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KBS-3H Heated supercontainer test

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Abstract

The heated supercontainer test was carried out in an above ground test facility at the Äspö HRL and is part of the KBS-3H project which is a joint project run by Swedish Nuclear Fuel and Waste Management Co (SKB) of Sweden and Posiva Oy of Finland.

The test outlining is basically a horizontal supercontainer, consisting of a heated canister surrounded by buffer blocks inside an outer perforated metal shell, Figure 1-3. And the main objective of the test is to study how the buffer is affected by the heated canister.

The primary purpose of this report is to provide a presentation of the heated supercontainer test, including its design, pre-modelling, basic instrumentation, buffer manufacturing, assembly, monitoring of the test, dismantling and analysis.

Sammanfattning

Det så kallade ”Heated supercontainer test” har genomförts i en ovanmarksanläggning vid Äspö-laboratoriet. Testet är en del av KBS-3H-projektet som drivs gemensamt av Svensk Kärnbränsle-hantering AB i Sverige och Posiva Oy i Finland.

Testet utgörs i princip av en horisontell supercontainer, som utgörs av en uppvärmd kapsel med buffert placerad inuti ett perforerat metalliskt skal, Figur 1-3. Det huvudsakliga målet med testet är att studera hur bufferten påverkas av den värmda kapseln.

Huvudsyftet med denna rapport är att ge en övergripande presentation av supercontainertestet, inklusive dess design, förmodellering, instrumentering, bufferttillverkning, montage, monitering av testet och brytning av testet med efterföljande analyser.

Contents

1 Introduction

1.1 General

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

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

The KBS-3H reference design is called Drainage, Artificial Watering and air Evacuation (DAWE). The DAWE design utilises that the KBS-3H components are installed on feet so that inflowing water drains underneath them. When all components are installed in a 150 m section the voids around the components in the section are artificially filled with water through the compartment/drift plug while the air is evacuated.

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

The KBS-3H design has been developed jointly by SKB and Posiva since 2002. This report has been prepared within the project phase "KBS-3H – System Design 2011–2017".

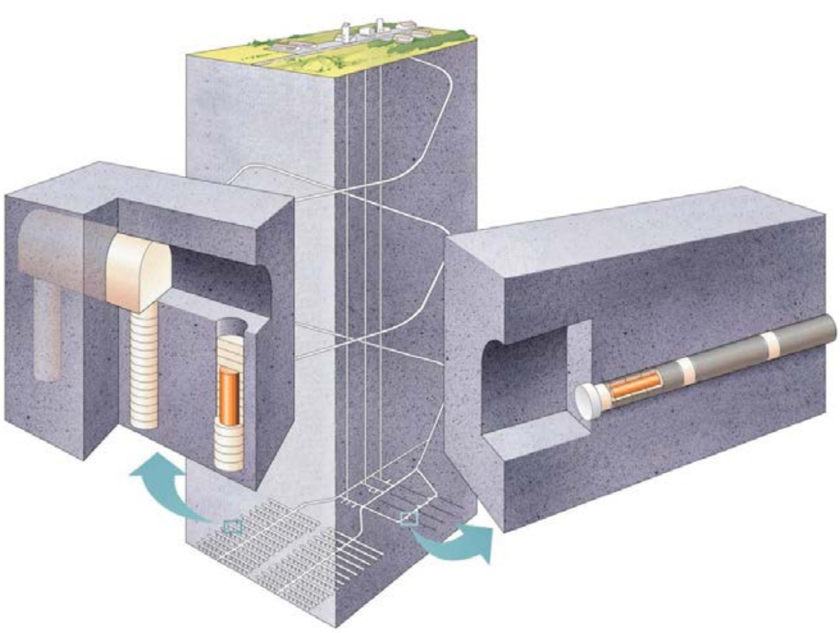


Figure 1-1. *Schematic illustration of the KBS-3 method with its three barriers: the canister, the buffer and the rock. The vertical reference design is illustrated to the left and the horizontal alternative to the right.*

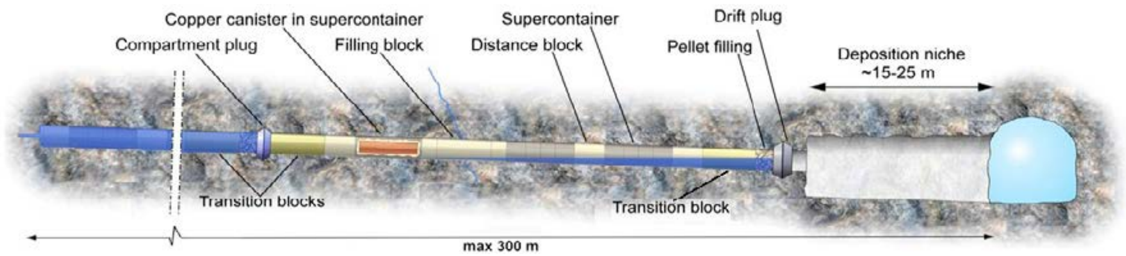


Figure 1-2. *Illustration of the KBS-3H design, the current figure illustrates the water filling of the second compartment.*

1.2 Heated supercontainer test

None of the earlier KBS-3H tests (scale tests or full scale tests) have been carried out with heated canisters. However, there is extensive experience on heated conditions from KBS-3V, both from tests and modelling. Recent work with heated conditions has been carried out within the BUSTER (Johannesson et al. 2014), and BÅT projects (Luterkort et al. 2017). The KBS-3V test/modelling results shows that the heat emitted from the canister causes a redistribution of water in the buffer blocks surrounding the canister, which can make the buffer crack after a certain exposure time period due to local drying.

The KBS-3H design differs from KBS-3V in several ways but it has been concluded that the issue regarding redistribution of water in the buffer can be a potential problem for the KBS-3H design. Cracking of the KBS-3H buffer can risk the integrity of the supercontainer and possibly lead to buffer loss. Buffer fall-out can also disturb the transport, deposition and DAWE air evacuation process.

For KBS-3H the cracking problem may occur if there is an interruption in the deposition process leading to a period of storage of the assembled supercontainer, something which is assumed to be 10 days at most. Secondly, it may occur during the time period after deposition but prior to water filling of the compartment, which with the current design also equals 10 days at most for the first supercontainer deposited in a drift. The maximum risk period is thus assumed to be 10 + 10 = 20 days.

To find out how big a problem the drying of the buffer during storage and installation is, a full scale test has been carried out simulating 10 days in storage at room temperature and 10 days in the drift aiming at cooler surroundings. The test was carried out inside the supercontainer transport tube which was closely sealed to avoid exchange of air with the test surroundings.

The basic test outlining is presented in Figure 1-3, a supercontainer placed inside a sealed transport tube.

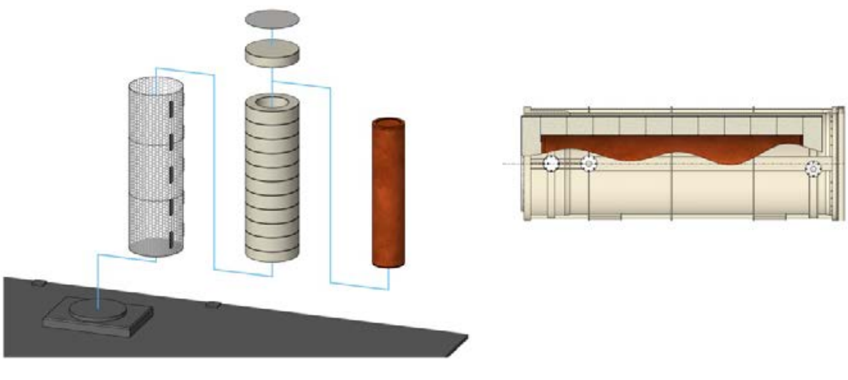


Figure 1-3. *Basic outline of the Heated supercontiner test, left figure illustrating the supercontainer assembly and the right figure illustrating the supercontainer placed inside a sealed transport tube in horizontal position.*

The heated supercontainer test also assesses a potential new buffer design with harmonised water content in blocks and rings, 14 ± 1 %, compared with the current reference design of 11 ± 1 % rings and 17 ± 1 % blocks.

1.2.1 Heated supercontainer test objectives

The objectives of the heated supercontainer test are:

- Quantify the amount of water that condensates from the buffer during storage and prior to water filling of the compartment (10 + 10 days).
- Assess the amount of cracking and buffer loss during storage and prior to water filling of the drift compartment (10 + 10 days).
- Assess the redistribution of water inside the buffer blocks.
- Assess how well the current supercontainer model predicts the redistribution of water, cracking and condensation.

Cracking is assessed by visual inspection and buffer loss is assessed by weighing the bentonite that falls out from the supercontainer. Condensate water will also be weighed. Redistribution of water in the buffer blocks is assessed by dismantling and analysis.

The model is assessed by comparing the test outcome with the pre-modelling.

1.2.2 Purpose and scope of this report

The purpose of this report is to present the work done and the data generated. Initial discussions on the results are also included; however, more in-depth analysis and post test modelling are left for future studies.

2 Pre-modelling and input to test design

The basic heated supercontainer test outline is presented in Figure 1-3.

2.1 Pre-modelling objectives

Pre-modelling was carried out in order to try to predict how the buffer in the supercontainer behaves during storage (maximum 10 days) and in the time period between deposition and the DAWE water filling procedure (maximum 10 days). It was also carried out in order to support decision making about the test conditions.

Two main alternatives were modelled for the storage period:

1. Horizontally placed supercontainer in a transport tube.
2. Vertically placed supercontainer in a transport tube.

One of the major differences in the two alternatives is the fact that when placed horizontally, the canister will undoubtedly be laying on the buffer rings and there will be an air gap on the upper side. For the vertical alternative the canisters contact with the buffer is mainly to the bottom block and in a less defined way it could lean on some of the inner part of the rings.

2.2 Modelling tool

A model previously used for KBS-3V (Luterkort et al. 2017) was applied to the KBS-3H conditions. The modelling has been performed in comsol multiphysics and details about the model can be found in Luterkort et al. (2017).

The model is under development but has proven good in predicting the KBS-3V setup.

2.3 Geometries and boundary conditions

In this model the thermal power in the canister is assumed to be 1 700 W, which leads to the maximum temperature allowed in the current design. Since it is not known what the initial temperature of the canister will be, the initial temperature is varied between 20 and 80 °C. The most likely scenario is that the temperature at the time of assembly is somewhere around 60 °C.

When it comes to the boundary towards the surroundings it is assumed that the heat is removed by adding a heat transfer coefficient, in this case it is assumed to be 7 $W/(m^2K)$. Thermal radiation is also used on the outer boundary. To calculate the heat transfer the external temperature is needed and in this case it is assumed to be 20 °C. To calculate the temperature drop over the air filled slots emissivities needs to be assigned to the different surfaces. In this model the emissivity of copper and bentonite are assumed to be 0.3 and 0.85 respectively. The surfaces in the transport tube is assumed to be 0.85 which would correspond to a painted or oxidised surface.

It should be noted that the environment in the outer slot is very sensitive to the thermal boundary conditions because a small difference in temperature will give a large difference in relative humidity.

2.3.1 Geometry horizontal supercontainer

To model this case a 2-D model was used. The cross-section in the middle of the canister is used for the horizontal modelling. The geometry is shown in Figure 2-1 where the supercontainer is placed slightly eccentric (approximately 7 mm) in the transport tube. This cross-section should be representative for the rings close to the middle of the canister as the major heat and moisture flow is in the radial direction. This model does not cover the top and bottom block, to do so a 3-D model would be needed. The geometry is based on the KBS-3H supercontainer reference dimensions.

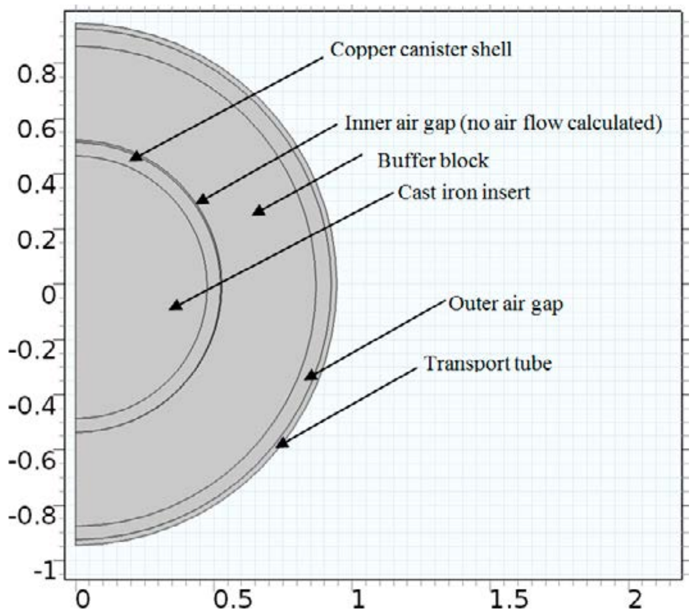


Figure 2-1. Geometry of a horizontal supercontainer.

2.3.2 Geometry vertical supercontainer

In the case of a standing canister a rotation symmetric model was used. It is assumed that all components are placed concentric. The geometry is shown in Figure 2-2. To simplify the model convection is assumed to be zero in the inner slot. This is not expected to affect the model. It is also assumed that there is no space between the transport tube and the supercontainer in vertical direction (between top of supercontainer and top of transport tube).This means that there is no air above the supercontainer. This simplifies the calculation because the vertical surfaces create convection cells that take very long time to calculate.

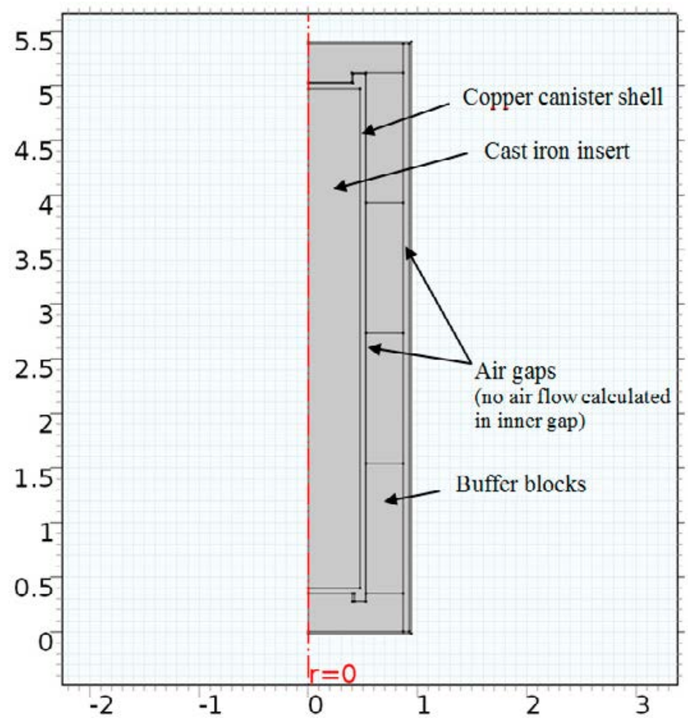


Figure 2-2. Geometry of a vertical supercontainer.

2.4 Pre-modelling results

2.4.1 Horizontal supercontainer, 10 days storage

Temperature

A clear effect of the canister lying on the buffer rings can be seen on the temperature distribution after 10 days, Figure 2-3. In Figure 2-4 the temperature evolution in horizontal direction (y = 0, Figure 2-1) is shown for a canister with an initial temperature of 60 °C.

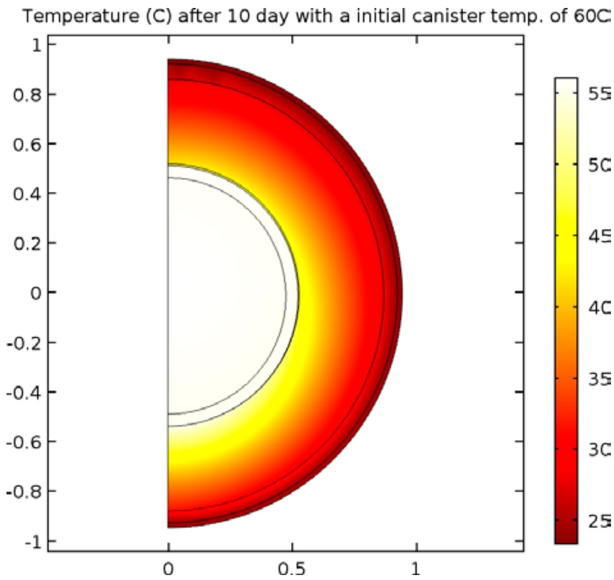


Figure 2-3. *Temperature distribution after 10 days with initial canister temperature of 60 °C.*

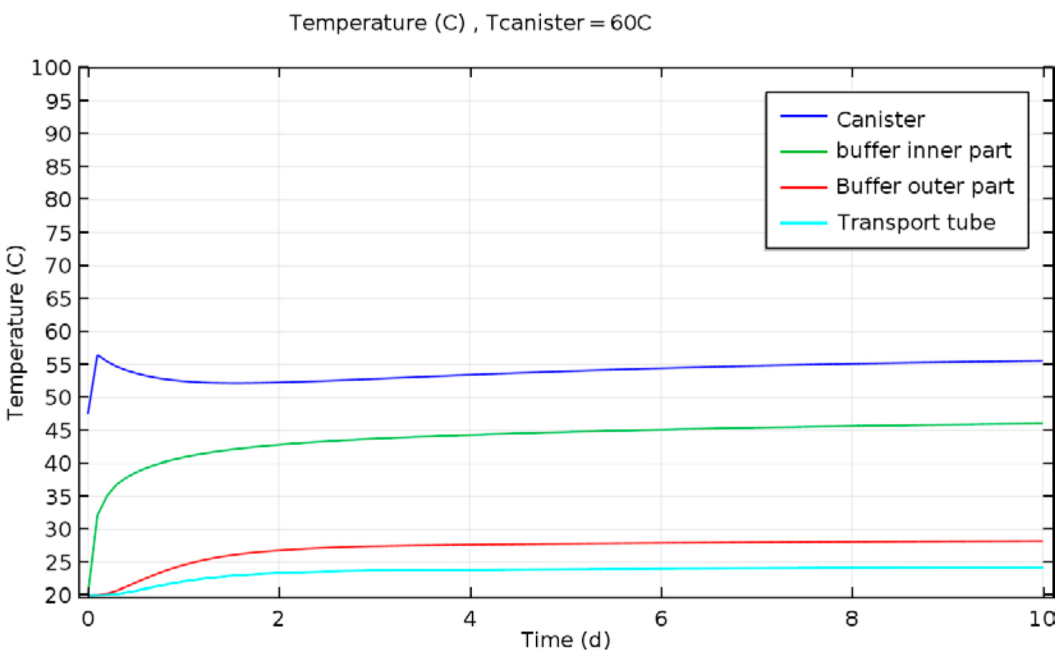


Figure 2-4. *Temperature evolution in horizontal direction (y = 0 in Figure 2-1) with an initial temperature of the canister of 60 °C. The reason the curve for the canister does not start at 60 °C is that linear discretisation is used and a very high (infinite) gradient exists.*

Water content

The increased temperature in the contact between the canister and the buffer make the buffer dry most in this area (lower part of the rings), see Figure 2-5. In the other parts the drying is less but most of the buffer is drying. In Figure 2-6 the velocity of the air in the outer slot can be seen, it can be noted that convection cells form on the top side of the buffer. The model predicts that the relative humidity will be around 100 % in the surface of the transport tube. This means that water could condensate on the transport tube. However, only small amounts of water are expected to condensate. It should be noted that this condensation is quite sensitive to thermal boundary conditions. If the temperature of the transport tube changes with only 1 degree C the situation might look different. With respect to water condensation it is preferable to keep the temperature constant. Any cold spot on the transport tube would act as a condensation point.

