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Technical conference paper

Abandonment of an extremely deep Cavern at Frisia Salt

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SMRI Spring 2009 Technical Conference
27-28 April 2009
Krakow, Poland

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Abstract

Since 1995 rock salt has been solution mined at the Barradeel concession near Harlingen in the Northwest of the Netherlands by FRISIA Zout at a depth between 2500 and 3000 meters making it the deepest salt mine in the world (Gillhaus 2006). This extreme depth has some implications for the mining process. At this depth the higher differential between rock and cavern pressure and the higher geostatic temperature than for conventional caverns accelerate the salt creep.

In 2004 the subsidence limit was almost reached at the BAS-1 and BAS-2 caverns. At this time the abandonment project of BAS-2 started. The BAS-2 cavern was shut-in for a long term high pressure shut in test and four bleed off and compression tests were performed. After the shut-in these pressures were recorded and are now simulated by a model incorporating creep, cavern heating and permeation.

Compression tests and the comprehensive model indicate that the cavern has been in a continuing permeating condition soon after shut-in and that the rate of fluid leak off stays below fracturing levels.

The BAS-2 cavern shows normal heat-up behaviour for a shut in cavern. The major expansion effects of heating up of the cavern contents and cavern surroundings have been incurred as a permeation process without any indication of formation fracturing.

As the differential between the virgin far field and cavern pressure, hence the squeeze rate, reduces in the future and the major effect of temperature expansion has been incurred it is considered very unlikely that fracturing conditions will occur in the future. Hence fluid will be displaced from the cavern in a permeation process.

The drive mechanism for permeation will weaken with time - as the cavern shrinks –and likely result in a ‘spongy’ salt/rock mass above an around the top of the cavern. Once the fluid pores and fluid filled spaces have no further communication with the cavern drive mechanism the migration process is expected to stop. The effects on subsidence of the expected migration process is thought to be marginal. The compression tests and the comprehensive model suggest the presence of high linear creep.

Key words: Cavern Abandonment, Hydraulic Fracturing, The Netherlands, Zechstein

Introduction

Since 1995 rock salt has been solution mined at the Barradeel concession near in the Northwest of the Netherlands by FRISIA Zout. The brine is lifted to the surface and transported to Harlingen where it is processed by vacuum evaporation. The salt is mined at a depth between 2500 and 3000 meters making it the deepest salt mine in the world (Gillhaus 2006). This extreme depth has implications for the mining process. At this depth the higher differential between rock and cavern pressure and the higher geostatic temperature than for conventional caverns accelerates the salt creep. The creep rate increases with cavern diameter. During production this means that salt can be produced at steady state. In other words the cavern volume became in a dynamic equilibrium with the brine production.

The salt creep leads to surface subsidence that is allowed to a maximum of 35 cm by the authorities. This makes subsidence the main production restriction for FRISIA Zout. In 2004 the subsidence limit was almost reached at the BAS-1 and BAS-2 caverns. At this time the abandonment project of BAS-2 started. The BAS-2 cavern was shut in for a long term high pressure shut in test and in the following years a few bleed off and compression tests were performed.

The aim of this research is to explain the pressure build-up in the shut in BAS-2 cavern. This paper can be subdivided into three parts. In the first part it will provide an overview of the geology, the well situation and the pressure data of the BAS-2 cavern. Then the various processes that are active in the cavern and influence pressure build-up will be identified and described. Finally based on the data gathered in the first two parts a prediction of further pressure build-up in BAS-2 will be made.

Local geology and cavern layout

The BAS-2 cavern is situated in a roughly 800m thick salt layer belonging to the Zechstein group of the Permian. At the cavern location the formation exists from roughly 2200m to 3000m. The Zechstein group consists of evaporite cycles that have their origin in a peri-marine to marine depositional environment (Boogaert 2008). It is a bedded salt deposit consisting for more than 95% of halite layers alternated with thin anhydrite and claystone layers at the cavern interval. This data is gathered from coring during the drilling of the BAS-1 cavern and cutting analysis during the drilling of the BAS-2 cavern. *Figure 1* shows a cross section of the Zechstein at the cavern location.

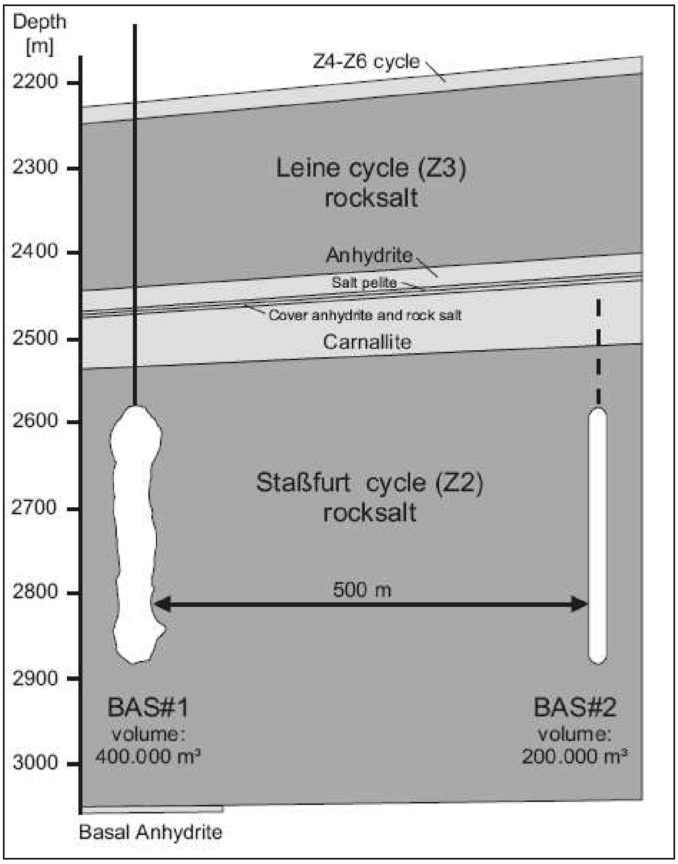

Figure 1. BAS-1 & BAS-2 cross section (Gillhaus 2006)

