R-13-42

Studies of vapor transport from buffer to tunnel backfill (Sauna effects)

Martin Birgersson, Reza Goudarzi
Clay Technology AB

December 2013

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00

ISSN 1402-3091
SKB R-13-42
ID 1406638

Studies of vapor transport from buffer to tunnel backfill (Sauna effects)

Martin Birgersson, Reza Goudarzi
Clay Technology AB

December 2013

Abstract

This report describes a set of tests of water up-take from vapor to a slot of bentonite pellets under various conditions regarding temperature, relative humidity and volumetric constrain. The primary objective for conducting these tests was to study the sealing ability of a pellet slot as it takes up water from a vapor phase under conditions relevant to the KBS-3 concept. This ability, in turn, couples to the wider question of whether substantial amounts of salts may accumulate during the water saturation phase in a warmer region near the copper canister in a KBS-3 repository, as incoming groundwater vaporizes and then condensates in cooler parts ("sauna" effect).

It was found that the sealing ability of the pellets slot increases with time as a consequence of water up-take, in all tests performed with conditions relevant to the KBS-3 concept. It was furthermore shown in all performed tests that the process was dominated by uptake of water which condensed as a consequence of existing temperature differences. Additionally, it was demonstrated that the sealing ability of a volumetrically constrained pellets slot is significantly larger in comparison to a slot which is allowed to expand during water up-take.

Sammanfattning

Följande rapport beskriver en uppsättning genomförda tester av vattenupptag i en pelletsfyllning av bentonit under varierade förhållanden gällande temperatur, luftfuktighet och möjlighet till volymexpansion. Det huvudsakliga syftet med testerna var att undersöka tätningsförmågan hos pelletsfyllningen då denna tar upp vatten ifrån en ångfas under förhållanden relevanta för KBS-3-konceptet. Denna förmåga kopplar i sin tur till den bredare frågeställningen huruvida ansenliga mängder salt kan tänkas ackumuleras under vattenmättnadsfasen i varma områden nära kopparkapseln i ett KBS-3-förvar, genom att det inkommande grundvattnet förångas och återkondenserar i svalare delar (”bastu”-effekt).

Resultaten visar att pelletsfyllningen ökar sin tätande förmåga med tiden som en följd av vattenupptag, i alla tester genomförda under förhållanden relevanta för KBS-3-konceptet. Resultaten visar vidare att processen domineras av upptag av vatten vilket kondenserat pga befintliga temperaturskillnader. Dessutom demonstrerades att tätningsförmågan hos en volymbegränsad pelletsfyllning är betydligt större än i system som tillåts expandera under vattenupptagsprocessen.

Contents

1 Background

1.1 The KBS-3 concept

In the KBS-3 concept for storing spent nuclear fuel (SKB 2011), the waste is deposited in crystalline rock ca 500 m below ground. The waste is contained in cylindrical copper canisters which are placed in drilled holes in the floor of tunnels excavated in the host rock. The canisters and the rock are separated by an engineered buffer of swelling bentonite clay. Also the tunnels are backfilled with bentonite material. The buffer bentonite as well as the tunnel backfilling is expected to take up water from the surrounding rock and eventually become fully water saturated. In this state the bentonite have the advantageous property of substantially reducing mass transfer rates. Thus, the bentonite buffer both reduces the possibility for corroding aqueous species to reach the canister as well as it reduces the rate of transfer of waste chemicals to the biosphere in the case of canister failure.

1.2 The potential problem

The host rock may have huge differences in its capacity of supplying water to the bentonite. Water will be mainly supplied from existing fractures but in regions far from fractures also water supply directly from the rock matrix becomes significant. If water containing salt enters the buffer region while this is hot, the water may "escape" as vapor while the salt is deposited (a "sauna" effect). If a major part of water used to saturate a part of the repository is entering in this way, substantial amounts of salt may be deposited close to a single canister (Karnland et al. 2009). Large amounts of deposited salt, in turn, could cause canister corrosion rates to increase. The process is illustrated in Figure 1-1.