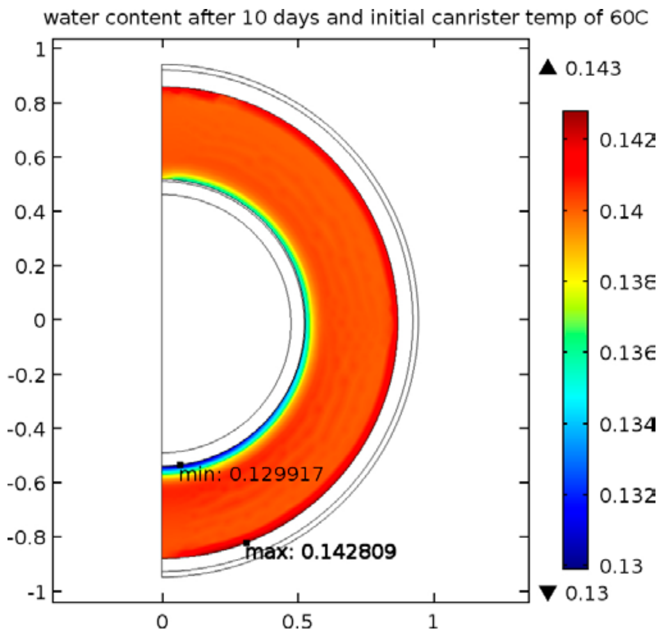


Figure 2-5. *Water content after 10 days with an initial temperature on the canister of 60 °C and water content 0.14.*

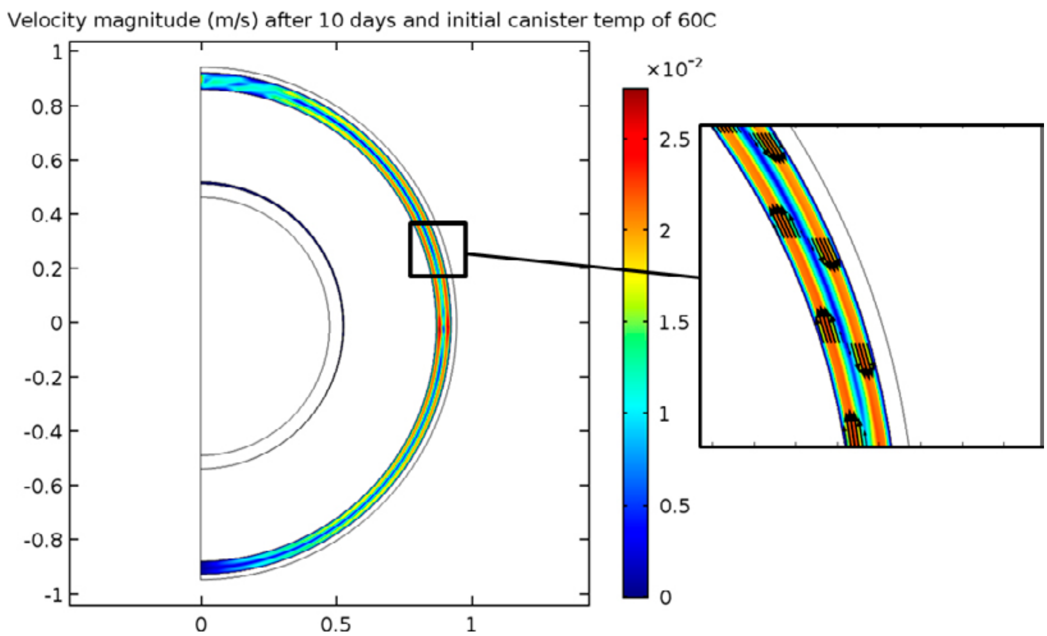


Figure 2-6. *Air velocity in the outer slot, note the convection cells forming in top. The initial temperature of the canister is 60 °C.*

Cracking

To estimate the crack depth a simple analytic model which was developed in Eriksson (2016) was used. The model is only tested on small scale solid bentonite blocks and it is therefore not known how well it works on full scale bentonite blocks or rings. Therefore the results are very uncertain. The model predicts that very little cracking will happen if the initial canister temperature is below 40 °C. With an initial canister temperature of 80 °C the crack depth is predicted to be approximately 1 cm on the inner side of the buffer rings after 10 days in the transport tube. The drying on the inside is very dependent on if there are any flow path for air between the inner gap and the outer gap. Any leakage between the gaps will increase the drying and therefore also the cracking. The current model assumes there is no leakage of air in the gaps between the blocks. There could also be thermal stresses from the asymmetric heat distribution which is not accounted for in this model.

2.4.2 Vertical supercontainer, 10 days storage

According to the model there would not be a very large redistribution of water during the first 10 days of storage. Most of the buffer is drying although there are small areas in the top and bottom that exhibits an increase in water content. This is due to the convection in the outer air slot where the air velocity reaches approximately 0.02 m/s. The relative humidity is below 100 % at the surface of the transport tube therefore it is likely that no water would condense on the transport tube. The temperature evolution at mid canister height is quite similar to the horizontal case.

With respect to cracking, the model predicts vertical to be more favourable than horizontal, with very little cracking in small local areas.

2.4.3 Simulating emplacement in the drift after storage

To get a better understanding what happens during the first couple of days in the deposition drift this was modelled as well. In this work the focus was on continuation after horizontal storage.

In the modelling of the time in the deposition drift thermal properties of the rock from Forsmark is used. This means a thermal conductivity of 3.5 W/(mK) and an initial temperature of 11 °C. A large enough rock mass is used so that the boundary is not heated. Otherwise the boundary conditions and equations used are the same. Figure 2-7 presents the previously calculated water content in the buffer rings from horizontal storage (10 days), as well as horizontal storage (10 days) followed by 10 days in the drift, both, in a section of the buffer directly underneath the canister. It can be seen that there is not much change during the time in the drift. The rock heats up and is approximately 24 °C after the supercontainer has been in the deposition drift for 10 days, as seen in Figure 2-8.

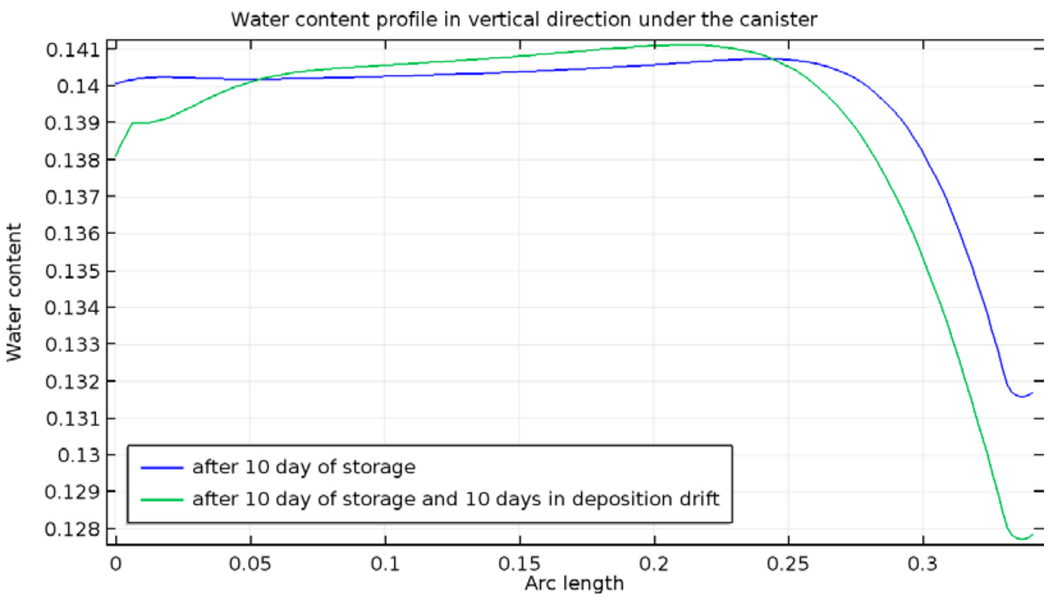


Figure 2-7. *Water content profile after 10 days of horizontal storage and after 10 days of horizontal storage +10 days in the deposition drift in a section of the buffer directly underneath the canister, i.e. at 6 o'clock. The canister is to the right in the figure.*

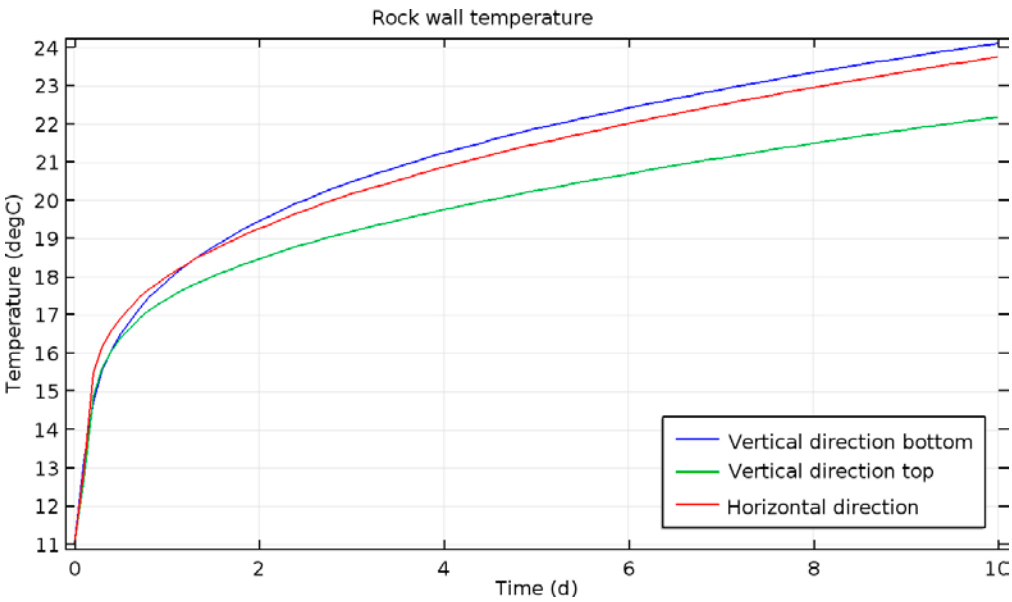


Figure 2-8. *Predicted rock wall temperature.*

2.4.4 Pre-modelling conclusions

The modelling concluded that vertical storage would reduce the amount of water that condensates on the transport tube and the drying of the buffer would also be less in the outer diameter of the buffer block. Horizontal storage, on the other hand, is in line with the currently planned handling in a repository scenario. Standing storage would also imply tilting the supercontainer when it is time for deposition. This tilting after storage with buffer which, at that stage, is potentially cracked was deemed risky by the project. Therefore it was decided to carry out the test with the supercontainer in horizontal orientation after assembly. It should be noted that the supercontainer has to be raised back from horizontal to vertical position after the test period, in order to facilitate dismantling and sampling, this is an extra tilt compared to a repository scenario. The block conditions have to be inspected as much as is possible inside the transport tube before this tilt.

No alternative with an open transport tube was calculated but it would most certainly increase drying of the buffer blocks as long as the temperature in the transport tube is higher than in the surrounding air. Thus storage in a closed transport tube was selected by the project.

Lower transport tube temperatures would be preferable compared to hotter once because the relative humidity does not change linear with temperature. This would mean that even if the temperature drop over the outer slot is the same the condensation should be larger if the temperature of the transport tube is larger. However, the influence would be limited and the project selected to carry out the first 10 days of storage in room temperature.

Furthermore the modelling, logically, suggests that the initial temperature of the canister influences the water redistribution after 10 + 10 days. One option would be to cool the canister prior to installation; however that would imply an extra working step in a repository scenario which should be avoided. Other options are to have the canister standing open in room temperature and equilibrate, which would make it in the order of 40 °C or to isolate it to have a higher, more conservative starting temperature in the order of 60 °C which could be a realistic temperature if the canisters are stored inside transport casks rather than in open air.

Regarding simulating the 10 days in the drift it is mainly a question on how to best achieve proper test conditions. The drifts in a repository should have very high humidity, close to saturated as in the Äspö KBS-3H drift at –220 m. It is also reasoned that the drifts have small volumes of air around the components once the supercontainers and distance blocks have been placed so the conditions should be quite similar to those in the transport tube during storage with the exception that the rock has a different heat coefficient and a lower temperature. Thus cooling the transport tube to rock temperature in a manner similar to Figure 2-8 (an average of the three cases) was judged a reasonable comparison that should be practically possible to do in a test set-up as well.

2.5 Selected test conditions

Orientation of supercontainer.	Horizontal for the full 20 days.
Canister thermal power output.	1 700 W.
Canister starting temperature.	Approximately 60 °C.
Transport tube temperature, storage.	Room temperature, ~ 20 °C, monitored.
Transport tube temperature; drift.	Start 13 °C, with increase to 24 °C according to Figure 2-8, monitored.
RH assembly hall, during assembly and test period.	Selected to correspond to the buffer blocks as measured, monitored.
Temperature assembly hall.	Room temperature, ~ 20 °C, monitored.
Supercontainer, storage.	Confined inside a sealed transport tube for 10 days.
Supercontainer, drift.	Confined inside a sealed transport tube, RH as developed, 90–100 % expected. 10 days.
Bentonite buffer rings and blocks, wc.	14 ± 1 %.
Bentonite buffer rings dry density.	1 885 kg/m^3.
Bentonite buffer block dry density.	1 753 kg/m^3.
Dismantling.	Vertical, for safety and working condition reasons, tilting from horizontal to vertical will be required.

3 Test facility, equipment, instrumentation and constraints

3.1 Test facility

The test was carried out in the "Högdelen" building of Äspö HRL, which is well suited for the purpose and equipped with necessary equipment for the supercontainer assembly. The Multi Purpose Test (MPT) supercontainer was also assembled in Högdelen (Kronberg 2016).

The test site was provided with a humidifier to control the environment during assembly, and with sensors for recording of humidity and temperature.

The blocks in the supercontainer are produced with a water content of 14 %, and at exposed periods the relative humidity in the test hall was kept at a level at which they were in equilibrium with the surrounding air, equalling a level of approximately 64 %. Plastic protection was also used to protect the exposed blocks.

3.2 Equipment

3.2.1 Supercontainer shell

An existing supercontainer shell in stainless steel was used for the test; it has previously been used for deposition tests at the –220 m level of the Äspö HRL. The supercontainer was modified with solid end plates in order to match the current KBS-3H reference design.

The shell straightness was checked and adjusted prior to assembly in order to ensure that the buffer would fit accurately. No major modifications had to be made to the supercontainer shell since the perforation could be used for sensor cabling.

3.2.2 Canister

An existing SF canister was used, which consisted of the standard type BWR canister with screwed lid and standard type cast iron inserts. It was fitted with 4 new adjustable heaters of maximum 1 000 W each.

For the lead-through the canister used was provided with a spacer and an additional lid, which made the canister 140 mm longer than the original canister, affecting the buffer height which had to be adjusted accordingly.

3.2.3 Buffer

For details, see Chapter 4.

10 ring-shaped blocks and 2 end blocks were used in the test. In the reference design there are 4 rings, however in this test, the heights of the rings and the solid blocks were limited by the used press to a maximum height of about 500 mm..

3.2.4 Sensors

For details, see Section 3.3.

The buffer rings, blocks and the canister were provided with temperature sensors and the transport tube was provided with temperature sensors as well as humidity sensors for measuring of the ambient air humidity.

For the installation of the sensors in the buffer, holes were drilled from the outside of the blocks, opposite to the installation of the sensors in the MPT where they were placed in-between the blocks (Kronberg 2016).

3.2.5 Transport tube

The existing transport tube with the heavy gamma gate (underneath when vertical), and a transport plate (top part when vertical) were used to allow for tilting the supercontainer in an horizontal orientation. The transport tube windows were modified with openings for cables from monitoring and heating equipment.

In order to maintain the transport tube as good as air tight; tape and silicone was used at gamma gate, and transport plate connection points, etc.

When tilted horizontally the transport tube was placed on its transport support, Figure 5-3.

3.2.6 Mobile Cranes

A five tonne crane was used for lifting the buffer components. The work was carried out in principle in the same way as for the MPT (Kronberg 2016).

For handling of the supercontainer, shell, canister and the transport tube, a heavy mobile crane was used.

3.2.7 Transport vehicle

For transportation of the transport tube the Clab truck, normally used for transport containers with spent fuel, was used.

3.2.8 Vacuum tool

A tool, which was developed for the KBS-3H block geometries and weights during the MPT, was used again for the heated supercontainer test (Kronberg 2016).

3.3 Instrumentation

3.3.1 Basic instrumentation outlining

Based on pre-modelling and experiences from earlier KBS-3V tests (Luterkort et al. 2017) it was decided to monitor the following parameters for all 20 days:

- Temperature
  - Canister
  - Inner side of buffer rings
  - Mid buffer rings
  - Outer side of buffer rings
  - Transport Tube metal
  - Ambient air
- Relative humidity, air
  - Ambient air
  - Air gap between supercontainer and transport tube
- Video/photos
  - Outer side of buffer rings with regards to cracks (during the test there is limited access inside the transport tube but a peep hole camera was used underneath the supercontainer)

Sensors for measuring the water content in the buffer were not used, recent experiences from the BÅT project was that these do not work in a good way, and water content data is anyhow attained by sampling after the test.

3.3.2 Geometry and labelling of directions and sections

Figure 3-1 illustrates the labelling of the four directions of the buffer blocks. Since the supercontainer was assembled vertically and then tilted horizontally the supercontainer feet are included for additional clarity.

Figure 3-2 illustrates the labelling of the blocks inside the vertical supercontainer.

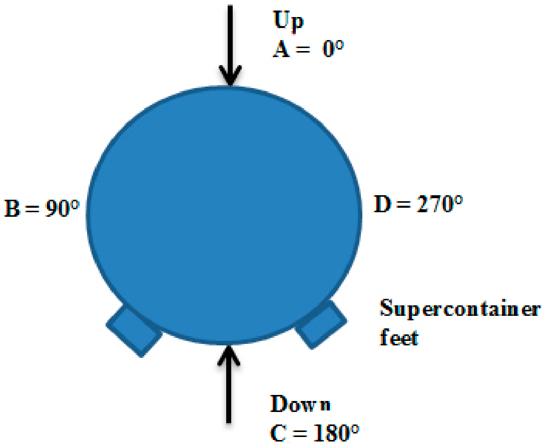


Figure 3-1. *Labelling of the directions of the buffer blocks inside the supercontainer shell.*

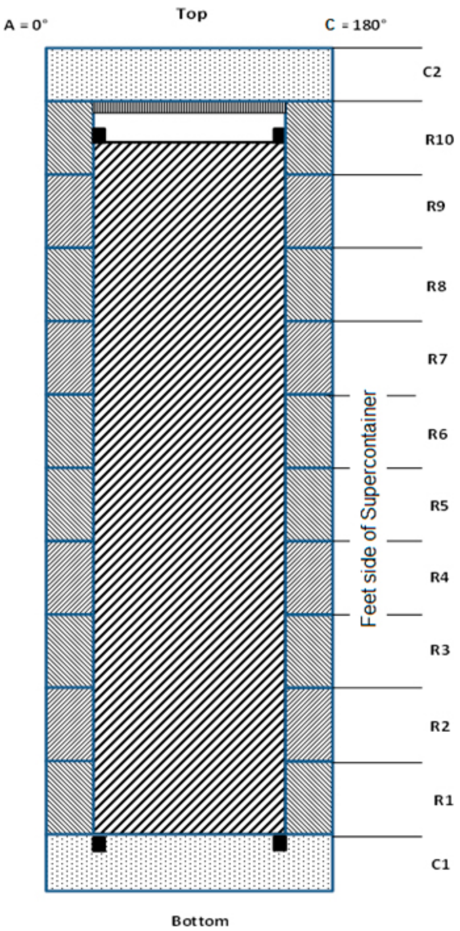


Figure 3-2. *Side view of the supercontainer with labelling of the blocks; C1, C2 and R1–R10. Direction A and C from Figure 3-1 are also marked.*

3.3.3 Sensor positions

Table 3-1 summarises the test instrumentation, and Figure 3-3 illustrates the position of the installed sensors in block R5 as an example. Further details are presented in the sections below.

Table 3-1. Heated supercontainer test instrumentation.

	Temperature	RH
Bottom block, C1	6	
R2	16	
R5	16	
R9	16	
Top block, C2	6	
Canister	6	
Transport tube	12	
Assembly hall		2
Air void between shell and transport tube		6
Sum:	*78*	*8*

Temperature sensors

Pentronic, type K series 8105000 thermocouples, were used in the test.

Temperature sensors were placed in block C1 (6 sensors), block C2 (6 sensors) and R2, R5 and R9 (with 16 sensors in each ring), see Figure 3-2 regarding block labelling. The sensors in the solid blocks, C1 and C2, were placed in the outer part (radially) of the blocks in 4 directions A = 0°, B = 90°, C = 180° and D = 270°, and in the centre of the blocks at two different depths from the canister (axially). The sensors in the rings were placed in the same 4 directions at 4 different radial distances from the surface of the canister, see Figure 3-3.

