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Summary report on "sauna" effects

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Summary report on “sauna” effects

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Abstract

This report consists of two parts. The first concerns two tests performed with the aim of studying vapor transport and sealing capacity in the inner slot between the bentonite blocks and the canister in a KBS-3 deposition hole. These processes are studied as part of an ongoing investigation on so-called "sauna" effects, i.e. the potential process of accumulating salts in a deposition hole due to vaporization and vapor transport during the early stages of a KBS-3 lifespan. The tests here reported were made to complement an earlier study (Birgersson and Goudarzi 2016) on the same subject. In this earlier study water was fed directly to the inner slot in the experimental set-up, while in the tests reported here, water was fed through a bentonite component, which is obviously a more realistic representation of an actual deposition hole. While one of the performed tests was judged as a failure due to unsatisfying performance of the test equipment, the result from the other test gave new information on the involved processes. In particular it was shown that:

- The process of taking up water (presumably in vapor form) was considerably slowed down when water was fed through a bentonite component as compared to directly feeding water to the inner slot. Not surprisingly, the bentonite component was thus shown to function as a water transfer resistance, reducing the inflow of water into the inner slot (as compared to having water directly fed to the inner slot).
- The bentonite component though which water was fed remained basically water saturated during the course of the test, although it was exposed to drying (vaporizing) conditions at the side facing the inner slot. The rate at which vapor was produced was consequently small as compared to the transport of (liquid) water through the component.

In the second part of the report it is argued for that the process of accumulating severe amounts of salts in a KBS-3 deposition hole during the water saturation phase is highly unlikely and can be disregarded. This conclusion is reached by invoking several independent arguments:

- Salt accumulation is possible only if virtually all inflowing water is evaporated, whereas, with already a smaller part of the inflowing water remaining in liquid form, the accompanying salt will be distributed within the buffer during the saturation process and no severe accumulation of salt will occur. Under the considered conditions, it is expected that part of the inflowing water will remain in liquid form.
- The available experimental results show that the vapor transport capacity is not large enough to be able to support the inflow rates required to give a substantial salt accumulation effects. This is true both for the inner slot region and the outer pellets filled region.
- In case of the inner slot it can also be argued that if it is possible to transport liquid water radially within the buffer from the rock wall to the canister (which is required in order to have vaporization occur at the inner slot), it is also possible to transport liquid water axially, and salt accumulation effects will therefore be avoided.
- The experimental results also demonstrate that major vapor condensation effects are likely to occur within a KBS-3 deposition hole. In order for salt accumulation to pose a problem, on the other hand, huge volumes of water must be transported exclusively in the form of vapor long distances up in the overhead tunnel section. The experimental results rather suggest that water condensation will occur within the deposition hole, which will saturate and consequently shut off any salt accumulation processes. A relatively quick saturation of the parts of the buffer closest to the intersecting fracture is also in agreement with results from state-of-the-art THM-models (Åkesson et al. 2010).

Sammanfattning

Denna rapport består av två delar. I den första redovisas två tester gjorda för att studera ångtransport i och förslutningsförmånga hos den inre spalten mellan bentonitblock och kapsel i ett KBS-3 deponeringshål. Dessa processer studeras som en del i en pågående undersökning av så kallade ”bastu”-effekter, det vill säga eventuell saltackumulering i ett deponeringshål som följd av ångbildning och ångtransport under de initiala faserna i ett KBS-3 förvar. Testerna som rapporteras här utfördes som ett komplement till en tidigare rapporterad studie rörande samma frågeställning (Birgersson och Goudarzi 2016). I de tidigare utförda experimenten matades vatten direkt till den inre spalten, medan i testerna som redovisas här så matades vatten via en bentonitkomponent, vilket uppenbarligen bättre representerar förhållandena i ett verkligt deponeringshål. Medan det första genomförda testet bedömdes som misslyckat då testutrustningen inte fungerade som tänkt, gav det andra testet ny information om de ingående processerna. Specifikt visades:

- Hastigheten på vattenupptagsprocessen minskade betydligt när vatten matades genom en bentonitkomponent, jämfört med att mata vatten direkt till den inre spalten. Föga förvånande fungerar alltså bentonitkomponenten som ett flödesmotstånd, viket minskar vatteninflödet till den inre spalten (i jämförelse med direktmatning).
- Bentonitkomponenten igenom vilken vatten matades höll sig i princip vattenmättad under hela testets gång, trots att det utsattes för torkande förhållanden i den inre spalten. Hastigheten med vilken flytande vatten förångas i den inre spalten var alltså liten i förhållande till transport av vatten genom bentonitkomponenten.

I den andra delen av rapporten argumenteras för att det är högst osannolikt att större mängder salt anrikas i ett KBS-3 förvar under mättnadsfasen och att processen kan avfärdas. Denna slutsats baseras på flera oberoende argument:

- Saltanrikning är endast möjlig om i stort sett allt det inkommande vattnet förångas. Så länge en andel av det inflödande vattnet förblir i flytande form kommer det medföljande saltet att fördelas i bufferten under mättnadsprocessen och större saltanrikning kommer därmed att undvikas. Under de förhållanden som råder i ett KBS-3-förvar förväntas en större del av det inflödande vattnet att förbli i flytande form.
- De tillgängliga experimentella resultaten visar att ångtransportkapaciteten inte är tillräckligt stor för att klara de inflödeshastigheter som krävs för att ge signifikanta saltanrikningseffekter. Detta gäller både för transport i den inre spalten mellan bentonitblock och kapsel, och i den yttre pelletsfyllda spalten.
- För den inre spalten gäller också att om det är möjligt att transportera flytande vatten genom bufferten från bergvägg till kapsel (vilket krävs för att förångningen ska ske i den inre spalten), så kommer flytande vatten även att transporteras axiellt och saltanrikning kommer därför att undvikas.
- De experimentella resultaten visar vidare att ånga i stor utsträckning sannolikt kondenserar i bentoniten i deponeringshålet. För att saltanrikningseffekter ska utgöra ett problem krävs istället att mycket stora mängder vatten transporteras uteslutande i ångfas, långa sträckor upp i den överliggande deponeringstunneln. De experimentella resultaten indikerar i stället att kondensation av ånga sker i bentoniten i deponeringshålet, vilken vattenmättas och följaktligen omöjliggör fortsatt saltanrikning. En relativt snabb mättnad av delarna av bufferten närmast sprickan är också i överensstämmelse med resultat från THM-modellingar av KBS-3-förvaret (Åkesson et al. 2010).

Contents

1 Introduction

The process of water saturation of bentonite components is, for obvious reasons, central in the performance of many geological repositories for radioactive waste. In the particular case of crystalline host rock, local inflow conditions may vary drastically, depending on the distribution of water bearing fractures. It is therefore generally necessary to consider a large number of different wetting scenarios, e.g. by numerically simulating coupled thermo-hydro-mechanical (THM) processes (see e.g. Åkesson et al. 2010).

Under conditions where the saturation process takes considerable time (hundreds or thousands of years) it may, in addition, be necessary to consider certain chemical and biological processes. A particular scenario which manifests certain chemical aspects is the so-called "sauna" effect, where salt from inflowing groundwater is locally deposited in the repository due to vaporization and subsequent precipitation. This effect requires:

- **That only a single (or a few) fracture feeds water to a larger part of the repository**
  If the repository is locally intersected by many fractures, the saturation time will be short, and the effect is negligible; because it is dependent on vapor transport, the effect requires unsaturated conditions.
- **That the fracture(s) enters the repository in a relatively hot part**
  The effect is dependent on separation of water and (dissolved) salt due to vaporization. Vaporization is only conceivable if it occurs in a relatively hot part from which the vapor subsequently can be transported to a cooler part where it condenses.
- **That "escape paths" for vapor remain open**
  If vapor is taken up by bentonite rather close to the vaporization point to such an extent that the bentonite saturates and seals, there is no longer a driving force for sustaining the process

SKB has for a long time investigated various aspects related to the "sauna" effect within a KBS-3 repository (Karnland et al. 2000, Birgersson and Goudarzi 2013, 2016). The "sauna" effect is of particular interest for the KBS-3 concept, because it constitutes a possible scenario where increased corrosion rates of the copper canisters are conceivable.