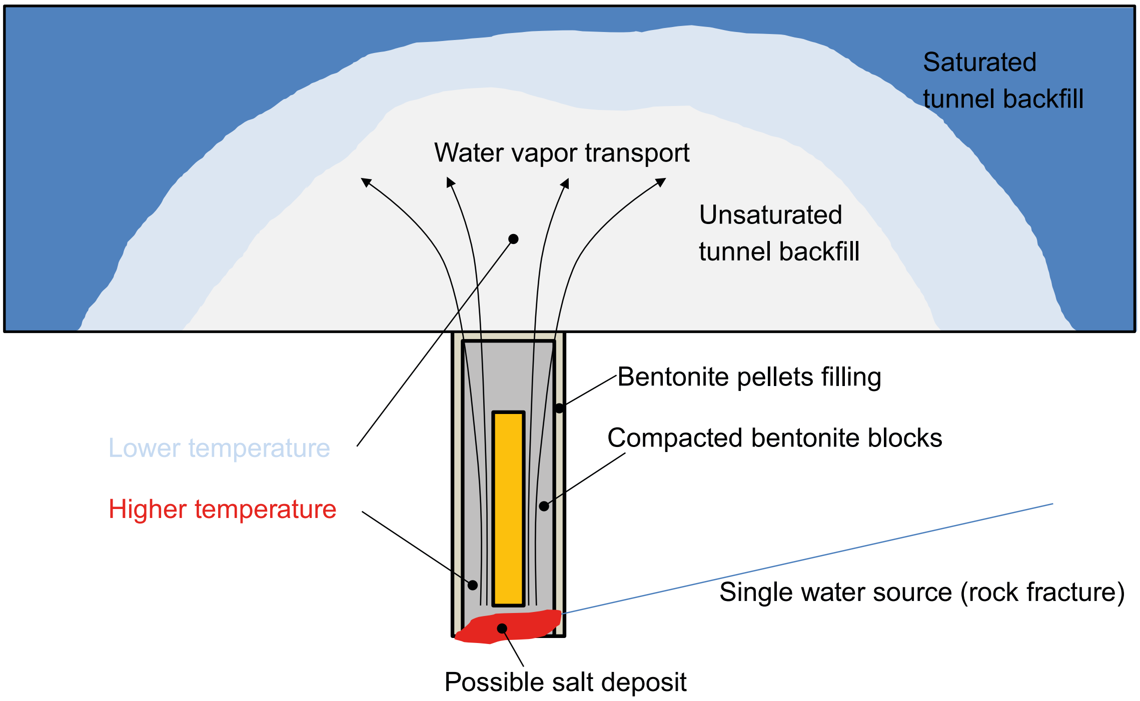

Figure 1-1. *Schematics of the "sauna" effect.*

To better quantify this type of possible corrosion rate enhancement, it is important to have enough knowledge of the coupled water uptake/vaporization and salt deposition processes. Largely, the study of such processes can be divided into the following groups:

- Interaction between saline (ground)water and partly saturated bentonite, i.e. how salt is deposited in bentonite (process at the fracture/buffer interface).
- Transport of vapor through unsaturated zones of compacted bentonite blocks (process in the buffer).
- Transport of vapor through unsaturated zones of bentonite pellets (process in buffer and buffer/tunnel backfill interface).

The following study focuses on the last of these groups. A set of qualitative test have been performed to investigate how water vapor is taken up by a system of bentonite pellets. In order for the salt enrichment process described above to proceed, sufficiently poor sealing of the pellets filling (e.g. at the buffer/tunnel backfill interface) is required. Therefore, special attention in the performed tests was given to how the pellets sealing ability evolved. A further reason for studying the sealing ability of a pellets filling – in addition to its coupling to a potential salt accumulation process – is that the buffer may lose some of its (initial) water due to vapor transport. A drier buffer will have a lower thermal conductivity (Åkesson et al. 2010) which consequently may lead to increased temperatures.

2 Tests

2.1 Basic set-up

The performed tests were all conducted utilizing the same basic set-up, schematically pictured in Figure 2-1. A metallic net was mounted on a stand which was placed in a modified stainless steel kitchen pot. A certain amount of bentonite pellets, with very low initial water content, was placed on the net. The lower part of the pot (below the net) were filled with water from an inlet in the bottom and heated to approximately 90°C. Consequently an increased water vapor pressure was generated and the basic aim with the study was to examine the interaction of this vapor with the bentonite pellets. As the bentonite pellet filling initially is very dry it has a large affinity for taking up additional water. This uptake may occur directly from the vapor phase or from possibly condensed liquid water in the system.

Table 2-1 lists the five performed test and their basic characteristic parameters. In the first test (Oven1), the whole pot was put in an oven and kept at approximately 90°C. In the subsequent tests (Room1 – Room4), the pot was placed in room temperature but heated at the bottom. The water temperature was then regulated to be approximately constant at 90°C.

In all tests with intentional temperature gradients (Room1 – Room4), relative humidity and temperature evolution was measured in certain points of the system. Further, in tests Room1 – Room3 the upper part of the pot was replaced by a plexiglass cylinder in order to enable visual inspection of the pellet sample during and after the course of tests.

Table 2-1. Tests.

Test Name	Oven1	Room1	Room2	Room3	Room4
Temp (°C)	90 (iso)	gradient	gradient	gradient	gradient
Dry mass (kg)	13	13	13	26	13
Pellet height (cm)	10	10	10	20	10
Lid	off/on	on	off	off	off
Volume constraint	radial	radial	radial	radial	radial and axial
Duration (days)	27	6	22	24	16

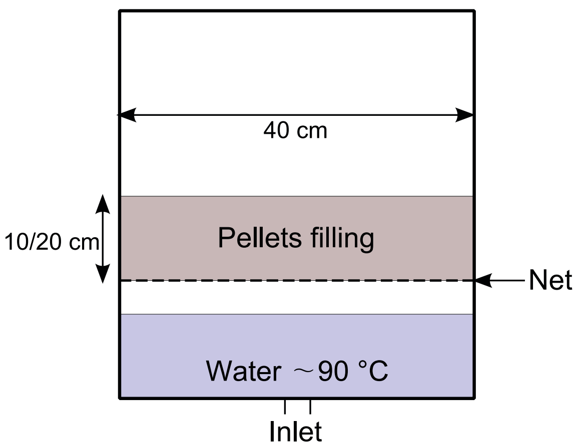

Figure 2-1. *Schematics of the basic test-set up.*

The top of the modified pot was either sealed with a lid or left opened and water was continuously lost to the environment, at different rates depending on test details. Therefore new water was occasionally provided through the bottom inlet during the course of the tests. The water uptake of the pellets as well as the total water loss was estimated by occasionally weighing of the whole system and by bookkeeping the amount of water refilled. Weighing was always performed by first emptying the pot of water.