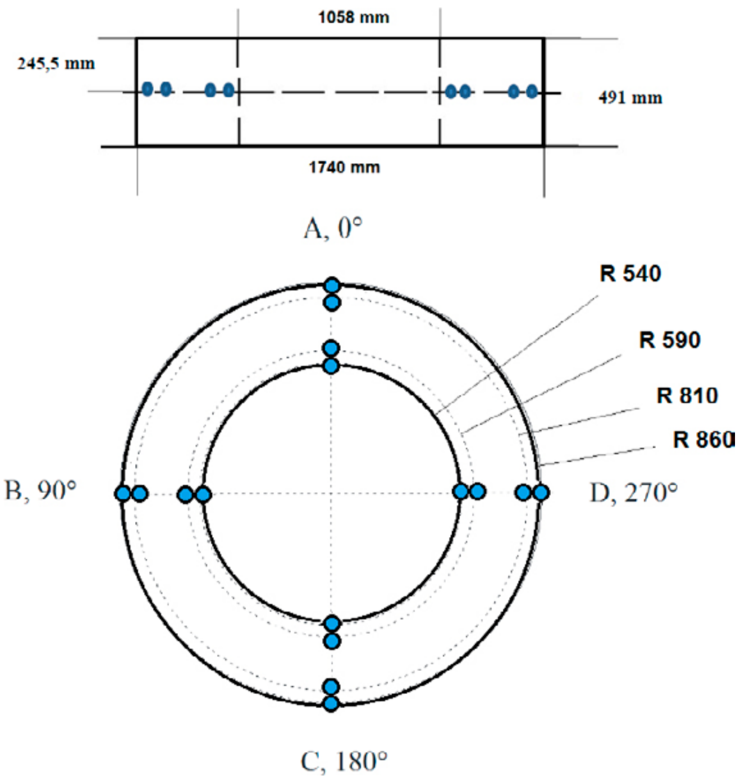


Figure 3-3. *Temperature sensors in ring R5.*

The temperature sensors in the transport tube (12 sensors) were placed in the same directions as the buffer sensors (A = 0°, B = 90°, C = 180° and D = 270°) at three different height levels (when vertical); bottom part, mid part and top part of the transport tube.

Temperature sensors were also placed on the canister (6 sensors); centred on the top of the canister and in direction A = 0°, B = 90°, C = 180° and D = 270° half way down the canister (centre part of block R5), the 6th sensor was placed position C = 180°, 100 mm from the canister bottom. For the A, B and D directions risk assessments prior to assembly recognised that the contact between these sensors and the canister could be compromised during tilting to a horizontal position when the canister leans on the C side while there are gaps in the other directions.

RH sensors

Two battery powered RH sensors, Monarch Instrument Track-It™ RH/Temp Data Logger with Display, were placed in the assembly hall on the safety scaffold around the supercontainer assembly working place, these sensors also provide temperature measurements.

The plan was to install 6 battery powered RH sensors of the same type as on the scaffolds on the shell surface in direction A = 0°, and C = 180°, in positions corresponding to blocks C1, C2 and R5, however, they were malfunctioning when delivered and the supplier could not provide new ones in time. Instead of delaying work, the project opted to re-use a wired version instead which was available at Äspö already, Kimo TH 200 type.

3.4 Constraints

Compared to a repository scenario, the heat elements in the canister have to be disconnected while the canister is placed inside the supercontainer and during the time it is being tilted horizontally. This means that even though the canister is pre-heated, it will drop quite considerably in temperature during installation day.

The test facility doesn’t allow for lowering the temperature in the whole building, instead a tent-solution had to be used for the cooling of the transport tube in the second phase of the test, for the cooling that simulate the cooler rock conditions in the drift.

The transport tube is mainly solid metal and inspection of the buffer development during the test period is limited to peep-hole cameras at the lowermost part, i.e. underneath the supercontainer.

4 Buffer manufacturing

The buffer manufacturing was done jointly with KBS-3V work (Luterkort et al. 2017). MX-80 bentonite was used.

Table 4-1 lists the reference design of the buffer blocks inside the supercontainer and Table 4-2 lists the reference design for the block dimensions.

Table 4-1. Reference buffer blocks inside the supercontainer.

Design parameter	Nominal design	Accepted variation
Solid buffer bocks inside the supercontainer		
Dry density	1753 kg/m^3	± 20
Water content	17 %	± 1 %
Ring shaped buffer blocks inside the supercontainer		
Dry density	1885 kg/m^3	± 20
Water content	11 % *	± 1 %

* This is the water content of the bentonite at the delivery. The water content is expected to vary between 10 % and 12 % depending on the weather conditions.

Table 4-2. Reference design, dimension and manufacturing tolerances for the bentonite buffer

	Outer diameter [mm]	Inner diameter [mm]	Length [mm]
Top Block	$1740\ ^{+1}/_{-2}$	$798\ ^{+0}/_{-2}$	$350\ ^{+1}/_{-1}$
Bottom block,	$1740\ ^{+1}/_{-2}$	$1058^{+1}/_{-1}/828\ ^{+0}/_{-2}$	$350\ ^{+1}/_{-1}$
Ring, SKB PWR/BWR	$1740\ ^{+1}/_{-2}$	$1058\ ^{+1}/_{-1}$	$1211\ ^{+1}/_{-1}$

The KBS-3H reference design has rings with a water content of 11 % and solid end blocks with a water content of 17 %. This design is due to difficulties in compacting to the required densities for the rings at higher water contents.

With blocks of two different water contents the relative humidity in the assembly hall cannot be properly optimised. Harmonising the different blocks water contents, similar to KBS-3V, would thus be favorable. Additionally it would be favorable from a material handling and logistics point of view.

Since the time when the 11 and 17 % design was fixed, SKB and Posiva have done lots of compactions and recent experiences pointed towards a 14 % harmonised water content being possible. Small scale compaction samples were made aiming at this and it was concluded that both rings and blocks should be possible to manufacture at 14 % water content. But it had to be demonstrated in full scale since the solid blocks have to be compacted at low pressures and the rings at very high pressures in order to reach the proper densities for the KBS-3H design (supercontainer and drift dimensions). It was decided that this demonstration should be carried out during the heated supercontainer test.

Thus, the MX-80 water content was adjusted to a water content of 14 ± 1 % in a large Eirich mixer at the Äspö Laboratory. The blocks for the test were subsequently compacted at a workshop in Ystad, Sweden, (Johannesson 2014). Similarly to earlier manufacturing the blocks were compacted in a rigid mould in axial direction (uniaxial compaction), see Figure 4-1. Both ring shaped and solid blocks were compacted in the same manner.

The compaction equipment used doesn't allow for the reference design height of the rings, rather they were machined so that 10 rings would fit the lead-through adjusted canister length at 491 mm each.

The blocks were compacted to densities consistent with the reference design, Table 4-1, and Table 4-3 presents the data of the actual blocks used in the heated supercontainer test. The blocks were stored in specially developed air tight transport vessels or in airtight plastic bags. The blocks were stored around 9 months prior to assembly. The final shape was achieved by machining using an ordinary metal lathe; this was done approximately two months prior to assembly. Due to small manufacturing series, three blocks that had slightly to low dry densities had to be used in the test, however, the effect on the heat transfer in the blocks and thus the test results should be quite limited. The reason for the low densities is mainly that it takes a few blocks before the settings in the mould are accurate.

Table 4-3. Data from the installation of the buffer blocks, blocks with a dry density outside the requirements are marked in red.

Block Position	Outer diameter (mm)	Inner diameter (mm)	Average height (mm)	Weight (kg)	Buik density (kg/m^3)	Water content (wt %)	Dry density (kg/m^3)
CI (bottom block)	1 740		350	1 576	1 958	0.139	1 719
RI	1 740	1 058*	491	1 561	2 124	0.144	1 857
R2	1 740	1 058*	491	1 558	2 120	0.140	1 860
R3	1 740	1 058*	491	1 584	2 155	0.139	1 892
R4	1 740	1 058*	491	1 587	2 159	0.136	1 902
R5	1 740	1 058*	491	1 587	2 159	0.141	1 893
R6	1 740	1 058*	491	1 568	2 133	0.141	1 869
R7	1 740	1 058*	491	1 576	2 144	0.142	1 878
R8	1 740	1 058*	491	1 576	2 144	0.138	1 883
R9	1 740	1 058*	491	1 575	2 143	0.139	1 881
RI0	1 740	1 058*	491	1 570	2 136	0.140	1 873
C2 (top block)	1 740		278	1 314	1 989	0.141	1 743

* Control at machining.

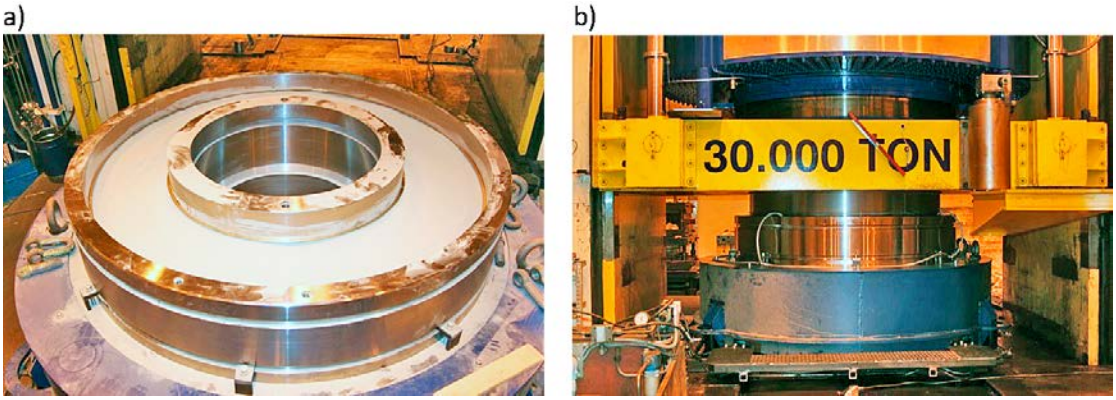


Figure 4-1. Compaction of buffer blocks. a) The bentonite filled in a rigid mould. b) The mould placed in the press used at the compaction of the buffer blocks.

5 Supercontainer assembly procedure

The assembly was carried out with the supercontainer in a vertical position; Figure 5-1 illustrates the main steps. All preparations that could be done prior to introducing buffer blocks and the canister had been made, i.e. the heavy gamma gate was placed as well as the supercontainer shell (step 1 in Figure 5-1). Given the experiences from the MPT, the assembly was straight forward and the solid bottom block and the 10 rings could be placed during 8 hours (step 2 in Figure 5-1).

Once all rings were in place, the stiffening plates used to support the shape of the shell were cut away (step 3 in Figure 5-1).

This was followed by drilling holes in the buffer for the sensors, and placing the temperature sensors. Holes going all the way through the buffer were also prepared for the canister sensors. These sensor installations and preparations took approximately 80 working hours.

The transport tube had been prepared with temperature sensors earlier, which had taken approximately 40 working hours.

The original plan was to place battery powered RH sensors on the shell, but as mentioned earlier, they were malfunctioning and could not be replaced in time, instead a solution had to be improvised where already available Kimo TH 200 RH sensors were installed.

The procedure described above allowed for all sensors except for those in the top buffer block and on the canister to be installed before the pre-heated canister was installed. The canister was pre heated with 15 mm insulation around it and approximately 150 mm on top of it. Several effect settings had been tested and it had been concluded that 2 500 W gave the requested temperature of approximately 60 °C. A power of 2 500 W was therefore applied to the heating elements for a few days before the canister was installed in the supercontainer.

Figure 5-2 illustrates final preparations for the canister lift. The canisters sensors and heaters had to be disconnected during the day when the canister was installed inside the supercontainer and turned horizontally, September 26th 2016.

Once the canister had been lowered into the supercontainer (step 4 in Figure 5-1) the canister temperature sensors were placed in the prepared holes. The top of the canister was directly accessible and the sensor placed there could be fitted thoroughly onto the canister surface.

Following the canister, the top buffer block and the solid metal top plate were placed (step 5 in Figure 5-1). Holes were drilled and temperature sensors installed in the top block.

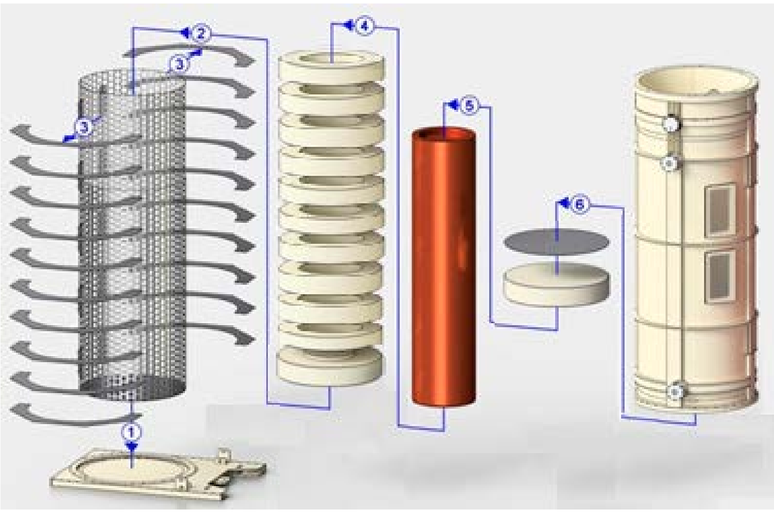


Figure 5-1. *Illustration of the supercontainer assembly sequence.*

The transport tube was then lowered carefully on to the supercontainer (step 6 in Figure 5-1). Sensor and heater cables were simultaneously taken out through the transport tube windows. The transport tube was subsequently lifted on to the transport tube support, tilted horizontally and sealed with a transport plate, Figure 5-3. All temperature sensors survived the lowering of the transport tube, however, the RH sensor cabling had been difficult to protect and 7 out of 9 were damaged when the tube was placed. Additional sensors were later placed through the transport tube window.

Clab's terminal vehicle was used to transport the whole package into its test location inside the assembly hall. The canister sensors were connected, and the heaters were reconnected and powered up to 1 700 W. All of the work described above, from placing the canister inside the supercontainer to the heaters being turned on was done during one day and the canister was disconnected for 12.5 hours in total. The following day all other sensors were connected.

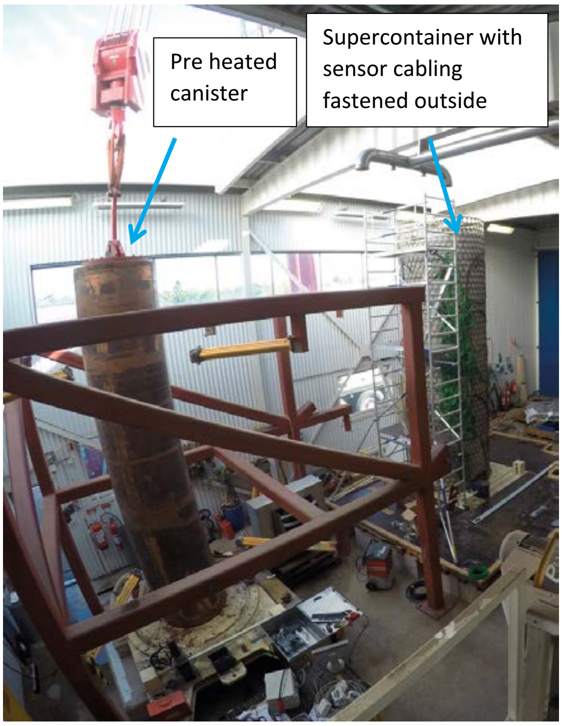


Figure 5-2. *Pre-heated canister being prepared for lifting and installation inside the supercontainer.*

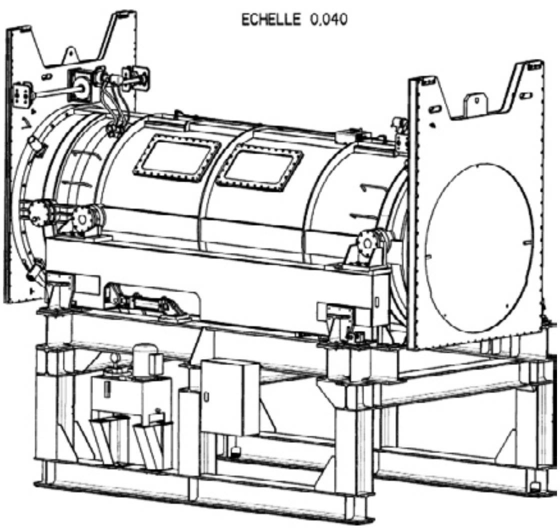


Figure 5-3. *Transport tube placed on the transport support with a supercontainer inside. The top gamma gate, to the right in the picture, was replaced by a transport plate.*

6 Test start and monitoring

6.1 Transport tube temperatures

Figure 6-1 upper shows the temperature development in the transport tube during the test. The wavy patterns during the first days are explained by the facility's temperature, Figure 6-1 lower. These are two independent logging systems. The facility temperature also explains the sudden increase in temperature starting on the 4th of October, Figure 6-1 lower.

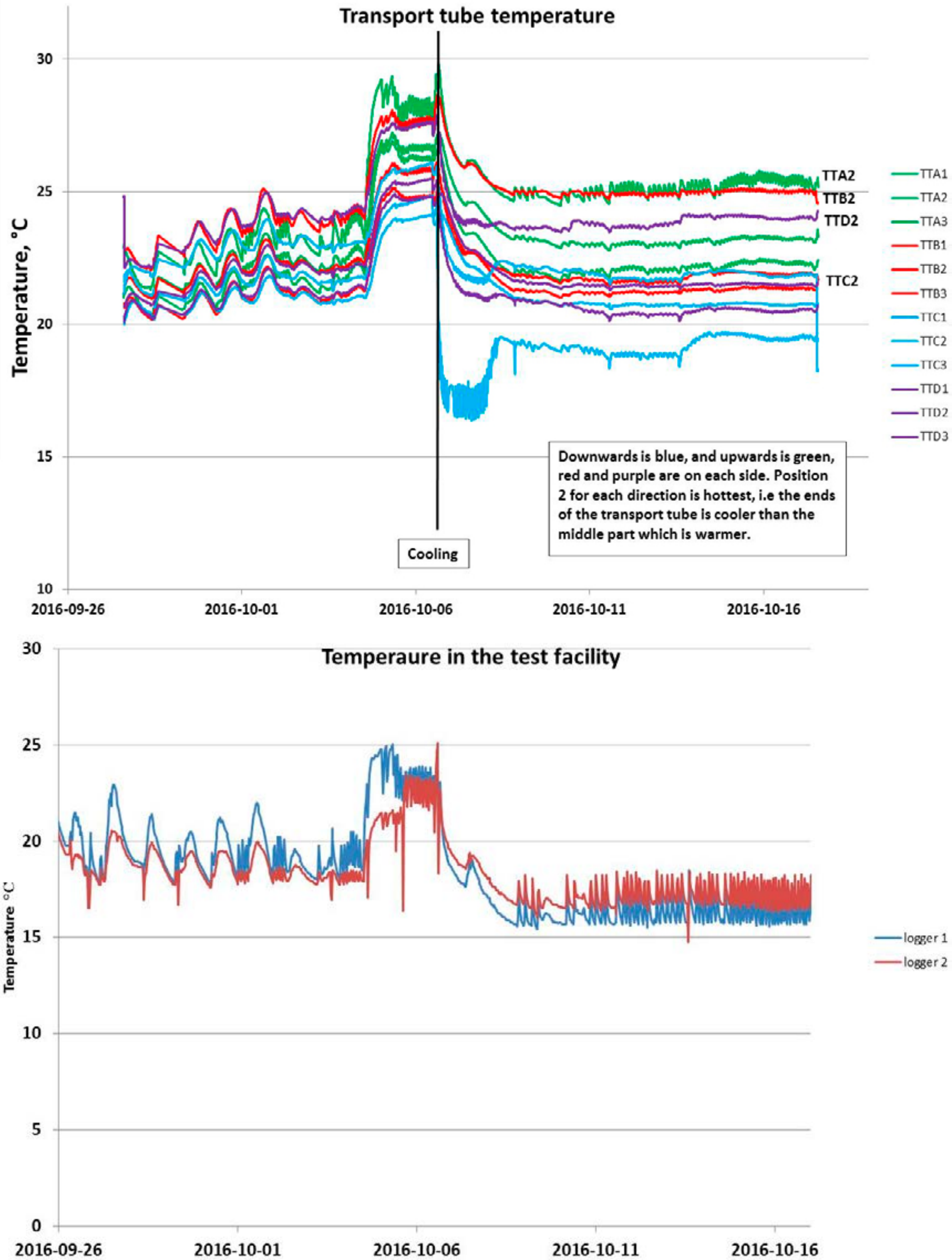


Figure 6-1. Upper: Transport tube temperatures during the test. Lower: temperature of the test facility.