Tests of water uptake when vapor was fed to a slot filled with bentonite pellets (Birgersson and Goudarzi 2013) showed that condensation plays a key role in the development.

In tests of vapor transport in slots between bentonite blocks and a heater (Birgersson and Goudarzi 2016), it was found that when the slots were directly open to the environment, considerable amounts of water could be transported through the slot without being taken up by the (dry) bentonite, whereas when the slots were covered by a massive bentonite block (as is the case in a KBS-3 repository), water condensation occurred in the block and only small amounts of water were lost to the environment.

This report is divided into two parts. The first part concerns two additional tests on vapor transport in an inner slot between bentonite and a heater, performed to complement the study reported in Birgersson and Goudarzi (2016). The second part of the report presents an evaluation of the likelihood and extent of possible salt accumulation during the water saturation stage in a KBS-3 repository, based on the results from the earlier tests as well as on other available information.

2 Complementary buffer slot tests

The tests performed in order to investigate vapor transport and sealing capacity of buffer slots (Birgersson and Goudarzi 2016) have been complemented with a test of slightly different design. In this design water was fed to the slot between bentonite and heater through a swelling bentonite component, while water was fed directly into the slot region in the earlier performed tests. The previous test design was thus modified by replacing the original bottom plate by a steel plate with a groove into which a bentonite ring was placed. A more detailed discussion on the previous test design is found in Birgersson and Goudarzi (2016).

In the new design, the bentonite component was fed water from below via a plastic filter. The outer and inner diameter of the bentonite ring was 18.2 cm, and 10.8 cm, respectively. The bentonite ring thickness was approximately 2 cm. Photographs of the set-up are shown in Figure 2-1.

The motivation for performing tests with water being fed through a bentonite component is that such a set-up is a considerably better representation of the actual situation in a KBS-3 deposition hole in comparison to having free water access directly in the slot between bentonite and heater. In deposition holes with intersecting fractures, water is obviously entering from the rock side and must thus pass through the entire thickness of the bentonite buffer in order to reach the inner slot between the bentonite and the canister. In the present tests the bentonite component is much thinner (2 cm) than the minimum width in a deposition hole (35 cm), and therefore the water transport capacity is reasonably considerably higher than in a real deposition hole (which also is necessary in order to perform the test within a reasonable time). Nevertheless, comparing the behavior of this test with and the previously performed tests gives information on how feeding water through a bentonite component influences the processes.

As in the previous tests, bentonite blocks (rings) were placed on top of each other on the bottom plate, thus creating the inner slot between copper heater and clay. Due to the modified design, the copper tube was now longer than the height of three bentonite rings, and a forth, thinner, ring had to be added (Figure 2-2). Similar to the earlier tests, on top of these four rings was placed a massive bentonite block, and the set-up was encapsulated in a plexiglass tube and the outer slot was filled with bentonite powder. The bentonite used both for blocks, powder and the ring in the bottom was MX-80.

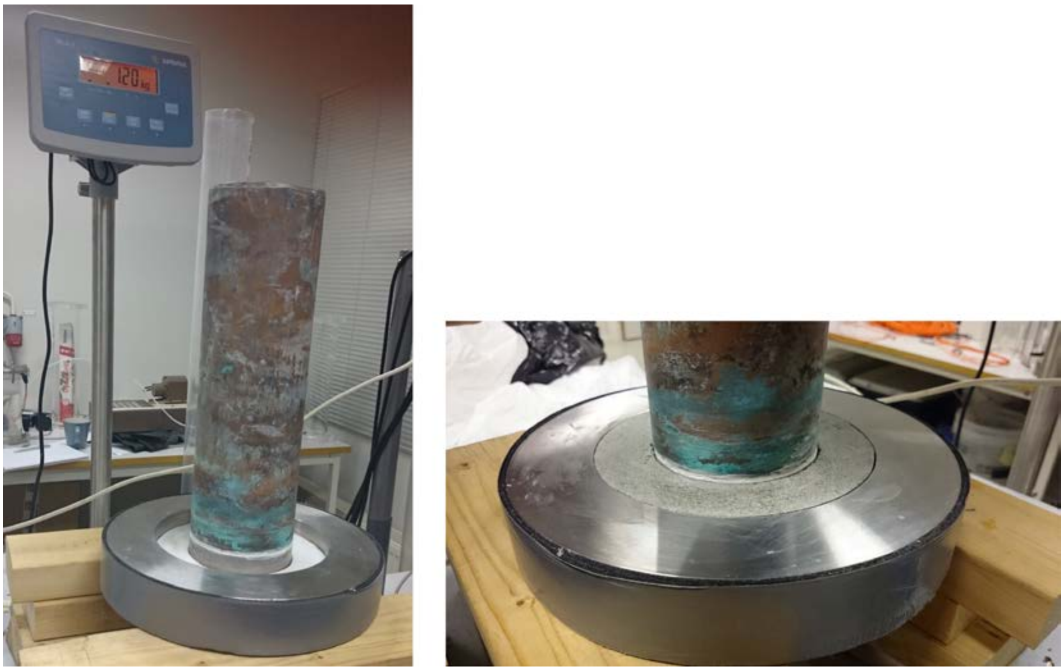

Figure 2-1. *Left: copper heater and steel bottom plate. The plastic filter (white) is visible at the bottom of the groove. The outer diameter of this groove is 18.2 cm, and the inner diameter is 10.8 cm. Right: bentonite ring emplaced.*

Figure 2-2. *Left: Four bentonite rings and a massive block stacked on top of each other. Right: The full set-up before starting the experiment.*

The powder and the blocks had an initial water-to-solid ratio of 16 %, while the bottom ring was aimed at being close to water saturation already at the beginning of the test. A photograph of the fully configured set-up is shown in Figure 2-2.

Water was fed to the system via in- and outlets at the bottom of the bottom plate. The water was circulated in the bottom filter by use of a peristaltic pump. Two tests were performed ("Test 8" and "Test 9"). From the behavior of the first one ("Test 8") it was suspected that the modified design did not work as intended – rather than inducing a water flow only in the plastic filter (see Figure 2-1), it appeared as if water was being pushed out into the slot (for details, see below). A slight modification of the set-up was therefore done before conducting Test 9: a mm-wide groove was routed between the inlet and outlet of the water feeding system (the pump) at the bottom in order for water to flow without having to be pushed through the plastic filter (and, evidently, up through the slot itself). With this modification, Test 9 behaved qualitatively different as compared to Test 8, which confirmed the flaw in the original design. Test 8 should therefore be considered as a failed test, but is anyway reported here for completeness.

In Test 8, the circulating solution was tap water, and in Test 9 the circulating solution was 0.6 M $CaCl_2$ (which was also used in parts of Test 7 in the previous tests).

Steel weights were put on top of the blocks to provide some counter force for possible upward swelling during the course of Test 8 (see right picture in Figure 2-2). The heater was kept at approximately 80 °C, similar to the previous tests. The main variables measured was mass of water fed into the system (referred to as "consumption" in the plots below), and the evolution of the mass of the full set-up, which gives the amount of water taken up by the bentonite (the whole set-up was placed on a scale, as seen in Figure 2-2). From these measurements also the water lost to the environment could be evaluated (by simply taking their difference).

2.1 Results

2.1.1 Test 8

The test was run for approximately one week. Water consumption and uptake is shown in Figure 2-3.

During the course of the test, major swelling of the set-up occurred. Swelling was noticed in particular at one side of the bottom, resulting in a tilt of the set-up, as shown in Figure 2-4.

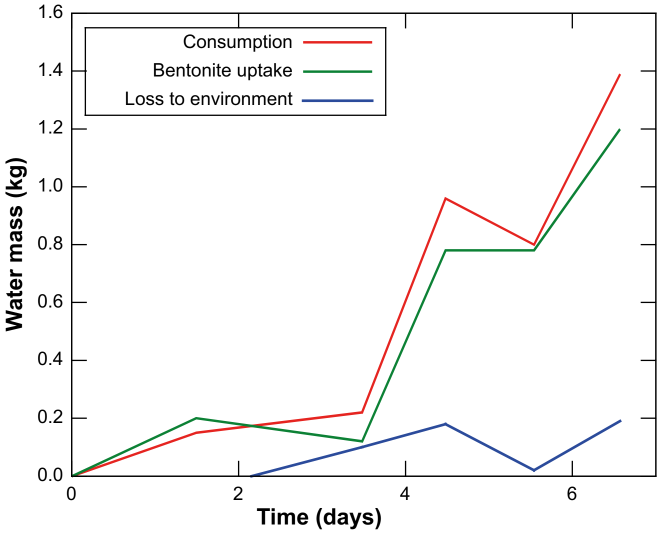

***Figure 2-3.** Water consumption and uptake in Test 8.*

***Figure 2-4.** Massive swelling occurred during the course of test. Moreover, the swelling was uneven, causing tilting of the set-up.*

Figure 2-5 – Figure 2-12 shows the state of various parts of the set-up at termination.

