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FRISIA cavern abandonment

BAS-3

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Contents

1 Management Summary

The abandonment of the BAS-3 cavern is imminent. Hard shut-in of the prematurely mined out BAS-3 cavern, has taken place in Q2 2010, and the cavern has to be abandoned in order to be able to sidetrack the well and mine the remaining permitted reserves from a new cavern. With current planning it will be possible to monitor the abandoned BAS-3 cavern for at least one year before closing off the cavern. A separate document will be made with the goals and specifications of the monitoring programme. This report is focussed on the abandonment or the BAS-3 cavern.

Active mining in BAS-2 has been discontinued in 2004 and a 6 year test has been carried out following a ‘hard shut-in’ procedure. With hard shut-in no volume is bled off from the cavern to compensate for thermal expansion of the brine and convergence of the cavity due to squeeze.

A thorough analysis has been carried out of the processes that can be expected when FRISIA caverns are permanently closed off, locking-in underground free brine volumes of several hundred thousands of m^3, typically up to 500,000 m^3 with a ‘hard shut in’ procedure that implies that no volume is bled off from the cavern to compensate for thermal expansion and cavern convergence.

Experts have been consulted and use has been made of available literature. The processes have been evaluated for the applicable geological situation and analysed with an engineered model. For the analysis, data have been used of cavern BAS-2 that has been shut in with a hard shut in procedure and observed and tested over a period of 6 years.

On the basis of the work done, the authors and reviewers come to a realistic ‘engineered expectation’ of the effects of hard shut-in for FRISIA caverns, showing a gentle process of closure of the underground volume over several hundreds or thousands of years with negligible or minimal subsidence. A sensitivity analysis shows a band of uncertainty around the time scale and migration volumes that does not materially affect the general picture of a gradual process with marginal effects at the surface.

A risk analysis of worst case events that are highly unlikely to happen does not reveal unacceptable risks according to an accepted industry risk assessment method. Additional subsidence that may take place in case of an unlikely worst case event is fully covered by an agreement with the Water Authorities stating that no measures are required and no costs are expected if the actual subsidence is 5 cm more than the forecasted maximum **[REF Stuurgroep Franekeradeel – Harlingen, 2009]**. If for some unknown reason the subsidence after shut-in is more than predicted this can still be corrected by adjusting the operational parameters of the newly created BAS-3 original cavern.

It is therefore concluded that hard shut in of FRISIA caverns, without an extensive post mining observation/bleed off period, taking account of considerable uncertainties is the best technical and environmental solution for a responsible and safe abandonment.

2 Introduction

2.1 General introduction

Since 1995 rock salt has been solution mined at the Barradeel concession in the Northwest of the Netherlands by FRISIA Zout BV. The salt is mined at a depth between 2500 and 3000 meters making it one of the deepest salt mines in the world. This 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 increases with cavern volume. During production this means that salt can be produced at steady state. In other words the cavern convergence rate finds a dynamic equilibrium with the salt removal rate by brine production. This results in a cavern of a more or less constant volume.

The salt creep results in a localised subsurface volume reduction in the vicinity of the cavern. This volume reduction leads to surface subsidence that is allowed to a maximum of 30 or 35 cm directly above the cavern. In 2004 the subsidence limit was almost reached at the BAS-1 and BAS-2 caverns. Production from BAS 2 was halted and BAS 1 was assigned to a standby function with sporadic production at high cavern pressure. In order to ensure a responsible abandonment of FRISIA caverns, the abandonment project of BAS-2 started as a test for responsible abandonment practices for the current and future FRISIA caverns and general learning for the solution mining industry.

BAS-2 has been closed off at surface since October 2004 under close monitoring of the pressure development. Contrary to common practice for shallower caverns, no bleed offs were required to compensate for thermal expansion and volume effects of the cavern, because the cavern pressure remained all the time comfortably below the available formation strength. Effectively the BAS-2 cavern was shut in ‘hard’ (allowing no bleed off), simulating conditions as if the cavern was sealed off immediately after the active mining phase. Besides close monitoring of pressure data, several temperature logs, compression tests and echo measurements have been performed to monitor the cavern behaviour. This has resulted in a unique set of data for shutting in deep caverns after a period of active mining in ‘high squeeze’ conditions. The results of the test are discussed in the report “BAS-2 high pressure shut-in monitoring period” and form the basis of this report.

Besides BAS-2, the nearby BAS-3 cavern has priority to be abandoned due to operational constraints. A sidetrack is planned to create a new cavern at the originally intended position in the near future. Prior to the sidetrack, the existing BAS-3 cavern has to be sealed off, leaving no practical means for pressure monitoring and bleeding off of the sealed cavern. The sidetrack can only be realized when the current cavern is abandoned by ‘hard shut in’. The focus of this report will therefore be on the abandonment of the BAS-3 cavern and most of the data is based on experience from the hard shut-in of the BAS-2 cavern.