The BAS-1 and BAS-2 wells were drilled from the same location and to a similar depth of around 3000 m. The BAS-1 well was drilled vertically and BAS-2 was drilled deviated resulting in a 500 m distance between the two wells at cavern depth. The size and depth of the BAS-2 cavern has varied throughout the cavern life. On the 9th of October 2004 just before the cavern was shut in, the last sonar measurement was performed. This measurement was not very successful as only the top and the bottom of the cavern could be described. Despite this a fair estimation could be made and the cavern volume was estimated to be 210000 m3. Soon after the shut in pressures and temperatures were reached that exceed the rating of existing sonar measurement tools. Therefore no volume measurements have been made since.

Cavern pressure development

Since 2001 pressure measurements of the BAS-2 cavern have been digitally recorded. Particularly the data of the period after the shut in is important for this research. There are a few events in the pressure curve that need an explanation. *Figure 2* shows the surface pressure curves of the BAS-2 7" tubing, 10 3/4” annulus and 13 3/8” plugged annulus from the first of October 2004, the shut in date, till the first of October 2008. Just after the shut in the cavern was pressurized with a compression test in order to minimize cavern convergence (first arrow). The other black arrows in *figure 2* show two other pressure tests.

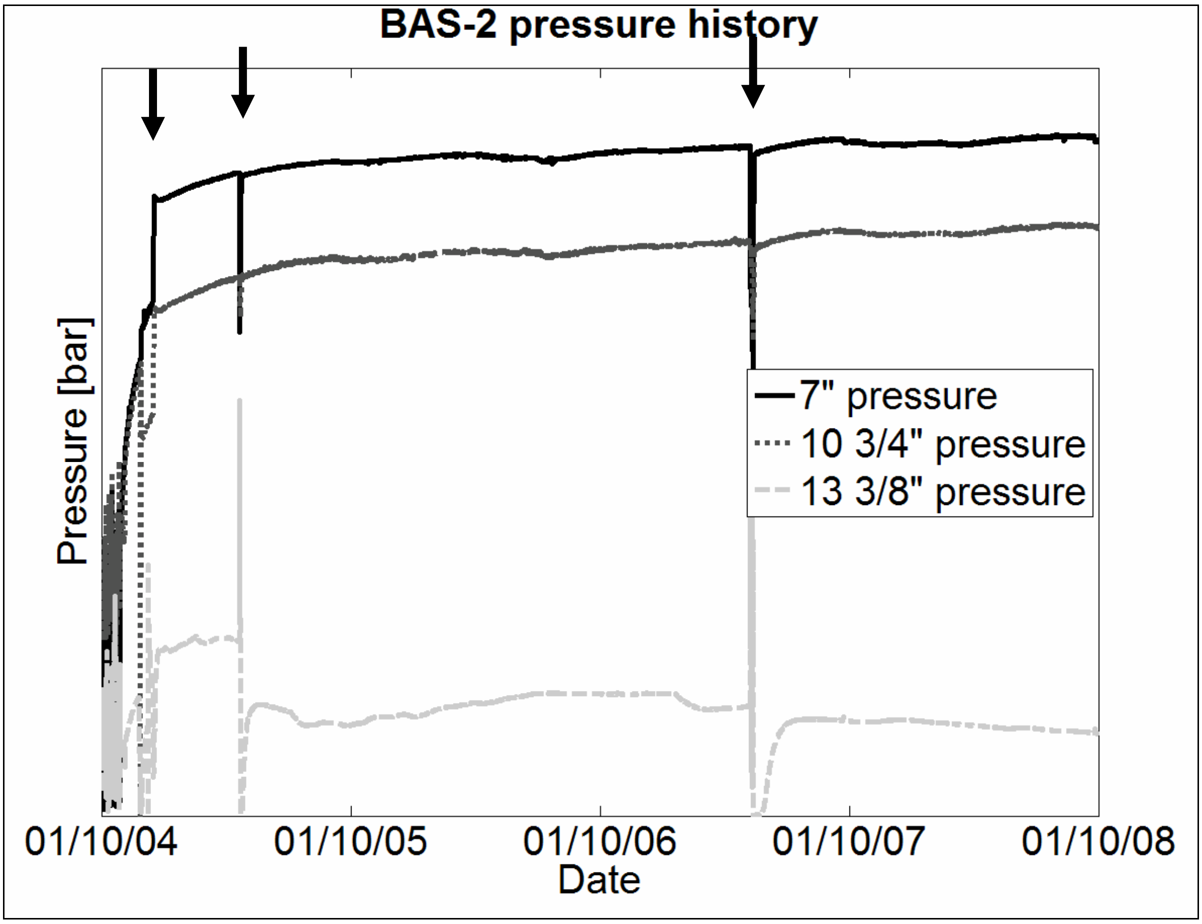

Figure 2. BAS-2 pressure development

The observed small pressure drops in this curve could generally be correlated with pressure reductions in the nearby BAS-1 cavern. These effects should be researched further.

Cavern processes

The following five processes are distinguished that play a role in the pressure build-up of the shut-in BAS-2 cavern.

