	r-coordinate (m)	φ coordinate (°)	z-coordinate (m)
T_k1	0.525	90	0.4
T_k2	0.525	180	0.4
T_k3	0.525	90	2.9
T_k4	0.525	180	2.9
T_k5	0.525	90	4.9
T_k6	0.525	180	4.9
T_b1	0.925	90	0.4
T_b2	1.025	90	0.4
T_b3	0.925	180	0.4
T_b4	1.025	180	0.4
T_b5	0.925	90	2.9
T_b6	1.025	90	2.9
T_b7	0.925	180	2.9
T_b8	1.025	180	2.9
T_b9	0.925	90	4.9
T_b10	1.025	90	4.9
T_b11	0.925	180	4.9
T_b12	1.025	180	4.9
inflow	0.875	100	3

Figure 3-3. *Placement of the temperature sensors used in the test. $\varphi - 0$ is towards the tunnel end (red arrow) and z is calculated from the bottom of the deposition hole.*

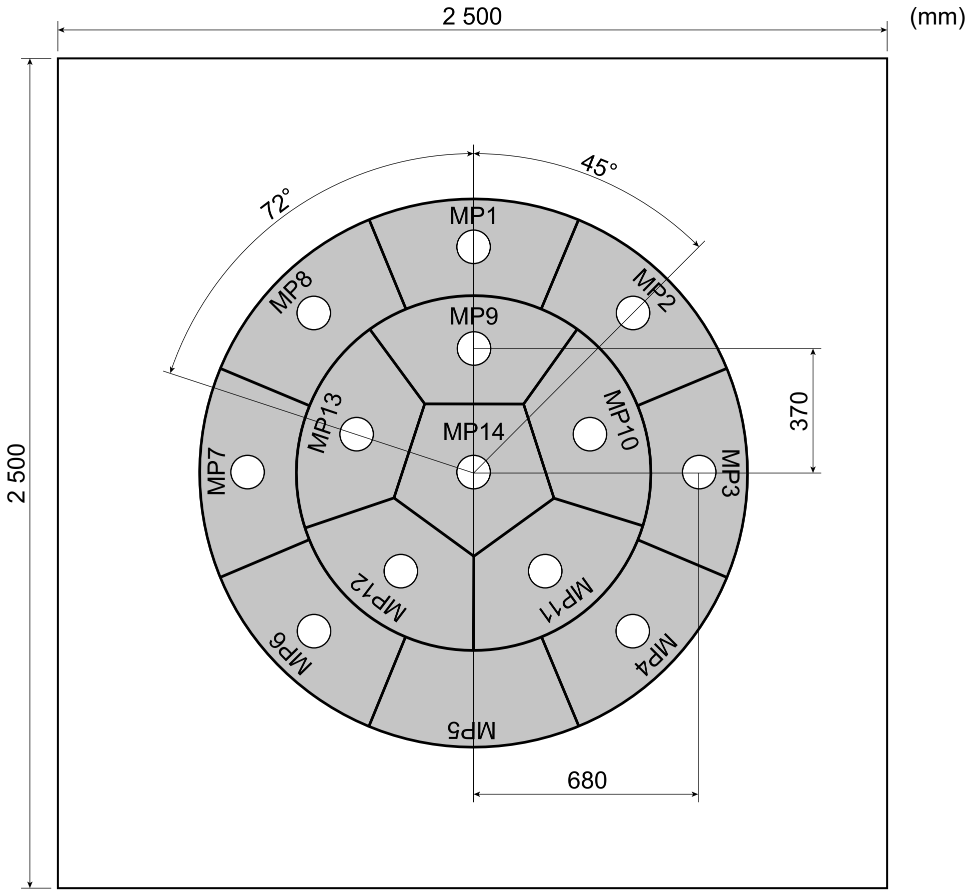


Figure 3-4. *Protective lid with openings for measuring block displacement. The openings are named measurement points, MP:s.*

3.4 Basic equipment

All practical work was done manually using basic equipment, listed in Table 3-1.

Table 3-1. List of basic equipment used during the test.

Type of equipment	Function
Lift basket for segmented buffer blocks	The basket is operated by an electrical telpher. It is used to lift the blocks into the deposition hole. The lift basket is designed to be able to lift 4 blocks at a time.
Vacuum lifting tool for segmented buffer blocks	Lift single buffer blocks. The tool is mainly used to lift the blocks from the lift basket and fine position them when stacking the buffer.
Scale	For measuring the weight of the block before installation.
Digital calliper	For measuring the height of the block before installation.
Levelling instrument	Measurement of the height of every installed block layer.
Lift basket for personal lift	The basket is used to transport staff down into the deposition hole. The basket has a diameter smaller than the inner diameter of the outer block ring so it can be used to transport people and equipment down into the deposition hole even when the outer block rings are in place.
Gantry crane incl. telpher	Crane on wheels that can be rolled over the hole. Mainly used for the lift basket.

Table 3-1. Continued.

Personal lifting system with harness	The system consisted of a swivel telpher beam mounted at the tunnel floor next to the deposition hole, a telpher approved for personal lifting and a harness allowing the worker to travel up and down the 8.6 m deep deposition hole while still being able to work without detaching the harness. For the system to be approved the harness must be connected to a second safety function in form of a fall arrest block. The arrest block was fastened in an approved lifting eye in the tunnel ceiling.
Canister with heaters	The canister is designed to deliver the same power as a real canister filled with nuclear waste. The heat from the canister is an important parameter to get an as realistic (according to the actual situation in the spent fuel repository) test as possible. The canister had earlier been used as a heater in other tests. To simulate the heat generated from one canister 1 700–1 750 watts is used during the test.
Deposition machine	The machine is used to place the canister in the deposition hole. The machine is transported to a position above the deposition hole using the Liftec-trailer.
Liftec-trailer	Used when transporting the Deposition Machine.
Sensors with associated measuring equipment	18 thermo element were installed to monitor the test during operation time. 2 RH sensors are installed to monitor the installation and operation time.

3.5 Preparations at test site before installation

Before installation some activities related to the test hole there were performed. For example: collecting test hole data, renewed measuring of water inflow and preparing installation equipment.

3.5.1 Characterization of the deposition hole

A characterization of the deposition hole has been made after it was drilled. This work is reported in Hardenby (2002). The mapping shows that there are some cracks in the wall close to the tunnel floor.

3.5.2 Geometry of the deposition hole

Measurement of the deposition hole diameter was made shortly after the hole was drilled (Andersson and Johansson 2002). The average diameter of the deposition hole was determined to be 1 762 m. Since this test hole has been used in several tests and there has been modifications made to the bottom plate it was decided to do a new depth measurement of the hole. The tunnel floor is not perfectly horizontal but the average distance between the tunnel floor and the bottom plate is 8 624 mm.

3.5.3 Natural water inflow

The inflow was measured for 11 days before the installation started, the average water inflow during this period was 3.7×10^{-4} litres per minute (0.53 litres per day). Historical inflow is presented in Table 3-2. The measurement is performed by removing all the water in the deposition hole. The deposition hole is then covered to avoid water loss due to evaporation. The deposition hole is then left for a couple of days and then the amount of water in the deposition hole is measured. The flow rate is then calculated by dividing with time under the measurement is performed.

Table 3-2. Measured water inflow to deposition hole CRT.

Year of measuring	2002	2015	2018	2019	2022
Measured water inflow (l/min)	2.05×10^{-4}	8.3×10^{-4}	8.8×10^{-4}	7.2×10^{-4}	3.7×10^{-4}

3.5.4 Checking the bottom levelling of the deposition hole

A prerequisite to facilitate the installation of a vertical block stack is that the bottom plate of the deposition hole needs to be flat and horizontal. Measurements carried out prior to installation showed that the bottom deviated only 1–2 mm from the horizontal plane and the surface was approved for installation without any further action.

3.5.5 Protecting the buffer during installation

Since there is a natural inflow of water from the rock into the deposition hole the relative humidity (RH) can reach 100 % in the bottom of the hole. Such high humidity would damage the installed bentonite blocks during the manual installation in the test which takes several weeks. In the final repository for spent fuel, the blocks will be installed with installation equipment so that the installation will be completed within a day. In this test, a plate made of stainless steel was used to protect the blocks from water coming from underneath, see Figure 3-5, left. The plate will not be used in the final repository but since the test period was only up to 30 days, the judgment was that this will have a minor effect on the results from the tests. During the initial phase of the installation, a plastic sheet shaped as a tube was attached to the plate, illustrated in Figure 3-5, right. This type of plastic cover has been successfully used before in for example Test_Seg_N (Nord et al. 2020) and the purpose is to prevent water to reach and thereby damage the buffer during installation. The plastic cover is attached to a release system that allows for removing the plastic from the surface before the pellets are filled into the gap. Inflowing water was collected in the bottom of the hole between the plastic cover and the rock and is pumped out through a preinstalled hose.

3.5.6 Artificial water inflow

To simulate a point inflow corresponding to 0.1 l/min (which is the maximum allowed inflow into a deposition hole), a water pipe was mounted along the wall of the test hole and at a depth corresponding to half the length of the canister. The water pipe used during the test was mounted at 100 degrees. See Figure 3-6, left. A pump with the right capacity was then mounted to this pipe. A water meter was also mounted from the pump to keep track of the flow of water throughout the experiment. As a precaution, an extra water pipe was fitted in case the main pipe would become blocked during the experiment. See Figure 3-6, left. The water used for the tests was formation water from the Äspö tunnel, kept in the tank in Figure 3-6, right.

Figure 3-5. *Left: The stainless plate in place in the bottom of the test hole. Right: Plastic tube attached to the plate and the test hole.*

***Figure 3-6.** Left: The water pipes mounted on the wall. Right: The water pump and the water tank.*

3.6 Sampling strategy

The strategy for sampling was to collect bentonite samples for water content and density analyses in all parts of the buffer. The sampling should cover the buffer in both axial and radial direction. In radial direction: the sampling pattern is illustrated in Figure 3-7, left. In axial direction: one sample was collected from the centre of each block in every radial position as illustrated in Figure 3-7, right. Direction A and C are placed in the tunnel's axial direction with A pointing towards the end of the tunnel. A 3D visualisation of the sampling pattern is presented in Figure 3-8.

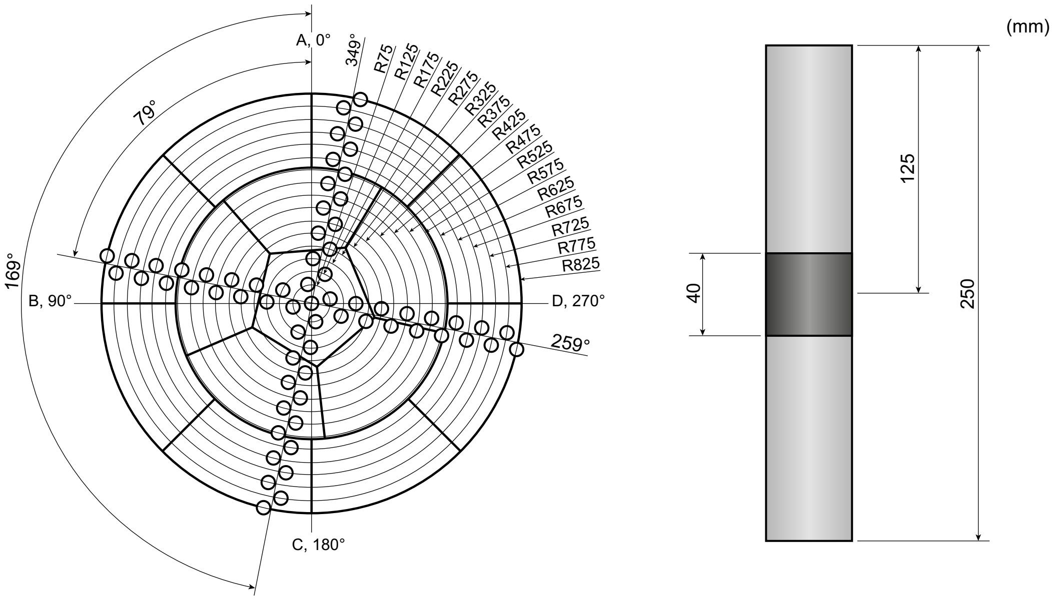


***Figure 3-7.** Left: radial sampling pattern. Right: axial core drilled sample from one block in one position.*

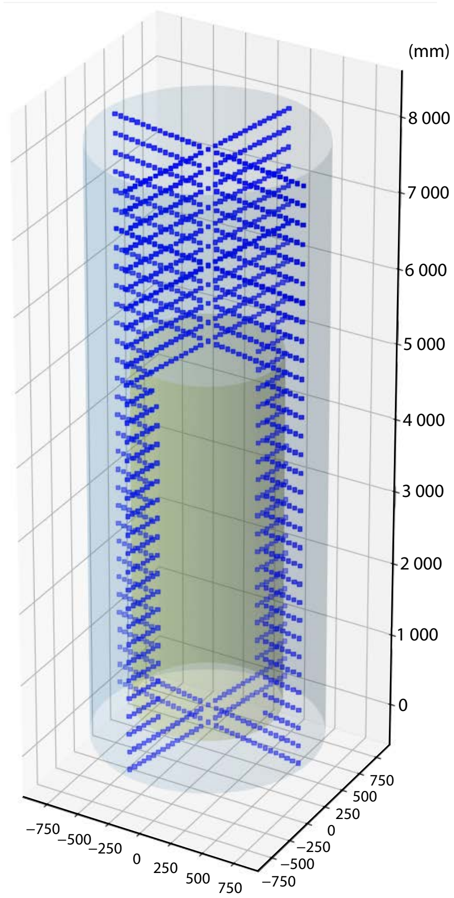


Figure 3-8. *3D Visualisation of the sampling done. Blue dots represent the sampling points.*

4 Test_Seg_0.1

The first test, Test_Seg_0.1 was installed in April 2022, run in May and dismantled in June and July the same year. The test had a test design as in Section 3.1 and an artificial water inflow of 0.1 l/min.

4.1 Installation

The installation, starting with placing first bottom block and ending with placement of the protective lid, was performed in 36 calendar days from 2022-04-04 to 2022-05-10. The main sequences of the installation are presented in the following sections. During the installation the weight of each block was noted.