The main concerns are that the brine volume contained in an abandoned cavern might migrate to the surface and have a harmful impact on the surface or on the salinity of drinking water layers and uncontrolled surface movements. This report will therefore investigate the stability of a salt cavern and the potential for flow of brine to a drinking water layer after abandonment. It will focus on the creep behaviour of the salt being the ’engine’ for leak-off and the permeation mechanism that allows leak-off from the cavern into the surrounding layers. Before these mechanisms will be discussed an introduction in the local geology and cavern situation will be given. It will end with a discussion of the results from our models.

2.2 Abandonment Scenarios

Two scenarios have been considered for the abandonment of the BAS-3 cavern:

- Bleed-off scenario
- Hard shut-in scenario

Bleed-off scenario

In this scenario the cavern is allowed to shrink by maintaining a cavern pressure close to a brine gradient. Bleeding off cavern volume will translate directly into subsidence. The outflow of the cavern will initially be of the order of 50 to 100 m^3/hr and then exponentially decrease while the volume of the cavern decreases. The majority of the bleed off operation will deliver extremely low flow rates over periods of many years, while it will not be possible to extract the cavern volume completely.

The low cavern pressure will result in high stresses in the cavern roof and walls, with a significant risk for scaling off and instability of the roof. This can damage the leaching strings and interfere with proper dilution of the brine. If the well gets blocked due pinching of the casings or salt plugging, the scenario shifts by default to hard shut in. Instability of the roof may be a progressive feature.

The remaining volume in the cavern will eventually have to be shut in and pressures will rise to near lithostatic conditions and result in similar permeation process as experienced in the hard shut-in scenario, be it with a smaller cavern volume.

Although bleeding off appears an easy solution, FRISIA considers it a solution that is likely to meet problems and result in poorly predictable and unnecessary subsidence. This scenario is therefore not analysed in further detail in this report.

Hard shut-in scenario

In this scenario, the cavern is closed off and the pressure allowed increasing to near lithostatic conditions soon after closure. Volume expansion due to temperature stabilisation and volume reduction due to cavern closure cause excess fluids to be squeezed out of the cavern. This process is discussed in detail in this report and is strongly favoured by FRISIA because it will reduce subsidence to a negligible level, and lead to a gentle closure process over many thousands of years with very few risks. An independent review of prof. Lux corroborates the FRISIA analysis and shows even slower closure rates than modelled by FRISIA.

Unfortunately there is no representative experience within the SMRI, because the conditions with FRISIA are not generally encountered by SMRI members. The existing SMRI recommendations about cavern closure and temperature stabilisation have little relevance for the FRISIA situation and new concepts have been developed in the course of the FRISIA abandonment study.

2.3 Objective of this study

It is the objective of this study to describe the risks associated with the abandonment of the BAS-3 cavern in the framework of a realistic ‘engineered expectation’ and possible ‘worst case outcomes’. It will focus on uncontrollable processes that might have a negative impact on the environment and future use of the local underground.

The following worst case outcomes merit consideration:

- Sudden strong subsidence,
- Contamination of shallow fresh water zones,
- Creation of sink holes,
- Surface brine eruptions,
- Sudden shocks/earthquakes.

After a thorough analysis of the down hole processes, a realistic ‘engineered expectation’ will be developed using a model and testing a wide range of variables. With these modelling results an evaluation will be made of the above named worst case outcomes.

2.4 Geology

All FRISIA caverns are situated in a thick salt layer, please refer to Table 1 for the complete stratigraphy of BAS-3. This is based on cuttings analysis and logging.

Table 1 BAS-3 stratigraphy [Pruiksma, 2007].

Material	Depth (tvd) [m]	Density [kg/m^3]	Young’s modulus [MPa]	Poisson’s ratio
Quaternary	0-563	1950	125	0.25
Tertiary	563-1107	2300	125	0.25
Cretaceous	1107-1506	2250	1500	0.25
Sandstone	1506-2103	2230	2000	0.25
Halite (ZE-III)	2103-2275	2185	11000	0.35
Anhydrite(ZE-III)	2275-2333	2900	10000	0.25
Carnalite (ZE-II)	2333-2384	1600	5500	0.35
Halite (ZE-II)	2384-2800	2185	11000	0.35
Base rock	2800	2700	25000	0.30

During the drilling of the BAS-1 and BAS-2 wells cores were extracted to get a better understanding of the local geology and the behaviour of the salt. All core descriptions are based on work done by **[Kohleder, 1994, 1995].** Figure 1 shows the depths where the cores have been extracted from. The BAS-1 cores have been extracted from 2600m till 2960m. This is almost the complete cavern interval while the BAS-2 cavern cores only have been taken at three depth intervals due to the expected geologic similarities between the two caverns. In the parts where coring did not take place drill cuttings have been analysed. The cuttings analyses of the BAS-2 and BAS-3 caverns show no relevant deviation from the BAS-1 coring interpretation. The salt layer around the BAS-3 cavern is situated a bit higher. Refer to Figure 2 for a geological cross section with a rough sketch of the cavern and geology of BAS-3.