- Salt creep
- Cavern heating
- Cavern fluid transport into the formation
- Additional salt dissolution and cavern fluid saturation
- Leakage of cavern fluid along the wellbore

These processes are described in the following sections.

Salt creep

One of the distinguishing properties of the FRISIA caverns is the high creep rate. This is due to the high pressure and temperature regime at the large depth of the caverns. There are a couple of theories in use that describe creep of rock salt. We use the Norton-Hoff power law with two branches *(formula 1)*.

$$\dot{\varepsilon} = B_1 \exp(-\frac{Q_1}{RT})(P_\infty - P_i)^{n_1} + B_2 \exp(-\frac{Q_2}{RT})(P_\infty - P_i)^{n_2} \quad (1)$$

When the rock salt temperature is considered to be constant the B, Q and R parameters can be represented by the parameter A_1 and A_2 of *equation 2*.

$$\dot{\varepsilon} = A_1 (P_\infty - P_i)^{n_1} + A_2 (P_\infty - P_i)^{n_2} \quad (2)$$

The creep is driven by the pressure difference between P_∞ and P_i. In which P_∞ represents the virgin lithostatic pressure and P_i the cavern pressure. The first branch of the creep formula, with parameters n1 and A1, describes the behaviour of the non-linear creep that dominates under high stress conditions. The second branch, with parameters n2 and A2, describes the behaviour of the linear creep that dominates under low stress conditions.

The creep of the BAS-2 cavern has been thoroughly studied by Deltares. In their studies the creep is linked to the measured subsidence and to salt crystal sizes found in the cores. Deltares found two sets of parameters that could be matched with this. They are listed in *table 1.* One of the variants is called the high linear creep and the other low linear creep. Both variants are used in the model but the actual value is expected to be somewhere in the middle.

Table 1. Creep parameters according to Deltares

Parameter	High linear creep	Low linear creep	Unit
A_1	5.8E-8	1.5E-7	$[MPa^{-n}][day^{-1}]$
n_1	3.6	3.6	
A_2	5.1E-6	1.0E-6	$[MPa^{-n}][day^{-1}]$
n_2	1	1	

The uniaxial expression *(2)* can be rewritten into a 3D formulation *(3)* for an infinitely long cylindrically shaped cavern in steady state which given by Van Sambeek **(Van Sambeek 2005)**:

$$\frac{\dot{V}}{V} = \sqrt{3}\left[\frac{\sqrt{3}}{n_1}(P_\infty - P_i)\right]^{n_1} A_1 + \sqrt{3}\left[\frac{\sqrt{3}}{n_2}(P_\infty - P_i)\right]^{n_2} A_2 \quad (3)$$

This is the formulation used in the model.

There is a big difference in the relative influence of the two creep branches at different differential stresses. The relative influence is defined as the creep of one of the branches divided by the total creep. For a typical differential stress found in the BAS-2 cavern, lithostatic stress minus cavern pressure is in the order of 30 bar, 4-5 years into the post mining phase the linear creep branch is dominant. This is especially the case for the high-linear creep variant where the influence is 99%, in the case of the low-linear variant this value is 88%. A visual representation of the relative influence can be found in appendix A.

Cavern heating

During the production years of BAS-2 water was injected in the wellhead at temperatures varying between 25℃ and 40℃. This is due to weather cond itions and improvements in the efficiency of the production cycle. The actual temperature before the water enters the cavern is higher because the casing acts as a heat exchanger. The geostatic temperature at the cavern interval is around 100℃. This means that during production the cavern temperature was lower than the geostatic temperature and thus had a cooling effect on the surrounding salt layer. After shut in the geostatic temperature will be slowly reinstated in the salt layer until a thermal equilibrium with the cavern is reached. Therefore the cavern temperature will rise accordingly. This process is modelled using the finite element method COMSOL Multiphysics. This software package enabled us to model conductive and convective heat flux to simulate conduction and the hot salt influx.

We also took another approach by calculating the characteristic time of heating of the BAS-2 cavern. According to Karimi et al. (2007) the characteristic time of a cylindrical sealed solution mined cavern can be described with *formula (4)*.

$$t_c \approx a \cdot \left[\frac{V_c}{100000} \right]^{2/3} \cdot \exp\left[-\frac{1}{2} \left(\frac{\ln(A/A_0)}{b} \right)^2 \right] \qquad (4)$$

Where a=4.67, A = H/D, A_0 = 0.91 and b=1.97

For the BAS-2 cavern with an aspect ratio A of 8.13 this amounts to approximately 4.1 years.

When the characteristic temperature and time is used in combination with the general expression (5) from Ehrgartner (1994) this shows a reasonably good match with the measured temperature build-up. This is illustrated in appendix B.

$$T = T_\infty - (T_\infty - T_0) \cdot e^{-t/\tau} \qquad (5)$$

The constant τ (tau) in Ehrgartners formula determines the shape of the curve. This makes it possible to fit the curve through the characteristic time. The disadvantage of this method is that this curve reaches the geostatic temperature much faster than one would predict. Therefore this method is a good alternative if you want a quick and easy answer for the temperature build-up in the first years after shut in but less suitable for long term temperature build-up calculations. It was therefore decided that the temperature data from Comsol Multiphysics will be incorporated in the pressure build-up model. A visual representation of the temperature build-up can be found in appendix B.

Now two models for the temperature rise in the cavern are established which can be used in the pressure model. There are two processes that are directly affected by the temperature rise. These are further salt dissolution and direct pressure rise due to thermal expansion of the brine. Further salt dissolution will be discussed further on.