In all tests except for Room4, the pellets was allowed to swell upwards (axial direction) without restriction. In contrast, test Room4 was performed in a pot where the pellet filling was kept in place.

In connection with weighing, the sealing of the pellets was tested by measuring the time it took to fill the pot with a prescribed amount of water at a prescribed injection pressure. Changes (increase) of this filling time during the course of the test indicates that the gas phase initially residing in the lower pot volume is not easily transported out through the pellets filling. The bentonite used was MX-80, pelletized in the size 2 cm. Initial water-to-solid mass ratio was approximately 10%.

2.2 Oven1

The first test was performed at approximately constant temperature by placing the whole pot in an oven at 90°C. A detail of the set-up is seen in Figure 2-2

The evolution of mass is displayed in Figure 2-3. This plot shows both the total amount of water consumed in the test (water lost to environment + water taken up by pellets filling), and the mass of water taken up by the pellets filling. During the first six days, the system was opened in the top, i.e. the pot was without lid. During this period a very weak mass increase is observed (if any). Thus, under these circumstances the water uptake of the pellets from the vapor is not very efficient and a substantial amount of vapor apparently flows through the pellets filling. The behavior is quite different when a lid was placed on the pot (day 6), which resulted in subsequent and quite steady water up-take up until termination of the test (day 27). During this period approximately 3 kg water was accumulated in the pellets filling. The water consumption is much larger when the pot is without lid, for obvious reasons. Also when the lid is on it can be seen that the water consumption is larger than the uptake in the pellets. Consequently the system is not completely sealed with the lid on.

The look of the pellets filling after termination of the test (day 27), displayed in Figure 2-4 and Figure 2-5 is quite interesting. It shows that the water taken up by the pellets is not uniformly distributed but concentrated to a "condensation nucleus". At termination, much of the pellets closest to the water source was still very dry (Figure 2-5). It thus appears that condensation of vapor has occurred locally, and that the major part of water take up by the pellets filling has been taken up in liquid form. The origin of the "condensation nucleus" is probably a spot on the pot with lowered temperature. Because the process of taking up water from condensed water is so dominating, it is difficult from this test to draw conclusions on the process of taking up water directly from the vapor phase.

Figure 2-2. Detail of the "pot" in the oven. The tubing connected to the inlet at the bottom is visible.

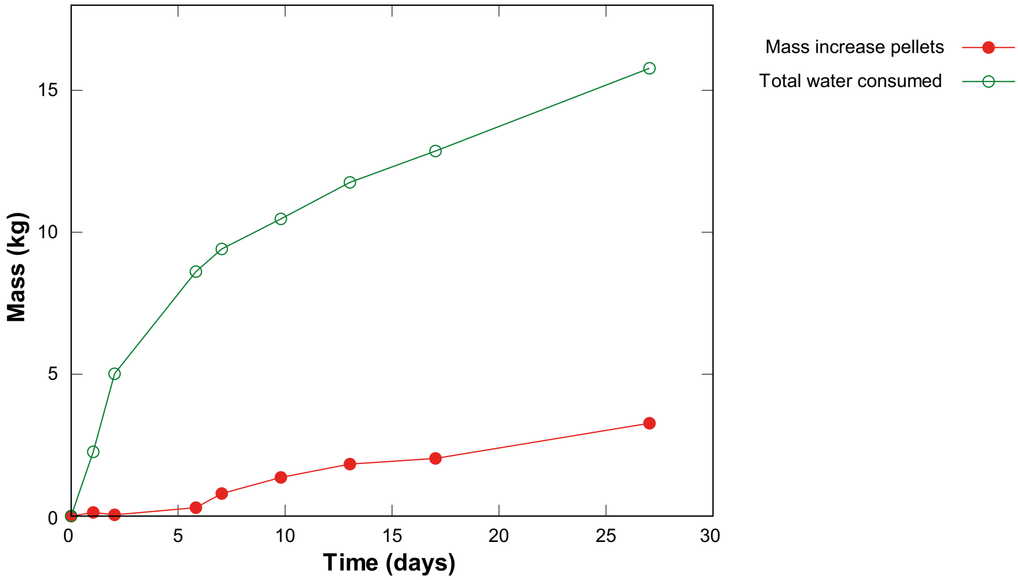

Figure 2-3. *Mass evolution in the Oven1 test. At day 6, a lid was placed on the pot.*

Figure 2-4. *The pellets layer as seen from above after the isothermal test (Oven1).*

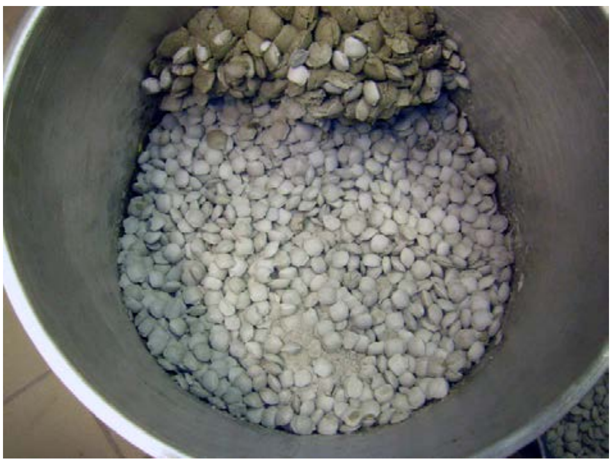

Figure 2-5. *Termination of Oven1 test. Most of the pellets are excavated. Note that the pellets adjacent to the net is dry as compared to the "condensation nucleus".*

2.3 Room1

The first test made in room environment was performed with a lid. The set-up is shown in Figure 2-6. With this configuration a complicated temperature distribution is expected during the test, while the relative humidity very quickly is expected to be near 100% everywhere. The set-up was equipped with two relative humidity and temperature sensors – one in the middle of the void volume above the pellets (see Figure 2-6), and one placed in the middle of the pellets (not visible in figure).