4.1.1 Installation of bottom blocks, C1 and C2

The installation began by placing layer C1 in the centre of the hole. The first layer was placed with one joint between two blocks facing straight downstream the tunnel towards the “A” direction illustrated in Figure 3-2. The blocks were stacked in an overlapping pattern, illustrated in Figure 4-1. As seen in Figure 4-2 there was a gap between the centre block halves that was cut by hand. These joints were left as they were and the judgement was that they would have a minor influence the test results. When used in the final repository for spent fuel the centre block will be manufactured in one piece and therefore this joint will not exist.

To make room for the canister bottom flange, a slot was created in bottom layer C2, like the Type II_2 blocks illustrated in Section 2.1. In this test the slot was done manually by core drilling. When the cores were removed all surfaces of the slot needed to be smoothened by hand. The canister flange and pictures of the slot are illustrated in Figures 4-3 and 4-4.

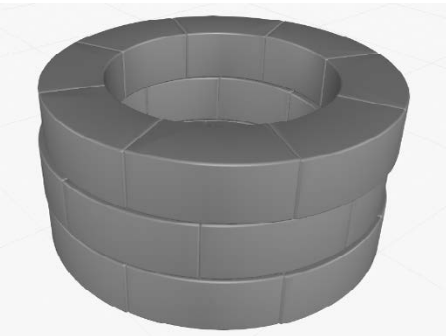


Figure 4-1. *Principle how the block joints are displaced relative to each other.*

Figure 4-2. *Installation of bottom layers. Left: layer C1, right: layer C2.*

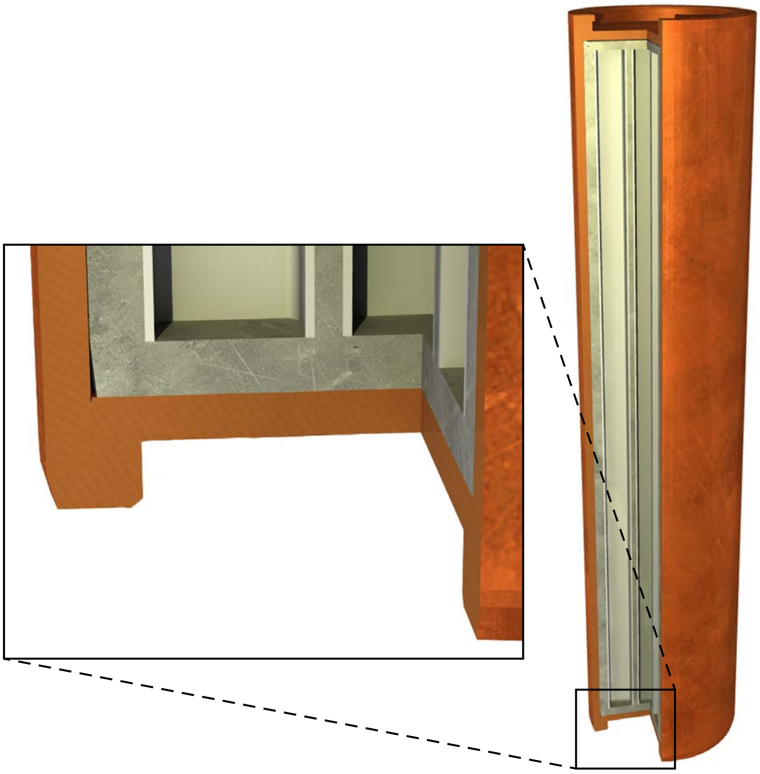


Figure 4-3. Cross section of canister showing the bottom flange.

Figure 4-4. Left: Core drilling of slot in layer C2. Right: Finished slot.

4.1.2 Installation of segmented rings R1–R20

The ring segments were stacked carefully and by using folding rule and spirit-level. Photographs from the installation are shown in Figure 4-5.

4.1.3 Installation of the canister

A deposition machine loaded with the canister was transported down to the test site and positioned over the deposition hole as can be seen in Figure 4-6. The deposition machine is an early prototype used only for tests like this.

The installation sequence with this prototype machine is a slow process which takes several hours. Figure 4-7 shows two photographs from the installation. The installation went as planned.

Figure 4-5. *Installation of ring layers. Top left: R3, Top right: R6, Down left: R11, Down right: R20.*

Figure 4-6. *Deposition machine.*

Figure 4-7. *Left: Canister installation in progress. Right: End of installation.*

4.1.4 Installation of top layers C3–C13

The installation of blocks above the canister was carried out without interruption. As described in Section 3.1 one extra full block layer was installed to fill out the space up to the tunnel floor (C13). At the top of the test hole there is a 250–300 mm volume between the top of the block stack and the floor of the tunnel. The extra bentonite layer and the open volume are not considered to significantly influence the result of this test. Figure 4-8 illustrates layer C13 after finished bentonite installation.

4.1.5 Installation of pellets

The plastic was removed just before pellet installation started. The pellets were poured into the gap manually. Figure 4-9 shows the deposition hole after installation of canister, block and pellets.

4.1.6 Protection lid

In the spent fuel repository the installed buffer is planned to be protected by temporary lids during the installation phase. The lids will be removed when it is time to install backfill over the deposition holes. In this test a prototype lid was manufactured. To prevent evaporation of water and to allow visual inspection, the lid was manufactured from thick, transparent Plexi Glass. The lid was perforated with openings that allowed measuring the vertical position (z-coordinate, see Figure 3-2) of each block in the top layer. This was made with a levelling instrument. The openings in the lid are shown in Figure 4-10.

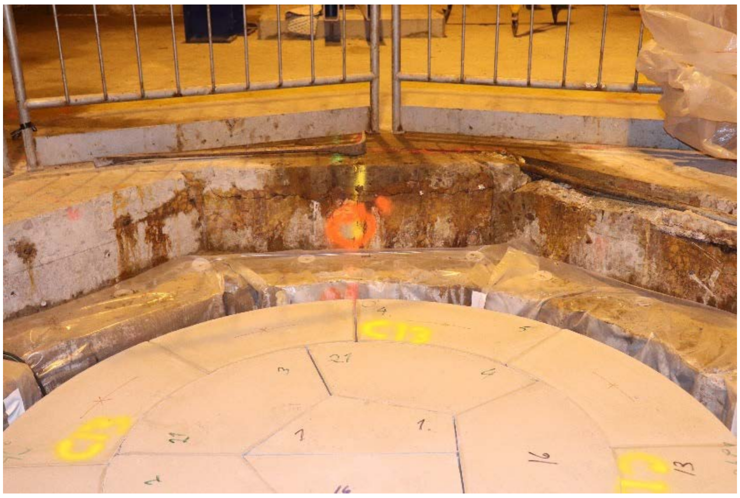


Figure 4-8. *All blocks and instrumentation is installed.*

Figure 4-9. *The pellets are installed between the block and the rock.*

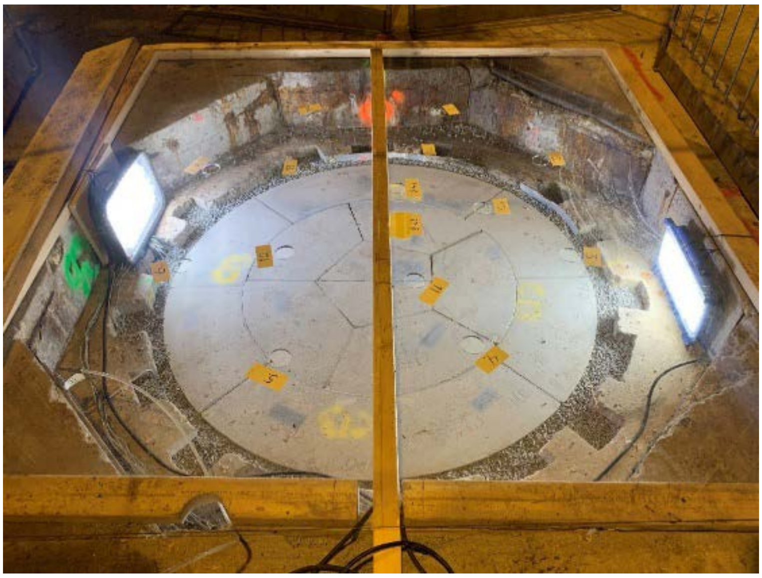


Figure 4-10. Protective lid with openings for measuring rod, marked with yellow adhesive tape, see also Figure 3-4.

4.1.7 Start of canister heaters and water pump

When the installation was finished and the protection lid was in place, the test was started by turning on the canister heaters and the water pump so that an inflow of 0.1 l/min into the deposition hole started. This was done at May 10th 2022.

4.1.8 Installed weight

The total weight of installed block was 26 886 kg. Total weight of installed pellets was 2 983 kg. From these values the average dry density is estimated to 1 603 kg/m^3.

4.2 The operational phase of the test

This section presents data from installed sensors, both relative humidity sensors and temperature sensors, together with the measured buffer top displacement. The two relative humidity sensors were installed in the buffer while the temperature sensors were installed in the buffer, on the canister surface and in the surrounding rock.

Three different stop criteria were set. When any of the criteria 1–3 were met, the test should end:

1. **The buffer heave reaches 150 mm**
   Which is a far larger swelling than can be accepted.
2. **The time reaches 14 days**
   Which is based on the time it would take to fully fill the macro pores in the pellet slot.
3. **The water starts to flow out on top of the buffer**.
   If the water flows out on the top surface measurements of upwards swelling would be difficult and the data set after this happens would not give much more information.

The test started at 2022-05-10 and ran until the morning of 2022-05-18 implying that the duration of the test was about 8 days. After this time the stop criteria 3 was met and the test was terminated. Dismantling and sampling of the buffer started immediately after the stop of the test.

4.2.1 Heating power

The power applied to the heating elements was 1 700 W throughout the operation of the test.

4.2.2 Canister temperatures

The surface temperature of the canister during the test is shown in Figure 4-11. The thermocouples were installed in two directions (B and C, see Figure 3-2) close to the bottom, at mid height and close to the top of the canister. The figure shows that the maximum measured temperature was about 46.5 °C at the top of the canister. The canisters initial temperature was the same as the surrounding which is not the case with a real canister as it would be hotter at the time of installation. However, the thermal effects are expected to be lower with the higher inflows. The lower temperatures in two points are probably because of the water inflow.

4.2.3 Rock temperatures

During the experiment, also the temperature in the surrounding bedrock was measured. This was done at three levels in the deposition hole, namely 400 mm, 2 900 mm and 4 900 mm from the bottom.

The sensors were installed in two directions at each level. Furthermore, sensors were installed about 50 mm into the rock i.e. at a radius of 925 mm and with an installation depth from the surface of 150 mm, corresponding to a radius of 1 025 mm. Data from the measurements at the three levels are presented in Figure 4-12.

The highest temperature was measured the level of 4 900 mm i.e. close to the top of the canister, while the lowest temperature was measured at 2 900 mm of the deposition hole, see Figure 4-12. Furthermore, the plots also indicate that the temperature was higher towards the right wall of the tunnel, i.e. in direction B where the water inflow was installed. The maximum temperature measured on the rock surface was about 24.5 °C.

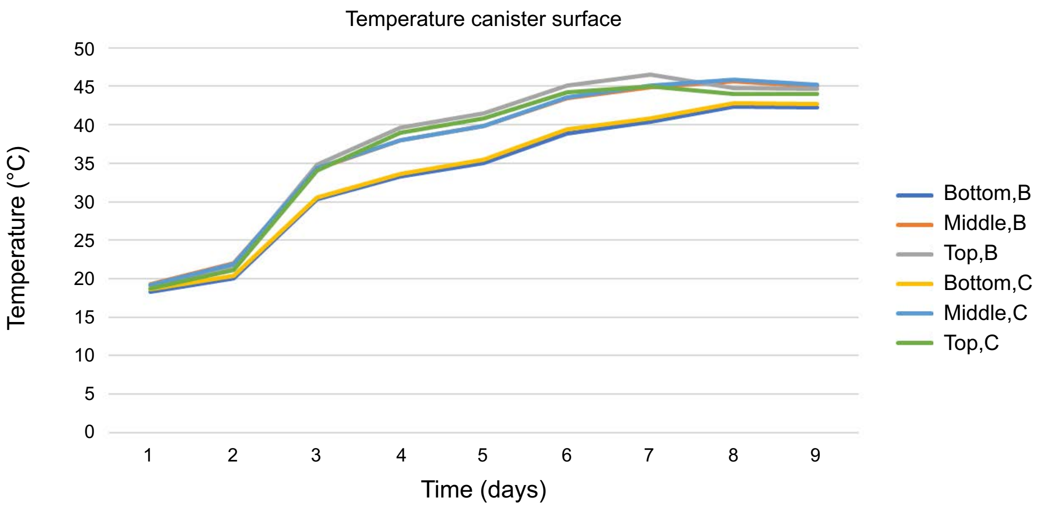


Figure 4-11. *The temperature evolution on the canister surface as function of time. The thermocouples are placed at the bottom, at mid height and at the top of the canister in two directions B and C.*