Cavern fluid transport into the formation

Under in situ circumstances, when the pressure is high enough to plastically deform the halite and to close off passageways at the crystal interfaces, halite is virtually impermeable (Lorenz 1981). Very low permeabilities in the range of 10^{-22} m^2 to 10^{-19} m^2 are mentioned in literature with generally an increased permeability in the horizontal direction for bedded salt deposits (Berest 1995; Lorenz 1981; Stormont 1991). Despite this low permeability water drips and seepage are quite commonly observed in mines and caverns (Lorenz 1981; Stormont 1991). This is most probably due to anhydrite inclusions and fractures induced by mining.

Around the BAS-2 cavern about 96% of the salt layer consists of halite. The other 4% consists of claystone, other salts and anhydrite. These layers have a higher permeability than the halite. Under the influence of halite movement in the active mining phase along these relatively stiff layers the permeability of these layers and the permeability and their interfaces are expected to increase. These layers may extend far away from the cavern. The volumetric influence of these layers is thought to be minor, however it cannot be excluded that these layers act as permeation channels. This could be a factor for the cavern venting mechanism that prevents hydraulic fracturing to occur.

Increased permeability can also occur if the cavern pressure is higher than the ambient lithostatic pressure. Especially at the roof of the cavern, the first place where the cavern pressure will exceed ambient pressure, this phenomenon can occur (Kenter 1990). This is because the pressure difference between the brine and the lithostatic pressure is smallest at the cavern roof. The theory is that at higher cavern pressure permeation along grain boundaries can occur.

There are several infiltration criteria that describe this process we have based our infiltration criterion on an adapted version of the IUB criterion described in Rokahr (2002). *Figure 3* shows the effective tangential stress plotted versus permeability for our criterion. The effective tangential stress in this case is defined as the cavern pressure minus the ambient pressure tangential to the cavern wall, e.g. the local lithostatic pressure extracted from compression tests. The pore pressure is assumed to be zero when opening a permeation channel between grain boundaries.

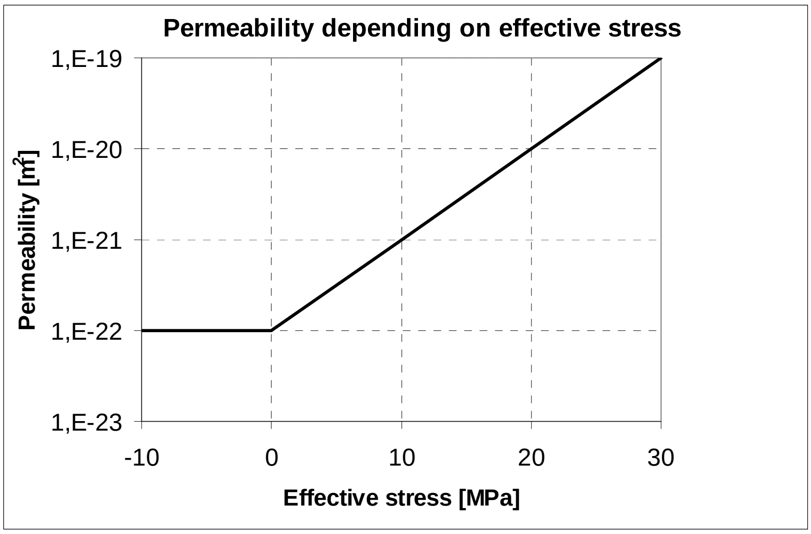

Figure 3. Permeability dependency on effective stress

Additional salt dissolution and cavern fluid saturation

At the time the cavern was shut in it had not been producing significant volumes of salt for a few months. The only injection of fresh water was during bleed off sessions in order to keep the surface pressure under the certified pressure level of the valves and piping system. Therefore the brine can be considered saturated from the start of the shut in period.

The temperature of the salt surrounding the cavern will restore to geostatic temperatures and therefore the brine will be heated up. When the brine is warmer it can dissolve more salt. Due to the fact that this is such a minor factor compared to other variables and the uncertainties in measuring this effect it is not incorporated in the pressure build-up model.

Leakage of cavern fluid along the wellbore

The 13 3/8" annular space of the BAS-2 Cavern has been cemented on the 11th of November 2003. Directly after plugging it was concluded that the plug was tight. Operational data does not indicate loss of fluid. Therefore the model assumes that the plug is tight.

Model

Before all above mentioned processes were incorporated in the model several runs considering only one or two of these processes were made. These runs show the influence of the separate processes on the complete model.

Figure 4 shows the results when only considering creep. One can see that the simulated pressure quickly reaches lithostatic. This is not observed in the measured pressure build-up probably due to venting of the cavern by permeation.

Figure 5 shows the results when only considering thermal expansion. One can recognize the temperature prediction from the Comsol model, mentioned earlier, which is used as input. It is clear that the pressure rise due to heating of the cavern has a big influence between 2-4 months after shut in.

Figure 6 shows the result from the model incorporating creep and cavern heating. It can be seen that the pressure rapidly rises and overshoots the virgin lithostatic pressure. This is not observed in reality and is evidence of significant permeation.

Figure 7 shows the result from the complete model incorporating creep, cavern heating and permeation. Creep and permeation are two way coupled in the model and the brine heating is one way coupled assuming that pressure change does not affect brine heating.