Figure 2-5 and Figure 2-6 show that rather extensive condensation and cracking occurred in the top block. In contrast to earlier results the condensation appeared over the whole inner top area, rather than being localized to a single point.

The ring located just below the massive top block showed basically no cracking. On the other hand, the bentonite had swelled extensively in the inner slot, as seen in Figure 2-7. This behavior is different from the earlier tests, which showed none or very minor swelling in the slot. The slot in the present experiment was, however, not water saturated – the water content was relatively low, as shown in Figure 2-8 (see also below).

The swelling in the inner slot was found to extend all the way down to the bottom of the set-up (Figure 2-9 and Figure 2-10). Everywhere the bentonite in the inner slot was rather dry (Figure 2-8). Also, the rings further down the stack were relatively free from cracks.

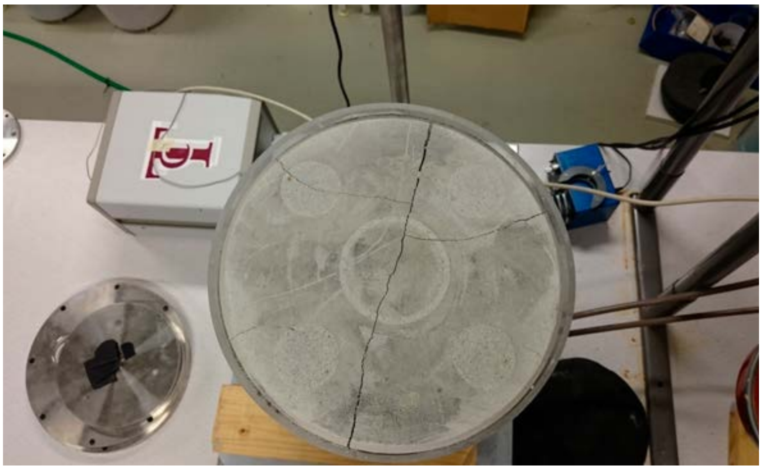

***Figure 2-5.** Top side of the top block in Test 8.*

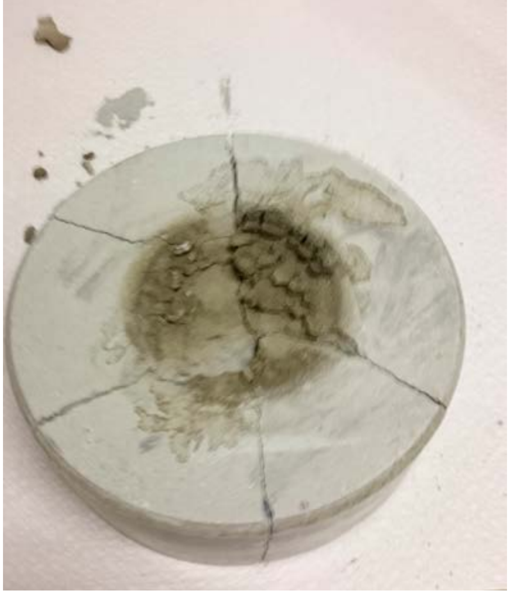

***Figure 2-6.** Bottom side of the top block in Test 8.*

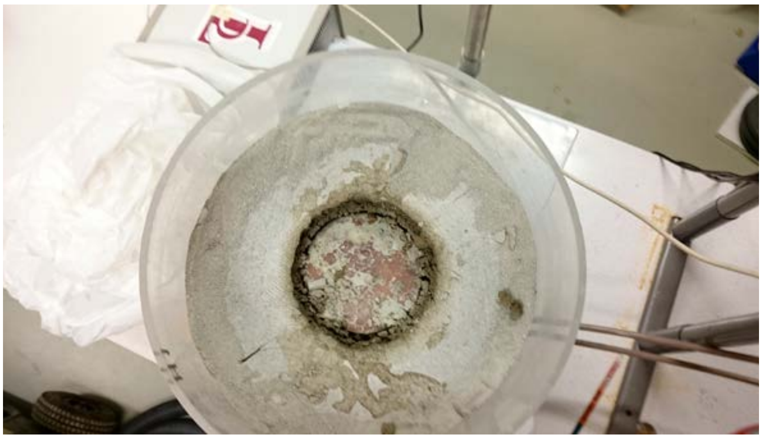

***Figure 2-7.** Top side of ring #4 in Test 8.*

Figure 2-8. *The texture of the bentonite in Test 8 which had swelled into the inner slot.*

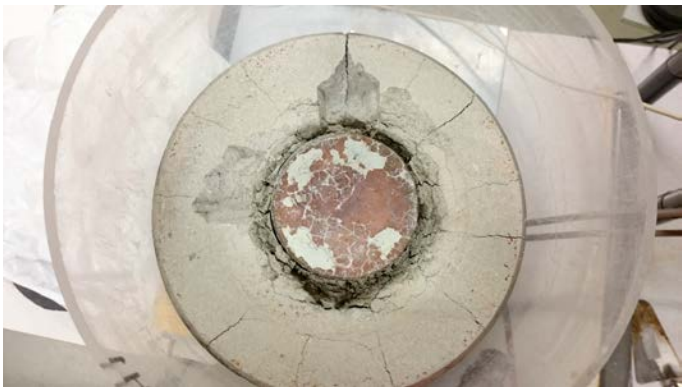

Figure 2-9. *Top side of ring #3 in Test 8.*

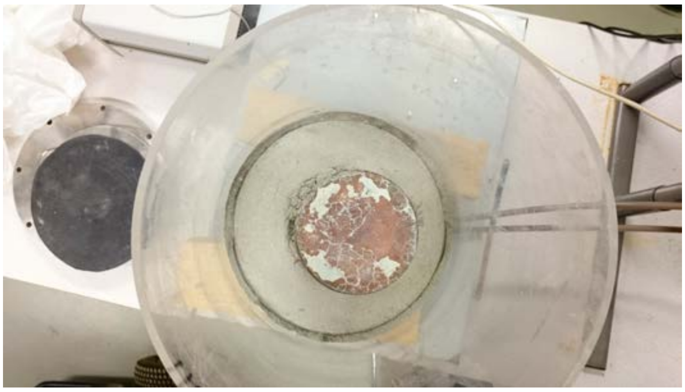

Figure 2-10. *Top side of ring #1 in Test 8.*

Figure 2-11 and Figure 2-12 show the state of the lower part of the set-up: obviously a lot of water had accumulated here, which explains the (uneven) swelling (Figure 2-4). Figure 2-12 also shows that the bottom bentonite ring had swelled upwards a significant amount. The outer parts of the bottom of the set-up were considerably more wet than the inner parts (see also Figure 2-14).

Figure 2-14 displays the water-to-solid mass ratios measured in samples taken during excavation. The approximate positions of these samples are indicated in Figure 2-13.

Figure 2-14 reveals that the wettest spots are the lower parts of the top block (Figure 2-6) and the outer part of the bottom of the set-up (which are very wet). Apart from these positions, the water distribution of the set-up is fairly even.