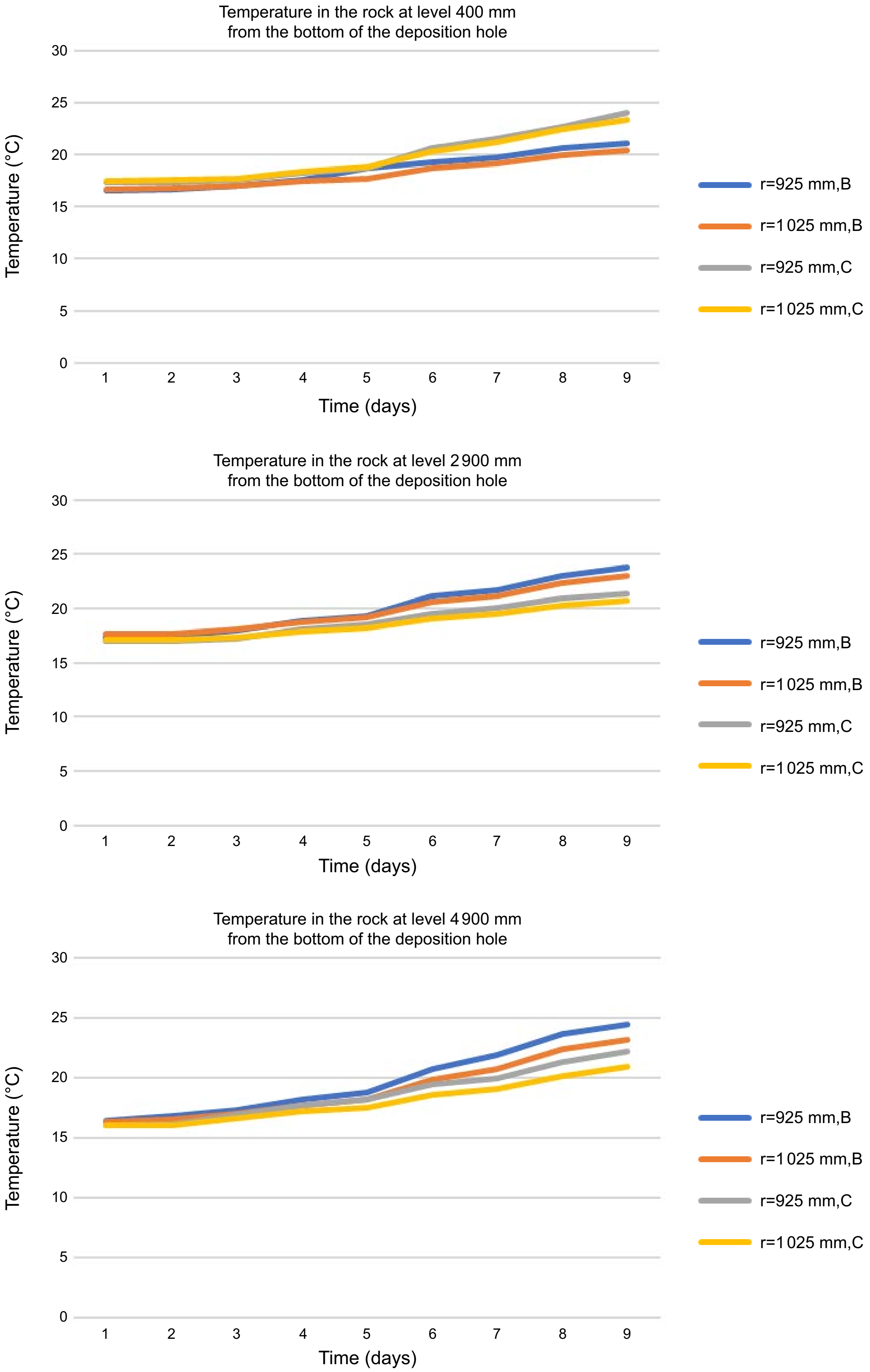


Figure 4-12. *The temperature evolution in the surrounding rock at three levels in the deposition hole. Top graph: 400 mm, middle graph: 2 900 mm and bottom graph: 4 900 mm, all from the bottom.*

4.2.4 Relative humidity

2 relative humidity sensors were installed in the buffer, both in layer R20 at the radius 535 mm in 90 degrees for Rh-1 and 270 degrees for Rh-2. The readings from the sensors are shown in Figure 4-13. The purpose of these measurements was to follow the water uptake of the buffer at two different locations within the buffer. The reason for the placement of the sensors was that an increase in water content in this was seen in earlier tests (Nord et al. 2020).

4.2.5 Buffer heave

The displacement of the buffer in the axial direction was measured with the use of a levelling instrument.

This was made at least 2 times a day in 14 positions of the top layer, see Figure 4-10. Water exited the buffer and was visible on the top layer after 192 hours and then the test was terminated. The results from the measurements are shown in Figure 4-15, where positive displacement means that the block has moved upwards. The following conclusions can be made from the measurements, see Figures 4-14 and 4-15:

- The maximum displacement of 38 mm was measured at the end of test period.
- The displacement rate was somewhat increasing with time.
- The displacement of the surfaces varied between 16 and 38 mm.
- The largest displacement was observed in direction 90 degrees (MP 6 and 7 in Figure 3-4) which is in the same direction as the inflow point placed at mid height of the canister.

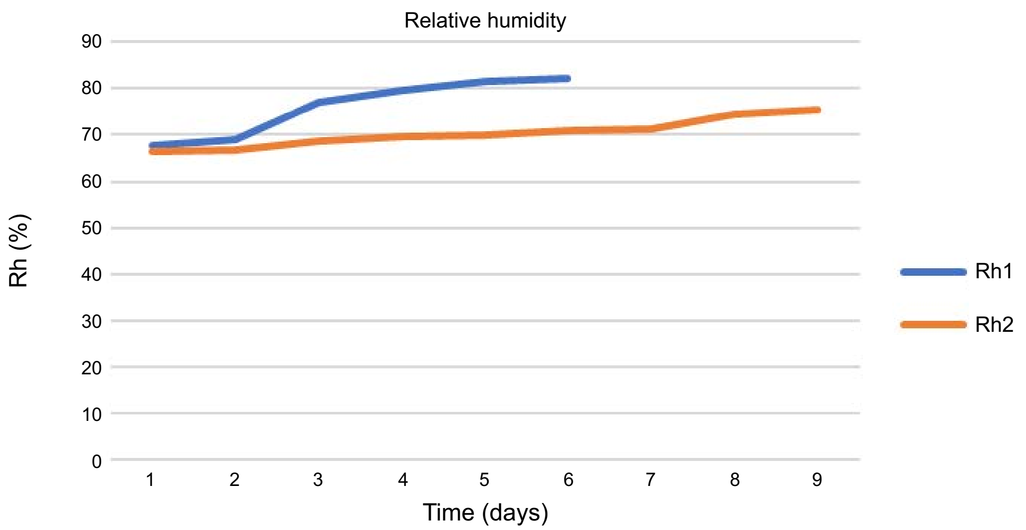


Figure 4-13. *The evolution of relative humidity in the buffer layer R20. The Rh1 sensor stopped working after six days, probably due to it being exposed to free water.*

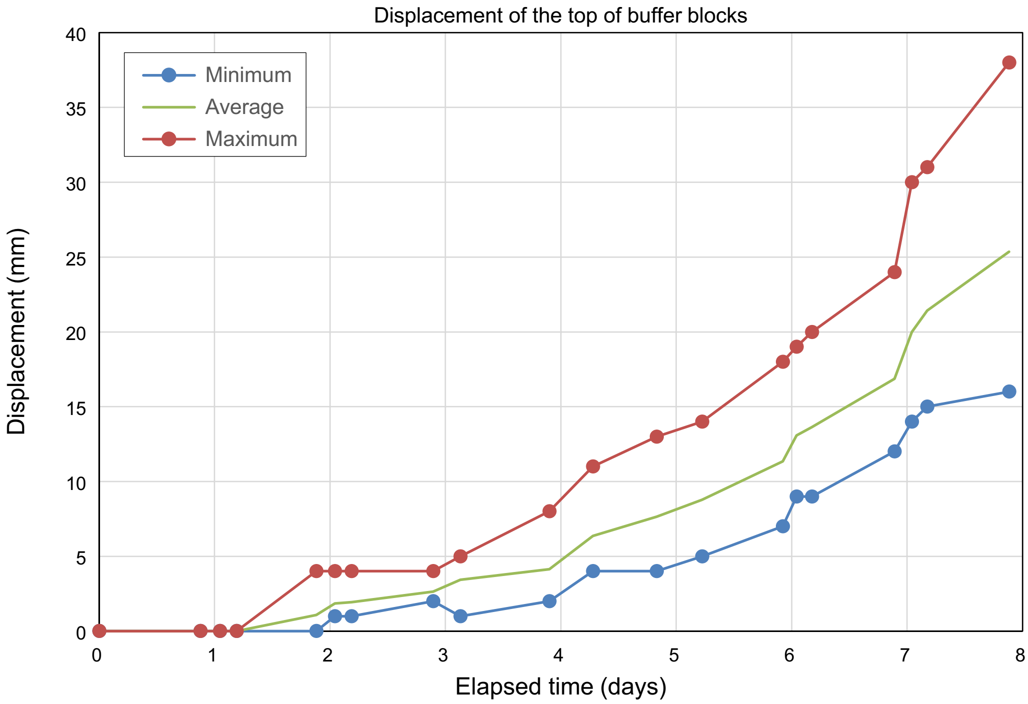


Figure 4-14. *Minimum, maximum and average displacement of the top buffer blocks.*

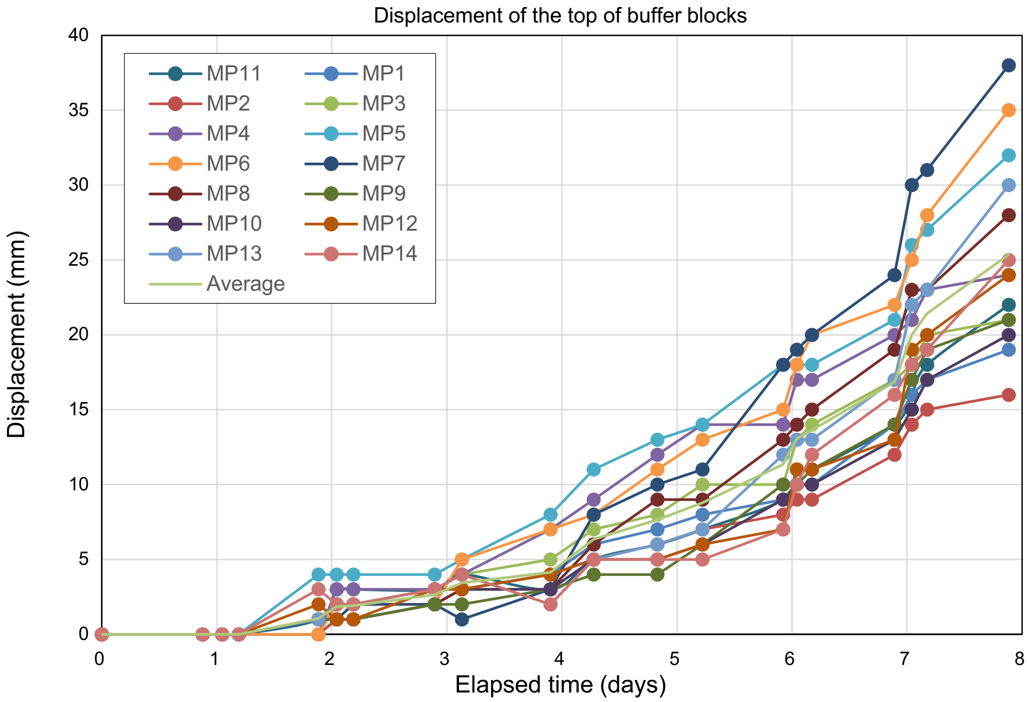


Figure 4-15. *Displacement of all of the top buffer blocks.*

4.3 Dismantling and analysis

4.3.1 Dismantling and sampling, field activities

In this section the field activities from dismantling and sampling are reported. The dates for dismantling the individual block layers are presented in Table 4-1. Results from analysis of the samples are reported in Chapter 5.

Table 4-1. Dates for dismantling of each block layer in Test_Seg_0.1.

Block layer	Date of dismantling	Block layer	Date of dismantling
C13	2022-05-20	R14	2022-06-20
C12	2022-05-23 to 2022-05-24	R13	2022-06-22
C11	2022-05-24	R12	2022-06-23
C10	2022-05-25	R11	2022-06-28
C9	2022-05-25	R10	2022-06-29
C8	2022-05-31	R9	2022-06-30
C7	2022-06-01 to 2022-06-02	R8	2022-07-03
C6	2022-06-02 to 2022-06-03	R7	2022-07-05
C5	2022-06-07	R6	2022-07-07
C4	2022-06-08	R5	2022-07-07 to 2022-07-11
C3	2022-06-09	R4	2022-07-12
R20	2022-06-13	R3	2022-07-14
R19	2022-06-14	R2	2022-08-18
R18	2022-06-15	R1	2022-08-19
R17	2022-06-16	C2	2022-08-24
R16	2022-06-16	C1	2022-08-29
R15	2022-06-20		

As described in Section 4.3.1, samples from the blocks were collected using core drilling in four directions. In addition, samples in the pellet slot between the outer blocks and the rock were collected by hand. Directly after core drilling the samples were protected by sealing them in marked plastic bags. The remaining pellets and parts of the buffer blocks were excavated and discarded.

A template made of plywood was used as guide when core drilling, as illustrated in Figure 4-16.

Figure 4-16. *Left: Wood template used when core drilling. Right: Core drill.*

Removal of protection lid

As can be seen in Figure 4-17, right, water exited the buffer in the pellet slot. This marked the end of the test and after this the test was terminated. The water exited right above where the water inflow is located. It could also be seen that the swelling was largest on the side where the inflow was located.

Dismantling and sampling of layer C12–C3

Figure 4-18 illustrates some examples from dismantling and sampling of layers above the canister. The blocks in layers C3–C9 were visibly affected by water but from layer C10 and downwards no water was visible on the blocks. The left pellet-filled slot was wetted from the water inflow.

Figure 4-17. *Left: Before the beginning of the test. Right: Layer C13 (top layer) after removal of the protection lid.*

Figure 4-18. *Left: Layer C12 sampling is finished. Right: Layer C10 with dry blocks.*

Dismantling and sampling of layer R20

The canister and R20 was exposed, see Figure 4-19, after removing the C3 block layer and the lid used to gather and protect the sensor cables. It was immediately discovered that the ring-shaped blocks were stuck to the canister. This meant that a decision was made to lift the canister only when it had been released from the block.

Dismantling and sampling of R19–R3

Figure 4-20 shows a photo from dismantling and sampling of the ring segments – work that had to be done in the gap between canister and rock wall since the canister could not be lifted until all ring-shaped layers were removed. As the dismantling work moved forward it got progressively slower and more difficult. Partly, it was a consequence of the difficulty of working in the gap between canister and rock. Furthermore, the natural inflow continued to wet the buffer making it tough and therefore challenging to sample using core drilling. It was decided to continue the dismantling and sampling down to R3 before pausing the work during four summer weeks.

Figure 4-19. *The canister was exposed after the removal of layer C3. The top of the canister is treated differently in this test than it will be in the repository due to the handling of sensor cables, for examples the small planks will not be used in real operation.*

Figure 4-20. *Sampling of layer R17 between the canister and the rock surface.*

Lifting the canister and dismantling the last layers, R2-R1 and C2-C1

The dismantling resumed in August. The two last ring layers were dismantled and after that the canister could be removed using the deposition machine. The sampling and dismantling of the two final block layers was finished on August 29.