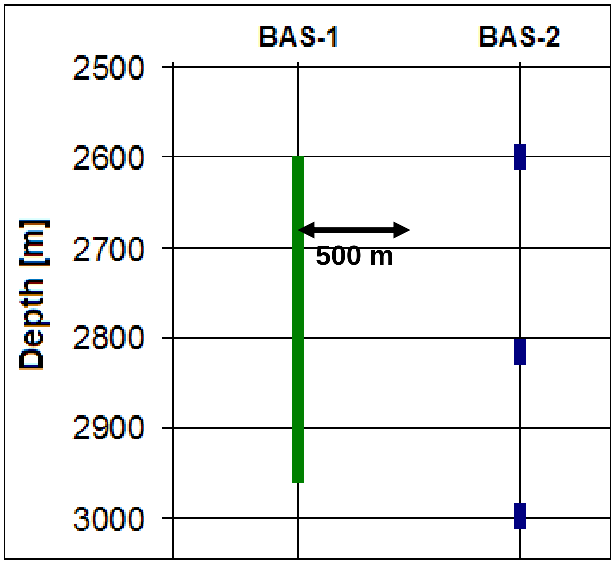


Figure 1 BAS-1 and BAS-2 coring intervals (tvd).

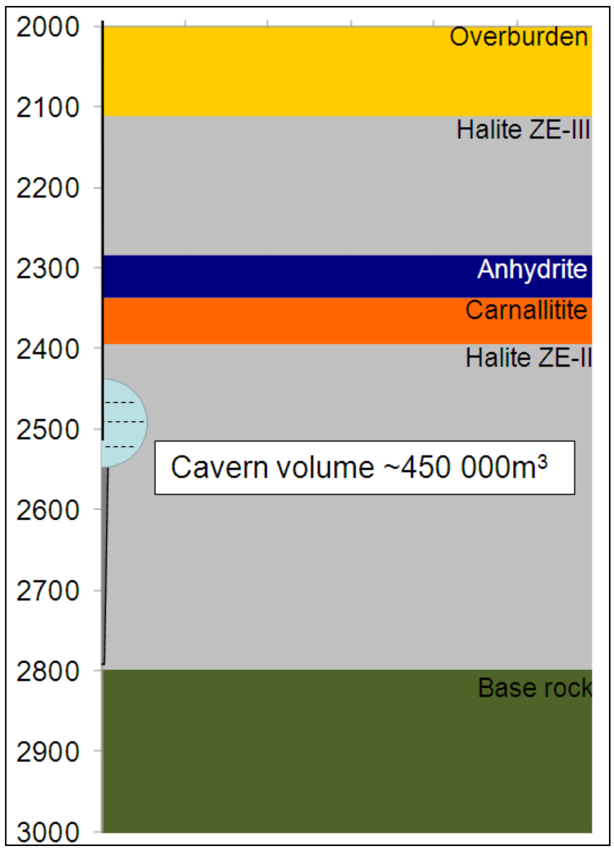


Figure 2 Geological cross section of BAS-3.

These cores and cuttings show that the cavern is located in the Z2 halite formation. This formation consists of several evaporate sub cycles, consisting of mainly halite, some other salts, Claystone and Anhydrite. According to the BAS-2 final well report more than 96% of the mining interval consists of halite. The Z2 halite is enclosed by the Z2 Carnallite on top and the Z2 Anhydrite at the bottom followed by the layers that form the base rock. The salt layers have a very small dip.

The Anhydrite and Claystone present in the salt layer predominantly consist of small stripes (1-4mm) and fine laminations (<1mm). Three sections around the BAS-1 cavern have been identified in the cores which have thicker Anhydrite layers. These are listed in Table 2, it is probable that similar thicker layers can be found around BAS-3 situated ca. 150 m shallower according to the generally shallower geological setting at the BAS-3 cavern position. The halite itself is present in layers varying between 1 and 30 cm. These layers consist of medium crystalline (0,5 – 2,0 cm) halite crystals with a tendency to increasingly finer crystals to the bottom.

Table 2 Thicker Anhydrite layer occurrences around BAS-1.

Depth (tvd) [m]	Anhydrite thickness [m]
2680	0.75
2856	0.06
2857	0.30

During the active solution mining period the insoluble fraction of the Zechstein formation falls to the bottom of the cavern and forms the sump. The insolubles are expected to bulk up and get an initial porosity of about 30%.