The evolution of these sensors during the first hours of the experiment is shown in Figure 2-7. The sensor located in the position above the pellets filling quickly increased to very close to 100% RH. As confirmed visually, vapor condensation occurred on this sensor. The temperature response was also faster at this position which is explained by the condensation (condensed hot water quickly raises the temperature). The temperature and humidity response of the sensor in the pellets was a bit slower but a couple of hours after test start also this sensor reached 100% RH and a steady temperature of approximately 90°C. Thus, very quickly in the test a steady sate was reached with a temperature difference of ca 30°C between the two sensor positions. It should be kept in mind that the temperature field most certainly was not one dimensional and it is expected that the temperature was lower closer to the container wall in the upper parts (at a given height).

The water uptake is shown in Figure 2-8. It can be seen that the water uptake is now much quicker as compared to the Oven1 test – within five days the mass increase of the pellets was ca 11 kg (the water uptake was even larger than this because mass measurement started almost a day after the heating started). The reason for this enhanced water uptake rate is because of general vapor condensation in the upper part of the system due to the imposed temperature field. The massive condensation can be seen in Figure 2-9.

An interesting difference to notice as compared to the Oven1 test is that the water uptake rate in this case is decreasing with time (Figure 2-8). As the water take-up of the pellets filling is completely dominated by the process of taking up liquid water from the top, this water uptake decrease indicates that the vapor transport capacity through the filling decreases during the course of time. Consequently, this behavior indicates that the pellets filling is sealing with time. The massive volume increase of the filling is also worth noting (compare Figure 2-6 and Figure 2-9).

Figure 2-6. *The Room1 test before started heating.*

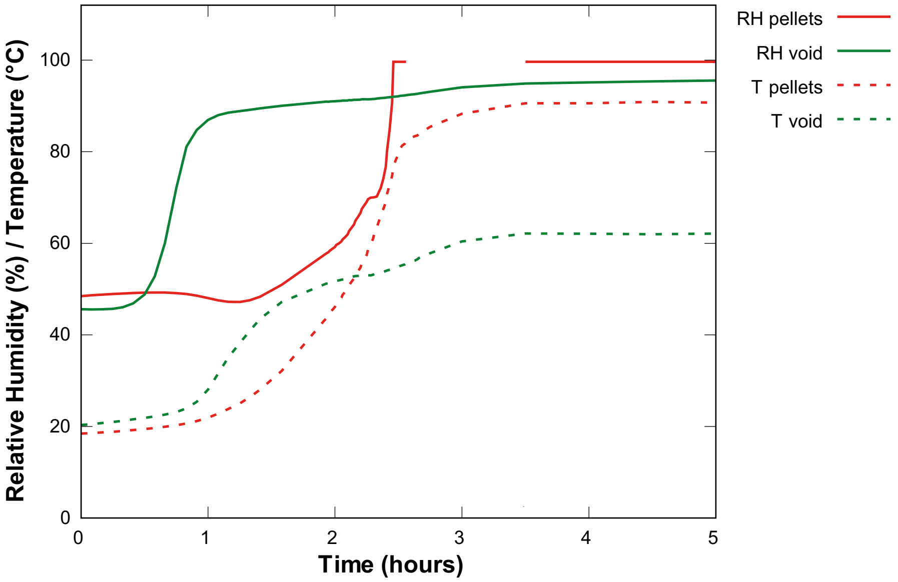

Figure 2-7. Temperature and relative humidity evolution in the initial stage of test Room1. The sensor placements can be viewed in Figure 2-6.

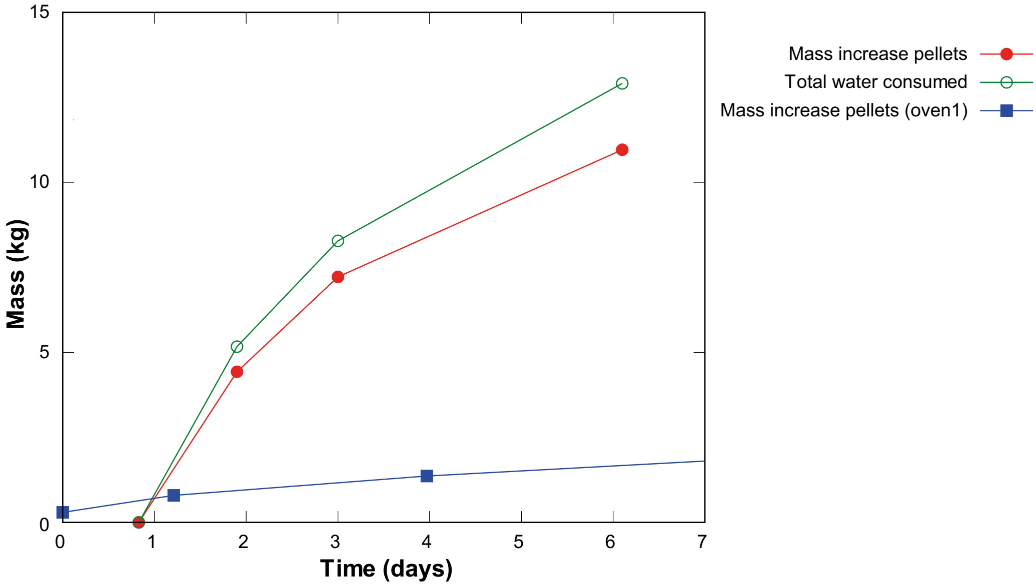

Figure 2-8. Accumulated mass gain of the pellets and total amount of consumed water in the Room1 test. For comparison is also shown the mass gain of the pellets in the oven1 test for the first seven days after a lid was placed on the pot in this test (Figure 2-3).