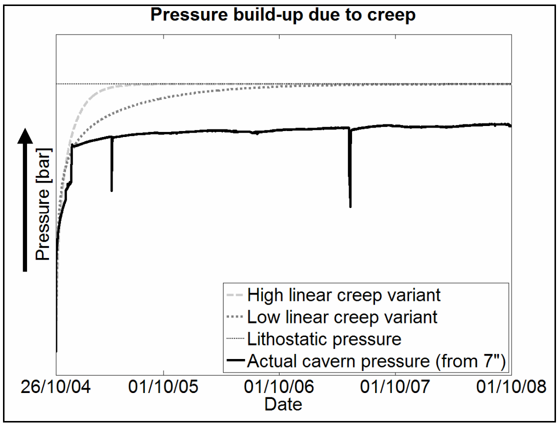

Figure 4. Long time scale pressure build-up only considering creep

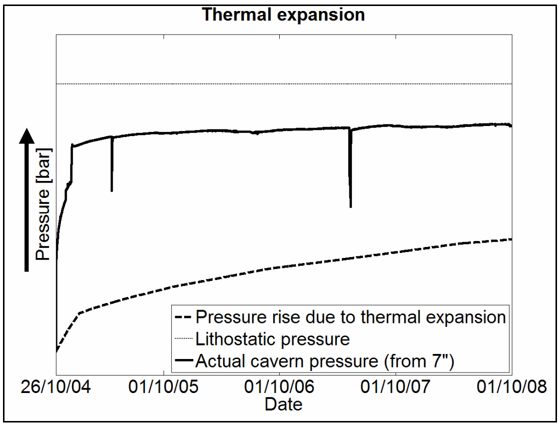

Figure 5. Long time scale pressure build-up only considering thermal expansion

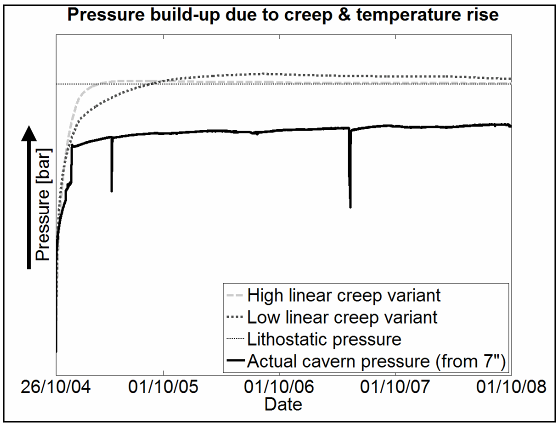

Figure 6. Pressure build-up due to creep and temperature rise

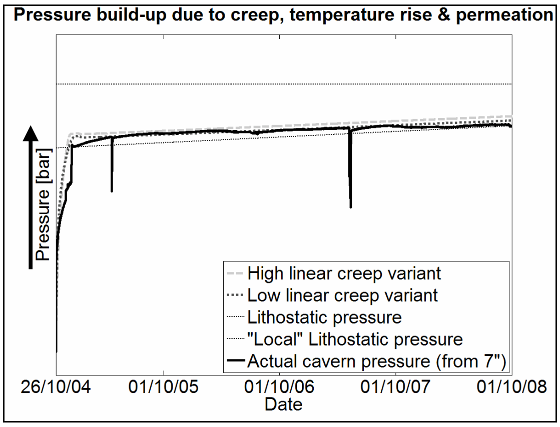

Figure 7. Pressure build-up due to creep, temperature rise and permeation

Besides creep and cavern heating, permeation plays a major part in this simulation when the cavern pressure starts to rise to and over the local lithostatic pressure. This is taken as a threshold value for permeation as discussed earlier. The temperature rise and cavern compressibility are calibrated to measured values, therefore the pressure rise as a result of this can be assumed to be correct

There are a few notable features in the long term pressure simulation:

1. In the first two months the simulated pressure build-up happens faster than the measured pressure build-up.
2. The simulated pressure build-up overshoots after two months and then drops.
3. After four months of simulation the simulated pressure follows the local lithostatic pressure curve.

The first point can be the effect of a pressure sink around the cavern, as a result of years of intensive leaching in the active mining phase. This pressure sink allows brine to permeate more easily in the first few months slowing down the pressure build-up. The fit could also be improved by adapting the creep parameters, or by adjusting the virgin lithostatic pressure.

The second point can be explained by the temperature increase, which is rapid initially after shut in but slows down later. In order to keep the simulated pressure build-up under lithostatic a ‘high' permeability has to be chosen. When the temperature rise is slowed down the cavern shrinkage due to creep alone is lower than the volume permeating into the salt layer resulting in a pressure drop in the second interval. This rising and falling of pressure is not observed in the actually measured pressure build-up curve. In reality the permeability will be high even at the start of the pressure build-up when the cavern pressure is lower. This is because the representation of the local lithostatic pressure as a straight line is not realistic, in reality it follows a curve like the measured pressure build-up and therefore the permeability will follow this curve as well.

This can be also be observed at the third interval when the pressure curve approaches the local lithostatic pressure line. In this segment the permeability becomes in a dynamic equilibrium with the creep and thermal expansion, therefore the pressure curve follows the local lithostatic pressure.

Compression tests

Just before and during the high pressure shut in period of BAS-2 four compression tests (CT's) have been performed. During a CT the cavern is bled off and then repressurized. During the pressurization the injected volume and the pressures are recorded. Using this data the hydraulic response [m^3/bar] can be plotted versus the cavern pressure. *Figure 8* shows the plot of the four CT's in relation to the lithostatic pressure, all at last cemented casing depth of 2533 m.