2.5 BAS-3 cavern

BAS-3 has been the primary brine producer for FRISIA in the period 2004 to 2007. During this period it has been intensively leached. The intensive leaching created a cavern volume of 535 000 m^3 in 2008. The volume by the time it will be abandoned is estimated at 450 000 m^3. The distance of the Carnallitite layer to the cavern roof was last measured in June 2009 and estimated at 42 meters.

Due to problems when drilling BAS-3 the well path in the cavern section was not vertical as planned. It deviated from vertical at the top to a maximum deviation of 50 degrees at the bottom. This deviation combined with small (vertical) leaching intervals and the intensive leaching caused the cavern to move rapidly through the interval available for mining. The movement was not only vertically through the salt section but also horizontally leaving a curved tail sump instead of a vertical sump. Please refer to Figure 3 for an impression of the current cavern situation.

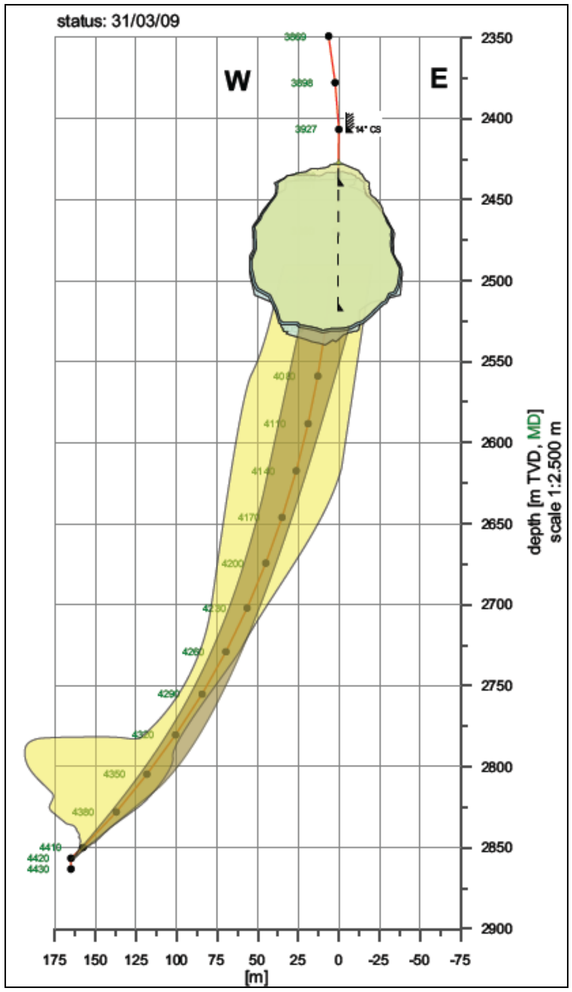


Figure 3 Impression of the BAS-3 cavern and sump tail shape [Fischer, 2010].

The cavern is separated from overlying Carnallitite by a halite roof. The Carnallitite layer is ca 50m thick consisting of an interbedding of carnallite (potassium/magnesium chloride mineral with higher solubility than rock salt) and insoluble material, please refer to the Carnallitite section (3.6) for more details. The Carnallitite layer is overlain by a ca 50 m thick Anhydrite bank. The Anhydrite bank is followed by a ca 175 m thick layer of predominantly halite. Please refer to Figure 2 for an overview.

Roof stability

Due to the intensive leaching of BAS-3 the cavern has developed itself as a spherically shaped cavern with a diameter of about 100 m in the widest middle section. Continued leaching will lead to a roof span of similar proportions and potential instabilities in the roof. When the cavern is shut-in the pressure will quickly rise to near lithostatic pressures and therefore reduce the load on the roof. The roof is therefore expected to remain stable under shut-in conditions from a mechanical point of view. This is supported by model studies carried out by Deltares **[Pruiksma, 2009]** using the high linear creep variant discussed further on in this report. Using the high linear creep variant is a conservative approach, a more realistic modelling approach with a non-linear creep mechanism would lead to an even better roof stability.

The roof will also be subjected to permeation, a process of slow migration ('seeping through') of brine from the cavern to the overlying strata. This process is discussed in detail further in this report. Permeation takes place along the crystal interfaces and may have a weakening effect on the salt matrix, resulting in a gradual decay of the roof and accumulation of bulked residue in the sump. The effect of a weakened halite roof when it is fully permeated has already been included in the Deltares studies **[Kruse, 2001, Pruiksma, 2009 page 12&13]** mentioned in the previous paragraph.

The conversion reaction that takes place when NaCl brine gets into contact with Carnallite creates a small volume increase. This process is discussed in detail further in this report. We expect that this volume increase will lead to a slight overpressure and that the additional volume will therefore permeate further on into the upper salt sequences, in analogy with the brine pushed out of the cavern due to convergence and brine temperature expansion. This small pressure increase is expected to have a negligible effect on the roof stability.