***Figure 2-9.** The Room1 test after ~1 day and ~6 days.*

The pellets filling was excavated after termination of the test as shown in Figure 2-10. It was confirmed that the water uptake occurred mainly from the edges due to liquid water "fed" from above. Quite dry pellets could be found in the center rather close to the bottom net. The water-to-solid-ratio was measured in some representative samples and the result is displayed in Table 2-2.

In conclusion, the water uptake process in this test was completely dominated by the process of water condensating in the top of the system and then "feeding" the pellets at the edges from the top.

***Figure 2-10.** Excavation of the Room1 test.*

Table 2-2. Measured water-to-solid ratios (w) in Room1 at termination of test.

Position	w
Top, wet pellet	3.7
Top, dry pellet	0.16
Bottom, dry pellet	0.19
Pellet, initally	0.11

2.4 Room2

In order to study the water uptake process with less influence of condensed water from above, a second room environment test was performed without a lid. Such a set-up implies uneven distributions of both temperature and relative humidity within the system – at and near the heated water the temperature is approximately 90°C, while RH is 100%, close to the top of the system the boundary condition is determined by the room, i.e. much lower temperature and RH. To achieve a more even temperature radially the whole set-up was isolated as shown in Figure 2-11. Furthermore, in this test combined relative humidity and temperature measurements was performed in two points within the pellets filling. One sensor was placed in the center of the pellets at mid-height, while the other was placed at the circumference also at mid-height. Note that these sensors changes position during the course of time due to swelling of the filling (see Figure 2-16).

Figure 2-12 shows the initial state of the pellets filling (seen from the top of the isolated plexiglass tube).

The total water uptake of the filling as well as the total water consumption is shown in Figure 2-13. The amount of water lost to the environment was in this case much larger as compared to the Room1 test (Figure 2-8) because this test was opened at the top. This shows again (compare the initial stage of the Oven1 test) that substantial amounts of vapor can, under certain conditions, pass through the pellets filling without being absorbed. It appears as if there is a kinetic barrier for the process of directly taking up water from a vapor phase.

Figure 2-11. *The insulated set-up of Room2 test. The system is open at the top (no lid).*

Figure 2-12. *The pellets before test start, as seen from the top of the set-up. The cables to the two RH/T-sensors in the filling is seen at the top of the picture.*

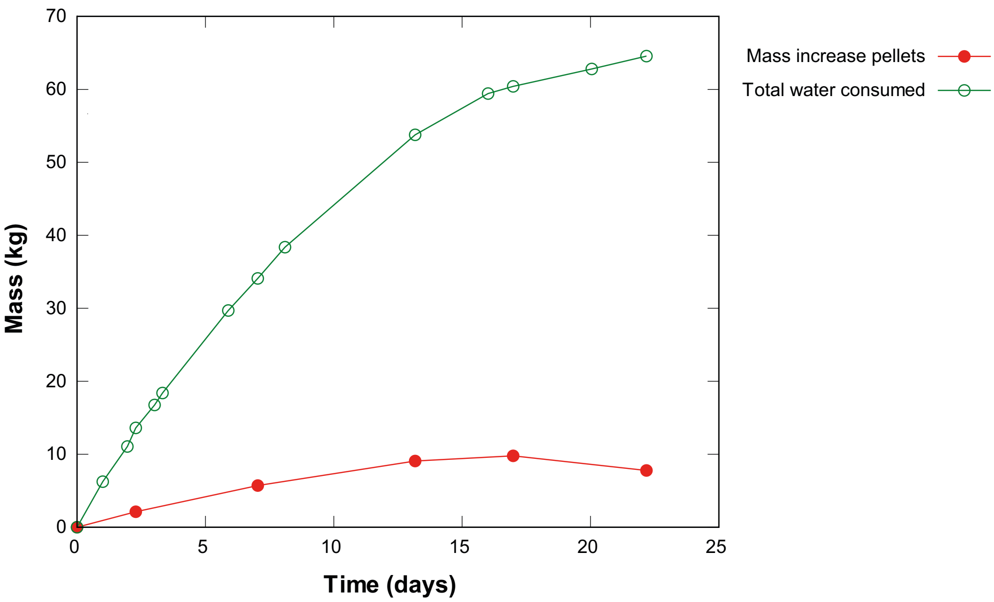

Figure 2-13. *Accumulated mass gain of the pellets and total amount of consumed water in the Room2 test.*

In this test it was noted that no visible condensation occurred on the plexiglass surfaces above the pellets. Hence no significant wetting from condensed water coming from above occurred in this test. Despite this fact the pellets took up substantial amounts of water (Figure 2-13). However, also this water-uptake is fully dominated by condensation, but now only within the pellets filling. The condensation can be seen in Figure 2-14. This picture also shows how the water up-take propagated as a front from what seems to be an initial condensation "nucleus" (the edge-sensor is a candidate). The front propagated "flat" across the pellets, i.e. independent of the circular geometry. It may be suspected that the same kind of behavior occurred in the Oven1 test (Figure 2-4 and Figure 2-5) where the final excavation revealed a water uptake region which may have evolved from an initial core (in that case a cooler spot on the pot edge). The Room2 test, however, was continued until the front had propagated across the entire filling.