Figure 2-11. *Bottom side of ring #1 in Test 8.*

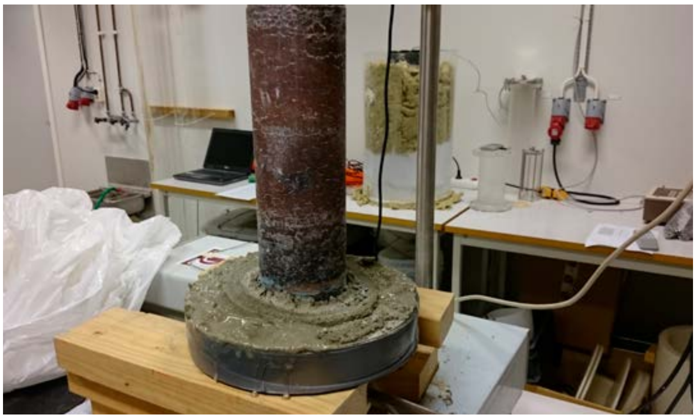

Figure 2-12. *Remaining bentonite (slurry and the bottom bentonite ring) in Test 8 after all bentonite blocks were removed.*

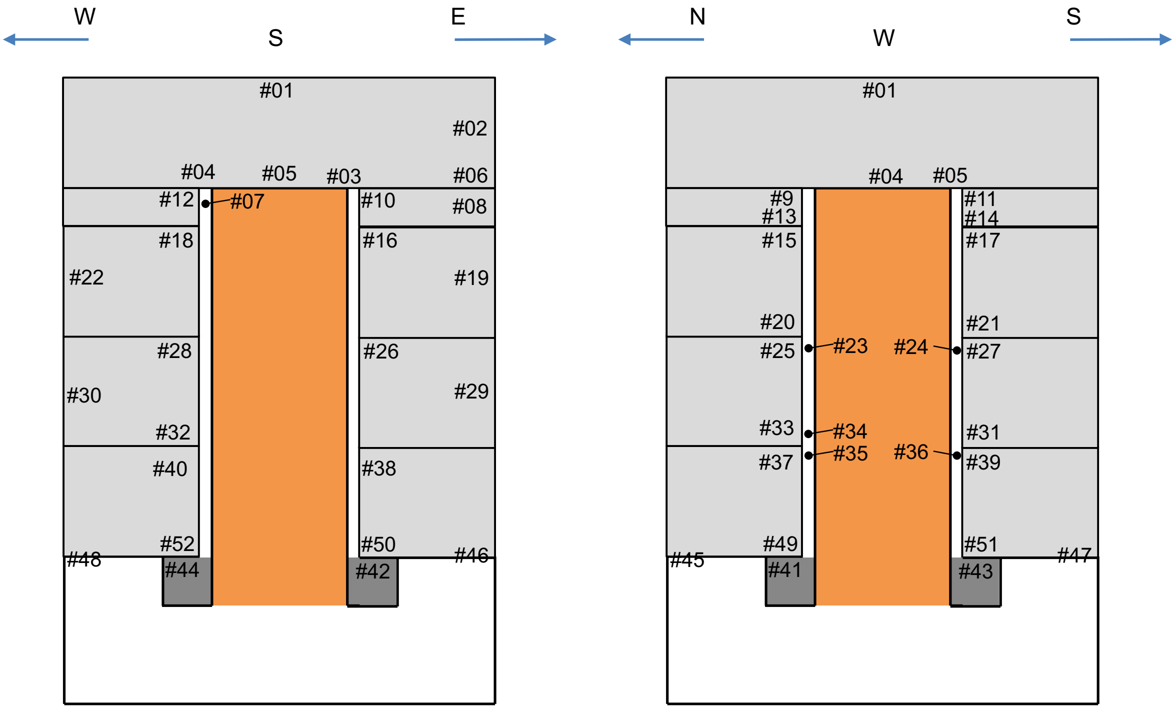

Figure 2-13. *Approximate positions of samples taken for water content determinations in Test 8. The right picture shows the set-up turned 90° as compared to the left picture.*

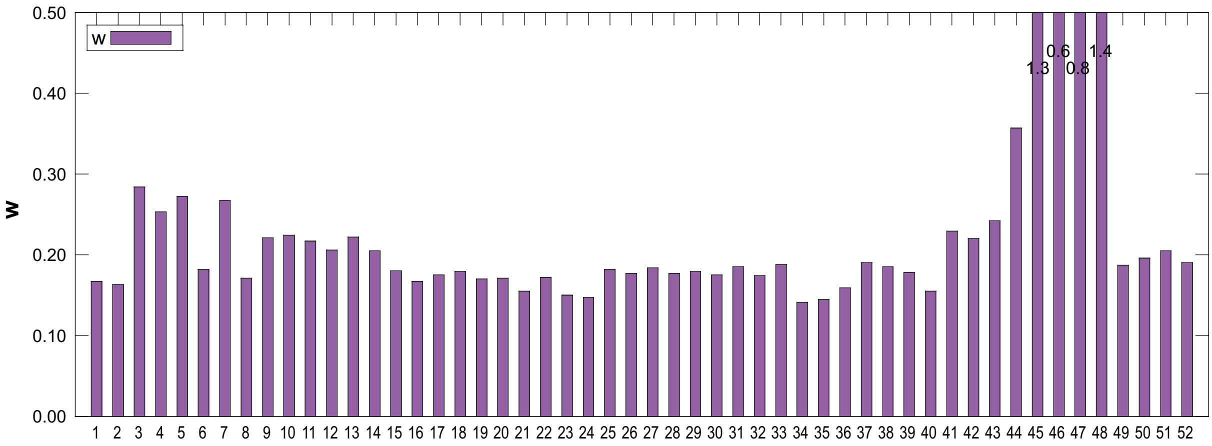

***Figure 2-14.** Water-to-solid ratio of all samples taken in Test 8. For position of the samples, see Figure 2-13.*

Additional comments

From the rather different behavior of this test as compared to the earlier performed, it is probably so that not only vapor transport has been involved in the present test. Water has most probably been pushed up through the slot as a consequence of pumping. This is also suggested from the quite irregular behavior of the water consumption/uptake curves (Figure 2-3).

It may also be noted that the counter weights were inefficient in preventing swelling, which is not unexpected concerning the rather large area of the swelling component.

Although the presence of water in the slot in the present test most probably is due to a malfunction of the set-up, it is interesting to note that water – which undoubtedly has been present in large parts of the inner slot (otherwise no swelling) – has accumulated at the top of the set-up. Thus, at some point, vapor transport (upwards) has occurred during the test. In contrast, basically no radial water transport, from the inner slot and outward, was detected.

2.1.2 Test 9

As previously mentioned, in Test 9 measures were taken to avoid water being pumped up in the bentonite slot by modifying the bottom plate with a groove between inlet and outlet. In this way the filter was kept saturated, while no pressure-build up occurred (the presence of the groove made the flow resistance low under all circumstances).

This test was run for approximately 50 days, and behaved very differently as compared to Test 8 with a considerably lower and much more regular water consumption rate (compare Figure 2-3 and Figure 2-15). This behavior confirmed both that the modification of the test set-up with a groove in the bottom plate gave the desired result, and that there reasonably was pressure build-up and resulting water flow in the slot in Test 8. Test 8 should consequently be considered a failure. It may also be noted that no problems with swelling of the lower part occurred in Test 9.

Total water consumption, water uptake, and loss as a function of time in Test 9 is plotted in Figure 2-15. Over the course of the 50 days of testing, approximately 0.25 kg water was lost to the environment, giving a loss rate of approximately 0.005 kg/day.

This loss rate is consistent with measurements in earlier tests, and confirms the conclusion made in Birgersson and Goudarzi (2016) that the slot is basically an isolated system in this set-up, the loss being due to drying of the outer parts of the set-up.

A general observation regarding the bentonite blocks in this test is that very little damage (cracks) had occurred as compared to several of the earlier tests performed with direct access to liquid water at the inner slot. This less "violent" behavior is similar to Test 6 in Birgersson and Goudarzi (2016) which was performed by restricting the water supply to 8 ml/day by means of a flow controlling unit. It is noted that this water supply rate is comparable to the average water consumption rate in the present test, which is approximately 17 ml/day. Note, however, that the water restriction in the present case is completely controlled by transport through the bottom bentonite ring (there is free access to water in the filter below). In this test, the rate of water being taken up by the bentonite is approximately 11 ml/day, to be compared with 3.5 ml/day in Test 6. The difference between these values is very close to the difference in the total water consumption in the two tests, which simply confirms that the inner slots are basically isolated systems.

Figure 2-16 shows the bottom side of the top block in Test 9. In contrast to several of the earlier performed test with a massive top block, no visual sign of a condensation nucleus was found.