Cooling, in order to simulate the deposition in the drift was initiated on the 6th of October. The aim was to lower the transport tube temperature to 13 °C, and then slowly increase it to 24 °C in order to simulate the behaviour inside the drift, as predicted by the model. Given that the entire facility could not be cooled a tent was built around the transport tube and it was cooled down, however, this proved insufficient and the temperature could not be lowered as much as intended. Thus, the test was run in conditions more like storage conditions for the full test period. However, the model predicted limited effects from cooling so the overall test results are still deemed to be representative.

During the second part of the test a pattern can be seen with the sensors at the bottom (C = 180°, blue) of the horizontal transport tube being cooler than those at the top (A = 0°, green). This is in line with hot air rising inside the air gap between the supercontainer and the transport tube. Another pattern that can be seen is that the centre of the transport tube is warmer than the two ends, and this is likely explained by the heavy gammagate and transport plate providing extra surface areas for cooling. It is also noted that equilibrium is reached in the transport tube during the test.

6.2 Canister temperatures

As described in chapter 5, the heaters and canister sensors were connected in the evening of September 26th, i.e. the same day as the canister was installed inside the supercontainer. At that stage, the canister temperature had decreased from approximately 60 °C to an average of 45 °C with the hottest part, the top of the canister, still at 52 °C at that time. Figure 6-2 illustrates the canister temperature development during the whole test period. During the first hours it can be noted that the canister temperature continued to drop somewhat. This is as expected as the blocks with room temperature cools the canister. The short gap of data during the first night was due to problems with the data acquisition system, however, the heaters were continuously delivering 1 700 W as planned.

Sensor data show that the C-direction (i.e. downwards when horizontal, blue in Figure 6-2) are hottest while the A-direction sensor (i.e. upwards when horizontal, green in Figure 6-2) are colder. The difference in the two positions is as large as, 8 °C where the model predicts about 0.5 °C. The reason is likely that the contact between sensor and canister is lost in the upward direction while it is good

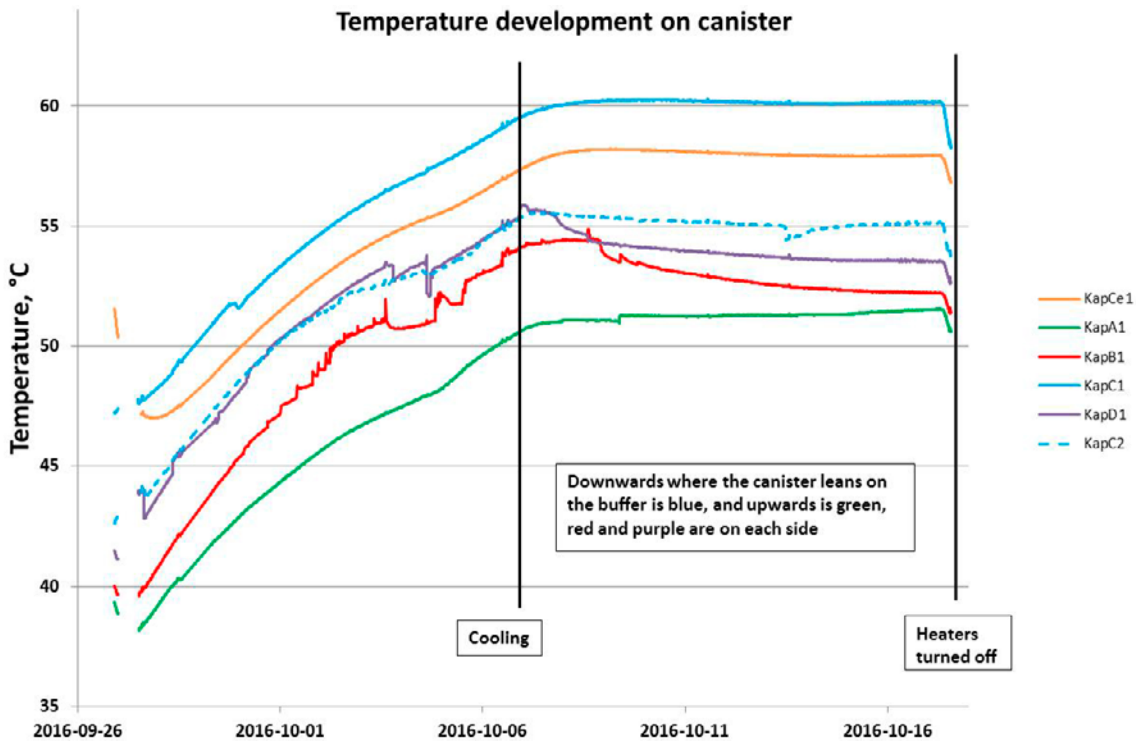


Figure 6-2. Canister temperatures during the test.

in the C-direction where the canister leans straight onto the sensor. Upward (A) and sideways (B and D) are likely misrepresented due to poor contact between the sensors and the canister; there is most likely an isolating air gap between the sensor tip and the canister. The 60 °C equilibrated temperature in the C-direction at the mid canister location (i.e. blue in Figure 6-2) and the 58 °C on the top of the canister (i.e. orange in Figure 6-2) are likely the most accurate canister temperatures.

It is noted that temperature equilibrium is reached in the canister during the test.

6.3 Buffer temperature

Figure 6-3 illustrates block R5 as an example of the temperature development in the blocks during the test period. It can be seen that the block temperatures equilibrates during the test period. The temperature data follows a logical pattern where the sensors in the buffer closest to the canister showing the highest temperature. The effect of the horizontal supercontainer is also evident as the lower sensors show the highest temperature due to the canister leaning on to the buffer on the lower side.

The gradient over the blocks is approximately 15 °C in the A-direction (upward when horizontal), and around 16–17 °C in the B and D directions (sideway when horizontal) and 22 °C in the C direction (downwards when horizontal). This is logical given the direct contact and higher temperatures in the C direction compared to the A direction where there is a small air void between the canister and the ring.

Cooling was initiated on the 6th of October, however, as mentioned in section 6.1, the cooling was insufficient and only a small temperature drop was achieved in the transport tube. A small response can be seen in Figure 6-3. There is also a small increase in the temperature a few days before cooling, on the 4th of October which matches the changes in the facility, seen in the transport tube, Figure 6-1.

Ring R5 is provided as an example but the temperature profiles look similar for all of the blocks. There were a few sensors placed on the wrong channels, but they could be identified when assessing the data.

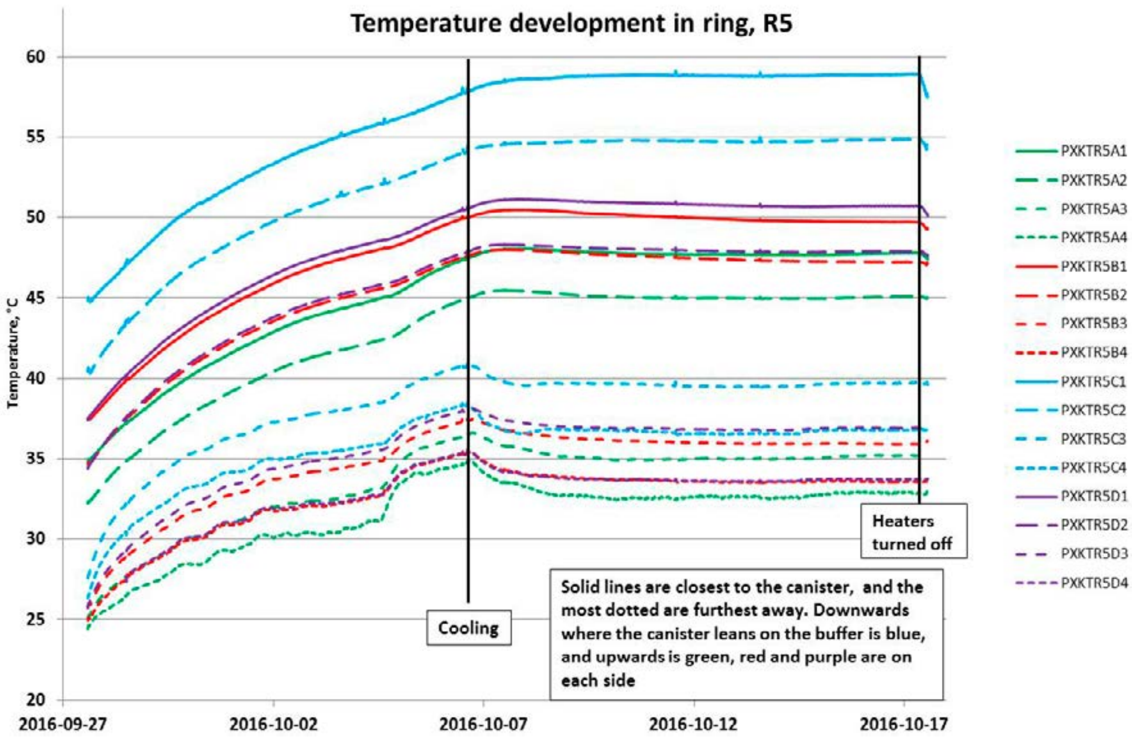


Figure 6-3. *Temperature development in ring R5.*

6.4 Relative humidity in the air void

The problems with the RH sensors, Section 3.3.3, continued and several of the replacement sensors got their cables snagged and pulled off during assembly. Eventually this led to just 3 sensors operating the full test time, all of them in the A-direction, i.e. upwards when horizontal. Figure 6-4 presents the data. A1 is located 2.6 m from the bottom when vertical, i.e. at ring 5, A2, is located 4 m from the bottom, i.e. at ring 8 and A3 is located 3.5 m from the bottom, i.e. at ring 7.

The RH in the air void between the supercontainer and the transport tube climbed quickly above 80 % and evened out around 90 % after approximately 3 days, this compares to 63.5 % which would be expected without the heaters turned on. The RH test data is difficult to compare to the model as the RH in the model varies with the position in the void (being highest close to the transport tube and lowest close to the blocks), the sensors exact position is not that detailed.

Sensor A1 seems to have been affected by changes in the transport tube temperature, first by the increased temperature in the test facility on the 4th of October, see Figure 6-1 lower, and then by the cooling when its reading decreased further. It is somewhat unclear why it would respond more than the other two sensors, but it could possibly be due to its exact location in the void (lengthwise between the supercontainer and transport tube).

6.5 Condensate water

Water accumulating at the bottom of the transport tube was measured, Figure 6-5. 1 161 ml of water was collected during the full test period.

In addition to the collected water, there was also loose bentonite with high water contents inside the transport tube when it was dismantled. If this water is added, the total amount of condensate water is more in the order of 2.6 kg, see Section 6.6 for further details.

The cooling of the transport tube is clearly noted in the amount of water collected, Figure 6-5.

Given that each block contains several hundreds of litres water the total amount of condensate water is small, approximately 0.1 % of the total amount of water.

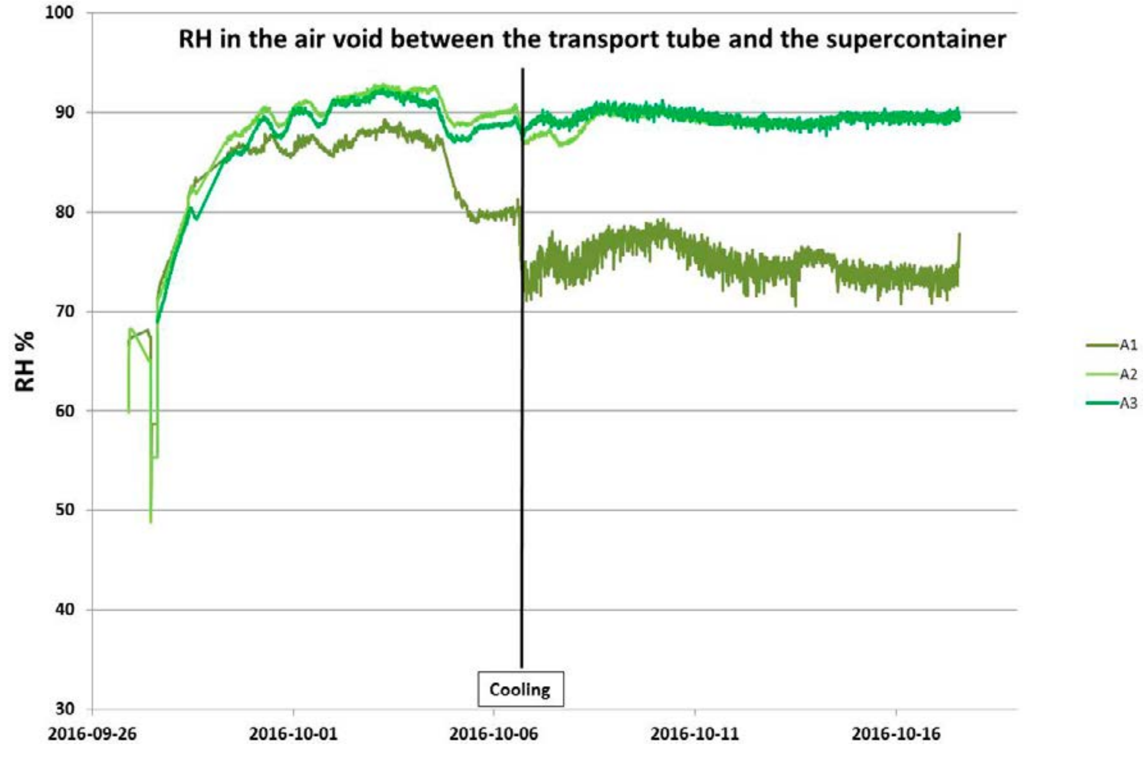


Figure 6-4. *RH measurements in the void between the supercontainer and the transport tube, all remaining sensors are located in the A-direction.*

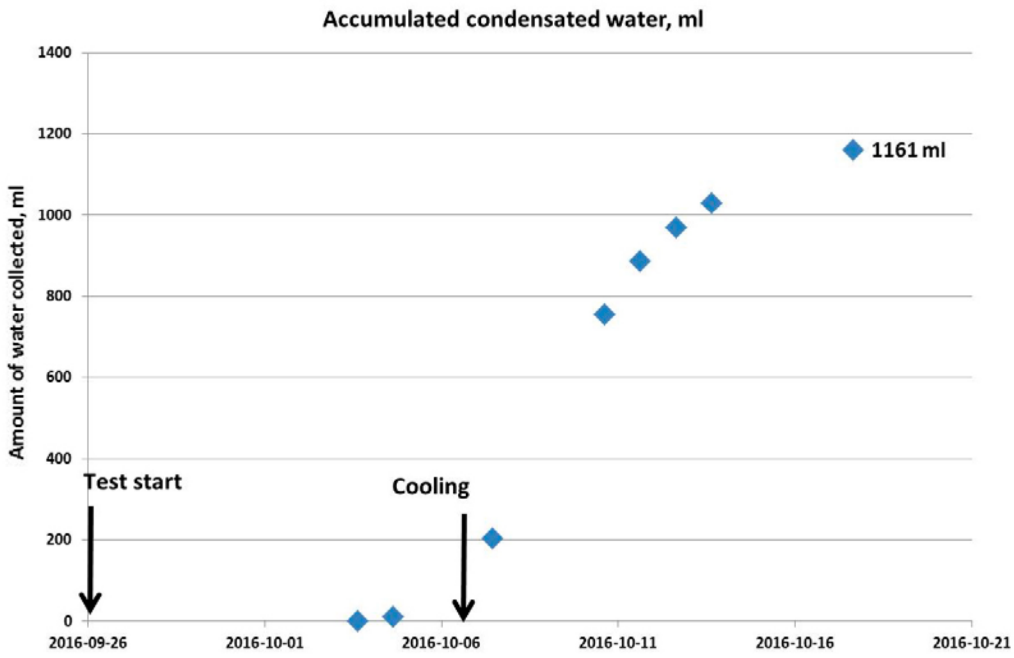


Figure 6-5. *Accumulated amount of condensate water collected during the test period.*

6.6 Visual inspection and measured bentonite loss

During the test period, a peep-hole camera was used to look underneath the supercontainer, Figure 6-6 illustrates one position on block R8. As can be seen in the photos, minor cracking has started after two days with 1 700 W (left photo), and after 3 days it has increased further (right photo). The photos presented are examples from ring R8, but there were cracking on other blocks after 3 days as well. However, even with the cracking, the amount of material coming loose from the supercontainer was limited. Once the test was terminated all that loose material was collected and weighed to 4.1 kg wet and 2.2 kg dry. Most of this material had come lose at the end blocks in the form of flaking, see Figure 7-1, possibly due to tension building up against the endplates of the supercontainer.

Overall 2.2 kg of dry buffer mass is a small amount of lost material, approximately 0.01 % of the total dry mass, which will not compromise the buffer function. There were no larger pieces either so the risk of bentonite clogging the gap underneath the supercontainer and possibly compromising the DAWE drainage is most likely small.

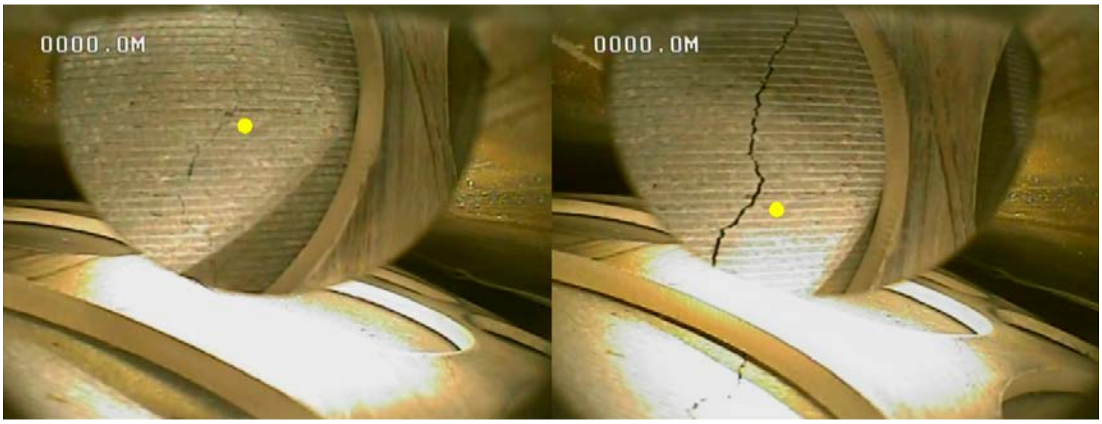


Figure 6-6. *Left, a photo from Wednesday the 28th September (2 days of heating with 1 700 W), and to the right a photo from Thursday the 29th September (3 days of heating with 1 700 W). The yellow dot is a reference point for comparison.*

It should be noted that the material collected was very wet, and have collected condensate water, 1.4 kg, thus the total condensate water is likely closer to 2.6 kg rather than the 1.16 kg collected, as seen in section 6.5 and Figure 6-5.

6.7 Assessment in relation to pre-modelling, temperature and condensate water

With respect to the buffer temperature development in the pre-modelling, taking position R5, i.e. mid canister, with a starting temperature of 40 °C as an example and comparing to ring R5 in the test, the modelled temperatures of the buffer rings is approximately 5–7 °C lower than the test data. The most likely reason for this is that the heat transfer from the transport tube to the surroundings has been overestimated in the modelling. However, when looking at the gradient over the rings (mid canister as example) the temperatures match well, in the A-direction 15 °C measured compares to 14 °C modelled, 16–17 °C measured in the B and D directions compares to 17 °C modelled and in the 22 °C measured in the C direction compares to 23 °C modelled.

With respect to condensate water the model predicts somewhat less than what was measured in the test, however, this is likely related to the thermal boundary conditions between the transport tube and the surroundings being somewhat incorrect, which can be seen in the temperature data.

7 Dismantling and analysis

7.1 Visual inspection of the supercontainer

The dismantling was initiated right away after the heaters had been turned off and the supercontainer rose vertically. It was noted that there was a quite extensive cracking pattern on the outer surface of the rings and as mentioned earlier, flaking at the supercontiner end blocks, Figure 7-1. The cracking was mainly on the surface however. There were a few cracks going all the way through the rings and some ending a couple of centimetres inside the blocks. During dismantling, each block was closely photographed, thus allowing for more detailed analysis on the amount and extent of the fractures. A photo analysis has not been done at this stage, but the data is stored and if KBS-3H is developed further such an analysis could be done.

7.2 Sampling

The fracturing of the blocks ruled out using the vacuum tool to dismantle the supercontainer, instead, each block had to be cut apart, snared, and lifted down by crane. Some samples were taken before and some after lowering the pieces to the floor.

Core holes were drilled in the top and bottom blocks for sampling, Figure 7-2, and sheets of bentonite were sawed out from the rings, Figure 7-3. The samples were brought to the laboratory and cut down further for water content and dry density measurements.