4.3.2 Position of the individual buffer blocks

Measurements of the vertical coordinate for the individual block layers were made both at installation and at dismantling of the test. The measurements were made at 8 locations on top of each block layer. From these data it was possible to determine an average vertical coordinate for each layer and from this data calculates the average height of the layers both at the start and after the test. By comparing these two data sets it was possible to calculate the changes in position for each individual section. Figure 4-21 shows how much each layer has risen during the test by presenting the difference in average height per layer before and after the test. A positive value implies a displacement upwards, a rise, of the block layer. The biggest displacement was observed in the layers near the top of the canister. The displacements are caused by the absorption of inflowing water into the buffer. The displacements caused by heat from the canister are negligible in this experiment due to the short duration of the test.

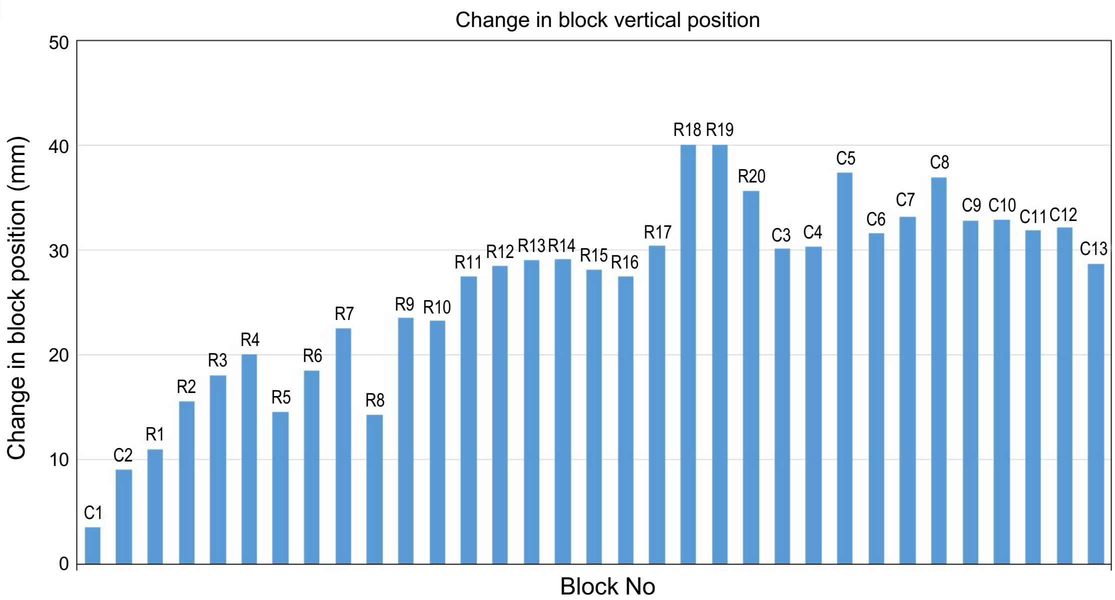


Figure 4-21. *Changes in block position between installation and dismantling.*

5 Test_Seg_0.01

The second test, Test_Seg_0.01 was installed in September 2022, run in September–October and dismantled in October–December of the same year. The test had a test design as in Section 3.1 and an artificial water inflow of 0.01 l/min.

5.1 Installation

The installation, starting with placing first bottom block and ending with placement of the protective lid, was performed in 15 calendar days from 2022-09-05 to 2022-09-20. The main sequences of the installation are presented in the following sections.

5.1.1 Installation of bottom blocks, C1 and C2

Installation of the first layers began after the protective film (see Section 3.3.5) was in place. The layers C1 and C2 are shown in Figure 5-1.

Figure 5-1. *Installation of bottom layers. Left: layer C1, right: layer C2 with core drilled slot for the canister flange.*

5.1.2 Installation of segmented rings R1–R19

The ring segments were stacked carefully and their positions were checked using folding rule and spirit-level. Pictures from the installation are shown in Figure 5-2. The naming of layers differs slightly from Test_Seg_0.1: Due to the lid for sensor cables on top of the canisters, extra bentonite material is used to fill the void created on top of the canister. For this test, the void was so large that entire inner ring blocks could be used, making the planned R20 layer become a complete layer. Therefore, this layer was called C3 making the top layer become C14 instead of C13 in Test_Seg_0.1. The same number of layers were used in both tests.

5.1.3 Installation of canister

The method for installation of the canister is described in Section 4.1.4. The installation of canister in Test_Seg_0.01 is shown in Figure 5-3.

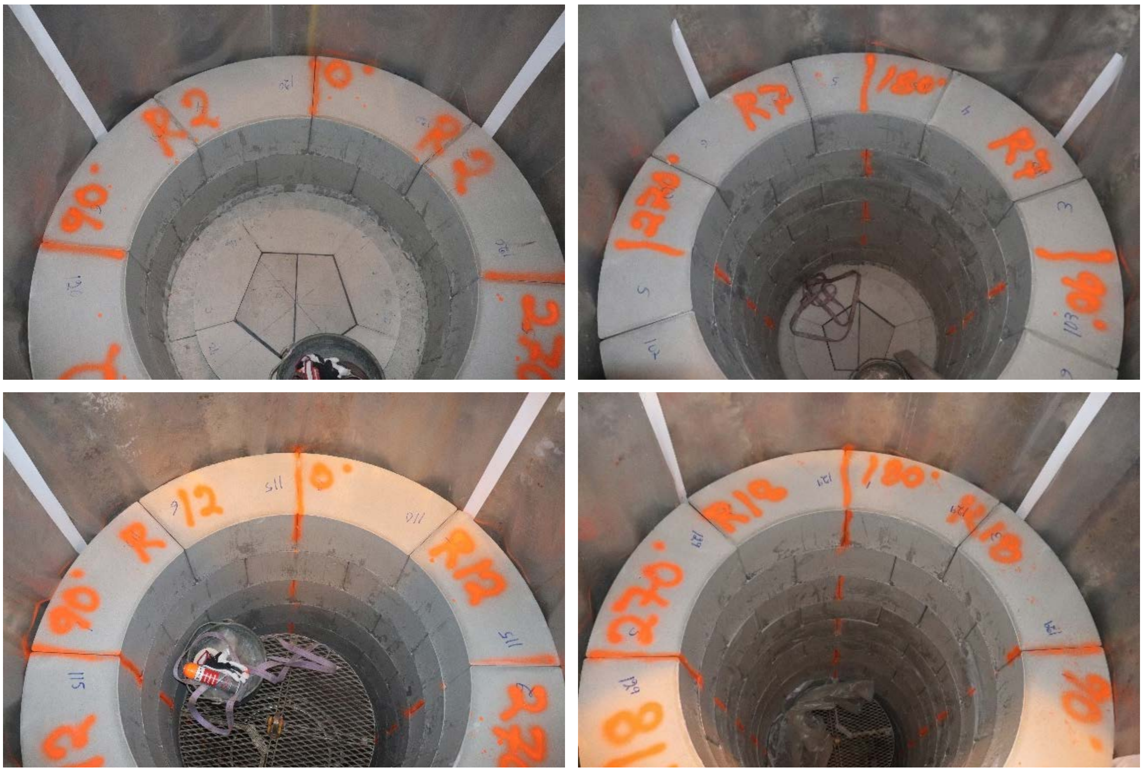


Figure 5-2. *Installation of ring-shaped layers. Top left R2, Top right R7, Lower left R12, lower right R18.*

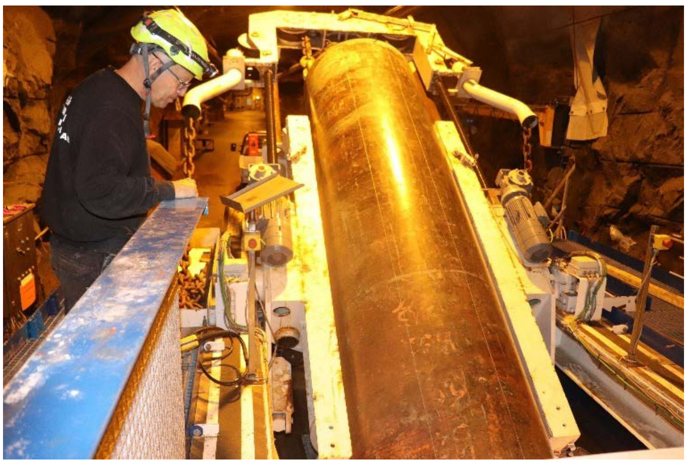


Figure 5-3. *Canister installation in progress.*

5.1.4 Installation of top layers and pellets

The installation of blocks above the canister was carried out without interruption as the previous installation. The last installed layer, the top layer, can be seen in Figure 5-4. The plastic film remained until the time for pellet installation and was removed just before pellet installation started. The pellets were poured into the gap manually.

5.1.5 Start of canister heaters and water pump

When the installation was finished and the protection lid was in place, the test was started by turning on the canister heaters and the water pump so that an inflow of 0.01 l/min into the deposition hole started. This was done on September 20th 2022.

5.1.6 Installed weight

The total weight of installed block was 27351 kg. Total weight of installed pellets was 2751 kg. From these values the average dry density is estimated to 1602 kg/m^3.

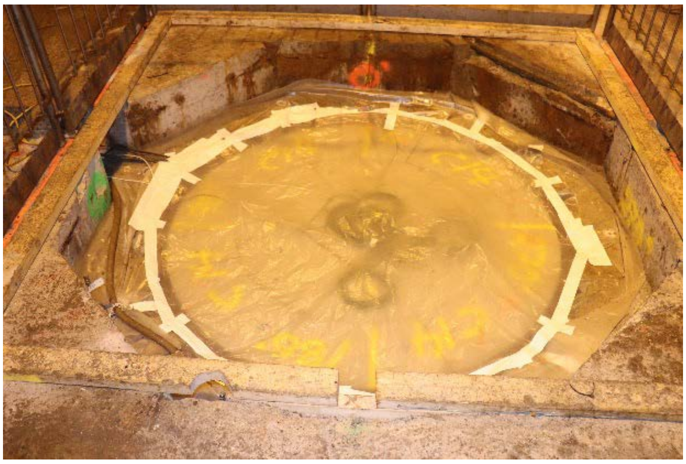


Figure 5-4. *All blocks and instrumentation is installed.*

5.2 The operational phase of the second test

This section presents data from the applied heat power, data from installed sensors, both relative humidity sensors and temperature sensors, together with the measured buffer heave.

Three different criteria were set for when the test should end:

1. **The buffer heave reaches 150 mm**
   Which is a far larger swelling than can be accepted.
2. **The time reaches 30 days**
   Which is based on the time it would take to fully fill the pores in the pellet slot.
3. **The water starts to flow out on top of the buffer**.
   If the water flows out on the top surface measurements of upwards swelling would be difficult and the data set after this happens would not give much more information.

The test was running for about 30 days, 2022-09-20 to 2022-10-19, thereby reaching the second stopping criterion. Directly after this period the sampling of the buffer started.

5.2.1 Heating power

The power applied to the heating elements was 1 700 W throughout the operation of the test.

5.2.2 Canister temperatures

The temperature measurements made on the canister surface are shown in Figure 5-5. The thermocouples were installed in two directions (B and C) close to the bottom, at mid height and close to the top of the canister. The figure shows that the maximum measured temperature was about 64 °C at the bottom of the canister. The points with lower temperature is in the direction of the water flow and the wet pellets have a higher thermal conductivity.

5.2.3 Rock temperatures

Data from the measurements at the three levels are presented in Figure 5-6.

The highest temperature was measured the level of 4 900 mm i.e. close to the top of the canister, while the lowest temperature was measured at 2 900 mm of the deposition hole, see Figure 5-6. The maximum temperature measured on the rock surface was about 36 °C.