Figure 2-17 shows the bottom ring of Test 9, seen from the bottom side. This ring had some minor cracks, but showed no visual signs of water condensation.

The bottom part of the set-up, showed in Figure 2-18, looked very different as compared to Test 8 (see Figure 2-12), confirming that Test 8 must have had liquid water pumped up in the slot. Although this part of the set-up is considerably more "dry" as compared to the slurry found in Test 8, it is very interesting to note that the bentonite ring through which the water was fed appears fully water saturated (this can be seen in a bit more detail in Figure 2-19). Thus, although the inner part of this ring had been exposed to the highest temperatures in the test (approximately 80 °C) for 50 days, no significant drying was observed. This observation demonstrates that the rate of liquid-to-vapor transfer, which evidently occurs in this region, is small in comparison to capacity of transporting (liquid) water through the bottom bentonite.

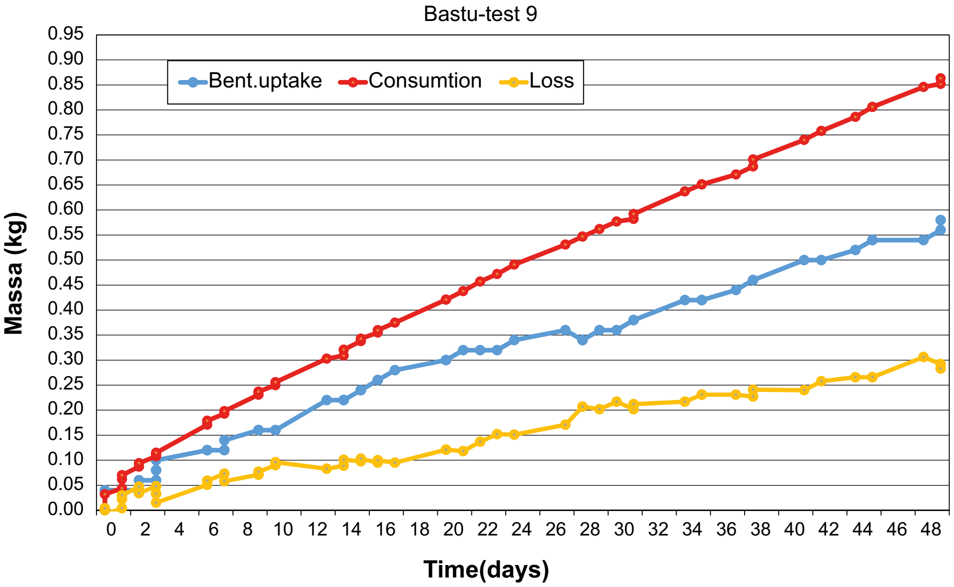

Figure 2-15. *Total water consumption, water uptake in the bentonite, and loss of water to the environment, measured in Test 9.*

Figure 2-16. *Bottom of top block in Test 9.*

Figure 2-17. *Bottom of bottom ring in Test 9.*

Figure 2-18. *Top of bentonite ring through which water was fed in Test 9.*

Figure 2-19. *Sampling of the bentonite in the ring thorough which water was fed in Test 9.*

During dismantling of the test, samples were taken at different places in the set-up and analyzed for water content. Figure 2-20 shows the approximate positions for each of the samples taken, and Figure 2-21 displays the measured water-to-solid mass ratios.

This data show much of the same trends as in earlier tests. There is a tendency of higher water-to-solid-ratio in the upper parts of the set-up, while there is no evidence of any radial gradients. This distribution may indicate that vapor condensation did occur also in this test, even if no visual proofs were found. It can also be noted that the water content of the outer part of the massive top block have lower water-to-solid mass ratio (samples 1 and 2). This is yet another indication that the water which is being lost to the environment in these tests originates from the outer bentonite parts (while the inner slot basically functions as an isolated system).

It is also worth noting the high water-to-solid mass ratios in the samples taken in the bottom bentonite ring through which water was fed (samples 26, 28, 29, and 31). This confirms the visual impression that this ring basically remained water saturated.

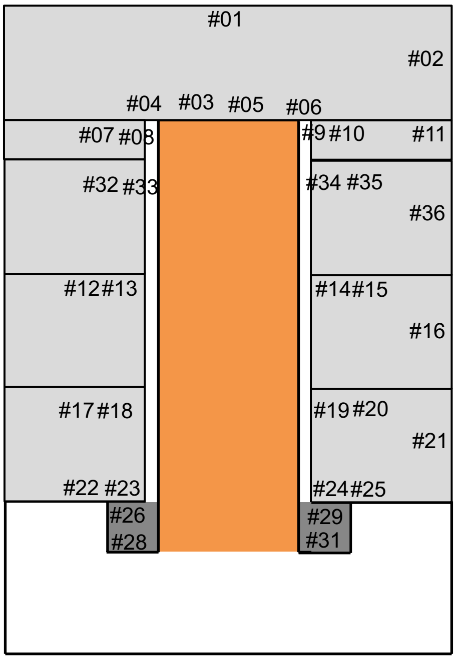

Figure 2-20. *Approximate positions of samples taken for water content determinations in Test 9. The measured water-to-solid mass ratios are shown in Figure 2-21.*

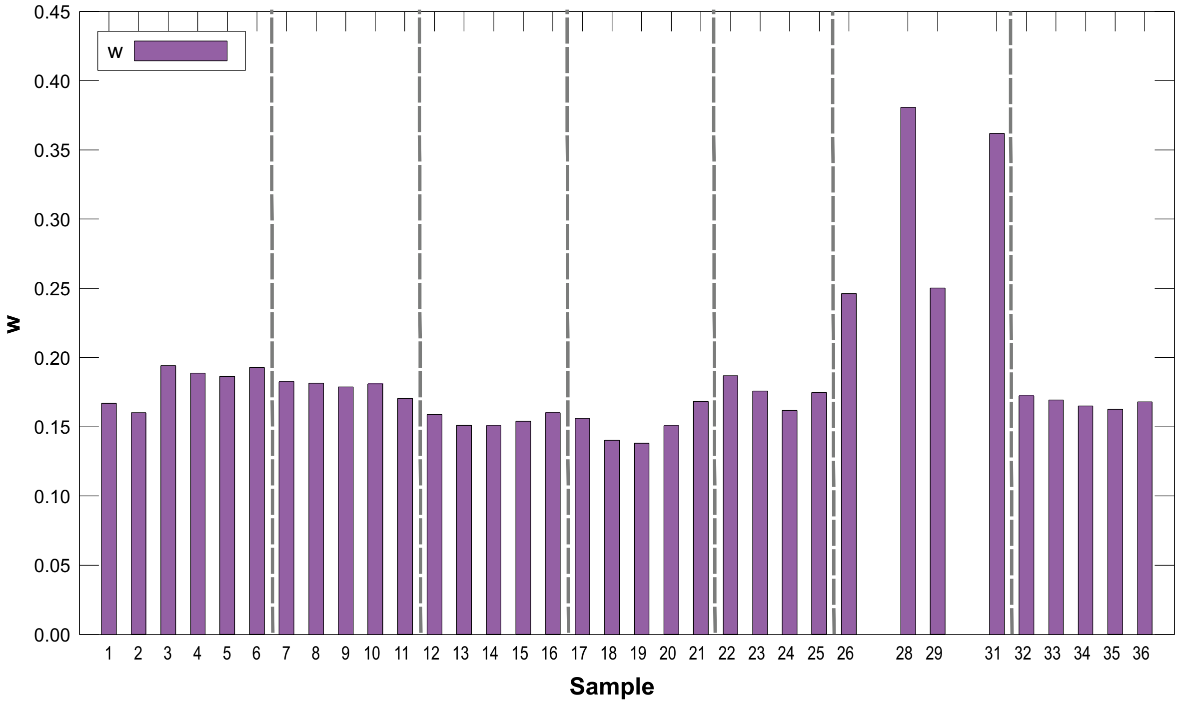

Figure 2-21. *Water-to-solid ratio of all samples in Test 9. For position of the samples, see Figure 2-20. It was not possible to obtain samples 27 and 30 because of the rather limited height of the bottom bentonite ring through which water was fed (2 cm). They are however still in this list in order not to interrupt sample-ID:s in the original sampling plan.*

3 Evaluation of the possibility of salt accumulation during the water saturation phase at the Forsmark site

In this chapter we will analyze the likelihood of significant salt accumulation occurring during the water saturation phase of a KBS-3 repository, for the specific conditions expected at the Forsmark site. By salt accumulation is here meant an increase of salt mass in a local region within the buffer, due to the combination of inflowing groundwater and vaporization. The evaluation is done by combining results from state-of-the-art THM-modelings of this process (Åkesson et al. 2010), available ground water flow models for Forsmark (Malmberg et al. 2013), and the results obtained from the "sauna" effect studies in Birgersson and Goudarzi (2013, 2016), including those reported in Chapter 2 of the present report. A summary of the performed tests in these two studies is given in Table 3-1 and Table 3-2, respectively.