At about 14 days, after a water uptake of approximately 8 kg, the mass increase of the pellets ceased. In this state massive swelling had occurred and the system had reached a steady-state where as much drying occurred at the top of the pellets as water was taken by condensation or direct vapor uptake within the pellets. Note that the amount of consumed water increased more slowly with time which indicates sealing of the pellets.

The temperature and relative humidity evolution in the first part of the test is plotted in Figure 2-15. It is quite interesting that the temperature initially is much larger on the edge than in the center. Reasonably the plexiglass conducts heat better than the dry pellets. Despite the higher temperature at the edge, the humidity quickly gets to 100% here while the humidity in the center drops initially. Condensation probably occurs on the sensor. After about 8 days it is seen that the temperature begin to drop systematically at both positions. This is because the sensors are pushed upwards to lower temperature regions by the swelling pellets.

Figure 2-16 show the set-up at termination with the insulation unmounted. Condensed water is visible everywhere at the plexiglass/pellet interface.

The pellets was excavated and revealed a mix of rather dry parts and more wet parts (Figure 2-17 and Figure 2-18). At the interface to the bottom net, a more homogeneous wet region prevailed (Figure 2-19). The existence of that complies with the observation that the amount of consumed water decayed with time (because a saturated layer of bentonite obviously slows down vapor transport).

Figure 2-14. *A straight front of condensation propagated across the pellets during the course of the Room2 test. Picture taken after approximately 6 days of testing.*

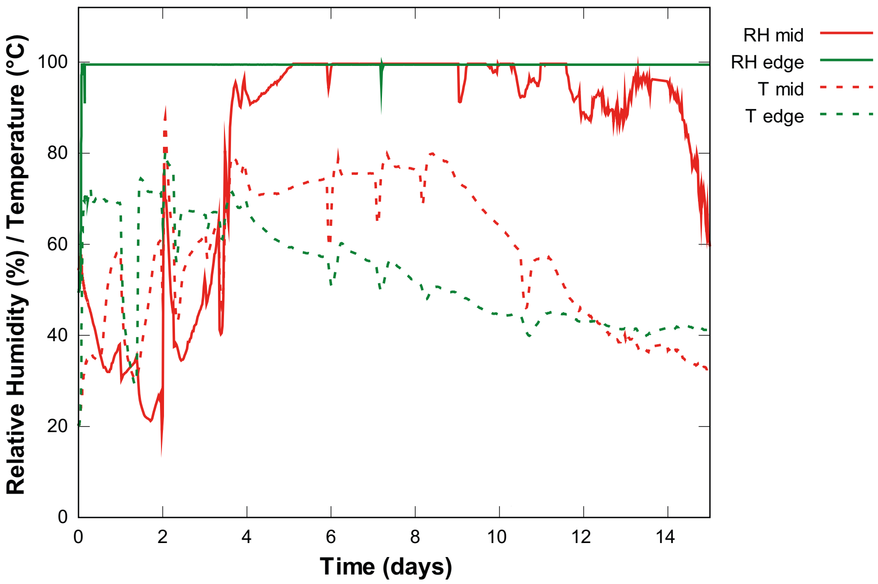

Figure 2-15. *Temperature and relative humidity evolution in the initial stage of test Room2.*

Figure 2-16. *The room2 test after termination.*

Figure 2-17. *Room2 at excavation. Note the drier rim of pellets to the right in the picture.*

Figure 2-18. *Excavation of the Room2 test. The picture show the pellets layer closest to the net. Also here was found relatively dry pellets in places.*

Figure 2-19. *At the bottom net a more homogeneous wetted zone had formed in the room2 test.*

2.5 Room3

The Room3 test was principally a replicate of Room2 with the exception that twice as much pellets was used. Thus the test was performed with an opened top, insulated circumference, and a ca 20 cm high pellets slot (26 kg). The results were very similar to Room2, demonstrating that the amount of pellets chosen are not very important for the general water uptake behavior observed under these conditions.

The water consumption and uptake is displayed in Figure 2-20 and the relative humidity and temperature evolution is found in Figure 2-21. Also in this test a propagating flat condensation front was observed, pictured in Figure 2-22. The pellets after termination is pictured in Figure 2-23.

2.6 Room4

The Room4 test was a version of the Room2 test with the difference that efforts were made to keep the pellets constrained volumetrically. This was done by performing the test in a specifically designed pot were a perforated plastic mat was covering the top of the pellets. The mat, in turn, was supported by metal rods, as pictured in Figure 2-24. This test is thus a better representation of the pellets in the KBS-3 concept, which is constrained by design.

A comparison of the water uptake and total consumption between this test and Room2 is made in Figure 2-25. As noted, the water consumption is reduced considerably in this test. It is furthermore seen that the system reaches a steady-state after just a few days, with no further water uptake in the pellets.