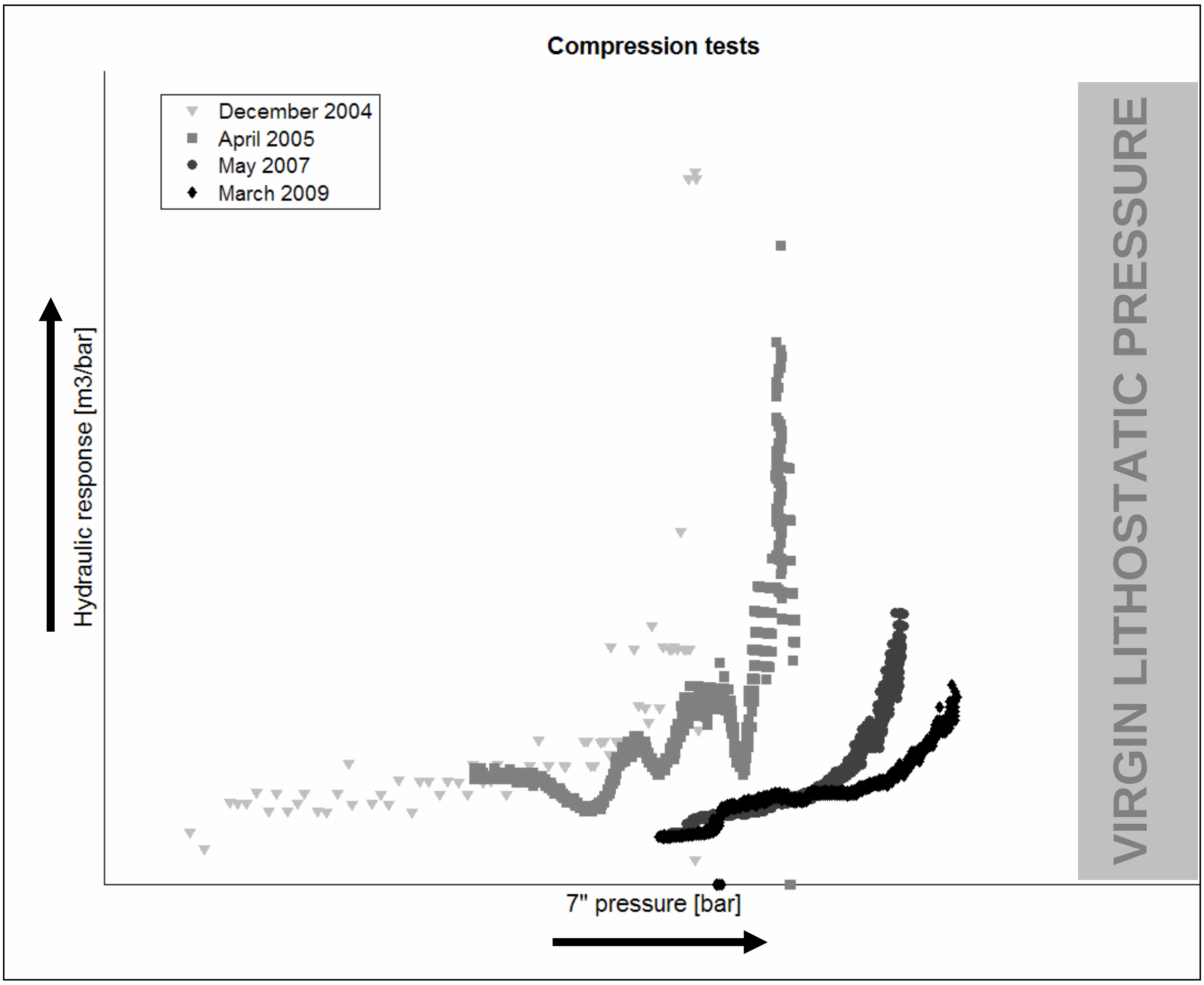

Figure 8. BAS-2 compression tests

In this plot it can be observed that at lower pressures the hydraulic response stays fairly constant, this is referred to as the elastic response and that at a certain point the hydraulic response starts to rise rapidly, this point is referred to as the leak-off point.

From the elastic response the compressibility of the cavern can be calculated with *formula 6* (McCain 1990).

$$\beta = \frac{1}{V} \cdot \left(\frac{\partial V}{\partial P} \right)_T \qquad (6)$$

The calculated compressibility of a brine filled cavern can be subdivided in brine and cavern compressibility. Typical values for these are respectively 2.7 × 10^{-4} MPa^{-1} (Boucly 1981; Crotogino 1981) for brine and 1.3 × 10^{-4} MPa^{-1} for spherical caverns (Boucly 1981). The latter value can vary significantly depending on cavern shape. In the case of a perfect spherical cavern compressibility factors will be lower than for a cylindrical or irregular shaped cavern (Berest 2001). In order to calculate the total compressibility factor these values can be added.

For the BAS-2 cavern test in 2007, when using an estimated cavern volume of 203000 m^3, the total compressibility factor would amount to 5.4×10^{-4} MPa^{-1}. This value is a bit higher than the standard value of $4.0 \times l0^{-4}$ MPa^{-1}mentioned above for a spherical cavern. This is probably because of the cylindrical shape of the cavern. This calculated value is used in the model. The value has dropped over time after shut in. This is probably because the salt has been recompressed for a fair bit already. The cavern volume is estimated by subtracting the estimated creep volume, which is the creep calculated over the measured cavern pressure, from the original volume at the shut in date. The volume is estimated by using the measured pressure data in order to calculate the most realistic creep volume.

The other value that we get from the compression test is the leak-off point. At this moment during a CT water can be pumped in the cavern with only a small pressure increase. This indicates that a lot of fluid is leaking into the formation. The leak-off point is taken as representative for the local lithostatic pressure used in the model. This is a measure for the rock strength at the cavern wall. The salt in the cavern wall is decompressed due to the squeeze process in many years of mining and therefore lower than the far field lithostatic pressure. In time this leak-off point has shifted towards virgin lithostatic, this means that the cavern is getting stronger. The rate of strength recovery has slowed down over the years.