If for some unknown reason this happens on a bigger scale and if for a short time a bigger than lithostatic pressure will exist, this pressure condition is comparable with the cavern situation during production. During production the lithostatic pressure at the roof (at circa 2500 m depth) is about 540 bar while the cavern pressure is about 340 bar; this gives a 200 bar pressure differential over the roof. During shut-in the cavern pressure is near lithostatic (20 bar under theoretical value of lithostatic pressure). This means that the extra pressure above the roof caused by a violent conversion reaction can increase to 180 bar, before a pressure differential over the roof develops similar to production circumstances where a stable roof could be maintained.

Sump

The insoluble material freed by leaching of the halite and material (including halite) spalling from the cavern walls and roof fall to the bottom of the cavern and form the sump. The initial porosity of loosely settled sump material is estimated to be around 30%. With the technique applied by FRISIA, leaching only takes place above the sump. Hence, the sump material will eventually become trapped between the salt walls and the porosity will drop due to the squeezing of the salt to an estimated final porosity of about 20% by the time the grain-to-grain and fluid pressure in the sump material fully resists the closure of the walls and stops the salt squeeze in the active mining phase.

In the abandonment phase the pressure in the cavern, and therefore in the pores of the sump material, is much higher than in the active mining phase. This will reduce the grain to grain pressure in the sump material and therefore inhibit further salt squeeze in the sump interval. Figure 4 shows the cavern pressure during the operational phase, the shut-in phase and the lithostatic pressure. It can be seen that the loading on the sump grains is significantly higher during the operational phase than during the shut-in. The brine in the pores of the sump can therefore likely be considered as a dead volume or “volume mort”. However we have evaluated a scenario in which the sump is assumed to shrink until the porosity is zero after abandonment.

In the sensitivity analysis two other scenarios will be considered, total compaction of the sump to zero porosity and complete salt penetration into the sump pores. Although we do not consider these scenarios as realistic, both are more likely to happen during the operational phase than during hard shut-in. This is for the same reasons as mentioned above where we have explained that the sump is expected to be stable during hard shut-in.

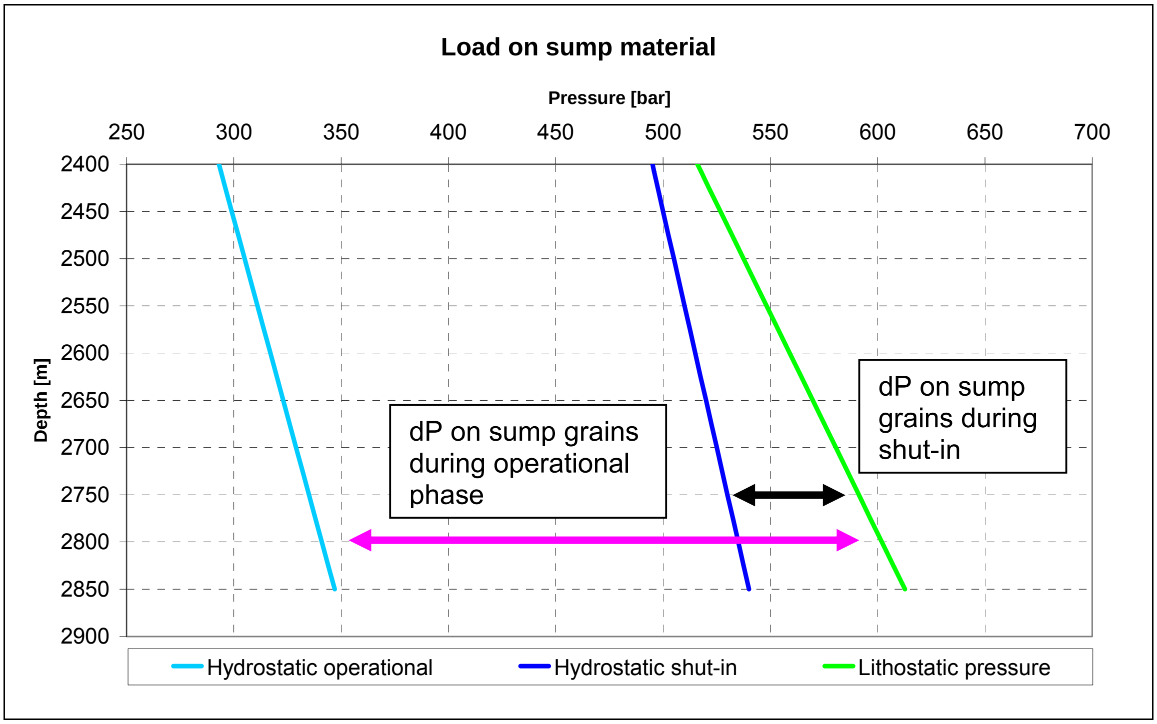


Figure 4 Loading of sump grains in operational and abandonment phase.