It should be recognized that the difference in water consumption between test Room2 and Room4 must be attributed to the fact that the pellets is volumetrically constrained as the system is still opened towards the atmosphere. The reduced water consumption is thus a consequence of better sealing during the swelling process induced by water uptake in the pellets; as the system is volumetrically constrained, individual pellets now fill up internal voids when they swell, rather than contributing to an overall increase of the slot volume. For the same reason, some "swelling stress" is certainly induced in the slot. Since the sealing process is much more efficient, the final total amount of water taken up by the pellets slot is actually lower as compared to an unconfined system (Figure 2-25). On the other hand, the volume increase in unconfined systems is, as seen, quite extensive (see e.g. Figure 2-23).

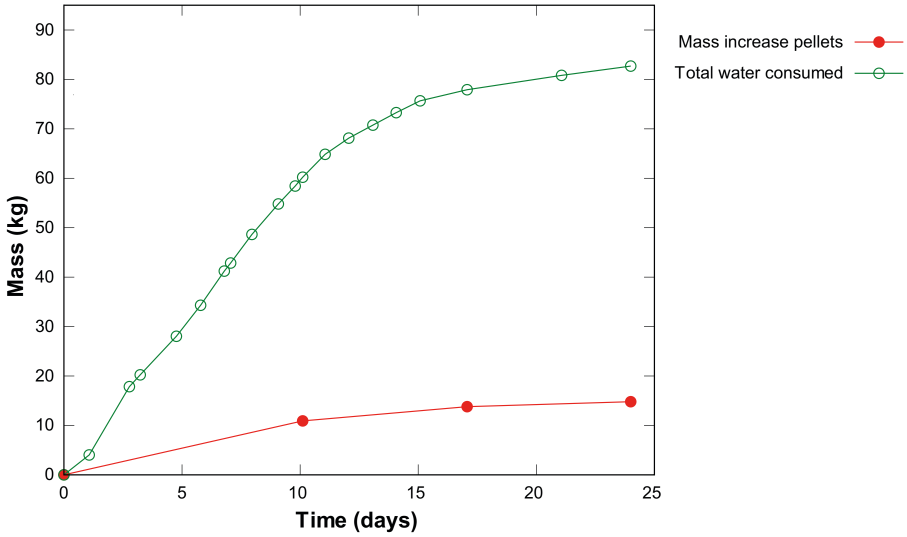

Figure 2-20. Accumulated mass gain of the pellets and total amount of consumed water in the Room3 test.

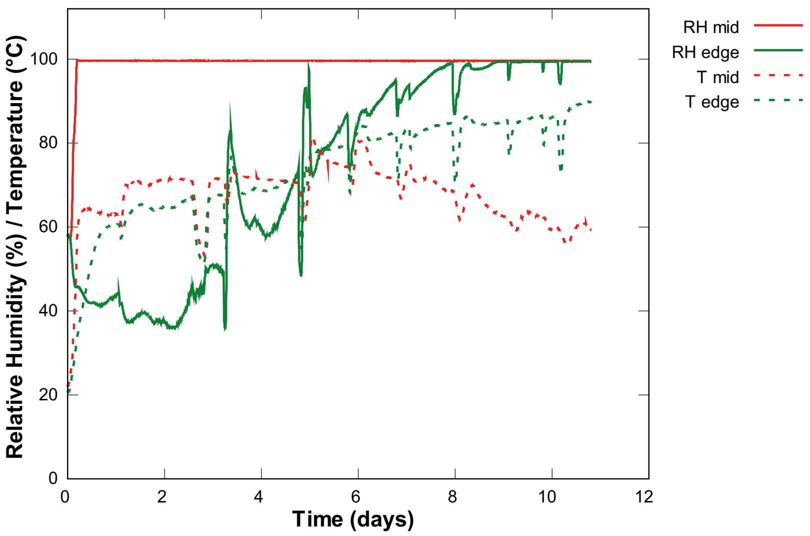

Figure 2-21. Temperature and relative humidity evolution in the initial stage of test Room3.

Figure 2-22. A straight front of condensation propagated across the pellets during the course of the Room3 test. Picture taken after approximately 7 days of testing. Note the similarity with Figure 2-14.

Figure 2-23. *The Room3 test after termination.*

Figure 2-24. *The plastic mat on top of the pellets filling in Room4 test. Also visible are the supporting rods which kept the pellets slot in place during the test.*

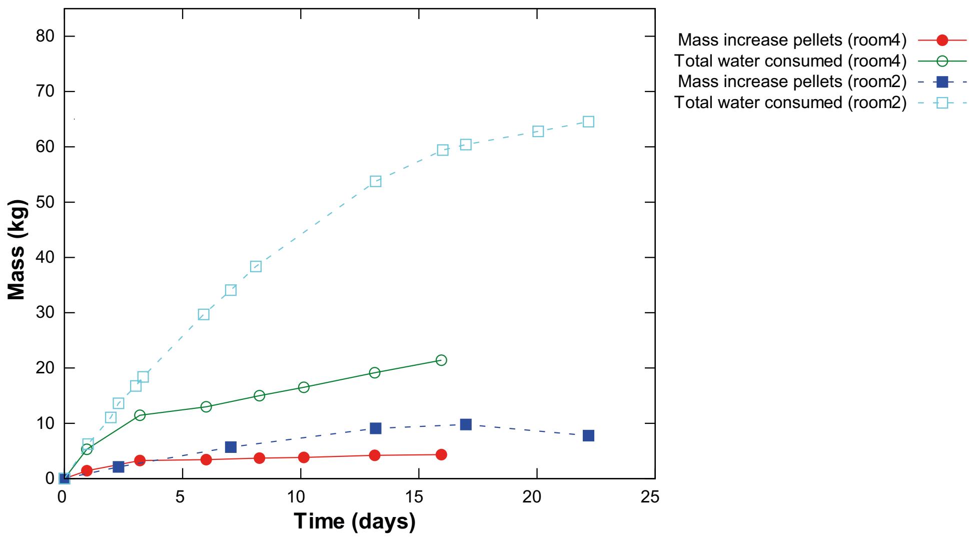

Figure 2-25. *Accumulated mass gain of the pellets and total amount of consumed water in the Room4 test. The same quantities for Room2 is also shown for comparison.*

The more efficient sealing which occurred in the present test was confirmed at excavation. The material, shown in Figure 2-26, looked quite different as compared to the previous tests, with the pellets more "glued" together.