From these CT's the 2007 test gives the most reliable result. The result is better than the 2004 test because minute data is used rather than hourly data. The 2007 test is better than the 2005 test because then due to the rapid bleed-off of the cavern geotechnical instabilities occurred. This is shown by the irregular shaped curve. Another fact supporting this is that during the 2005 test lumps of insolubles came along with the brine to the surface. The rapid pressure release almost certainly had a negative effect on the mechanical stability of the cavern wall. The accuracy of the CT test in general is limited to the accuracy of the flow meter, which is quite low for these small volume flows.

When looking at the 2009 test an irregularity can be seen in the elastic response. During this test the injection pump was stopped for a short repair after this repair the volume flow increased by 30%. This increased volume flow should not have a significant affect on the elastic response. The fact that the (pseudo) elastic response does significantly change is an indication that the cavern fluid permeates quite easily into the formation even under low pressure conditions.

In *figure 2* the pressure history including the compression tests can be found. One can see that the pressure does not drop but stays constant and even rises quite quickly to the pre bleed-off value after a compression test. This indicates that, after stopping the pump, creep (and thermal expansion of the brine) are strong enough to maintain and even raise the cavern pressure. It also shows that no permanent fractures to a more permeable layer are created because in that case a pressure drop would be expected.

The pump-in cycle of the CT's has generally been at 10 m3/hr, i.e. very much higher than would be expected of permeation caused by low linear creep. The fact that after reaching the maximum pressure and stopping of the pumps only a minor drop in pressure is observed, indicates that the rate of permeation has continually been higher than indicated by the low linear creep model. This is seen as further evidence that the linear creep term in the BAS-2 conditions is relatively strong.

Discussion

There is - in the opinion of the authors – overwhelming evidence from the BAS-2 post mining monitoring experiment that the predominant mechanism of fluid escape from the cavern is permeation.

This begs the question where the volume displaced from the cavern will migrate to and remain over time. Our hypothesis is that the fluid is stowed in fluid filled pores in the salt mass above the cavern and (part of) the pressure sink due to active mining. If one assumes that due to this process the fluid filled pores will constitute 2% of the salt mass, some 10^6 m3 rock would be affected. Assuming that a 300 m thick salt package is available above the cavern a cylindrical volume with a diameter of ca 200 m would be affected. In the case of BAS-2 this would be geometrically completely possible. Laboratory experiments in representative conditions to prove this hypothesis would be helpful.

Permeation is thought to lead to (semi) isolated fluid pores that are no longer in direct communication with the pressure regime in the cavern. In any case a significant dynamic pressure loss must be assigned to the migration process. This dynamic pressure loss must be subtracted from the static pressure in the cavern. Hence the drive for upward migration reduces when moving away from the cavern. The cavern drive mechanism for permeation will decrease over time as the cavern shrinks in size.

A secondary mechanism of stowage of displaced volume will be below near impermeable layers such as anhydrite banks. In this case pools displaced fluid may be trapped. Such pools may give rise to a lateral permeation process, however due to limited vertical hydraulic communication, the drive mechanism for such permeation can be expected to be weak or absent.

The end result would be that after completion of the migration process a ‘spongy’ salt/rock mass will exist above and around the top of the cavern where the fluid is trapped in pores and spaces that have no further communication with the pressure regime in the cavern. This condition is considered likely to be stable on the long term.

The volumetric effects of the fluid migration due to the described permeation process, under the assumption that there will be no escape of fluid to laterally continuous permeable horizons, are expected to be marginal. In the low linear creep case, the rate of cavern shrinkage will we low and the permeation process slow. In the high linear creep case the shrinkage rate will be higher, but the salt will be supplied from the far field. In both cases the effect on subsidence is expected to be marginal, with some widening of the bowl in the high linear creep variant. The CT tests suggest that the rate of permeation is relatively high, indicating that linear creep is active.

Conclusions

Compression tests and the comprehensive model indicate that the cavern has been in a continuing permeating condition soon after shut-in and that the rate of fluid leak off stays below fracturing levels.

The BAS-2 cavern shows normal heat-up behaviour for a shut in cavern. There is a small irregularity in the measured temperatures but there are too few data to treat it as an event. This irregularity can be the result of using several different companies to perform the measurements. The major expansion effects of heating up of the cavern contents and cavern surroundings have occurred without bleeding down the cavern. Venting of the cavern is thought to take place with a permeation process, there is no indication of formation fracturing.

As the differential between the virgin far field and cavern pressure, hence the squeeze rate, reduces in the future and the major effect of temperature expansion has occurred it is considered very unlikely that fracturing conditions will occur in the future. Hence fluid will be displaced from the cavern in a permeation process.

The drive mechanism for permeation will weaken with time - as the cavern shrinks –and likely result in a ‘spongy’ salt/rock mass above and around the top of the cavern. Once the fluid pores and fluid filled spaces have no further communication with the cavern drive mechanism the migration process is expected to stop.

The effects on subsidence of the expected migration process is thought to be marginal. The compression tests and the comprehensive model suggest the presence of high linear creep.