Table 3-1. Summary of the tests performed of vapor transport and water uptake in pellets fillings (Birgersson and Goudarzi, 2013).

Test in pellets (R-13-42)

Test name	Thermal conditions	Lid	Filling thickness	Swelling conditions
Oven1	Isothermal 90 °C		10 cm	Free axial swelling
Room1	Gradient 90 °C	Lid	10 cm	Free axial swelling
Room2	Gradient 90 °C	No lid	10 cm	Free axial swelling
Room3	Gradient 90 °C	No lid	20 cm	Free axial swelling
Room4	Gradient 90 °C	No lid	10 cm	Constrained axial swelling

Table 3-2. Summary of the tests performed on vapor transport and water uptake in bentonite slots (Chapter 2 of this report and (Birgersson and Goudarzi 2016)).

Tests in inner slot (TR-15-09 and this report)

Test name	Bentonite blocks	Water supply	Thermal condition
Test 1	1 ring	Full water supply	Gradient 80 °C
Test 2	1 ring	Full water supply	Gradient 80 °C
Test 3	1 ring	No water/full water supply	Gradient 80 °C
Test 4	2 rings	Full water supply	Gradient 80 °C
Test 5	3 rings, 1 massive block	Full water supply	Gradient 80 °C
Test 6	3 rings, 1 massive block	Limited water supply 8 ml/day	Gradient 80 °C
Test 7	3 rings, 1 massive block	Various water supplies	Gradient 80 °C
Test 8	3 rings, 1 massive block	FAILED	Gradient 80 °C
Test 9	3 rings, 1 massive block	Water fed via bentonite	Gradient 80 °C

3.1 The scenario under consideration

We will consider the case where a single fracture intersects a deposition hole and thereby provides water for saturating a substantial amount of the surrounding bentonite. When the temperature in the region where water enters is elevated, vaporization of the water is conceivable, which in turn may result in accumulation of salt. Implicitly it is thus assumed that the fracture enters the deposition hole near the canister. We will assume the incoming water to be dominated by chloride, at a concentration of 0.2 M, which is in line with assumed groundwater compositions of the Forsmark site (e.g. Sena et al. 2010).

We will consider inflow rates in the range 10^{-7}–10^{-1} L/min, which covers the range of inflows, at atmospheric conditions, evaluated from ground water flow models of the Forsmark repository (Malmberg et al. 2013).

A first important point to make, illustrated in Figure 3-1, is that the mere presence of a vaporization process is not sufficient for drawing the conclusion that any significant salt accumulation mechanism is at play. On the contrary, in order for salt to accumulate to any significant degree, it is required that the major part of the incoming water is vaporized and transported as a gas some distance. Only in such a case will there be a significant salt concentration increase in the liquid left behind. As an example, consider a liquid-to-vapor conversion rate of 90 % of the inflow rate, which would give a 10-fold increase of the concentration of the incoming water, i.e. the solution being transported in liquid form would have a chloride concentration of 2 M. Although this concentration is high enough to raise concerns (e.g. the requirement in SR-site in order to exclude chloride assisted canister corrosion is a chloride concentration below 2 M (SKB 2011)), the actual accumulation of salt even in this case is not severe, since the solution is still being transported away from the inflow point (flow q_{liquid} in Figure 3-1). In the following evaluation, we will therefore consider the case of *all* incoming water being vaporized and transported away as a gas phase, leaving behind precipitated (solid) salt. This assumption is not very realistic, but is pursued here in order to evaluate limits of the extent of possible salt accumulation during the saturation process in a KBS-3 repository. In particular, it should be noted that this assumption is not compatible with the state-of-the-art THM-models used e.g. for evaluating the water saturation phase within SR-Site (Åkesson et al. 2010). These models account for water transport both in terms of vapor diffusion and in terms of advection of a liquid phase (Darcy's law), and have been extensively validated, also in systems at high temperatures and with large temperature gradients (e.g. Börgesson et al. 2016a, b).

Salt accumulation effects in bentonite have indeed been observed, but only under special circumstances, where it is reasonable to expect the liquid-to-vapor transformation rate to be comparable to the inflow rate, e.g. in experiments where liquid transport is effectively restricted to one dimension (Fernández and Villar 2010), or if boiling has been induced (Kaufhold et al. 2017).

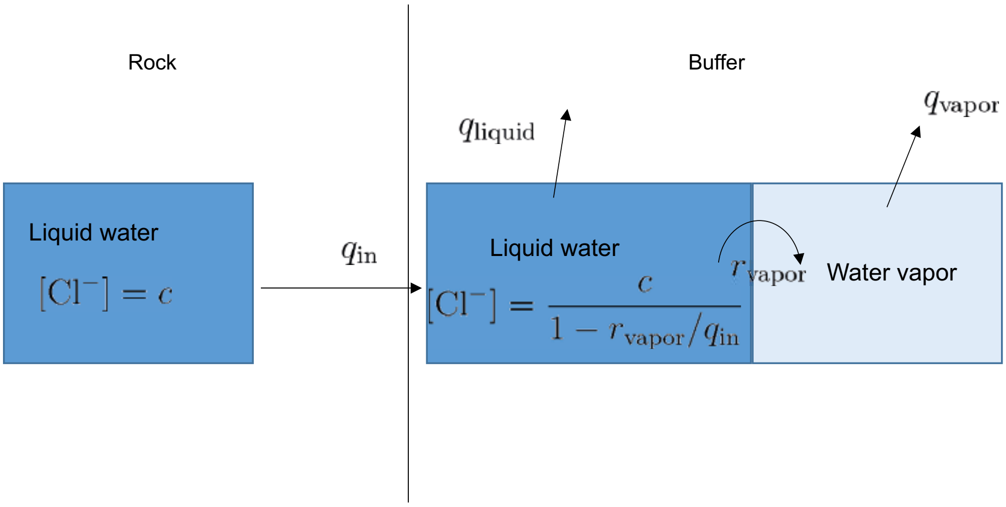

Figure 3-1. *If liquid water with chloride concentration c is entering the buffer from the rock at a rate* q_{in}*, while the rate of transformation between liquid and vapor in the buffer is* r_{vapor}*, the concentration of the remaining liquid water is* $c/(1-r_{vapor}/q_{in})$*. This solution will continue to flow (i.e. contribute to saturation) within the buffer. Only in the case that* r_{vapor} *is comparable in size to* q_{in} *will there be a significant salt accumulation effect.*

3.2 Time scale

As a vaporization process requires elevated temperatures and temperature gradients, it is expected that possible salt accumulation effects will be influential only in the early stages of the repository lifespan. A maximum bentonite temperature of 90 °C is estimated to be reached in a KBS-3 repository already within 10–20 years after closure, while a peak temperature at the rock wall at canister mid-height of approximately 60 °C is expected to be reached after about 30–50 years (Åkesson et al. 2010). After approximately 100 years, the corresponding temperatures are ~ 65 °C and ~ 55 °C, respectively, and after 1 000 years, the difference between these temperatures are only a few degrees, both being close to 40 °C. The saturated vapor pressure at 40 °C is approximately 7 kPa, to be compared with 47 kPa at 80 °C (which has been the water temperature in the majority of experiments conducted within the present studies). Thus, this 7-fold decrease of the saturated vapor pressure, combined with the fact that only minor temperature gradients remains after 1 000 year, suggests that possible effects of vaporization will be negligible after this time period. Moreover, even without intersecting fractures, the repository is saturated via the rock matrix, and is therefore estimated to be completely saturated after 1 000–2 000 years, under the assumption that the matrix hydraulic conductivity is 10^{-13} m/s (Åkesson et al. 2010). In the following we will therefore assume the inflow scenario discussed above to last for the first 1 000 years of the repository lifetime.