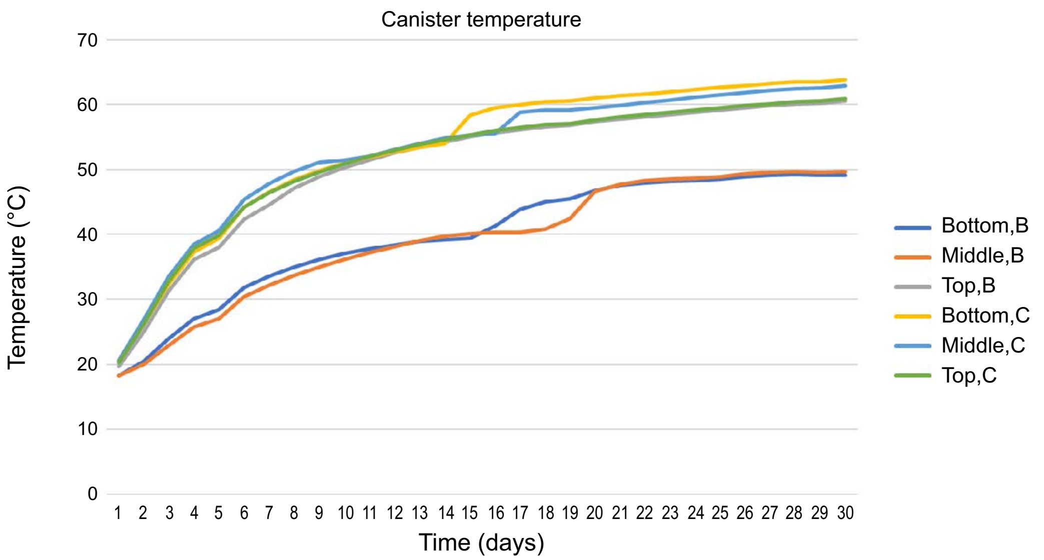
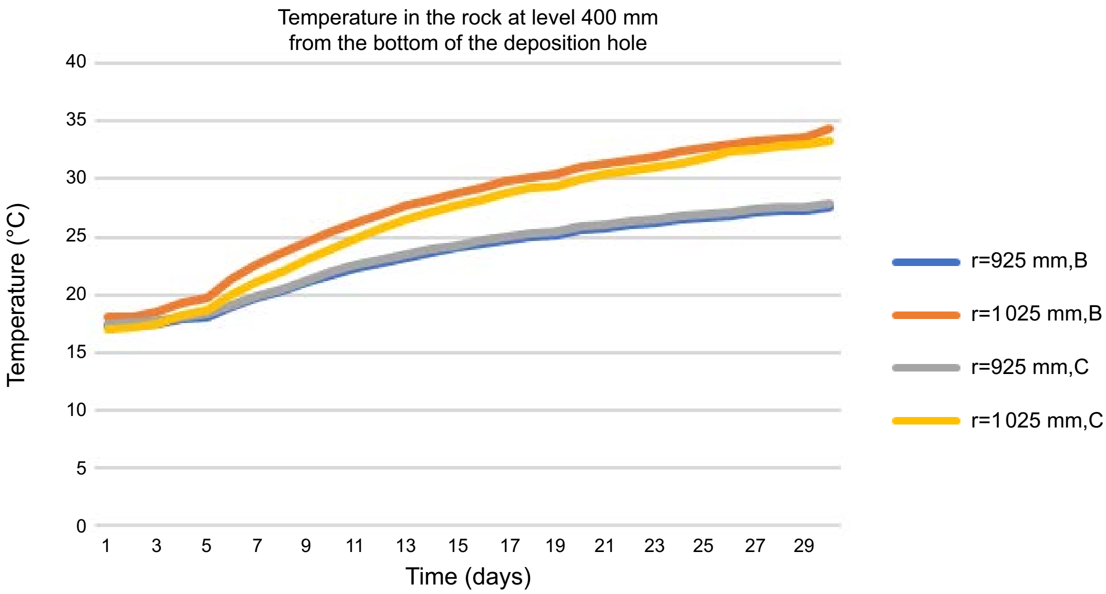
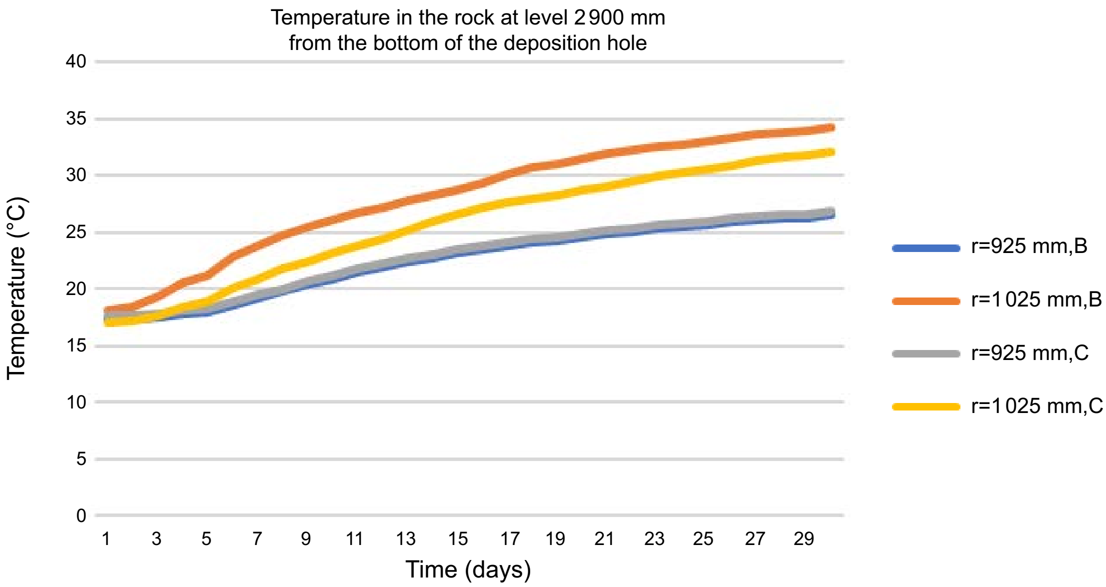


Figure 5-5. *The temperature evolution on the canister surface as function of time. The thermocouples are placed at the bottom, at mid height and at the top of the canister in two directions B and C.*





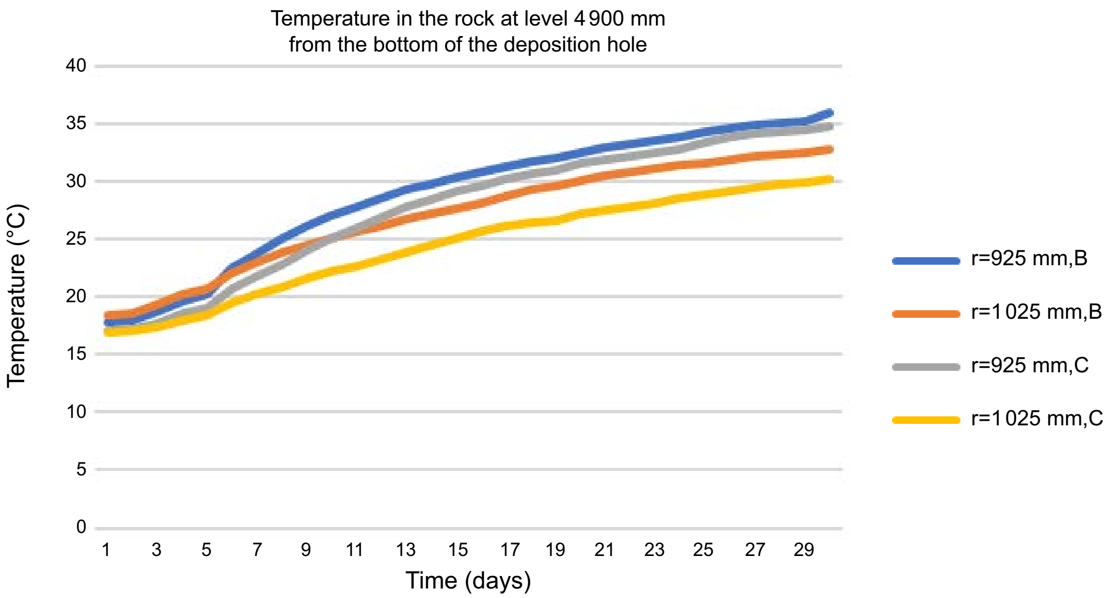


Figure 5-6. *The temperature evolution in the surrounding rock at three different levels in the deposition hole Top graph 400 mm, middle graph 2 900 mm and lower graph 4 900 mm from the bottom.*

5.2.4 Relative humidity

The relative humidity sensors were installed in the buffer, both in layer R20 at the radius 535 mm at 90 degrees for Rh-1 and 270 degrees for Rh-2. The evolution of relative humidity in Test_Seg_0.01 is presented in Figure 5-7.

5.2.5 Buffer heave

The displacement of the buffer in axial direction was measured with the use of a levelling instrument. This was made at least 2 times a day in 14 positions of the top layer, see Figure 4-10. The results from the measurements are shown in Figure 5-9, where positive displacement means that the block has moved upwards. The following conclusions can be made from the measurements see Figures 5-8 and 5-9:

- The maximum displacement of 58 mm was measured at the end of test period.
- The displacement rate was somewhat increasing with time.
- The displacement of the surfaces varied between 46 and 58 mm.
- The average buffer heave was 52 mm.

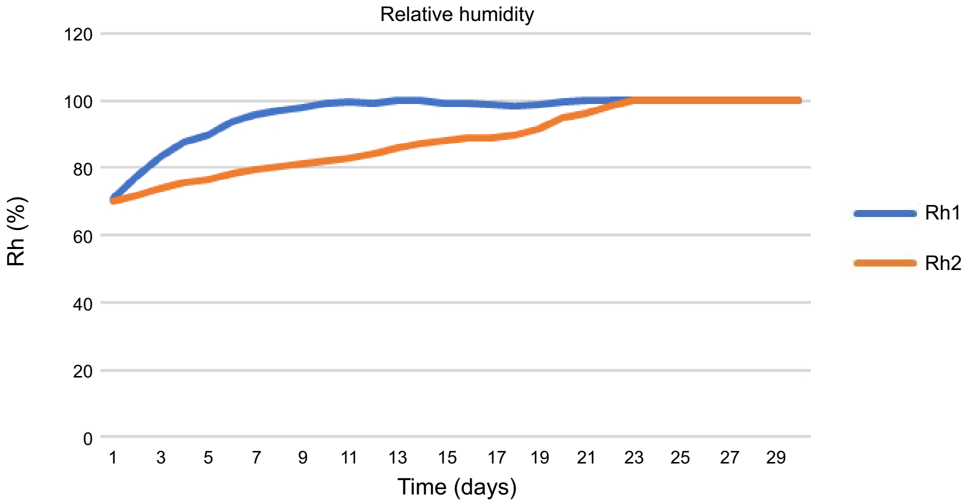


Figure 5-7. *The evolution of relative humidity in the buffer layer R20.*

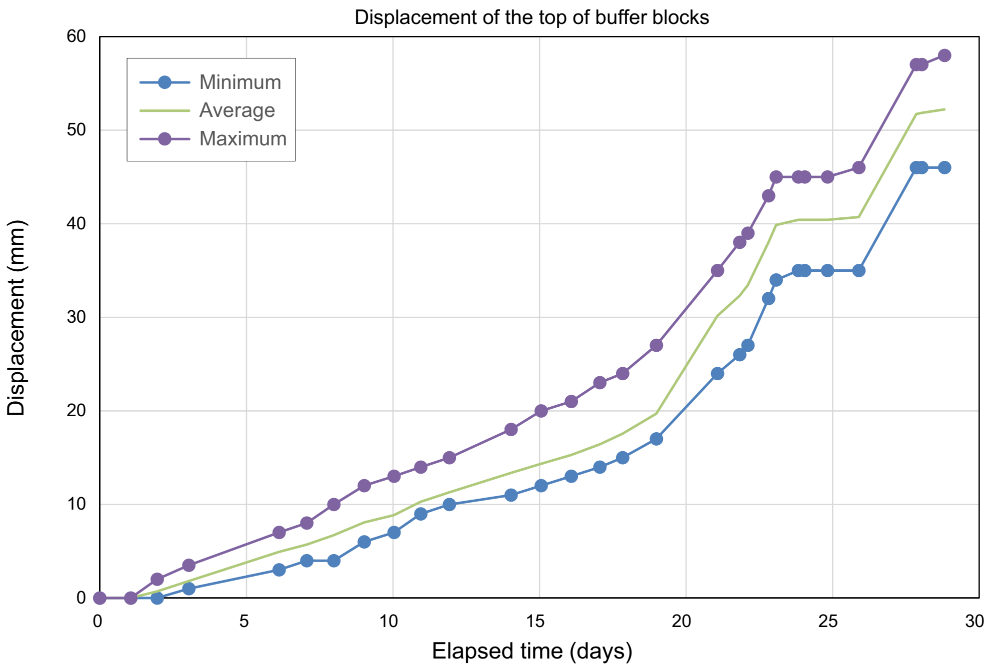


Figure 5-8. *Minimum, maximum and average displacement of the top buffer blocks.*

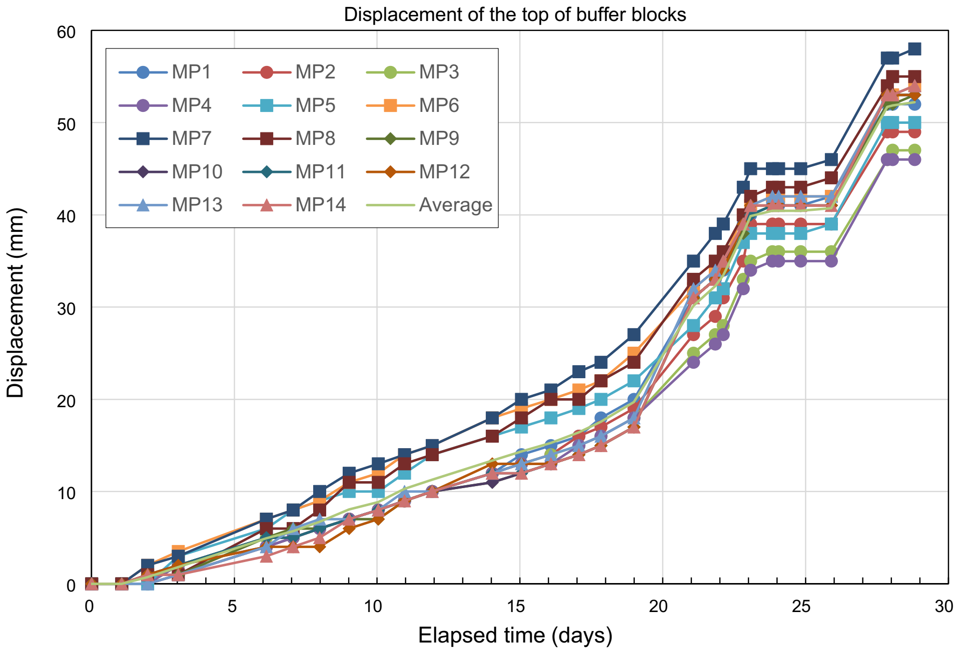


Figure 5-9. *Displacement of all of the top buffer blocks.*

5.2.6 Dismantling and analysis

In this section the field activities from dismantling and sampling are reported. The dates for dismantling the individual block layers are presented in Table 5-1. Results from analysis of the samples are reported in Chapter 5.

Table 5-1. Dates for dismantling of each block layer in Test_Seg_0.01.

Block layer	Date of dismantling	Block layer	Date of dismantling
C14*	2022-10-26	R14	2022-11-18
C13	2022-10-26	R13	2022-11-21
C12	2022-10-27 to 2022-10-28	R12	2022-11-22
C11	2022-10-28	R11	2022-11-23
C10	2022-10-31	R10	2022-11-28
C9	2022-11-02	R9	2022-11-29
C8	2022-11-02	R8	2022-11-30
C7	2022-11-03	R7	2022-12-01
C6	2022-11-04	R6	2022-12-05
C5	2022-11-07	R5	2022-12-06
C4	2022-11-08	R4	2022-12-07
C3*	2022-11-10	R3	2022-12-08
R19	2022-11-10	R2	2022-12-08
R18	2022-11-14	R1	2022-12-14
R17	2022-11-15	C2	2022-12-21
R16	2022-11-16	C1	2022-12-22
R15	2022-11-17		

* The naming of layers differs slightly from Test_Seg_0.1, see Section 5.1.2.

Removal of protection lid

As can be seen in Figure 5-10 no water reached the top surface during the 30 days of operation.

Dismantling and sampling of layer C14–C3

Figure 5-11 illustrates some examples from dismantling and sampling of layers above the canister.

Dismantling of layer R19

The canister was exposed after removing the blocks from layer R19 as illustrated in Figure 5-12.