3 Cavern abandonment aspects

The following aspects that play a role in the pressure build-up after shut-in are distinguished:

1. Cavern brine heat-up and thermal expansion
2. Additional salt dissolution and cavern fluid saturation
3. Salt creep
4. Cavern fluid transport into the formation (Permeation)
5. Other migration paths along the well bore
6. Impact of the Carnallitite layer
7. Containment and confinement
8. Buoyancy of the cavern
9. Instability of the cavern roof

These aspects are discussed in the following chapters.

3.1 Cavern brine heat-up and thermal expansion

Just before shut-in of a cavern the brine temperature is ca 65°C due to the injection of relatively cold (40 °C) injection water during the active mining phase. After shut-in the brine will heat up to the geostatic temperature.

Figure 5 shows the temperature build-up in the BAS-2 cavern after shut-in in October 2004 as published in the BAS-2 monitoring report. Cavern BAS-3 has been shut-in since April 2010. Hitherto no down hole temperature measurement has been performed.

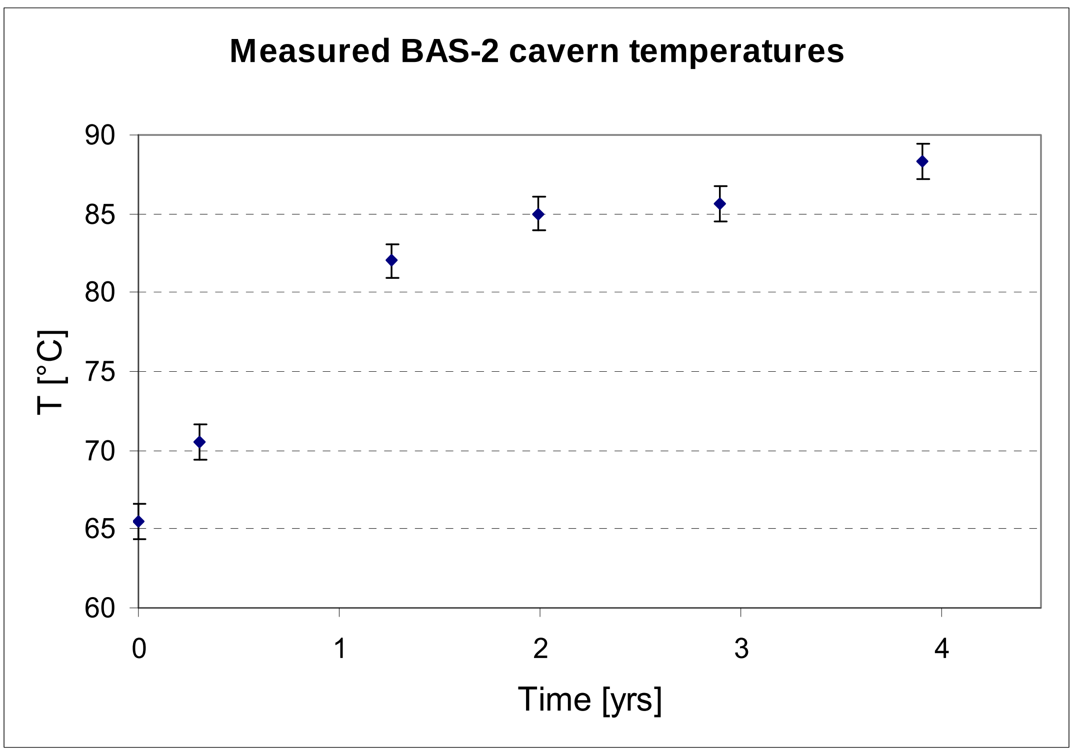


Figure 5 Temperature build-up BAS-2 cavern after shut-in in October 2004.

The temperature build-up can also be modelled. A quick method of estimating the timing of the cavern heat-up is to calculate the characteristic time of heating. This is the time after which 75% of the original temperature gap is restored and can be calculated with the formula provided by **[Karimi, 2007]**:

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

Where Vc is the cavern volume [m3], a=4.67, A = H/D, A_0 = 0.91 and b=1.97.

The results of applying these formulas on BAS-2 and BAS-3 can be found in Table 3. It can be seen that the characteristic time 4.2 [yrs] and temperature 91 [°C] match quite well with the measured values displayed in Figure 5.