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Appendix B Graphical representation of the cavern heating

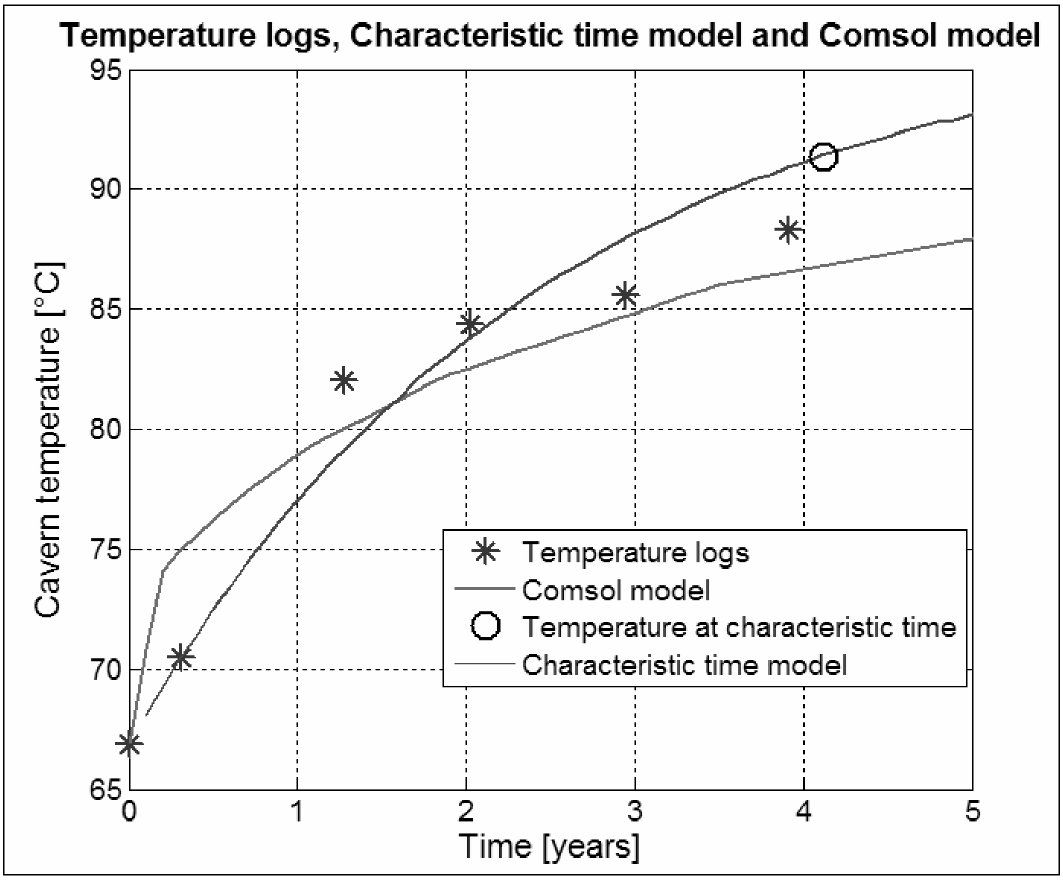

Figure 11. Cavern temperature build-up after shut-in simulations (short term)

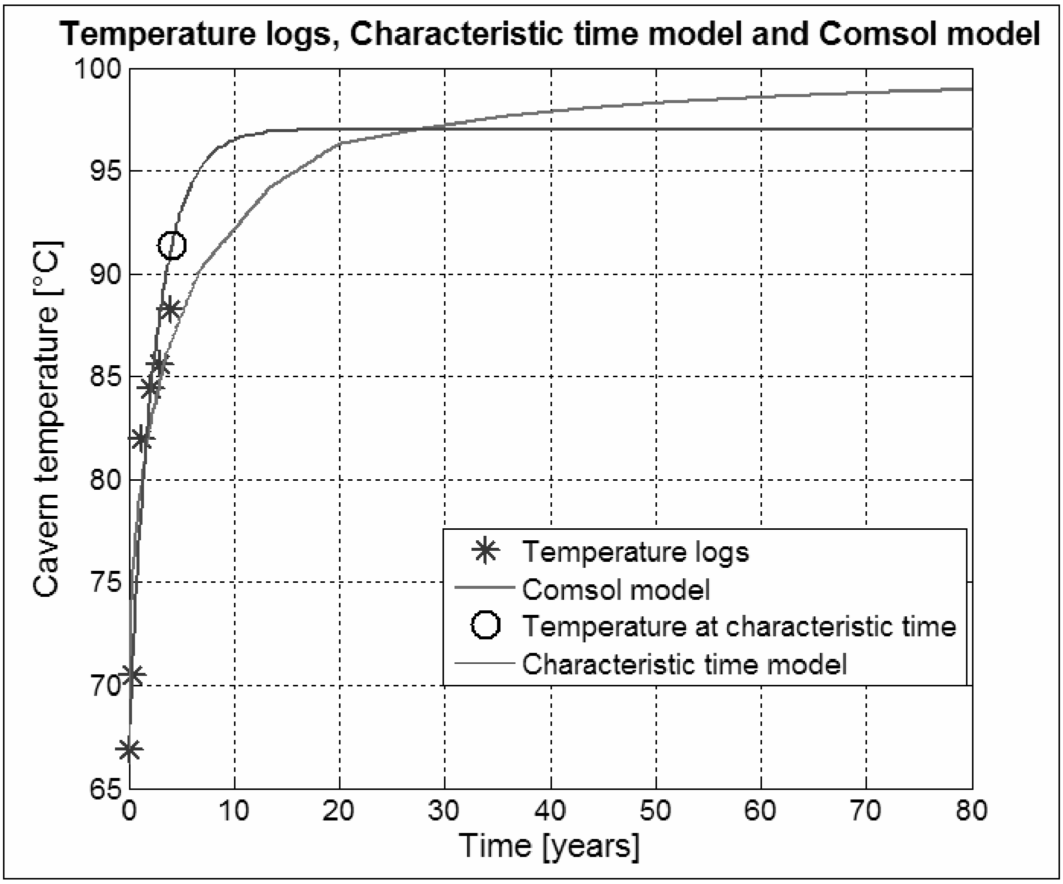

Figure 12. Cavern temperature build-up after shut-in simulations (long term)