Dismantling and sampling of R18–R1

It was immediately noted that the ring blocks were stuck to the canister also in this experiment. This meant that a decision was made to lift the canister only when it had been released from the blocks. Figure 5-13 shows a photo from dismantling and sampling of the ring segments – work that had to be done in the gap between canister and rock wall.

Lifting the canister

In Figure 5-14 a photograph shows the canister after all the ring-shaped block layers have been sampled and removed. The canister is now exposed and ready to be lifted.

Dismantling the final layers, C2 and C1

After removal of the canister the final two layers could be sampled and dismantled. The last parts of the buffer were removed just before Christmas on December 22nd.

Figure 5-10. *Left: Top layer at the end of the test. Right: Sampling of top layer finished.*

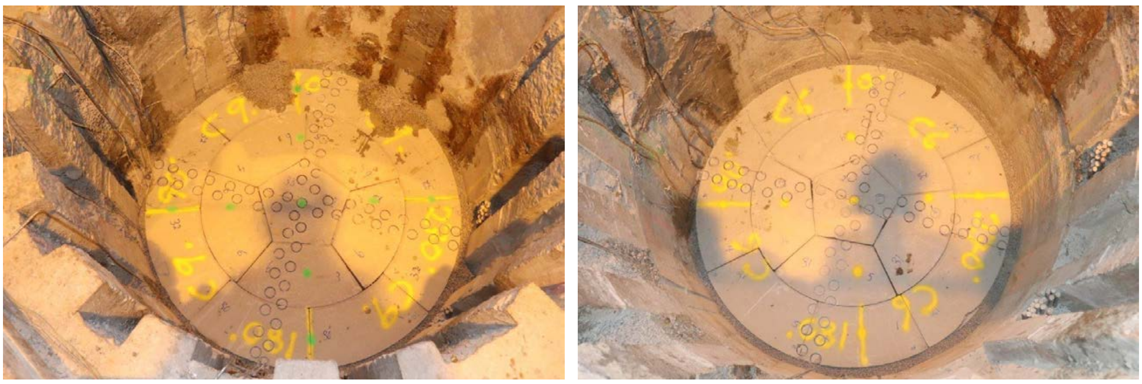


Figure 5-11. *Dismantling and sampling from layer C9 (left) and C6 (right).*

Figure 5-12. *Sampling of layer R-18.*

Figure 5-13. *Sampling of layer R-16 between the canister and the rock surface.*

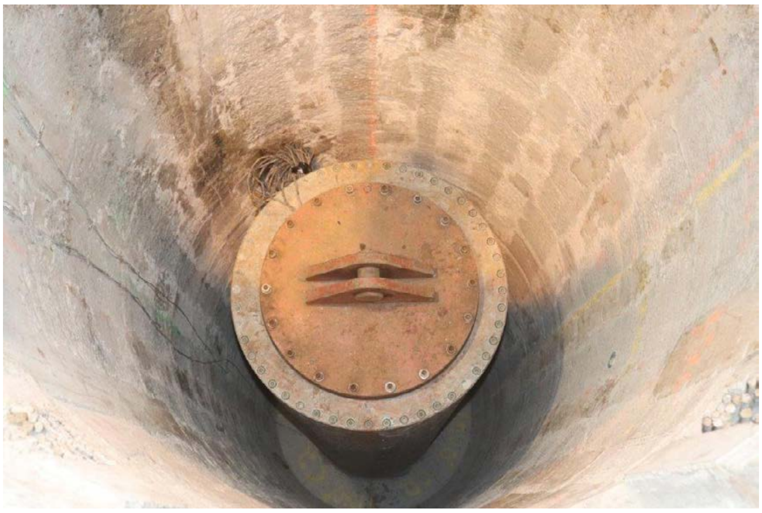


Figure 5-14. *The canister is exposed in all its length and is ready to be lifted.*

5.2.7 Position of the individual buffer blocks

Measurements of the vertical coordinate for the individual block layers were made both at installation and at dismantling of the test. The measurements were made at 8 locations on top of each block layer. From these data it was possible to determine an average vertical coordinate for each layer and from this data calculates the average height of the layers both at the start and after the test. By comparing these two data sets it was possible to calculate the changes in position for each individual section. Figure 4-21 shows how much each layer has risen or sunk during the test by presenting the difference in average height per layer before and after the test. A positive value implies a displacement upwards of the block layer. At all level except the bottom layer a positive displacement was observed. The displacements are caused by the absorption and redistribution of water in the buffer, the added displacement caused by heat are probably negligible due to the relatively short duration of the test.

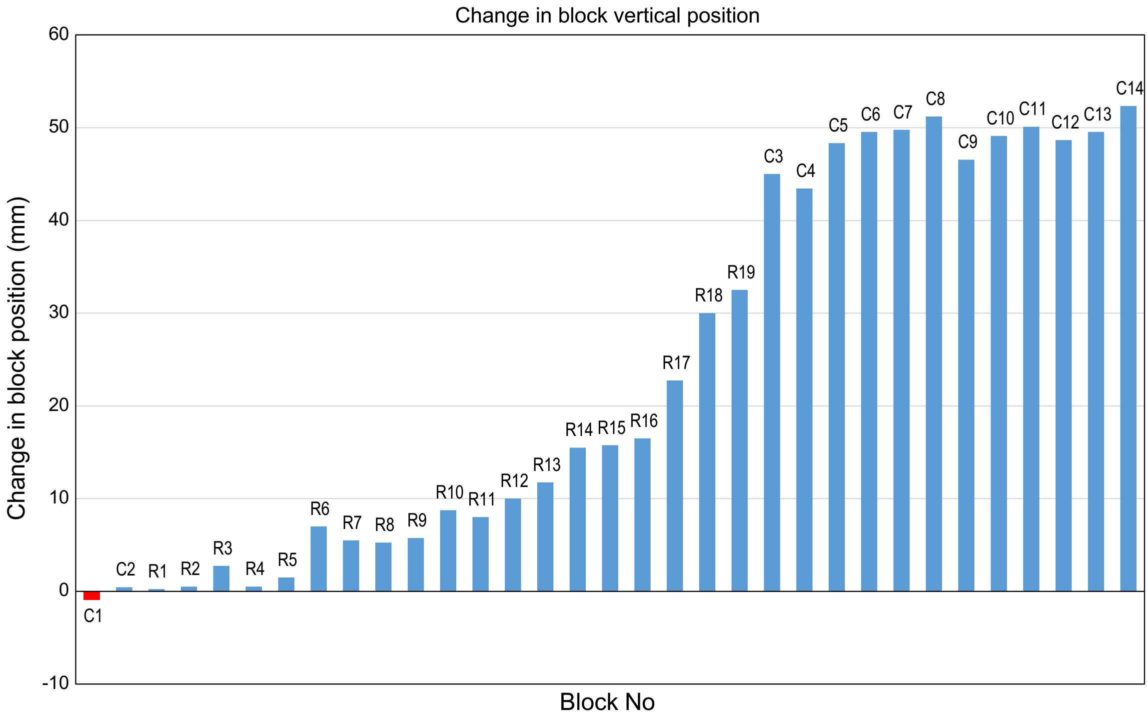


Figure 5-15. *Changes in block position between installation and dismantling. The naming of layers differs slightly from Test_Seg_0.1, see Section 5.1.2.*

6 Evaluation of the buffer THM behaviour during the installation phase

6.1 Available data

Three different full-scale tests have been done with different inflows and a segmented buffer. Additionally, one test was also done with the earlier buffer design with ring shaped and cylindrical blocks. Of these tests two has been done with the natural inflow, which has been relatively low, 0.00083–0.00037 l/min. The two other tests that were done was done with artificial inflows where a point inflow was placed at mid height of the canister, 3 m above the bottom of the deposition hole. All the test was performed in the same deposition hole however the natural inflow seems to vary a little bit between the tests and has been measured before the test. The values measured before the test is shown in Table 6-1. The tests have been carried out with a wide range of total inflows.

Table 6-1. Full-scale, in situ tests of bentonite buffer used for the evaluation and conclusions in this report.

Name	Natural inflow (l/min)	Artificial inflow (l/min)	Block layer type	Reference
Test_Solid_N	8.3×10^{-4}	-	Solid	Luterkort et al. 2017
Test_Seg_N	7.2×10^{-4}	-	Segmented	Nord et al. 2020
Test_Seg_0.01	3.7×10^{-4}	0.01	Segmented	This report
Test_Seg_0.1	3.7×10^{-4}	0.1	Segmented	This report

In this section the THM (Thermal, hydraulic and mechanics) processes are evaluated based on the data in shown in Table 6-1. The differences between the tests are compared. In Chapter 7 some conclusions regarding how long the buffer can be left in the deposition hole before the swelling is so large that it to causes problems for the installation of backfill.

6.2 General observations

The major difference between the two tests with artificial inflow done in this report and the two earlier tests with natural inflow is that the inner slot was water filled in the tests with artificial inflow. This slot is a gap between the buffer and the canister which is nominally 10 mm wide. The slot is required to make the installation of the canister possible. The inner slot which has been water filled, and consequently the bentonite has swelled into it, is shown in Figure 6-1. The volume of the inner slot is estimated to be approximately 160 litres. Therefore, it would take approximately 1.1 days to full up this slot if the inflow was 0.1 l/min and 11 days if the inflow was 0.01 l/min.

In Test_Seg_0.1 the water started exiting at the top of the pellet filling after 8 days and therefore, this test was ended on this criterion. The other tests were ended on the time criteria.

6.3 Thermal processes

The temperature measurements from three of the tests, Test_Seg_N, Test_Seg_0.01 and Test_Seg_0.1, are shown in Figure 6-2. The graph shows that the temperature is higher in the test with natural inflow than in the ones with artificial inflow. The higher the inflow is the lower temperature seem to be. This is likely due to both that extra water increases the thermal conductivity and more importantly that the inner slot is filled up with water. The inner slot acts as a thermal insulator because of the poor thermal conductivity of air. Therefore, when the slot is filled with water the thermal conductivity over the inner slot will increase and the temperature of the canister should therefore decrease. The test with 0.1 l/min seams to follow the temperature curve for the test with natural inflow (Test_seg_N, approximately

0.001 l/min), see Figure 6-2, from the beginning and after a while it reduces. The test with 0.01 l/min follows the same trend and start to deviate from the 0.001 l/min test a few days later. This suggests that in the 0.1 l/min test the inner slot start to fill up after 1–2 days and in the 0.01 l/min test the inner slot start to fill up after 4–10 days.

Figure 6-1. *The inner gap is closed since water entered the gap and caused the bentonite to swell.*

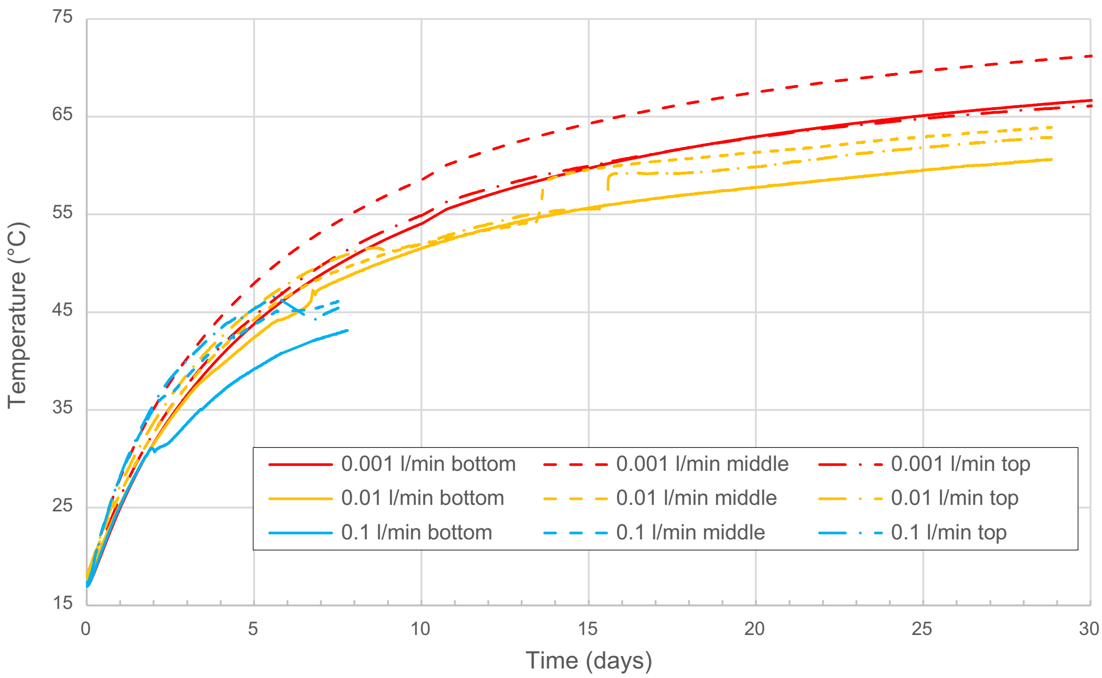


Figure 6-2. *Temperature measured at the bottom, mid height and top of the canister.*

6.4 Hydraulic processes

6.4.1 Pellet slot

The pellet slot has been sampled for water content at eight angles every 250 mm in the height direction. The result for the water content of the pellet slot is shown in Figure 6-3 for Test_Seg_N, Test_Seg_0.01 and Test_Seg_0.1. For Test_Seg_N with only natural inflow, less than 0.001 l/min (see Table 6-1), the wetting pattern is shown to the left in Figure 6-3. For the two tests with artificial inflow wetting pattern is centred around the inflow point. The wetted area of the pellet slot in the test with an inflow of 0.01 l/min is relatively small. This is because the inner slot has been filled with water and therefore a lot of water has ended up there. It is not completely clear what filled up first, the pellet slot or the inner slot. However, the temperature measurements deviate from the test with natural inflow quite early from the start from the test. This indicated that the inner slot filled up first and after that the wetting of the outer slot started.

For the test with an inflow of 0.1 l/min the temperature follows the test with only natural inflow for the first two days and after that the temperature increase reduces and becomes lower than for the case with natural inflow. It is therefore likely that during the first two day the water inflow ended up in the pellet slot and thereafter started to fill up the inner slot. From the temperature drop in the top sensor it can be assumed that the inner slot was fully filled after approximately 6 days. This suggest that the water continued to fill up both the pellet slot and the inner slot from day 2 to day 6. If all the water would have ended up in the inner slot then it would have filled up in approximately one day.