3.3 Maximum salt accumulation

For a given inflow rate (q_{in}), the amount of accumulated chloride in the specified scenario is

$$n_{Cl} = q_{in} \cdot c \cdot t = 1.05 \cdot 10^8 \text{ mol/L} \cdot \text{min} \cdot q_{in} \qquad \text{(Equation 3-1)}$$

where the inflow rate is assumed to have units L/min, $c = 0.2$ M is the chloride concentration, and $t = 1\,000$ years $= 5.256 \cdot 10^8$ min, is the assumed total time for the process.

In Table 3-3 the corresponding amount of accumulated chloride as given by Equation 3-1 for the considered range of inflow rates is listed. In this table the amount of accumulated chloride is also listed in terms of corresponding total mass of NaCl, in terms of the corresponding the mass fraction of NaCl with respect to the total buffer mass (23 600 kg), and in terms of the total chloride concentration if distributed in a fully saturated buffer (6 450 liter).

Possibly detrimental effects due to accumulated salt will only be manifest after the saturation process is complete, since canister corrosion requires the presence of (liquid) water. In the saturated state, salt which may have precipitated locally during the saturation process will relatively quickly diffuse out in the entire buffer region (and eventually out in the entire repository). As a criterion for whether a certain amount of accumulated salt in the adopted scenario poses a problem regarding canister corrosion we will therefore use the corresponding concentration when the precipitated chloride is distributed in the fully saturated buffer – if this concentration is below molar values, the effect of salt accumulation on the corrosion process is negligible. Using this criterion, Table 3-3 shows that the amount of accumulated salt in the adopted scenario begins to pose a problem for inflow rates in the range 10^{-5}–10^{-4} L/min. Considering the very pessimistic assumptions adopted, we will use 10^{-4} L/min as a critical limit – for inflows below this value, the potential amount of possibly accumulated salt is too small to be of any concern.

Note that the total amount of water entering the deposition hole at an inflow rate of 10^{-4} L/min during 1 000 years corresponds to the pore volume of approximately eight deposition holes. In order to actually deposit the ~600 kg of NaCl given by this analysis, it is thus required that this amount of water is transported *exclusively* in form of vapor far out in the overhead tunnel section. Such a process can be judged as highly unlikely by simply noting the strong tendency for vapor condensation observed in many of the tests performed within the "sauna" effect project (see further Section 3.6). Furthermore, state-of-the-art THM simulations of the saturation process from a single fracture sectioning a deposition hole predicts that a saturation front reaches the canister within only 2–35 years for water inflows in the range 10^{-5}–10^{-3} L/min (Åkesson et al. 2010, Malmberg et al. 2013). These simulations thus suggest that possible vaporization effects at most can only be active during the first few years after closure, giving negligible salt accumulation.

Table 3-3. Amount of accumulated chloride in the adopted inflow scenario for different values of inflow (q). The second column lists the total amount of water during the 1 000 year duration, both in liters and in terms of percentage of the total pore volume of a deposition hole (6 450 l). The third column lists the amount of chloride accumulated (Equation 3-1), and the fourth and fifth columns lists the corresponding mass of NaCl, in absolute terms and as a mass fraction of the whole buffer dry mass (23 600 kg), respectively. The last column lists the corresponding concentration of chloride if distributed in the entire pore volume of the deposition hole (values in red corresponds to oversaturation with respect to NaCl).

q (L/min)	Total water volume (L)	Amount Cl (mol)	mass NaCl (kg)	mass fraction NaCl	Cl concentration (M)
$1 \cdot 10^{-7}$	$5.26 \cdot 10^{1}$ (0.82 %)	$1.05 \cdot 10^{1}$	0.61	0.00 %	0.00163
$1 \cdot 10^{-6}$	$5.26 \cdot 10^{2}$ (8.2 %)	$1.05 \cdot 10^{2}$	6.1	0.03 %	0.0163
$1 \cdot 10^{-5}$	$5.26 \cdot 10^{3}$ (82 %)	$1.05 \cdot 10^{3}$	61	0.26 %	0.163
$1 \cdot 10^{-4}$	$5.26 \cdot 10^{4}$ (820 %)	$1.05 \cdot 10^{4}$	610	2.6 %	1.63
$1 \cdot 10^{-3}$	$5.26 \cdot 10^{5}$ (8 200 %)	$1.05 \cdot 10^{5}$	6 100	26 %	16.3
$1 \cdot 10^{-2}$	$5.26 \cdot 10^{6}$ (82 000 %)	$1.05 \cdot 10^{6}$	61 000	260 %	163
$1 \cdot 10^{-1}$	$5.26 \cdot 10^{7}$ (820 000 %)	$1.05 \cdot 10^{7}$	610 000	2 600 %	1 630

3.4 Possibility to accumulate salt in the inner slot

We now relate the evaluated critical inflow rate to the information on vapor transport capacity that has been gained in the performed tests, starting with vapor transport in the inner slot between bentonite and canister.

Test 6 was performed with restriction of water inflow to $5.5 \cdot 10^{-6}$ L/min (8 ml/day), i.e. far below the adopted critical limit 10^{-4} L/min. Despite this very restricted inflow, Test 6 clearly demonstrated that the bentonite gained water during the entire course of the test (approximately 90 days). This behavior, in turn, shows that the rate at which water was transported out of the slot region is lower than $5.5 \cdot 10^{-6}$ L/min. In fact, since the rate at which water was lost to the environment in this test was no larger than the loss rate recorded in the test where no water was injected (Test 7), it can be concluded that the water transport rate out of the slot region is *much smaller* than $5.5 \cdot 10^{-6}$ L/min (the water lost originate from drying of the outer parts of the tests, which was also seen in Test 9, see Section 2.1.2). Translating this result to a full scale geometry is done by scaling with the ratio between the slot circumferences in a KBS-3 deposition hole and in these tests, i.e. 1.05 m/0.1 m = 10.5. It can thus be concluded that the transport rate out of the slot region in a KBS-3 deposition hole is *much smaller* than $10.5 \cdot 5.5 \cdot 10^{-6}$ L/min $\approx 6 \cdot 10^{-5}$ L/min. This transport rate is so small that it will limit any possible salt accumulation effect in the slot region to such an extent that it can be disregarded.

Note that this conclusion was reached without even considering the possibility for liquid water to enter the inner slot region in the first place, which of course is a further requirement for salt accumulation to occur there. However, if liquid water is able to be transported radially, from the rock wall into the region of the inner slot near the canister, it is certainly so that it can and will be transported in liquid form also in the axial direction. It is consequently impossible to have a vaporization process occurring in the inner slot without simultaneous liquid water transport away from the inflow point, which in turn inhibits salt accumulation.

3.5 Possibility to accumulate salt near the deposition hole rock wall

The only remaining possibility for salt accumulation in the scenario under analysis is that it will occur in the pellets slot in the vicinity of the water bearing fracture in the rock wall. The temperatures in this region are significantly lower than in the bentonite nearest the canister; a peak value of 60 °C is estimated. This implies that the effect of vaporization is mitigated as compared to the conditions of the major part of the performed tests. Moreover, possible salt accumulation in the region of the outer pellets slot is a much less severe process than having salt accumulated close to the canister.

The main question is how large vapor transport capacity that can be ascribed to the outer pellets slot. An upper limit can be set by looking at the performed tests on vapor transport through pellets slots. Two of these where conducted with a thin pellets fillings (10 or 20 cm initial thickness) unconfined in the axial direction ("room2" and "room3"). Looking at the maximum water consumption rates in these tests gives a vapor transport capacity of $\sim 3 \cdot 10^{-3}$ L/min (65 kg water lost to the environment in the first 15 days in test "room3"). Being unconfined, this set-up is however not very representative of the pellets slot in a KBS-3 repository deposition hole (in addition to being far too thin). In the test performed where measures were taken to restrict vertical movements ("room4"), the maximum water consumption rate was considerably lower, $\sim 7 \cdot 10^{-4}$ L/min (15 kg lost in the first 15 days).