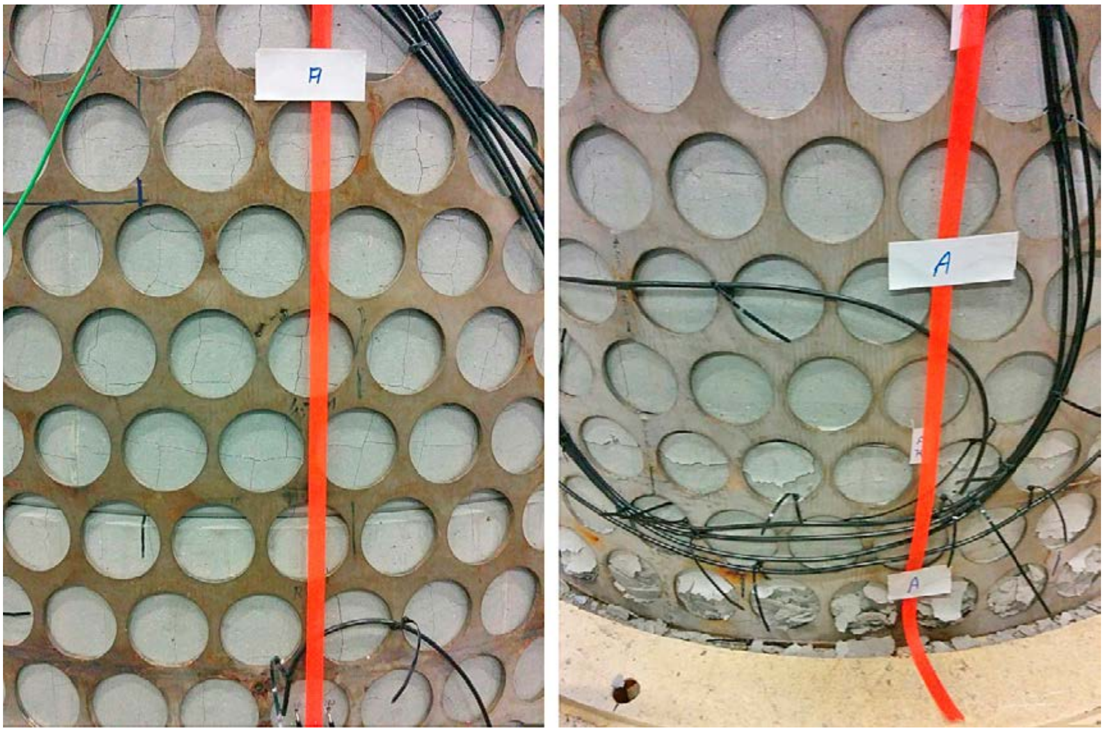


__Figure 7-1.__ Left, cracking pattern on outer surface on the rings, right, flaking on the bottom block, C1.

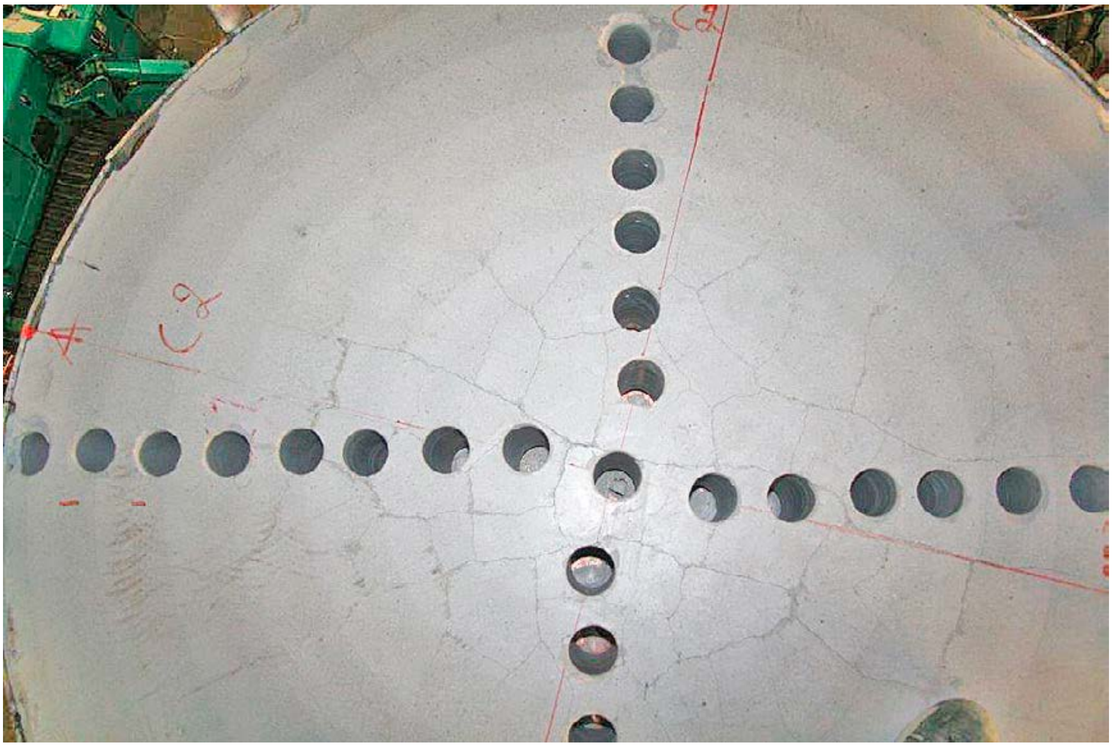


Figure 7-2. Sampling of the solid end blocks, top block.

Figure 7-3. Sampling of the buffer rings.

7.3 Water content and dry density analysis

Figure 7-4 gives an example of the water content profile in ring R5, downwards and Figure 7-5 is showing the dry density in the same direction. It can be seen that the surface against the canister has dried to some extent. The outer buffer surface towards the air void, between the supercontainer and the transport tube has also dried but actually more than the inner surface. The model predicted an opposite situation and it is currently not fully explained why the outer surface seems to have dried faster, however, it could possibly be due to the air circulation outside of the blocks. It should also be noted that there likely are density variations inside the blocks before test start, which actually can look quite similar to the variation seen in Figure 7-5, and future test should include several reference blocks to assess this in more detail.

All measurements in the supercontainer are presented in Appendix 1. They all show similar patterns although there is less drying on the outside of the blocks towards the sides and upwards of the buffer (when horizontal).

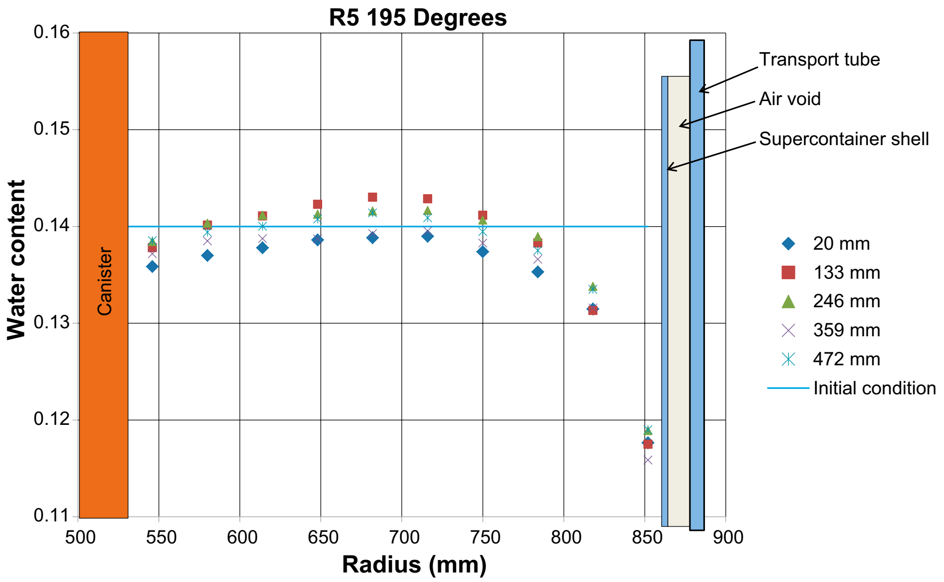


Figure 7-4. *Water content data from ring R5, downwards, on the side where the canister leans on the buffer surface. The initial condition in the figure is the requirement value, and 14 ± 1 % is allowed at manufacturing.*

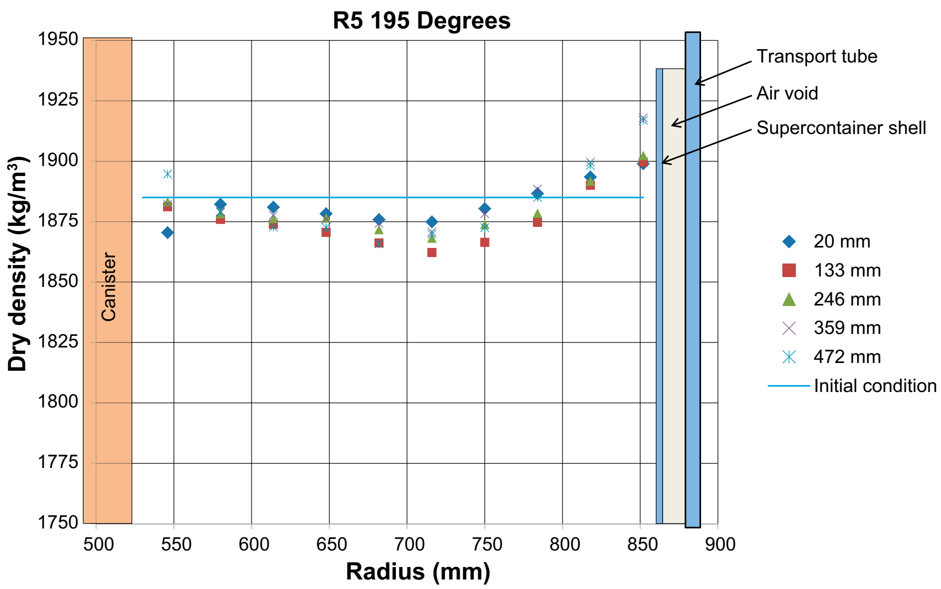


Figure 7-5. *Dry density data from ring R5, downwards, on the side where the canister leans on the buffer surface. The initial condition in the figure is the requirement value, and 1 885 ± 20 kg/m³ is allowed at manufacturing.*

7.4 Assessment of water content and cracking in relation to pre-modelling

With respect to the water content changes they are small overall, which is in line with the model. The drying is however more extensive in the outer parts of the block than closest to the canister, this is opposite to the modelling and will have to be studied further if KBS-3H development is continued.

The cracking was more extensive in the test than the model had predicted. Cracking is, however, known to be difficult to predict, but the heated supercontainer test has provided additional data for further modelling development.

8 Conclusions

8.1 General

The heated supercontainer test has provided valuable experiences on how the heat from the canister influences the supercontainer buffer during assembly and deposition. It is clear that the buffer will start to dry and that water will be redistributed inside the buffer, however, the changes are limited over the short time periods that are of interest for the KBS-3H design. The amount of condensate water was also small during the test.

It is also clear that the buffer surface will start to crack inside the supercontainer before the DAWE water filling can be carried out, however, the supercontainer shell seems to maintain the integrity of the component well and the buffer mass loss should not compromise the required buffer densities and the buffer that may fall on to the deposition drift floor will most likely be so limited that it will not clog the water drainage underneath the components.

Future tests could be carried out where bentonite flakes are dropped on the bottom of a deposition drift at different water flow rates, it could then be assessed if these small amounts of bentonite flakes begin to compile and clog together with a risk of dams building up.

The test has also provided lots of valuable data in support of future model development.

Another important conclusion is that full scale blocks of MX-80, both rings and solid blocks, can be manufactured with a water content of 14 % and proper dry densities. This would allow for harmonising the water content in the KBS-3H buffer blocks. However, before such a change is done, long term safety aspects would have to be assessed. Changing the water content changes the thermal conductivity for example.

With respect to modelling, the KBS-3H design is more difficult to model than KBS-3V, mainly due to the asymmetrical position of the canister when horizontal and the air gaps where air can circulate. It is expected that if additional modelling was done, using the boundary conditions from the test, the predictions would improve further. The temperature evolution should be fairly straightforward to model while more work would be needed regarding the tensions which lead to cracking.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.com/publications.

Eriksson P, 2016. Investigation of alternatives to the buffer protection. SKB P-16-07, Svensk Kärnbränslehantering AB.

Johannesson L-E, 2014. KBS-3H. Manufacturing of buffer and filling components for the Multi Purpose Test. SKB P-14-07, Svensk Kärnbränslehantering AB

Johannesson L-E, Kristensson O, Åkesson M, Eriksson P, Hedin M, 2014. Tests and simulations of THM processes relevant for the buffer installation. SKB P-14-22, Svensk Kärnbränslehantering AB.

Kronberg M, 2016. KBS-3H. Preparations, assembly and installation of the Multi Purpose Test. SKB P-14-27, Svensk Kärnbränslehantering AB.

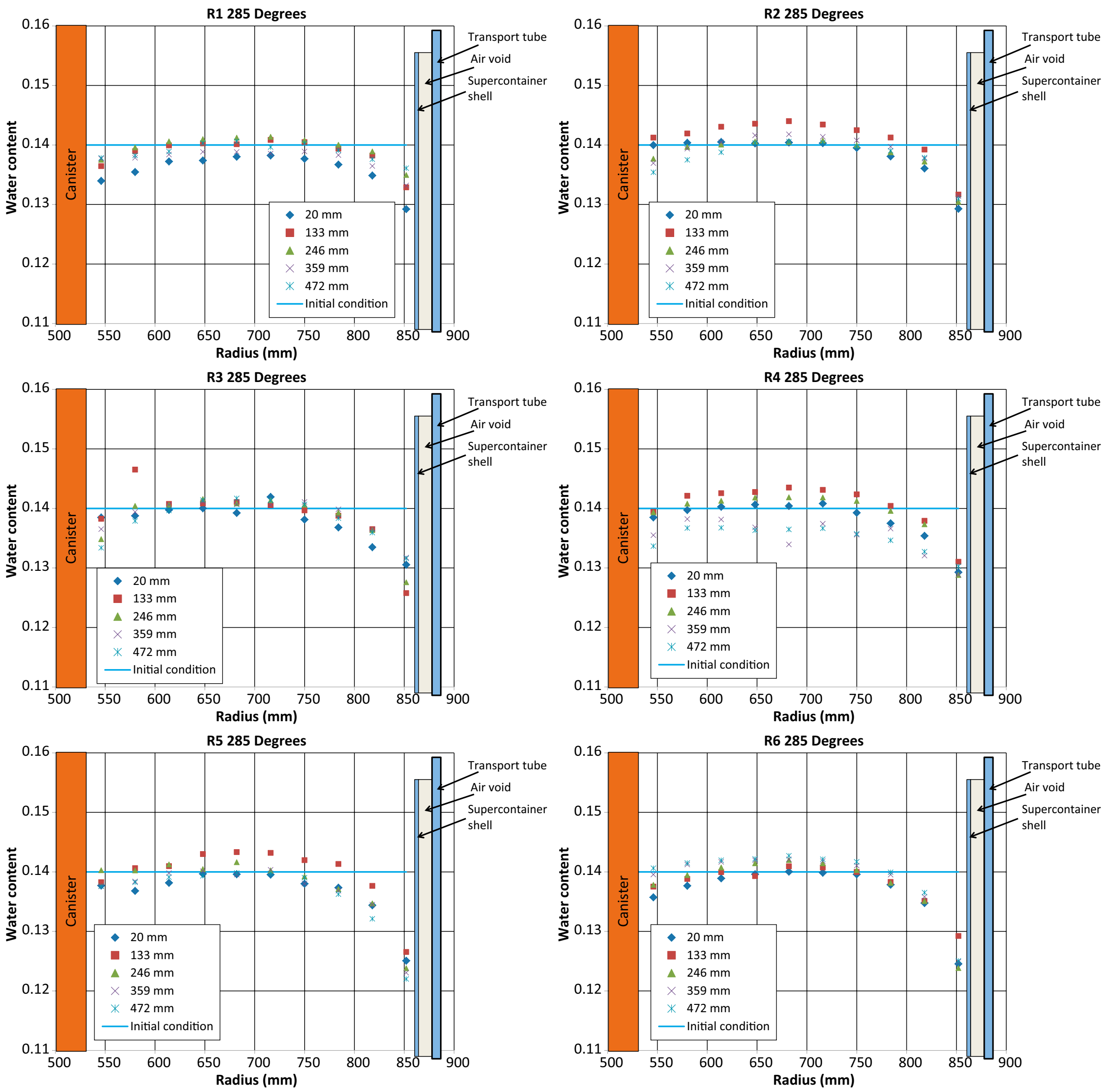
Luterkort D, Johannesson L-E, Eriksson P, 2017. Buffer design and installation method. SKB TR-17-06, Svensk Kärnbränslehantering AB

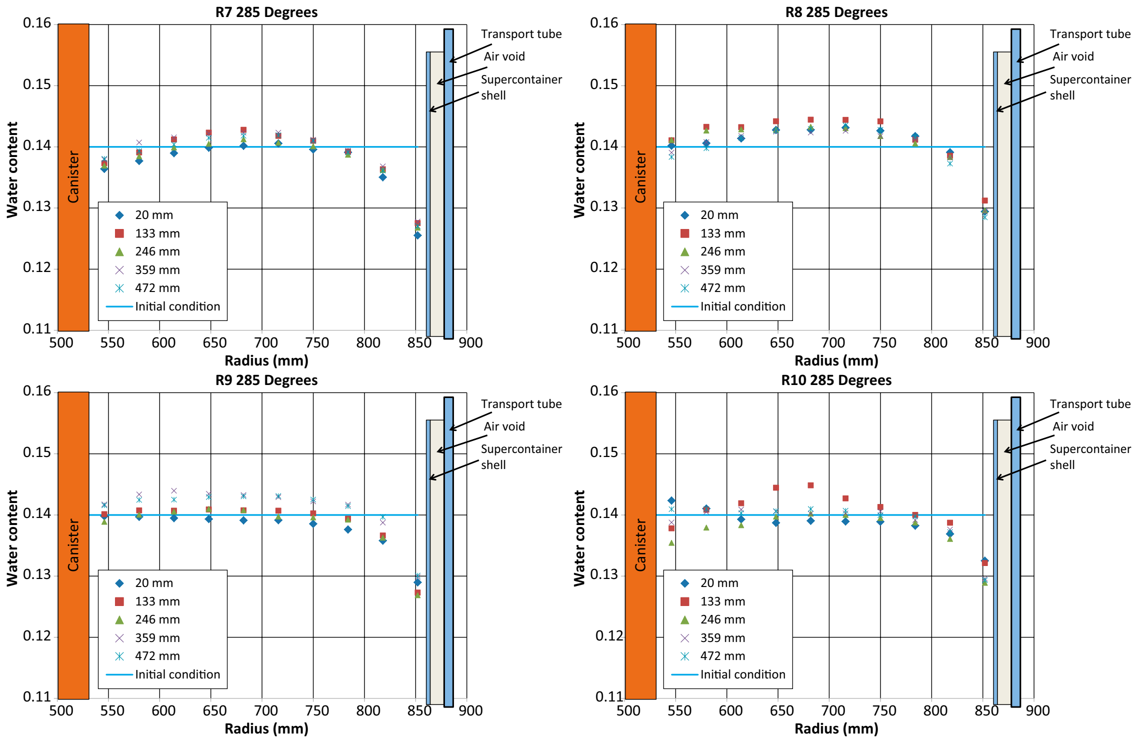
Posiva, 2010. Nuclear waste management at Olkiluoto and Loviisa power plants: review of current status and future plans for 2010–2012. TKS-2009, Posiva Oy, Finland.