Both tests done with artificial inflow show an accumulation of water at the bottom of the deposition hole. This is likely caused by water filling up the inner slot and after that exiting from the inner slot to the pellet filling in the gaps between the buffer blocks in the bottom.

The natural inflow from the wall of the deposition hole is small compared to the artificial inflow. However, the natural inflow continues after the test during the dismantling. This dismantling took 101 days for Test_Seg_0.1 and 57 days for Test_Seg_0.01 and during this time 145 litres respectively 82 litres of water can enter the system which can have an effect on the evaluation of the data. In Figure 6-4 the inflow pattern for the tests with artificial inflow is compared with the inflow from the natural inflow. There is a clear correlation between the areas where wetting has occurred in the case with natural inflow. It is likely that these areas of darker colour originate from the inflow from the rock.

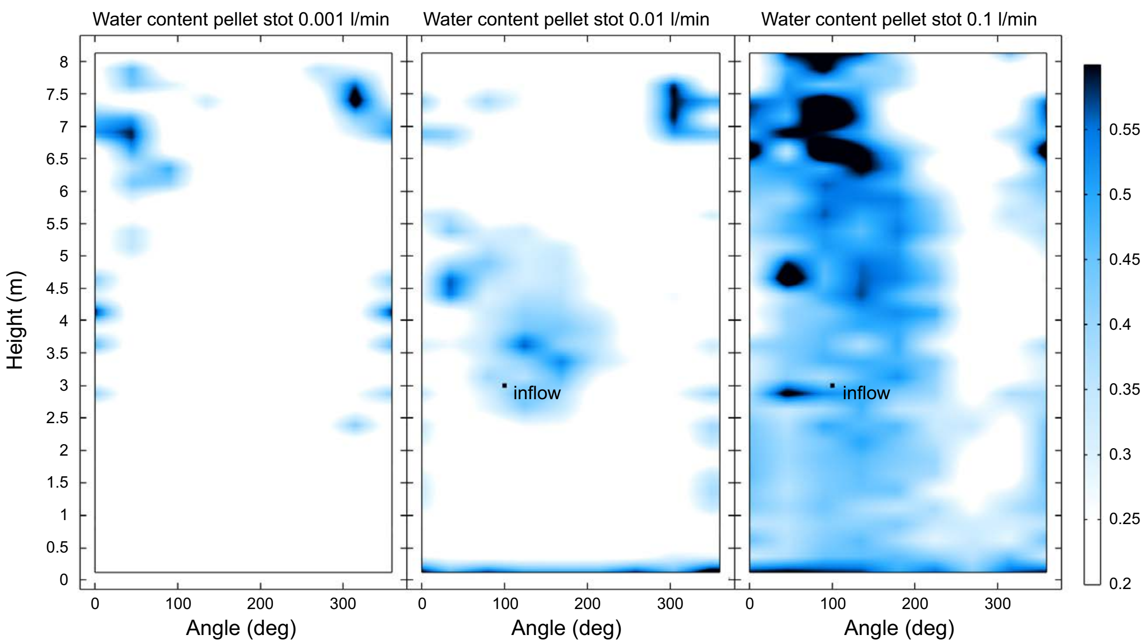


Figure 6-3. *Water content in the pellet slot for the three tests done with segmented buffer. Left: Test_Seg_N, middle: Test_Seg_0.01, right: Test_Seg_0.1.*

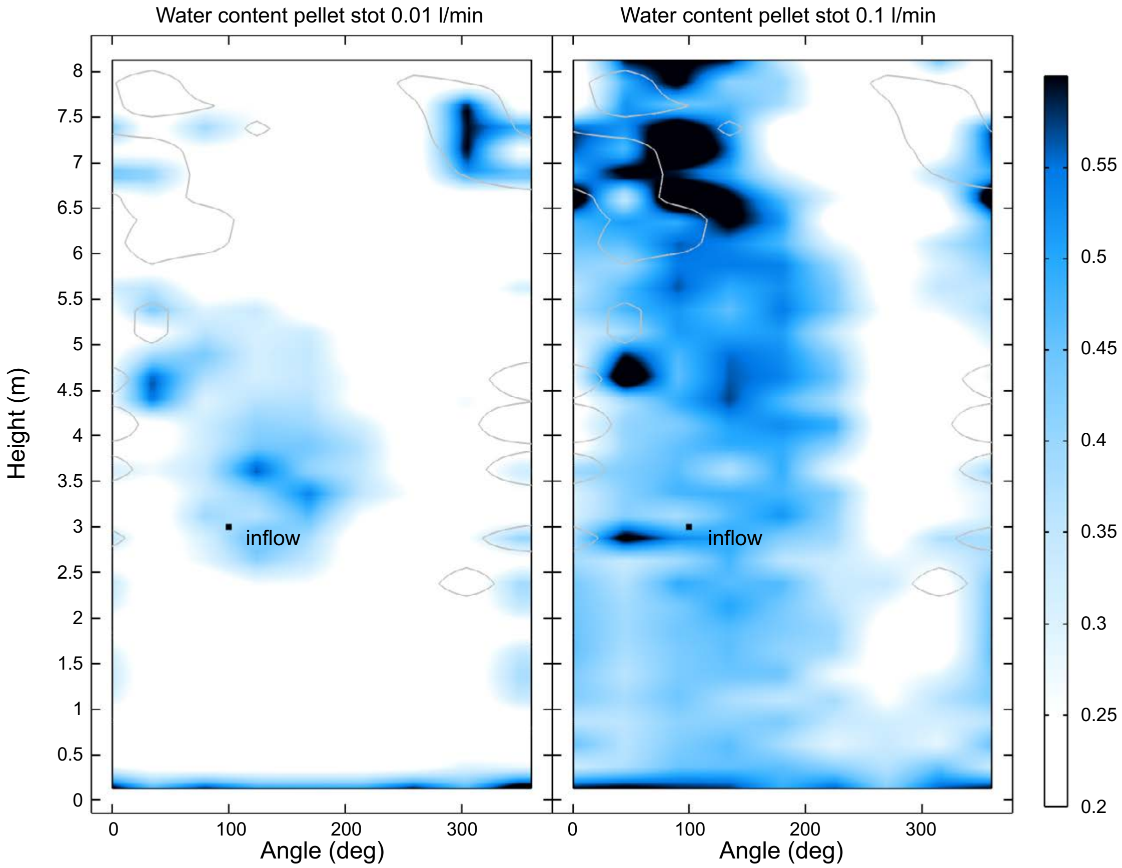


Figure 6-4. *Wetting of the pellet slot, the areas with natural inflow is indicated with grey isocurves. Left: Test_Seg_0.01, right: Test_Seg_0.1.*

6.4.2 Buffer blocks

The water content of the buffer blocks has been measured in four different directions. When the test with natural inflow and solid buffer blocks is compared to the test with natural inflow and segmented buffer blocks, Figures 6-5 and 6-6, it can be seen an area above the canister which is wetter for the test with segmented blocks. This was assumed to be due to the vapour transport in the slots between the blocks (Nord et al. 2020). Similar wetting pattern of the buffer can be seen in the newer tests with artificial inflow. However, it is not clear if the wetting has been done by liquid water or water vapour.

In Figures 6-7 and 6-8 the water content in the buffer is shown for the two tests with artificial inflow. It looks like the water has been transported into the inner slot from the wetted areas of the pellet slot.

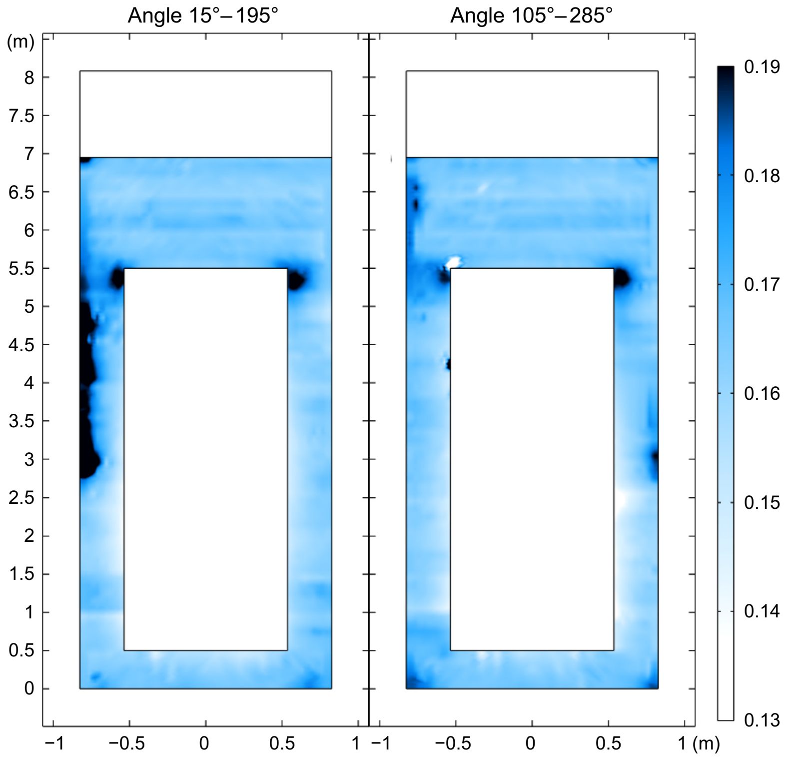


Figure 6-5. *Water content in the buffer blocks in Test_Solid_N with solid blocks and a natural inflow. The scale has been cut of at 13 % and 19 % to be able to see the wetted areas.*

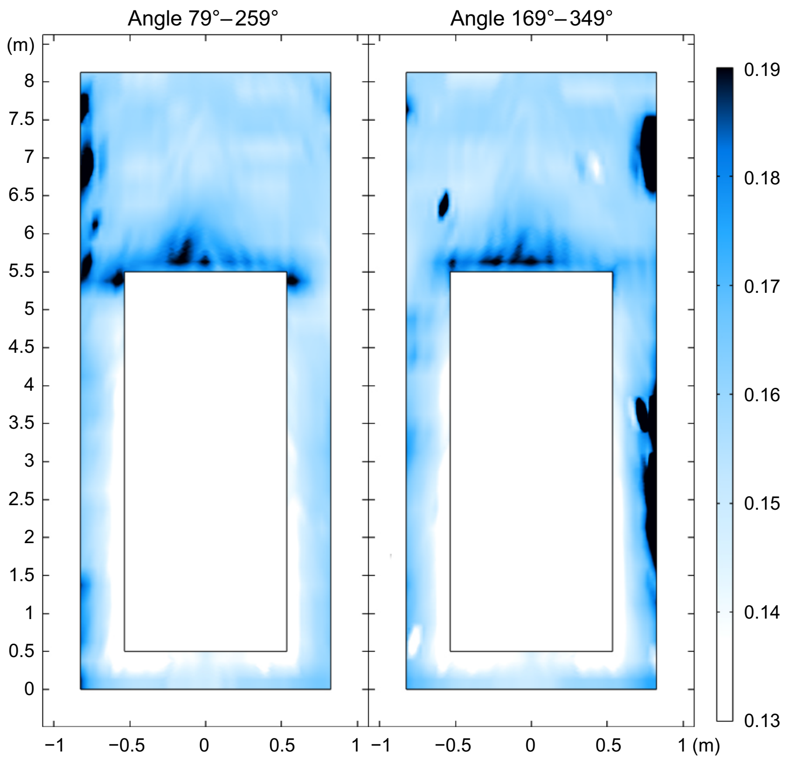


Figure 6-6. *Water content in the buffer blocks in Test_Seg_N with segmented blocks and a natural inflow. The scale has been cut of at 13 % and 19 % to be able to see the wetted areas.*

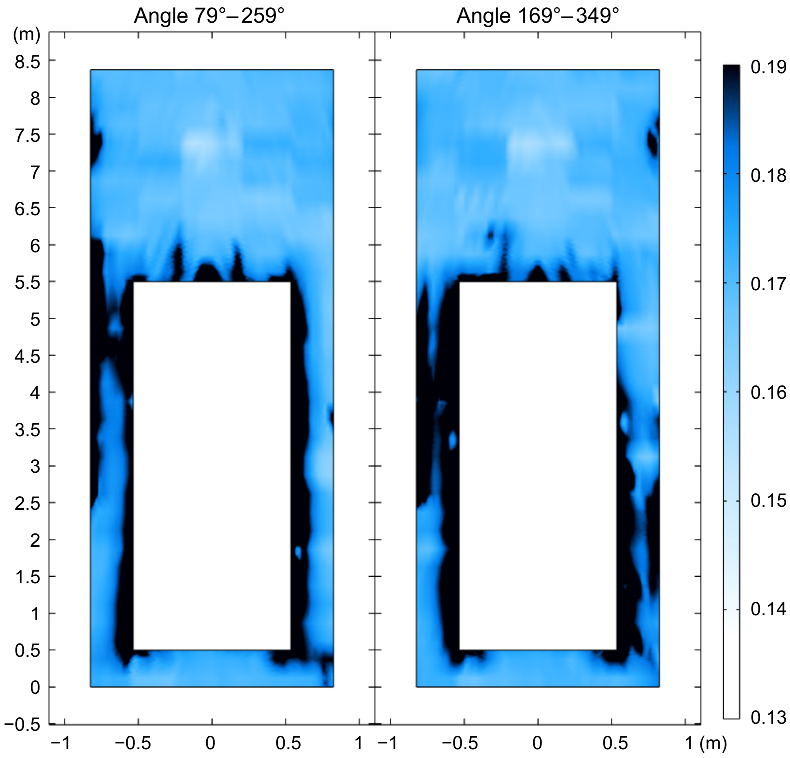


Figure 6-7. *Water content in the buffer blocks in Test_Seg_0.01 with segmented blocks and an artificial inflow of 0.01 l/min. The scale has been cut of at 13 % and 19 % to be able to see the wetted areas.*