Although the test "room4" better represent the conditions of the pellets slot in a KBS-3 repository, it should be emphasized that the latter value still represents an overestimation of the total vapor transport capacity in a KBS-3 pellets slot. The pellets filling in a KBS-3 repository is several meters high, while the test conditions were such that laboratory conditions (room temperature and RH) prevailed close to the (warmer and much thinner) pellets filling. Furthermore, the exposed water surface in the lab test covered the entire cross section area of the pellets filling, $A_{filling} = \pi \cdot (0.2 \text{ m})^2 = \pi \cdot 0.04 \text{ m}^2$, while in the KBS-3 repository the water is instead fed from a fracture with area $A_{fracture} = \pi \cdot 1.75 \text{ m} \cdot \delta$, where δ is the aperture (and the fracture is assumed to be oriented horizontally). Fracture apertures are expected to be below 0.1 mm (Hedström et al. 2016), and inserting $\delta = 0.0001$ m gives $A_{fracture} = \pi \cdot 0.000175 \text{ m}^2$, i.e. a factor ~230 smaller than $A_{filling}$. (Note that the cross section area of the KBS-3 pellets filling is $A_{KBS-3} = \pi \cdot [(0.875 \text{ m})^2 - (0.85 \text{ m})^2] = \pi \cdot 0.043 \text{ m}^2$, i.e. very similar to $A_{filling}$.) Thus, although it is difficult to exactly quantify the factor by which to scale the measured water consumption rate measured in test "room4", it is highly likely that the corresponding value for KBS-3 conditions is below the adopted critical limit of $1 \cdot 10^{-4}$ L/min (simply the difference in water vapor pressure at 90 °C and 60 °C gives a factor 0.3).

The above result imply that the maximum vapor transport capacity in a KBS-3 pellets filling is too small to be able to sustain an inflow rate of $1 \cdot 10^{-4}$ L/min in terms of vapor only. It can thus be argued that either the inflow is too small to pose a problem regarding salt accumulation (see Section 3.3), or the incoming water will be (partly) transported in liquid form and thus prevent any major salt accumulation from occurring. It may also be noted that major water condensation occurred in the pellets in all of the performed tests, as discussed further in the next section. The result that the inflowing water remains (partly) in liquid from also agrees with the behavior of state-of-the-art THM-models for the saturation process (Åkesson et al. 2010, Malmberg et al. 2013).

3.6 Comment on water condensation

The arguments put forward in the previous sections for that severe salt accumulation effects will not occur during the water saturation phase of a KBS-3 repository have mainly been based on estimations of vapor transport capacity evaluated from the performed tests in pellets fillings and bentonite slots. It should also be recognized that one of the major findings in the performed studies is the strong tendency for vapor to condensate in localized points under conditions relevant to a KBS-3 deposition hole, in particular in the presence of temperature gradients. A striking example of vapor condensation in a growing "nucleus" is shown in Figure 3-2, which shows the state of the test Room2 reported in Birgersson and Goudarzi (2013). In this test vapor is transported through a pellets filling at a maximum rate of $\sim 2 \cdot 10^{-3}$ L/min (approximately 50 kg of water in the first 15 days), which certainly demonstrates that a significant amount of vapor can be transported through dry bentonite pellets without being absorbed. On the other hand, what is also occurring is a rather extensive uptake of water in form of a localized condensation "nucleus" which expands during the course of the test. Eventually this "nucleus" covers the entire area of the set-up, and the water loss rate lowers significantly, being $\sim 5 \cdot 10^{-4}$ L/min at the end of the test.

The demonstrated tendency for water condensation in the performed tests strongly suggests that even if significant vapor transport should occur during some phases of the water saturation processes, this vapor will condense in the upper part of the deposition hole rather than being transported far out in the tunnel backfill.

Figure 3-2. *State of the pellets filling in test Room2 in Birgersson and Goudarzi (2013). The photo shows the pellets filling from above; the water source is below, and the direction of the vapor transport is out of the picture. A clear division is seen between very wet pellets (the top part) and dry pellets (bottom). The water uptake occurred in such a way that the wet part "propagated" across the filling until eventually all pellets were wet. During the course of this process, a substantial amount of vapor was able to pass through the dry part of the pellets filling without being taken up by the dry bentonite.*

Note that the total amount of NaCl which is deposited in the scenario described in Sections 3.1–3.3 requires that the vapor does *not* condense in the upper part of the deposition hole. The amount of NaCl deposited under a considerably more realistic scenario where condensation occurs is related to the available pore water volume in the deposition hole, and becomes independent of inflow rate (assuming that it is large enough for saturation to occur within the considered 1 000 years). With an accumulated inflow corresponding to the total pore volume of a deposition hole, the accumulated amount of NaCl is only approximately 75 kg (340 mol).

3.7 Summary

In this chapter it has been argued that severe salt accumulation effects as a consequence of vaporization of the incoming water in a fracture sectioning a deposition hole in a KBS-3 repository is highly unlikely. There are several reasons for this:

- For significant amounts of salt to accumulate, the major part of the inflowing water must transform into vapor, rather than continue to flow in liquid form. For the relevant inflow geometry, it is highly unlikely that the liquid flow is suppressed to such an extent. It is also verified in state-of-the-art THM models that significant liquid flow is maintained.
- The experimental results strongly suggest that the vapor transport capacity within a KBS-3 buffer is not large enough to support significant amount of salt accumulation.
- The experimental results also indicate that vapor will be taken up in a condensation nucleus, thus shutting off the process.

Given the knowledge obtained from the performed tests on how vapor interacts with bentonite components, a plausible scenario involving vapor transport during the water saturation phase is illustrated in Figure 3-3.

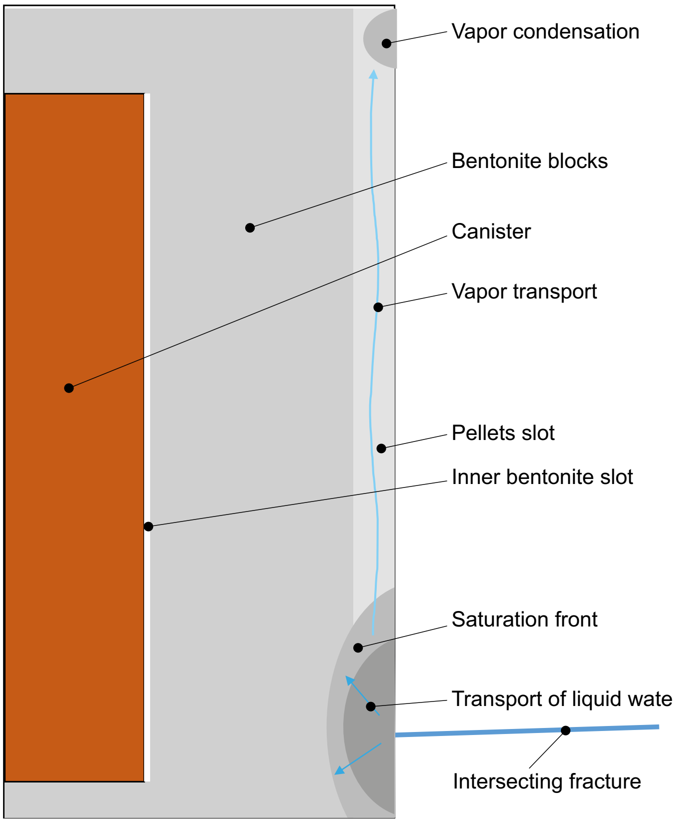

Figure 3-3. *Illustration of how vapor transport could influence the water saturation process in case of a single fracture intersecting the deposition hole close to the lower part of the canister, based on the knowledge gained from the performed tests and the present state-of-the-art THM-models of the saturation process. At the intersecting fracture, water is partly transported in liquid from, causing a redistribution of the incoming salt and thus avoiding severe salt accumulation. The propagation of such a saturation front is compatible with the result from state-of-the-art THM-models of the saturation process. Vapor transport may be present, but only to a significant degree in the outer pellets slot; in the inner bentonite slot, it has been demonstrated that the vapor transport capacity is too small. Finally, possible vapor being transported axially in the pellets slot is very likely to condensate as liquid water in the upper part of the deposition hole.*

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