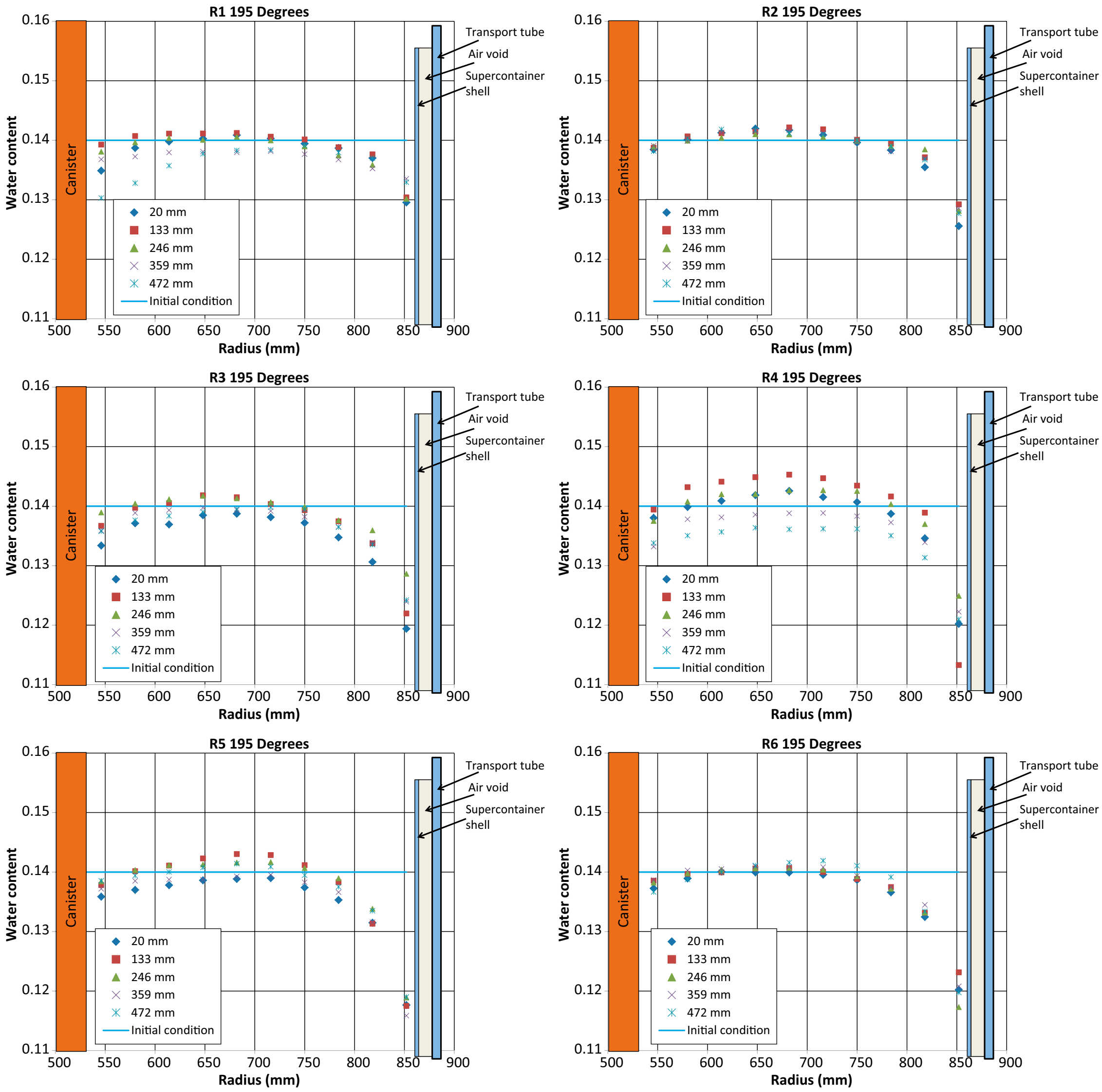
SKB, 2012. KBS-3H. Complementary studies, 2008–2010. SKB TR-12-01, Svensk Kärnbränslehantering AB.

SKB, 2013. RD&D Programme 2013. Programme for research, development and demonstration of methods for the management and disposal of nuclear waste. SKB TR-13-18, Svensk Kärnbränslehantering AB.

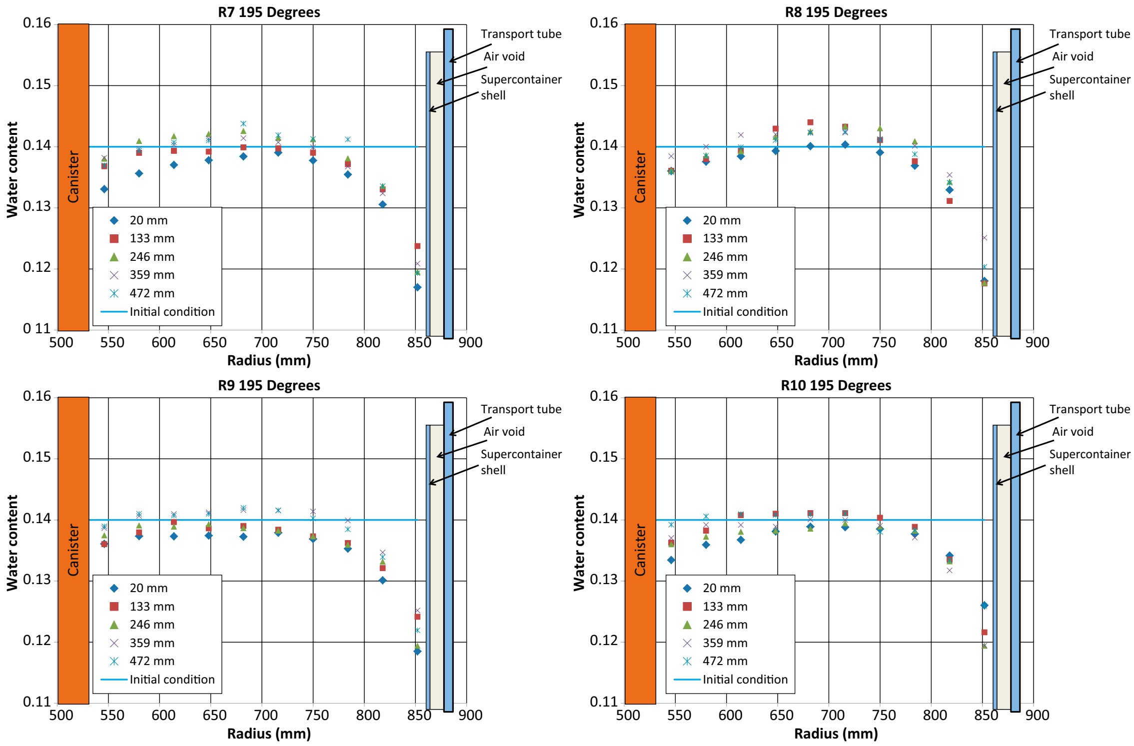
Water content

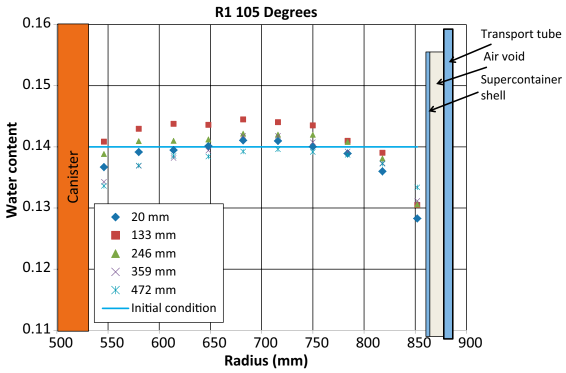


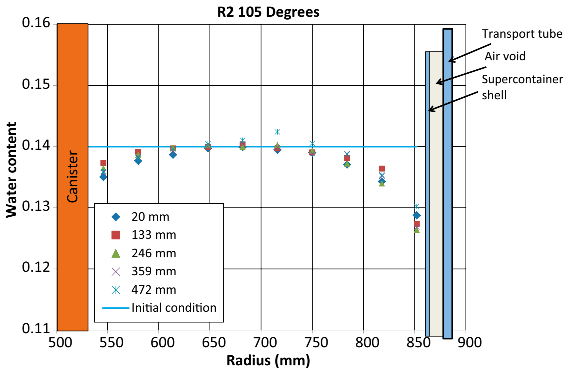

R7 285 Degrees
R8 285 Degrees
R9 285 Degrees
R10 285 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition

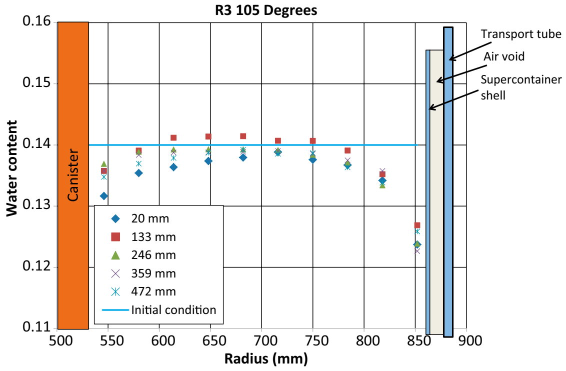


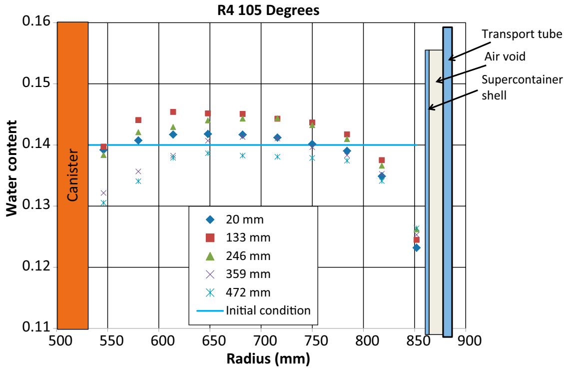
R1 195 Degrees
R2 195 Degrees
R3 195 Degrees
R4 195 Degrees
R5 195 Degrees
R6 195 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition

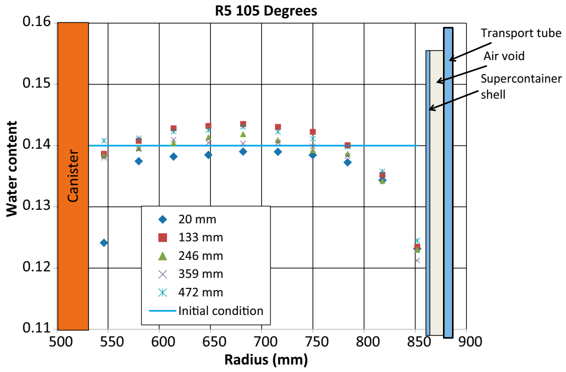

R7 195 Degrees
R8 195 Degrees
R9 195 Degrees
R10 195 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16
0.15
0.14
0.13
0.12
0.11
500
550
600
650
700
750
800
850
900

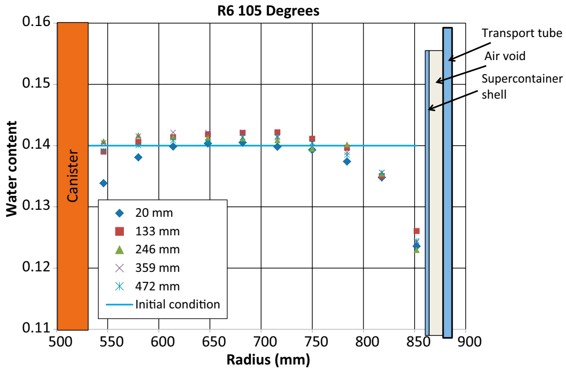

R1 105 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16 0.15 0.14 0.13 0.12 0.11
500 550 600 650 700 750 800 850 900

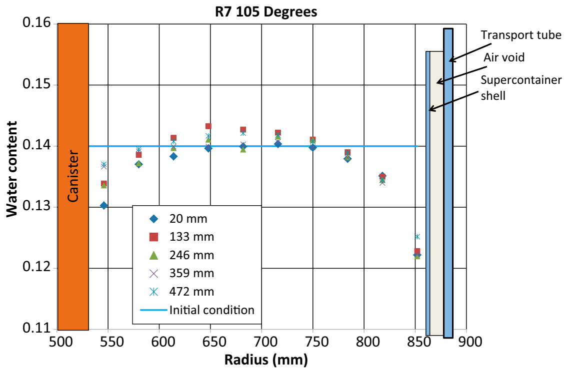

R2 105 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16 0.15 0.14 0.13 0.12 0.11
500 550 600 650 700 750 800 850 900

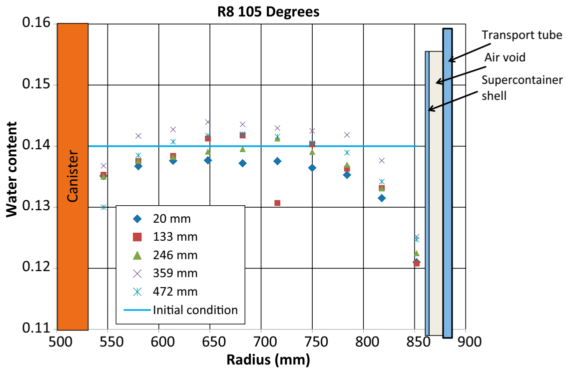

R3 105 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16 0.15 0.14 0.13 0.12 0.11
500 550 600 650 700 750 800 850 900

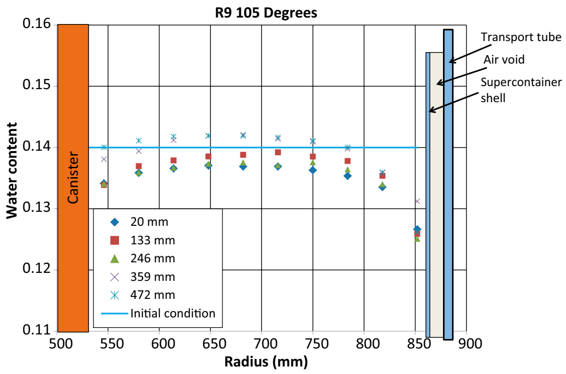

R4 105 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16 0.15 0.14 0.13 0.12 0.11
500 550 600 650 700 750 800 850 900

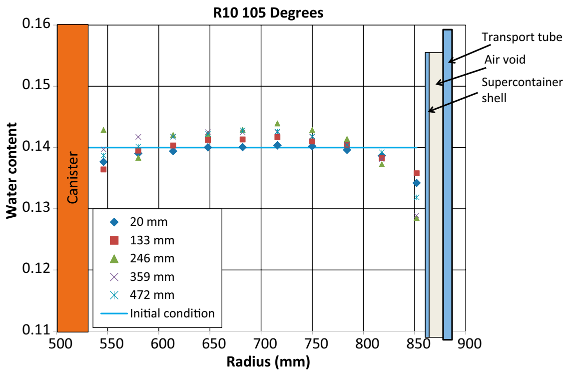

R5 105 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16 0.15 0.14 0.13 0.12 0.11
500 550 600 650 700 750 800 850 900

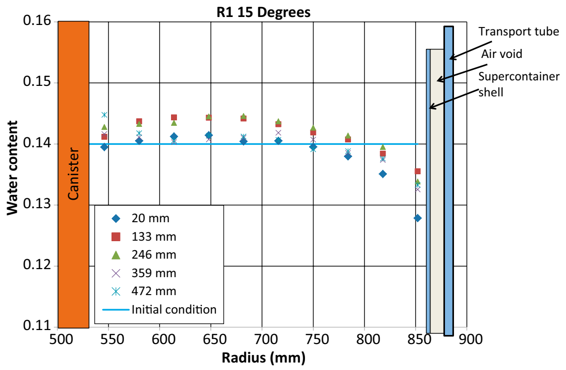

R6 105 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16 0.15 0.14 0.13 0.12 0.11
500 550 600 650 700 750 800 850 900

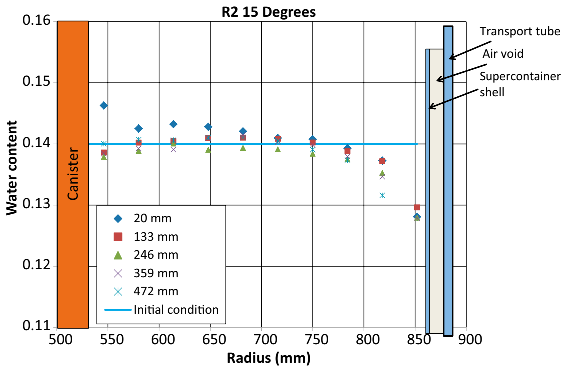

R7 105 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16 0.15 0.14 0.13 0.12 0.11
500 550 600 650 700 750 800 850 900

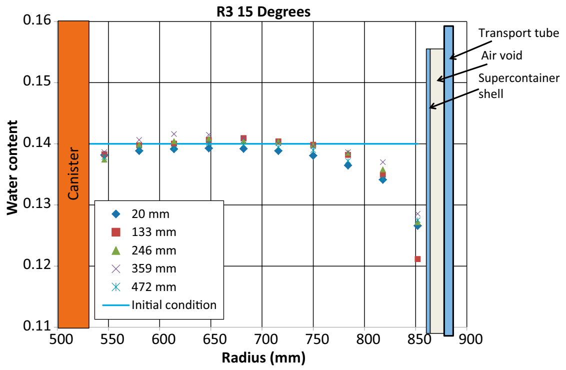

R8 105 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16 0.15 0.14 0.13 0.12 0.11
500 550 600 650 700 750 800 850 900

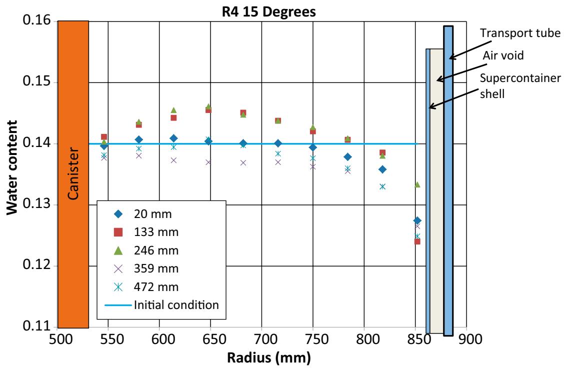

R9 105 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16 0.15 0.14 0.13 0.12 0.11
500 550 600 650 700 750 800 850 900

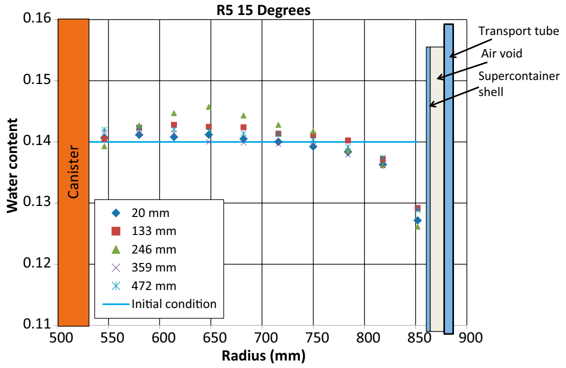

R10 105 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16 0.15 0.14 0.13 0.12 0.11
500 550 600 650 700 750 800 850 900

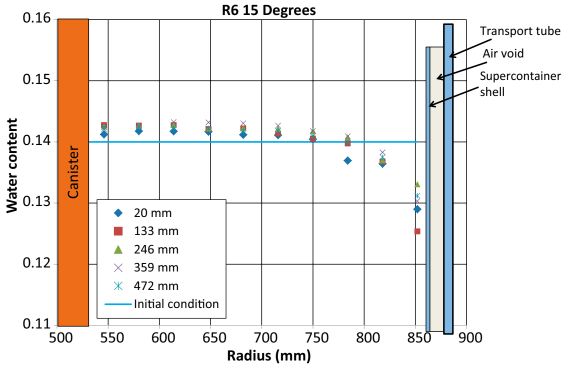

R1 15 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16
0.15
0.14
0.13
0.12
0.11
500
550
600
650
700
750
800
850
900

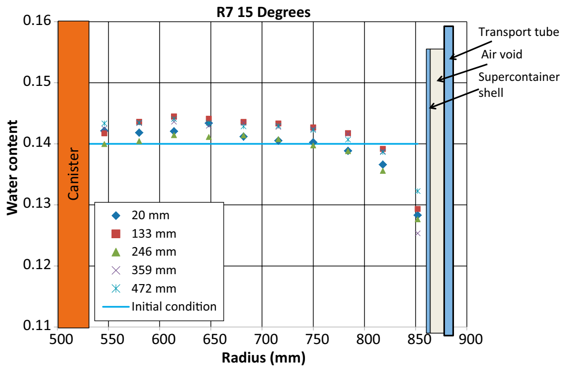

R2 15 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16
0.15
0.14
0.13
0.12
0.11
500
550
600
650
700
750
800
850
900

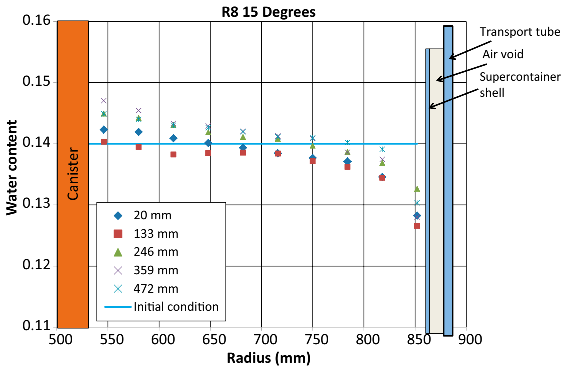

R3 15 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16
0.15
0.14
0.13
0.12
0.11
500
550
600
650
700
750
800
850
900