Figure 2-26. *Excavation of Room4.*

3 Conclusions

A set of semi-quantitative test have been performed in order to study one aspect of the “sauna” effect: water-uptake and sealing ability of bentonite pellets in temperature and/or relative humidity gradients. Regarding the appropriateness of the experimental approach, it can be concluded that water condensation inevitably occur under the performed conditions. Furthermore, the water uptake due to water condensation does completely dominate in these tests. Consequently, these types of tests are not optimal for giving quantitative information on the process of water uptake directly from the vapor phase, as it is “overshadowed” by effects related to vapor condensation. On the other hand it can also be concluded that vapor condensation will always be of importance in the “real case”, i.e. the KBS-3 design, as e.g. quite substantial temperature gradients are expected. Thus, a key to fully understanding the water-uptake and possible sealing of parts with bentonite pellets is this condensation phenomena. All performed tests indicates that the water uptake due to condensation starts in a “nucleus” which then grows by condensing even more water at its edges. The evolution of such a “nucleus”, which may be very wet (water-to-solid ratio larger than 3) appears to be independent of the system geometry (Figure 2-14 and Figure 2-22).

Further it can be concluded that the performed mass measurements not only are useful for the obvious purpose of quantifying the water uptake, but that they also contain information on the sealing ability of the pellets. It was seen in all tests, which evolved long enough, that the uptake rate decreased with time. This observation indicates that the pellet system seals with time – the vapor transport capacity consequently diminishes with time.

The explicitly performed inflow tests, on the other hand, was not useful for quantifying the sealing obtained in this study. This should not be seen as an indication that sealing did not occur, but that the inflow test method is too insensitive.

Finally, it was clearly demonstrated that restriction of the swelling had a major impact on the resulting rate of water consumption. I can thus be concluded that swelling restriction, which is the relevant condition in KBS-3, have a major effect in reducing the vapor loss.

The processes explored in the present work are schematically illustrated in Figure 3-1:

a) Direct vapor loss to the surroundings from the water source.
Substantial amount of vapor was able to flow through the pellets filling without being absorbed by apparently rather dry bentonite. Doubling the size of the pellets filling did not change this behavior to any large degree. The process, however, were influenced by swelling and sealing of the pellets and typically weakens with time, demonstrating that the pellets filling evolve towards a more sealed state.

b) Direct vapor uptake by the bentonite pellets. Although not observed here, it is known that water-uptake may occur directly from a vapor phase (Birgersson et al. 2009).

c) Condensation of water vapor.

d) Uptake of condensed water by the bentonite pellets. This is the dominating water up-take process under the conditions of this study.

e) Loss of water from the bentonite pellets to the surroundings as vapor (drying).

The present results does not give unambiguous answers to whether a “sauna effect” can be dismissed or not based on the sealing properties of pellets, but should be complemented by e.g. THM-simulations of relevant cases.

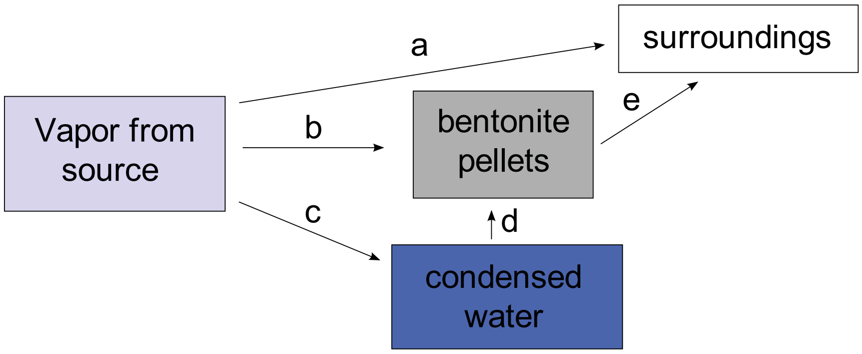

Figure 3-1. *Processes explored in the present study.*

References

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

Birgersson M, Börgesson L, Hedström M, Karnland O, Nilsson U, 2009. Bentonite erosion. Final report. SKB TR-09-34, Svensk Kärnbränslehantering AB.

Karnland O, Olsson S, Dueck A, Birgersson M, Nilsson U, Hernan-Håkansson T, Pedersen K, Nilsson S, Eriksen T E, Rosborg B, 2009. Long term test of buffer material at the Äspö Hard Rock Laboratory, LOT project. Final report on the A2 test parcel. SKB TR-09-29, Svensk Kärnbränslehantering AB.

SKB, 2011. Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project. SKB TR-11-01, Svensk Kärnbränslehantering AB.

Åkesson M, Börgesson L, Kristensson O, 2010. SR-Site Data report. THM modelling of buffer, backfill and other system components. SKB TR-10-44, Svensk Kärnbränslehantering AB