With this time and temperature an average volume increase rate, or in case of no permeation the pressure increase rate, can be calculated for the period before reaching the characteristic time. In reality the first years of this period the rate will be higher than just before reaching characteristic time because the temperature rise is driven by the temperature difference that is initially bigger. After reaching the characteristic time the temperature differential is only 25 percent of the original and the temperature rise will slow down accordingly. In other words in the first period of shut-in the biggest volume or pressure increase related to temperature rise will take place and after the characteristic time is reached the temperature rise will continue to slow down and eventually go to zero.

Table 3 Cavern volumes and temperatures.

Cavern	BAS-2	BAS-3	
Volume	208 000	450 000	[m^3]
13 3/8" casing shoe depth	2533	2408	[m] TVD
Cavern temperature after production	65	65	[°C]
Geostatic temperature	100	95	[°C]
Temperature @ characteristic time (CT)	91	88	[°C]
Temperature increase until CT	26	23	[°C]
Volume increase ΔV	2 402	4 455	[m^3]
Theoretical pressure increase ΔP (no permeation)	289	248	[bar]
Aspect ratio	7.7	1.3	[]
Characteristic time	4.2	12.5	[yr]
Average temperature rise per year*	6.2	1.8	[°C/yr]
Resulting average volume increase per year*	567	356	[m^3/yr]
Resulting average theoretical pressure increase per year*	68	20	[bar/yr]
**before reaching characteristic time*			

These calculations show that the theoretical pressure build-up due to reinstatement of the geostatic temperature in case of no permeation would be of the same order as the pressure differential between cavern and lithostatic pressure during active mining. It will therefore be a major factor in the pressure build-up during the characteristic time. The temperature driven brine volume expansion is independent of the cavern pressure, apart from the compressibility of the brine volume itself.

The characteristic time of BAS-2 is calculated to be 4.2 years; this gave a good match with the measured temperatures in the monitoring period **[van Heekeren, 2010]**. For the BAS-3 cavern a significantly longer characteristic time of 12.5 years is calculated and a marginally lower temperature of 88 [°C]. This means that due to the larger volume of BAS-3 the volumetric expansion rate due to heat-up and the related pressure increase rate is lower than in the BAS-2 cavern.

3.2 Additional salt dissolution and cavern fluid saturation

At the time BAS-3 was shut in, it has not been producing significant volumes of salt for a sustained period. Therefore the brine can be considered saturated from the start of the shut-in period in Q2 2010. As discussed in the previous paragraph the temperature of the salt surrounding the cavern will restore to geostatic temperatures and therefore the brine will be heated up. When the brine becomes warmer it can dissolve more salt, however this effect is very small for NaCl brines. Due to the fact that this is such a minor factor compared to other variables this effect it is not incorporated in the model.

3.3 Salt Creep

Creep is movement of salt under pressure gradients. This is sometimes also referred to as convergence or squeeze. One of the distinguishing properties of the FRISIA caverns is the high creep rate compared to caverns at ‘normal’ depth. This is due to the high lithostatic pressure and temperature at the large depth of the FRISIA caverns. There are several theories in use that describe creep of rock salt:

- Based on matching with finite element calculations (linear and non linear models).
- Extrapolated from steady state production experience (only non-linear).

For both methods, FRISIA has good experience using the Norton-Hoff power law with one or two branches.

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

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*.

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

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

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

A cylindrical geometry is used to be able to divide the cavern into several cuts in order to model the cavern behaviour at the various depth intervals. This cylindrical geometry also makes it easier to include the sump in the modelling. This is a conservative approach because a cylindrical cavern has a higher convergence rate than a spherical one.

Using the Norton-Hoff law with a high linear creep branch has been suggested by TNO **[Breunese, 2003]** and is adopted by Deltares (previously Geodelft) in the 2005 Deltares report **[Pruiksma, 2005]** for the BAS-2 cavern**.** The values for the BAS-2 cavern used in the referenced report have been adapted to the different temperature regime at the shallower BAS-3 cavern **[Pruiksma, 2007]**.

In the Deltares 2005 **[Pruiksma, 2005]** report creep is linked to the measured subsidence and to salt crystal sizes found in the cores. Deltares found two sets of parameters that matched these parameters, see Table 4. One of the variants is called the high linear creep and the other low linear creep. Experiences of the last years indicate that the actual values are more on the low linear creep side.

Table 4 High and low linear creep parameters [Pruiksma, 2005].

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	

During steady state production of BAS-1 a reference squeeze rate has been determined. This reference squeeze rate can be converted via a single non-linear Norton-Hoff formula to squeeze rates at other operating conditions (volume, pressure, temperature). A non-linear method can be used in this case because the linear part is very small compared to the non-linear part at operating conditions. The reference conditions can be found in Table 5.

Table 5 BAS-1 non linear reference squeeze rate.