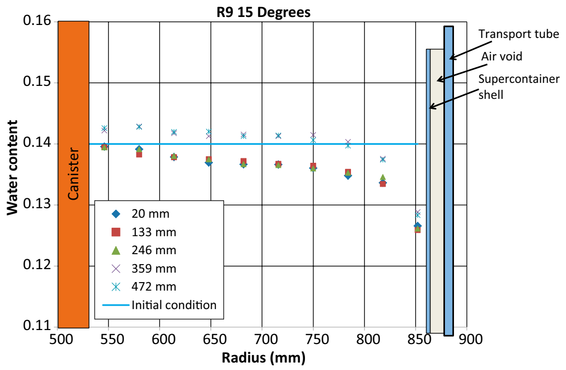

R4 15 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16
0.15
0.14
0.13
0.12
0.11
500
550
600
650
700
750
800
850
900

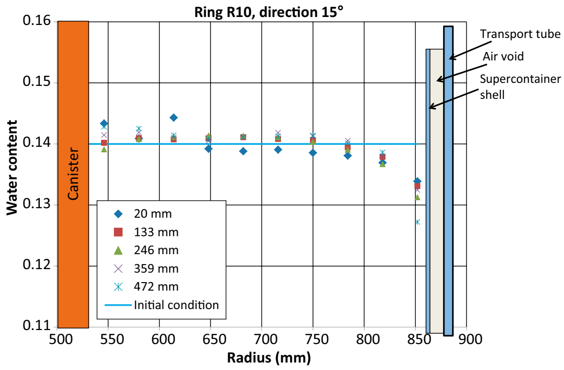

R5 15 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16
0.15
0.14
0.13
0.12
0.11
500
550
600
650
700
750
800
850
900

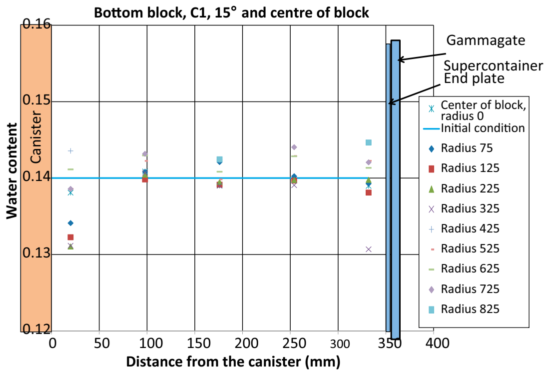

R6 15 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16
0.15
0.14
0.13
0.12
0.11
500
550
600
650
700
750
800
850
900

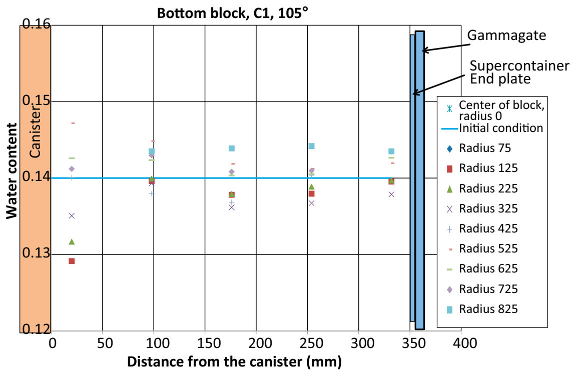

R7 15 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16
0.15
0.14
0.13
0.12
0.11
500
550
600
650
700
750
800
850
900

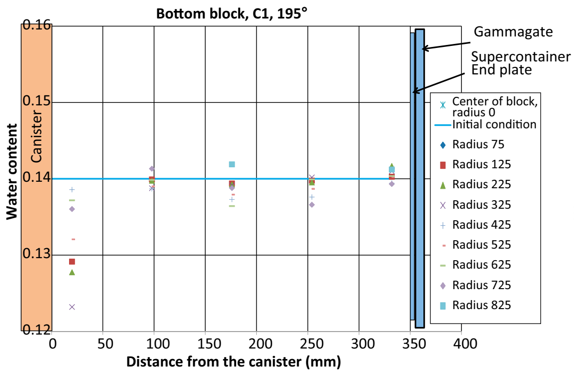

R8 15 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16
0.15
0.14
0.13
0.12
0.11
500
550
600
650
700
750
800
850
900

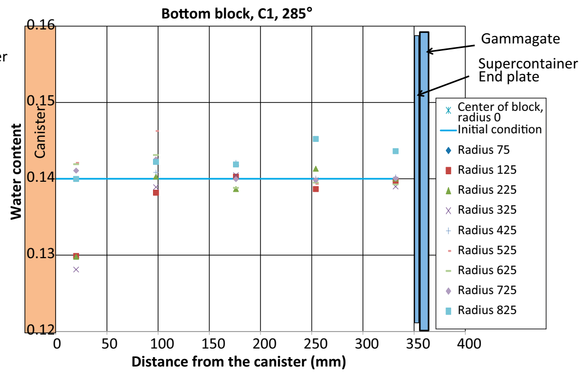

R9 15 Degrees
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16
0.15
0.14
0.13
0.12
0.11
500
550
600
650
700
750
800
850
900

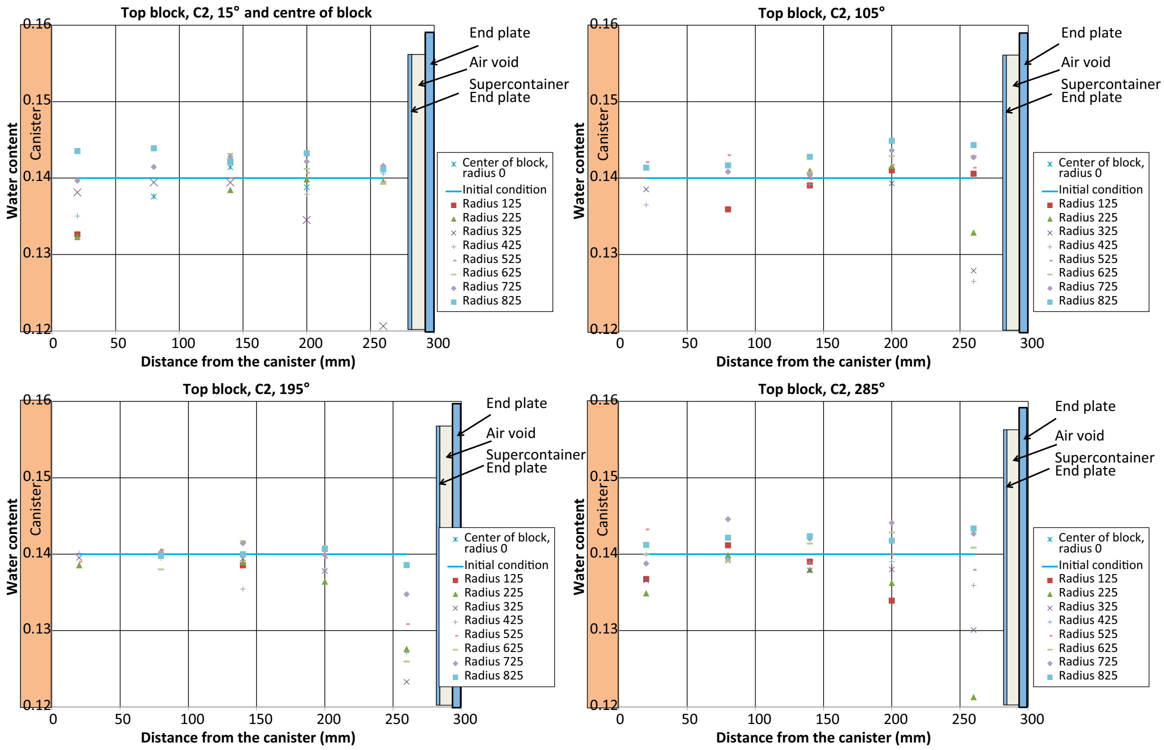

Ring R10, direction 15°
Water content
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
0.16
0.15
0.14
0.13
0.12
0.11
500
550
600
650
700
750
800
850
900


Bottom block, C1, 15° and centre of block
Water content
Canister
0.16
0.15
0.14
0.13
0.12
0
50
100
150
200
250
300
350
400
Distance from the canister (mm)
Gammagate
Supercontainer
End plate
Center of block, radius 0
Initial condition
Radius 75
Radius 125
Radius 225
Radius 325
Radius 425
Radius 525
Radius 625
Radius 725
Radius 825

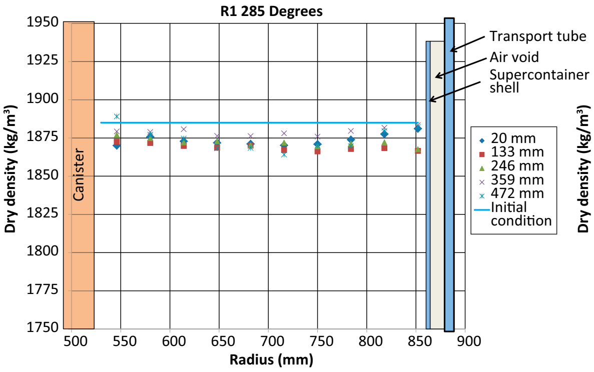

Bottom block, C1, 105°
Water content
Canister
0.16
0.15
0.14
0.13
0.12
0
50
100
150
200
250
300
350
400
Distance from the canister (mm)
Gammagate
Supercontainer
End plate
Center of block, radius 0
Initial condition
Radius 75
Radius 125
Radius 225
Radius 325
Radius 425
Radius 525
Radius 625
Radius 725
Radius 825

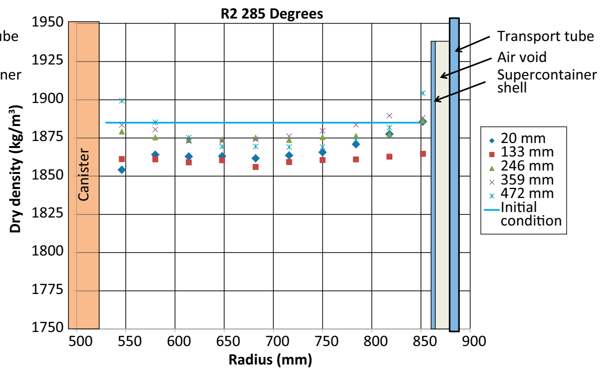

Bottom block, C1, 195°
Water content
Canister
0.16
0.15
0.14
0.13
0.12
0
50
100
150
200
250
300
350
400
Distance from the canister (mm)
Gammagate
Supercontainer
End plate
Center of block, radius 0
Initial condition
Radius 75
Radius 125
Radius 225
Radius 325
Radius 425
Radius 525
Radius 625
Radius 725
Radius 825

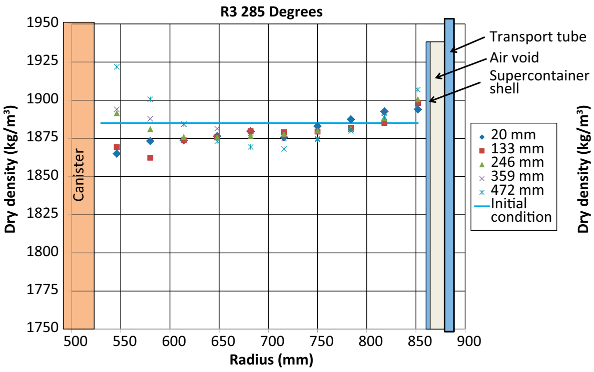

Bottom block, C1, 285°
Water content
Canister
0.16
0.15
0.14
0.13
0.12
0
50
100
150
200
250
300
350
400
Distance from the canister (mm)
Gammagate
Supercontainer
End plate
Center of block, radius 0
Initial condition
Radius 75
Radius 125
Radius 225
Radius 325
Radius 425
Radius 525
Radius 625
Radius 725
Radius 825

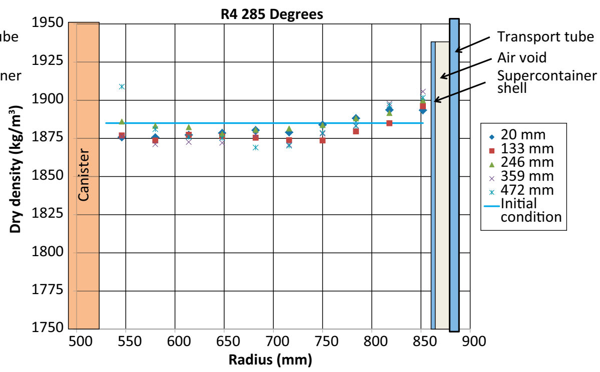

Top block, C2, 15° and centre of block
Top block, C2, 105°
Top block, C2, 195°
Top block, C2, 285°
Water content
Canister
Distance from the canister (mm)
End plate
Air void
Supercontainer
End plate
Center of block, radius 0
Initial condition
Radius 125
Radius 225
Radius 325
Radius 425
Radius 525
Radius 625
Radius 725
Radius 825
0.12
0.13
0.14
0.15
0.16
0
50
100
150
200
250
300

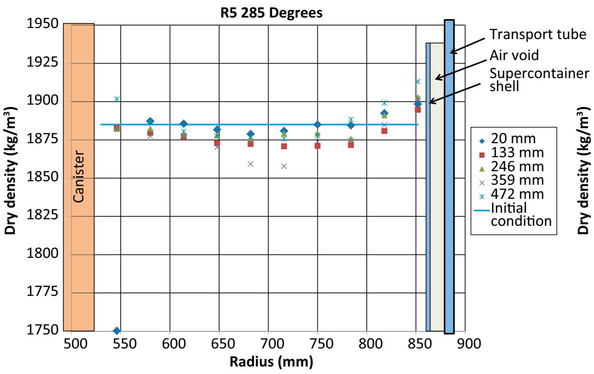
Dry density

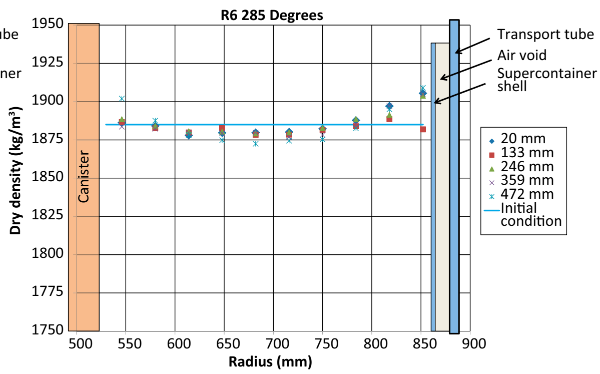

R1 285 Degrees
Dry density (kg/m³)
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition

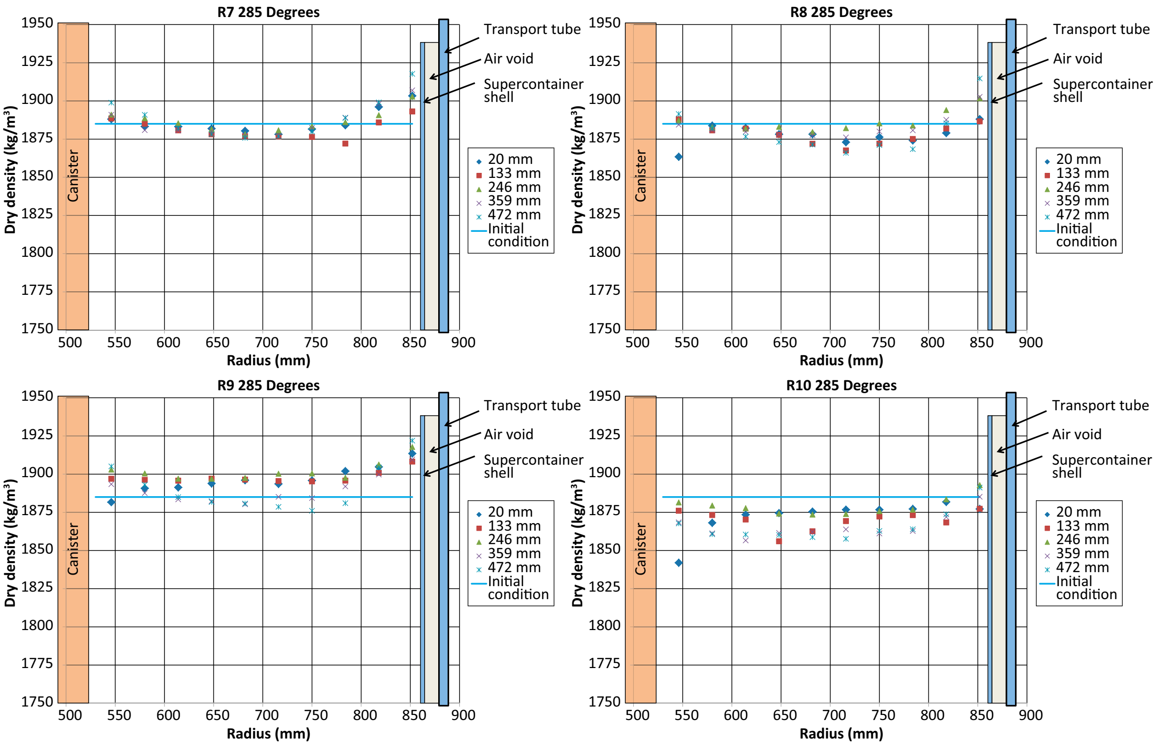

R2 285 Degrees
Dry density (kg/m³)
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition

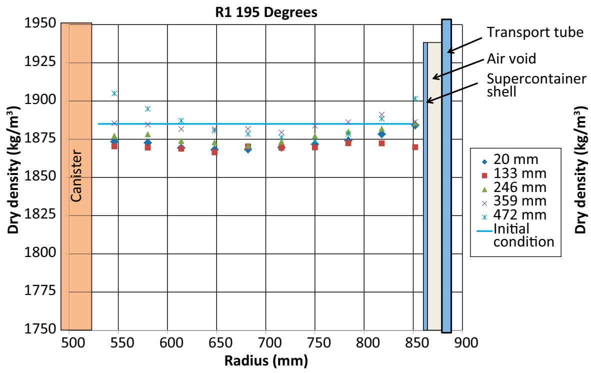

R3 285 Degrees
Dry density (kg/m³)
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition

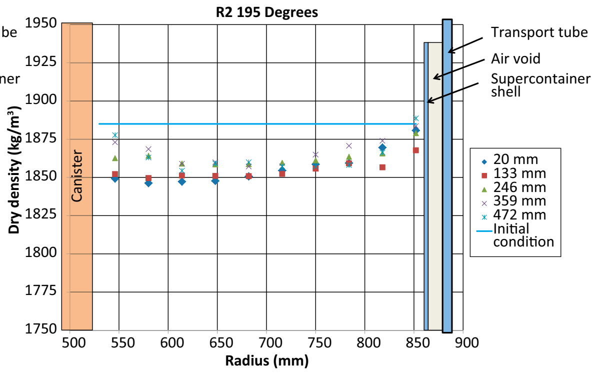

R4 285 Degrees
Dry density (kg/m³)
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition

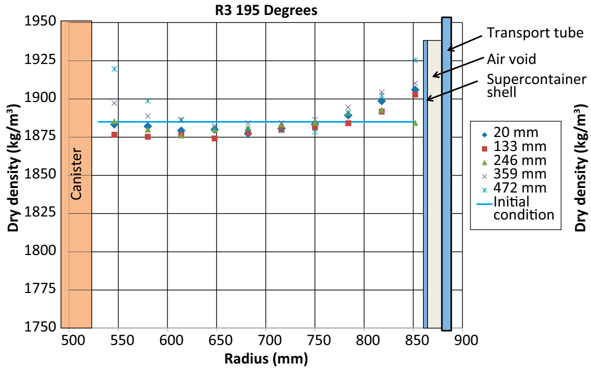

R5 285 Degrees
Dry density (kg/m³)
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition

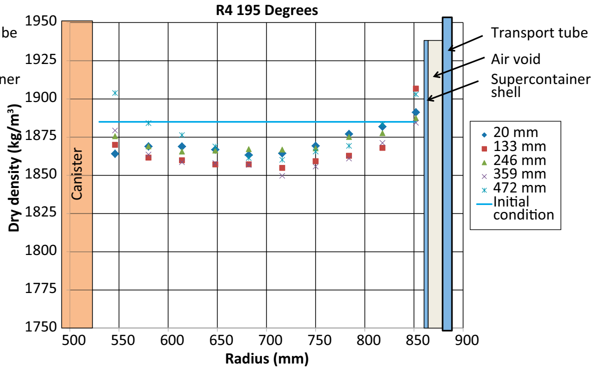

R6 285 Degrees
Dry density (kg/m³)
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition

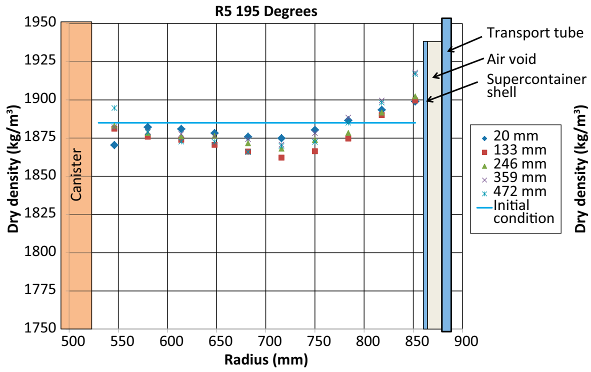

R7 285 Degrees
R8 285 Degrees
R9 285 Degrees
R10 285 Degrees
Dry density (kg/m³)
Radius (mm)
1950
1925
1900
1875
1850
1825
1800
1775
1750
500
550
600
650
700
750
800
850
900
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition

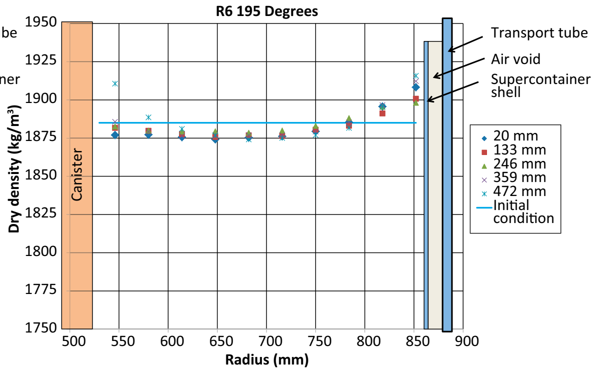

R1 195 Degrees
Dry density (kg/m³)
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition

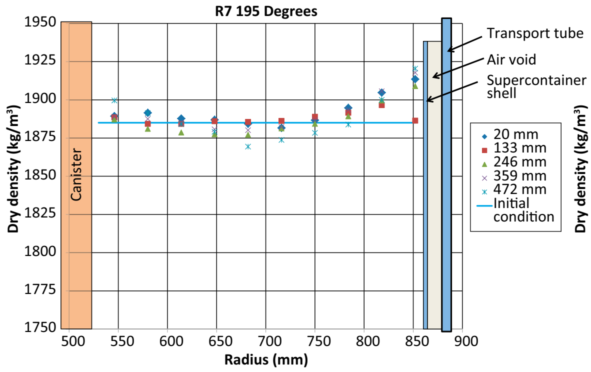

R2 195 Degrees
Dry density (kg/m³)
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition

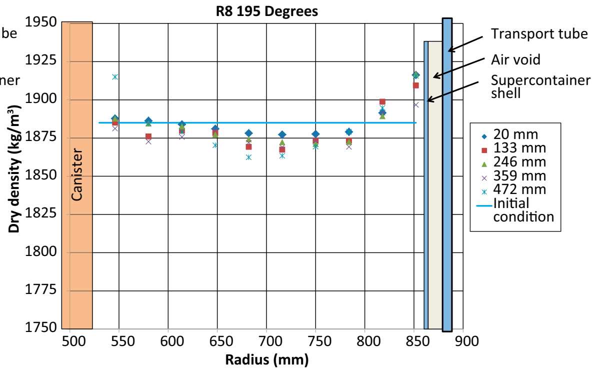

R3 195 Degrees
Dry density (kg/m³)
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition

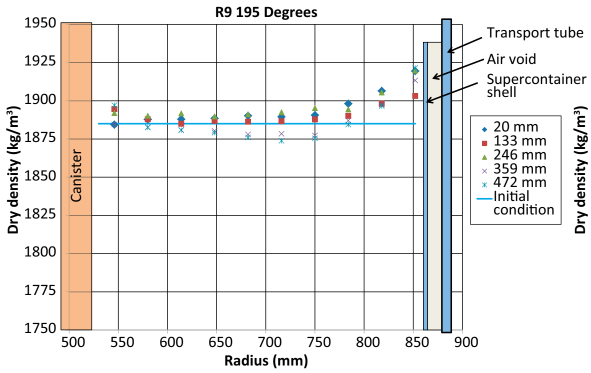

R4 195 Degrees
Dry density (kg/m³)
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition

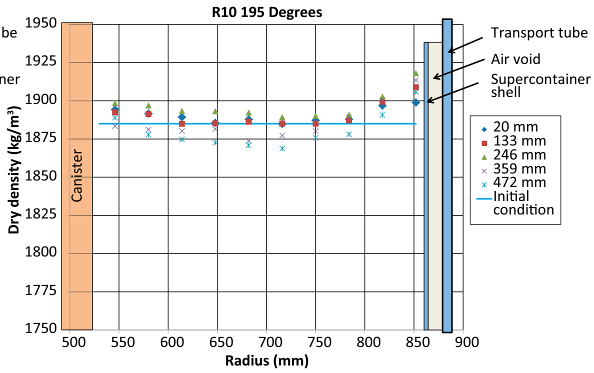

R5 195 Degrees
Dry density (kg/m³)
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition

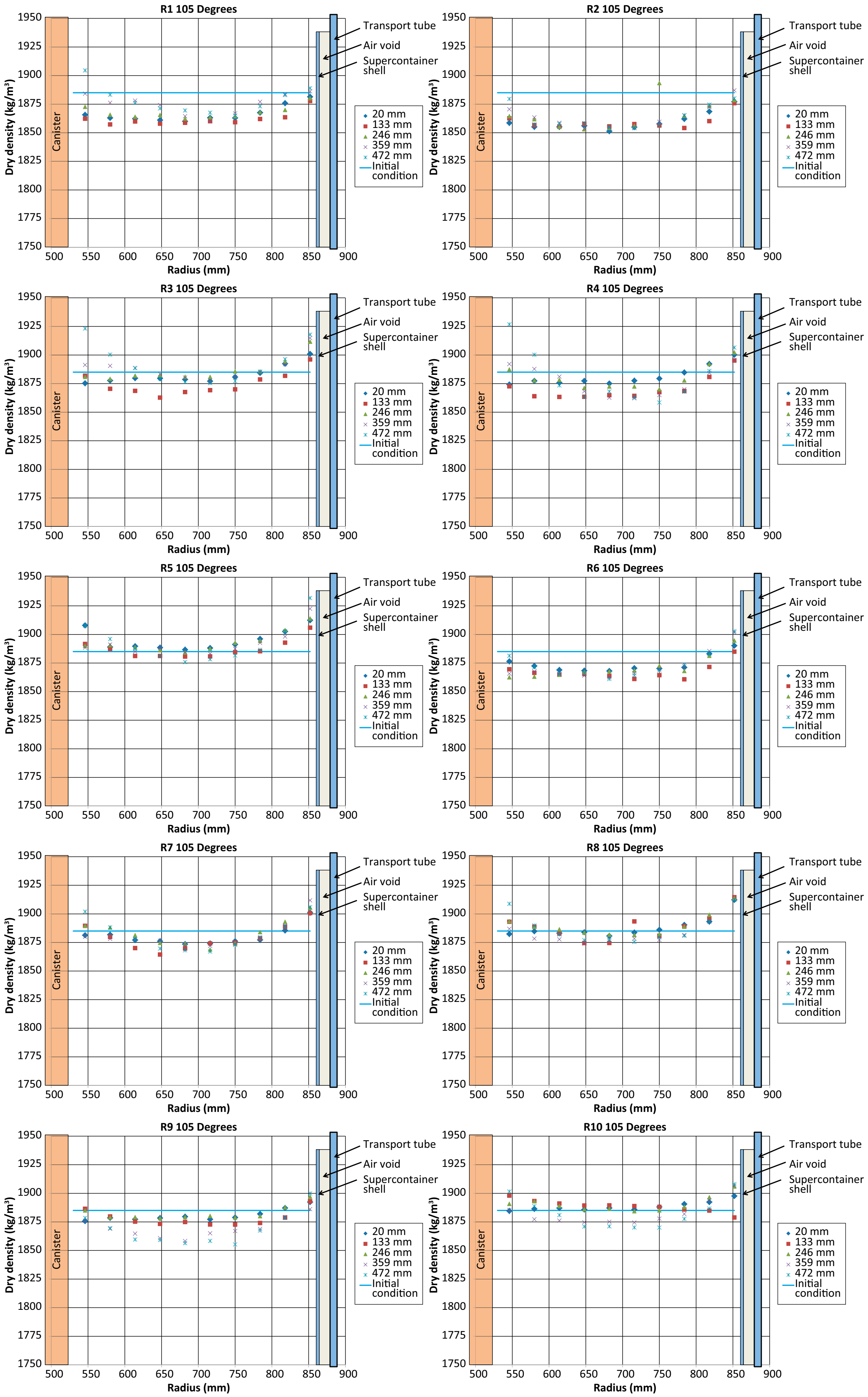

R6 195 Degrees
Dry density (kg/m³)
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition

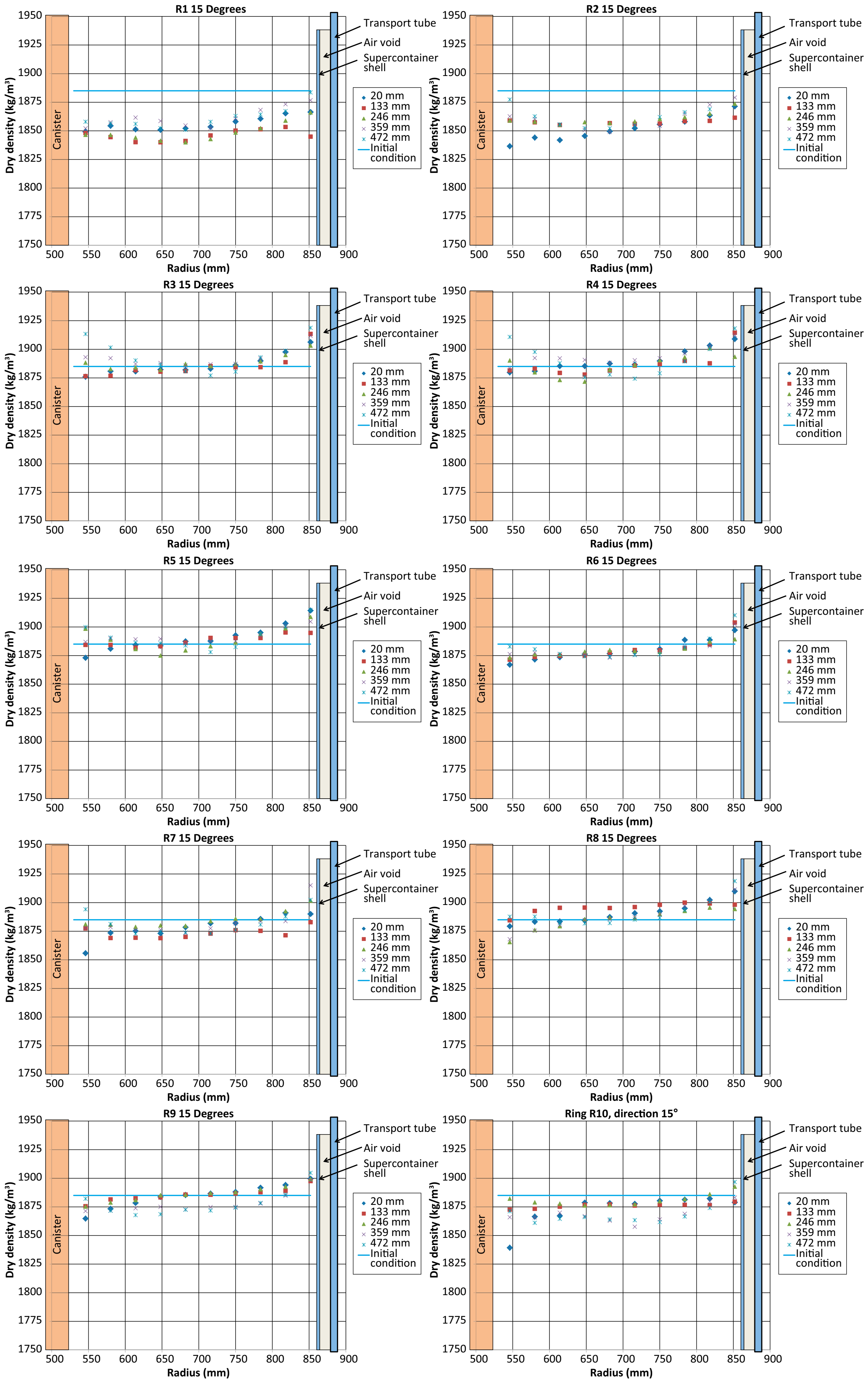

R7 195 Degrees
Dry density (kg/m³)
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition

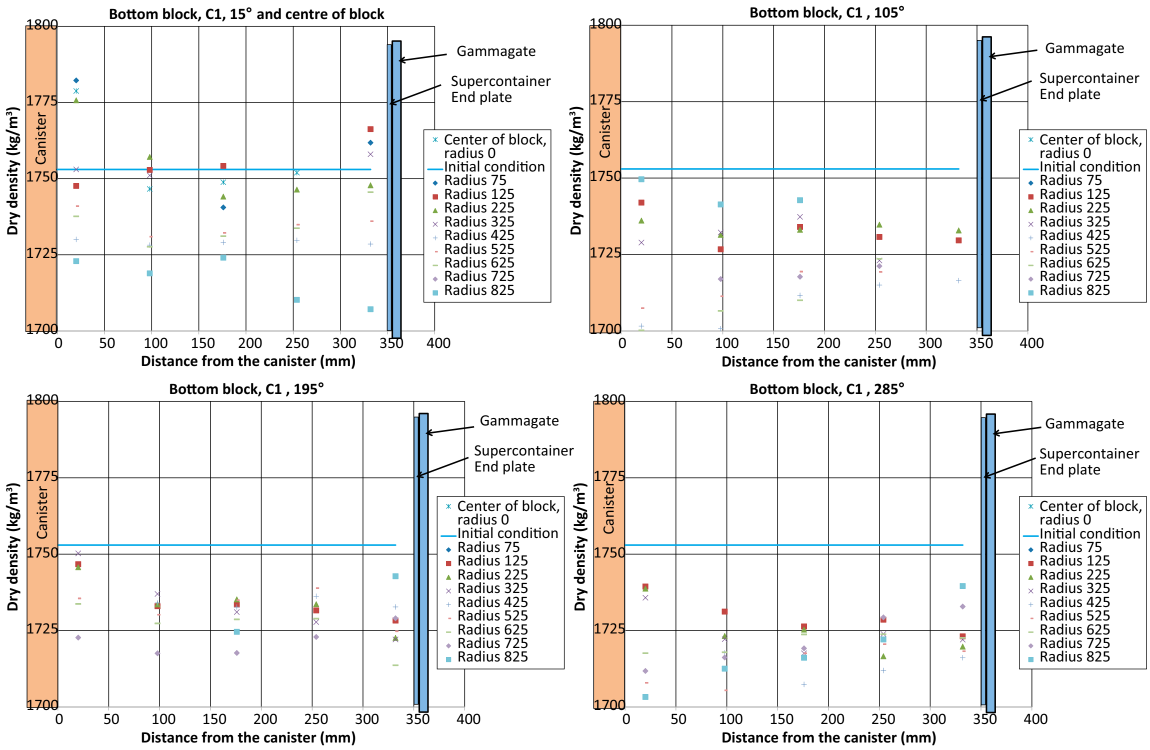

R8 195 Degrees
Dry density (kg/m³)
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition


R9 195 Degrees
Dry density (kg/m³)
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition

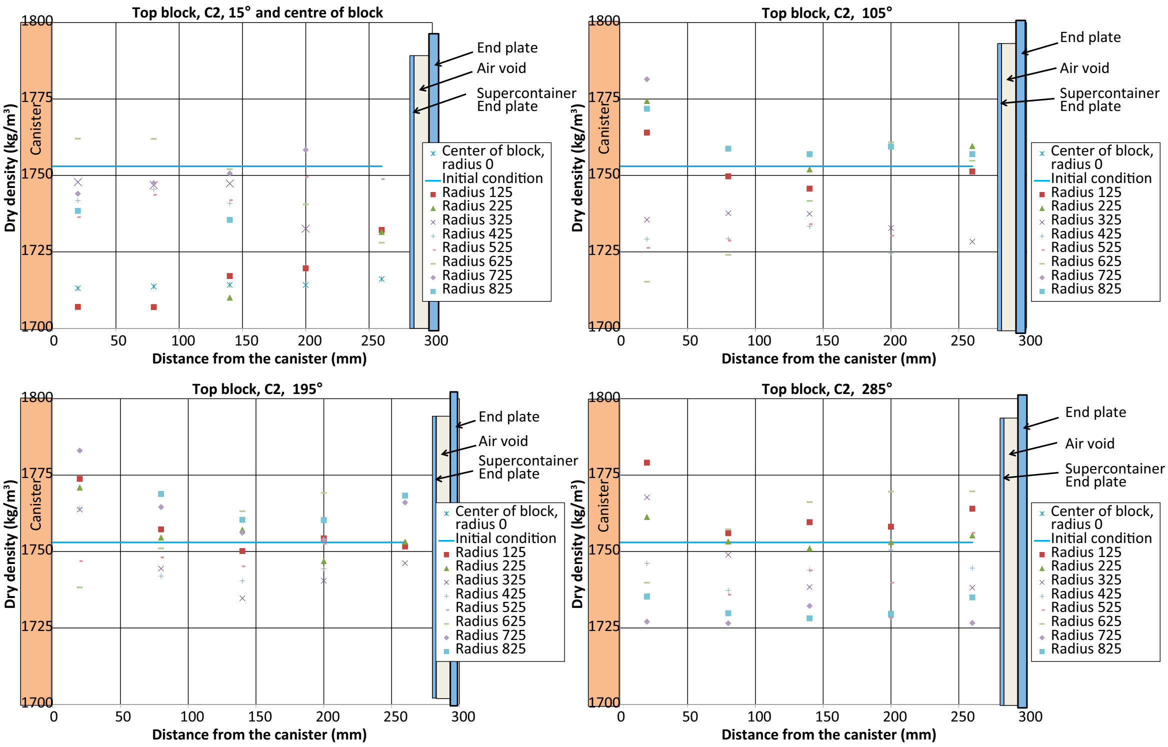

R10 195 Degrees
Dry density (kg/m³)
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition


R1 105 Degrees
R2 105 Degrees
R3 105 Degrees
R4 105 Degrees
R5 105 Degrees
R6 105 Degrees
R7 105 Degrees
R8 105 Degrees
R9 105 Degrees
R10 105 Degrees
Dry density (kg/m³)
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition
1950
1925
1900
1875
1850
1825
1800
1775
1750
500
550
600
650
700
750
800
850
900


R1 15 Degrees
R2 15 Degrees
R3 15 Degrees
R4 15 Degrees
R5 15 Degrees
R6 15 Degrees
R7 15 Degrees
R8 15 Degrees
R9 15 Degrees
Ring R10, direction 15°
Dry density (kg/m³)
Radius (mm)
Canister
Transport tube
Air void
Supercontainer shell
20 mm
133 mm
246 mm
359 mm
472 mm
Initial condition



Bottom block, C1, 15° and centre of block
Bottom block, C1 , 105°
Bottom block, C1 , 195°
Bottom block, C1 , 285°
Dry density (kg/m³)
Canister
Distance from the canister (mm)
Gammagate
Supercontainer End plate
Center of block, radius 0
Initial condition
Radius 75
Radius 125
Radius 225
Radius 325
Radius 425
Radius 525
Radius 625
Radius 725
Radius 825



Top block, C2, 15° and centre of block
Top block, C2, 105°
Top block, C2, 195°
Top block, C2, 285°
Dry density (kg/m³)
Canister
Distance from the canister (mm)
End plate
Air void
Supercontainer End plate
Center of block, radius 0
Initial condition
Radius 125
Radius 225
Radius 325
Radius 425
Radius 525
Radius 625
Radius 725
Radius 825

Arkitektkopia AB, Bromma, 2018

SKB is responsible for managing spent nuclear fuel and radioactive waste produced by the Swedish nuclear power plants such that man and the environment are protected in the near and distant future.

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