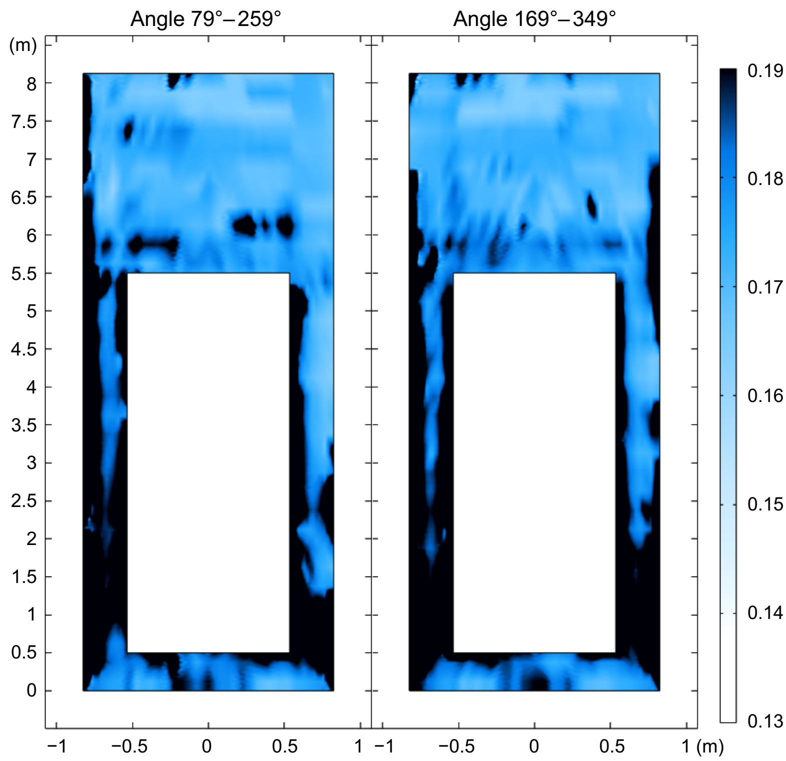


Figure 6-8. *Water content in the buffer blocks in Test_Seg_0.1 with segmented blocks and an artificial inflow of 0.1 l/min. The scale has been cut of at 13 % and 19 % to be able to see the wetted areas.*

6.5 Mechanical processes

The swelling of the buffer blocks is correlated to where the inflow points are, see Figure 4-15 and Figure 5-9 where MP1 and MP2 is located towards the inflow point in Test_Seg_N while MP6 and MP7 are located closest to the water inflow in Test_Seg_0.01 and Test_Seg_0.1. In the angles where the inflows are located the upwards swelling is larger than in the drier areas. In Test_Seg_N the difference in top displacement, difference between maximum maximum top displacement and minimum top displacement, over the top area is largest. The most even swelling is in Test_Seg_0.01.

In both the tests with artificial inflow the inner slot filled up rather quick. In Test_Seg_0.01 the inner slot seems to have filled up first and less water than expected ends up in the pellet slot. Due to the even wetting of the inner slot the swelling becomes relatively symmetric.

In Test_Seg_N a small inflow is located on one side of the deposition hole and therefore only on side is wetted, while in Test_Seg_0.1 and Test_Seg_0.01 the initial filling of the inner slot is causing these tests to be symmetric.

The rate of swelling also is highly dependent on the water inflow. In Figure 6-10 the max swelling and in Figure 6-9 the average swelling for the three different tests, Test_Seg_N, Test_Seg_0.01 and Test_Seg_0.1 can be seen.

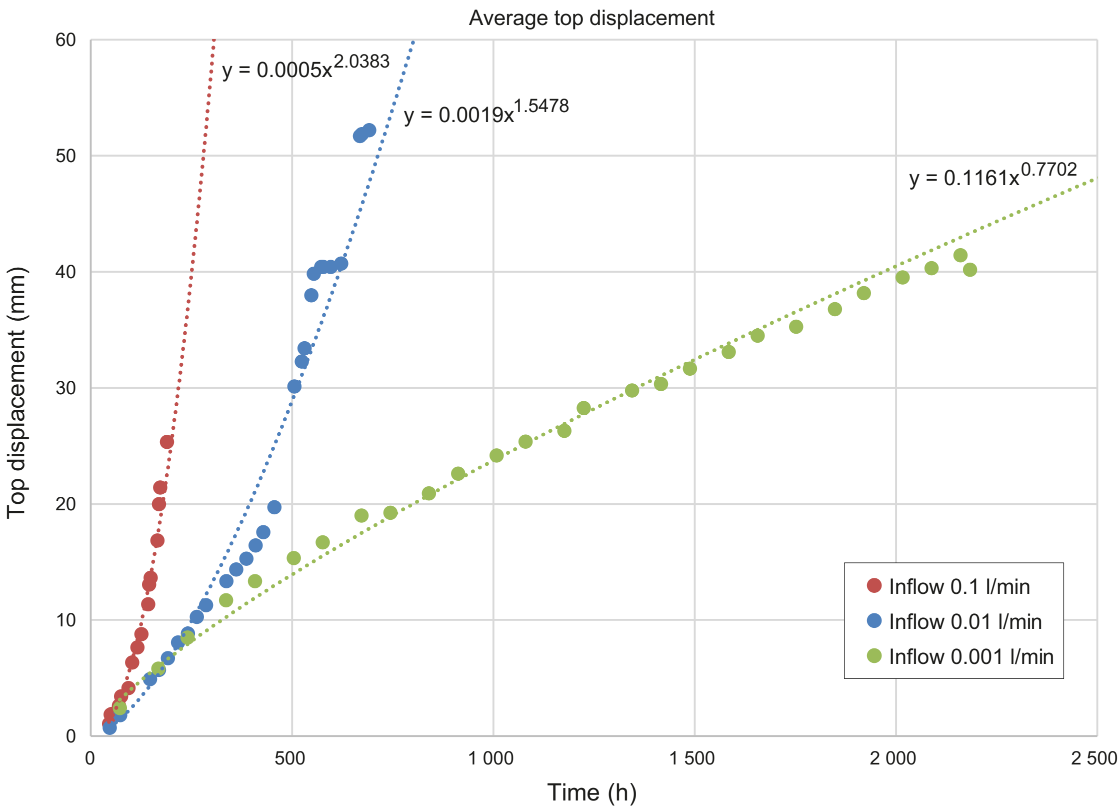


Figure 6-9. *The average upwards swelling in the three tests done with segmented buffer blocks.*

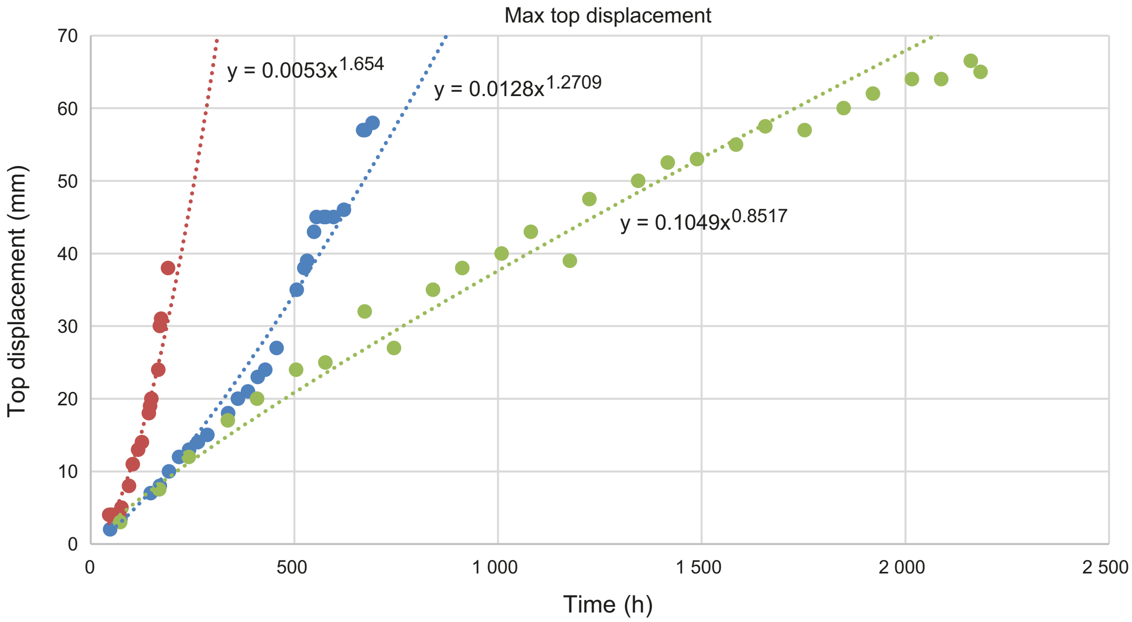


Figure 6-10. *The maximal upwards swelling in the three tests done with segmented buffer blocks.*

7 Evaluation of time available for installation with different inflows

The THM behaviour of the buffer during the installation phase is important to know in order to predict how long the buffer can be left in the deposition hole before the backfill needs to be installed. The main problem by allowing the buffer to stand too long in the deposition hole is that the height of the buffer might increase and thus cause a problem when installing the backfill blocks. It has been judged that 50 mm upswelling would be an acceptable contribution to the parameters affecting the position of the top of the buffer in relation to the bottom of the backfill blocks.

With 50 mm upswelling, the top buffer layer would be in the pellet bed and there would still be enough space to install the pellet bed. An attempt to estimate the time before the backfill needs to be installed has therefore been done based on the data achieved in all four tests in the test series, see Table 6-1. By applying estimating curves to the data, the time before the backfill needs to be installed can be plotted for different inflows, see Figure 7-1. If a safety factor of 1.3 is applied to these values then the time before the backfill needs to be installed for different inflows can estimated. The estimated times are also shown in Table 7-1.

Table 7-2. Estimation of the time before the buffer swells 50 mm upwards for different inflows.

Inflow in deposition hole (l/min)	Max time before backfill installation (days)
0.001	63
0.01	22
0.1	8

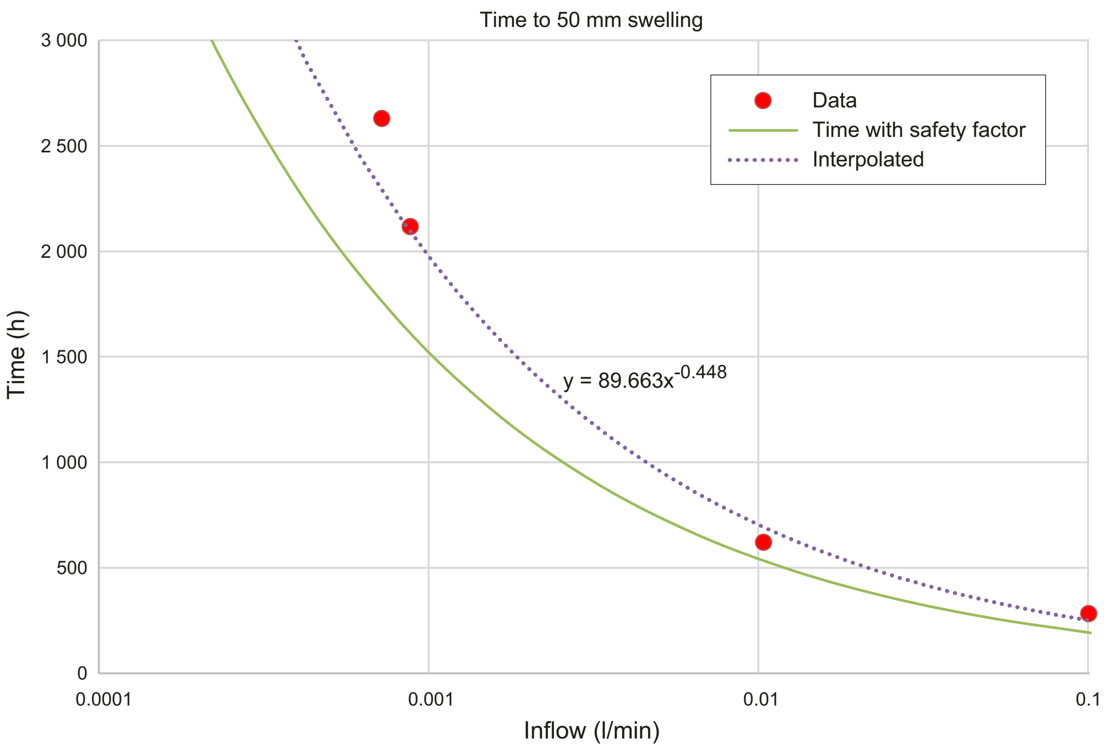


***Figure 7-1.** Estimation of the time before the buffer swells 50 mm upwards for different inflows and interpolation between these points.*

8 Conclusions and recommendations

The main purpose of the full-scale experiments was to learn more about different aspects of Thermal, Hydraulic and Mechanical (THM) processes during the installation phase of the buffer until it is supported by the backfill. Analysed data from the tests will be used to update, evaluate and calibrate the early-THM models and to get a better understanding of the THM processes. The data generated should be enough to develop and calibrate models. However, more work needs to be done with modelling to capture how different parameters affects the result.

During the tests data and knowledge has been gained on how long time that would be acceptable between the installation of the buffer and the backfill. The tests clearly show the influence of water inflow into the deposition holes. With the help of the data generated it is possible to set up an expression on how long after the installation of the buffer the backfill needs to be installed, se Figure 7-1. The time limits that have been estimated from the data give a basis for designing installation sequences for buffer and backfill. However, more work needs to be done with modelling to assess the influence of the location of the inflow and also to further refine the time limits.

The highest inflow of the two performed test with artificial wetting was 0.1 l/min, which is the highest allowed inflow to a deposition hole in the repository for spent nuclear fuel. The test with this inflow also serves the purpose of testing the maximum allowed value of inflow to investigate the buffer behaviour in this situation. It has been uncertain before how the buffer would withstand such high flow rates. Simple estimates had been done earlier but the tests showed that the time available for installation of the buffer and backfill for this case could be doubled, 8 days compared to 4 days from the earlier simpler estimates.

A third purpose was to test the performance of extruded pellets as buffer pellets. Earlier investigations (Lundgren and Johannesson 2020) has indicated that it is possible to use extruded pellets but it has not been demonstrated in a full scale in situ test before. Based on the tests there seem to be no significant difference between the roller compacted pellets and the extruded. Therefore, this test confirms conclusions from earlier studies (Lundgren and Johannesson 2020).

The work in this report is based on a limited number of tests and the results are therefore uncertain. If THM modelling could be done in a way that reasonably well describes the system more data can be generated to better add different inflows and wetting patterns.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.com/publications.
SKBdoc documents will be submitted upon request to document@skb.se.

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