		BAS-1 REF	
Reference squeeze rate	SQref	29.20	$[m^3/hr]$
Activation energy	Q/r	6201	[K]
Salt temperature	Tref	376	[K]
Pressure differential	ΔP	227	[bar]
Volume	V	424 000	$[m^3]$

These values are corrected for the lower temperature in the shallower positioned BAS-3 cavern and are used as the non-linear squeeze variant for the modelling:

$$SQ=SQref*(\exp(Q/RT)/\exp(Q/RTref))*(\Delta P/\Delta Pref)\wedge 3,6*(V/Vref) \quad \ldots\ldots \quad (4)$$

Using the reference squeeze rate, (reference) temperature $T_{(ref)}$ [K], (reference) pressure differential $\Delta P_{(ref)}$ [bar] and (reference) volume $V_{(ref)}$ $[m^3]$, an analysis of the theoretical convergence rate at a large range of pressure differentials for the various methods for a 300 000 m3 BAS-1 cavern was made, see Figure 6. The non-linear squeeze rate (Extrapolated) is plotted together with several benchmark pressure differentials and their respective convergence rate in an attempt to calibrate the reference curves to measured data. The benchmark points are deduced from historic BAS-1 data:

- **HP bleed-off**, from the high pressure bleed-off period in 2009-2010.
- **To HP**, from the pressure rise back to HP after a short production period in 2010.
- **Steady state**, from the period 2001-2004 when the cavern was in a more or less steady-state and good data is available.

For the graph it was assumed that the salt temperature has not changed in this period and the values have been corrected for cavern volume.

It can be seen that for pressure differentials lower than 150 bar, the expected pressure range of a shut-in cavern, there is a reasonable agreement between the benchmark points and the low linear and non-linear creep variants. Above a 150 bar differential pressure the benchmark points are higher than the low linear and non-linear creep variants. The match for the non-linear variant has been improved by doing a curve fitting exercise. The non linear best fit curve has an exponent n of 4 and an A_1 value of 2.8E-07 MPa^{-n}/day (Ref formula 2). In literature, values in this range are found. For this study we did not use this best fit curve but we have used the lineair and non-lineair variants that were used in past studies in order to stay consistent with them. This is a conservative approach because the best fit curve has the lowest creep rate in the low pressure differential range (<30 bar) found in an abandoned cavern.

Figure 7 is a detail of Figure 6. In this detail the behaviour of the various creep models at lower differential pressures can be seen. It is now even clearer that the low linear and non-linear models best represent the benchmark values. This is an important observation for the abandonment phase when the differential pressures are low and a high linear creep model would suggest relatively high creep rates.

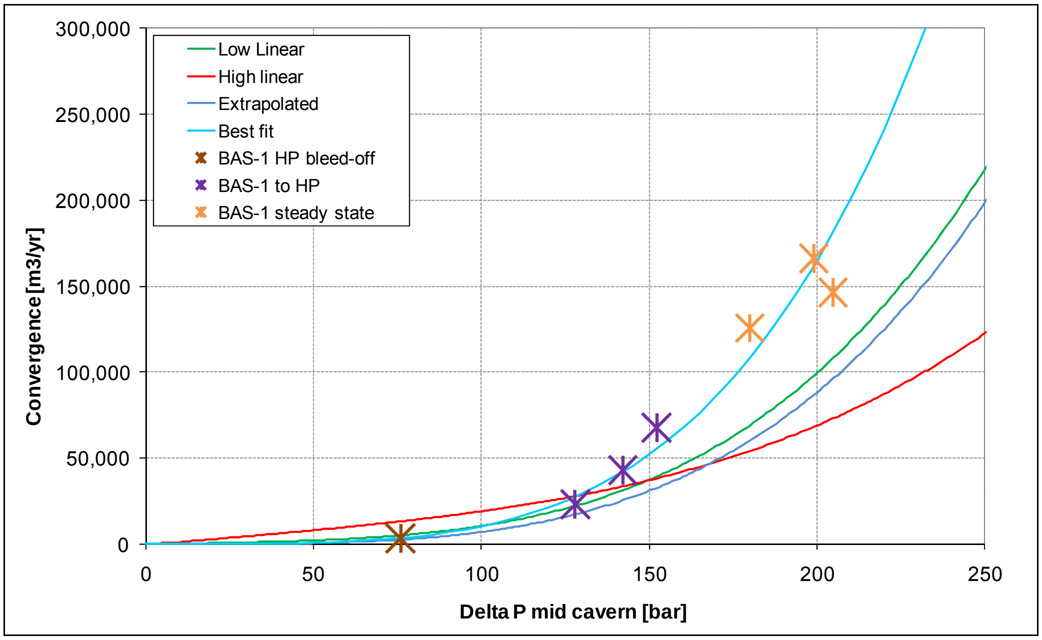


Figure 6 Convergence rate at a large range of pressure differentials.

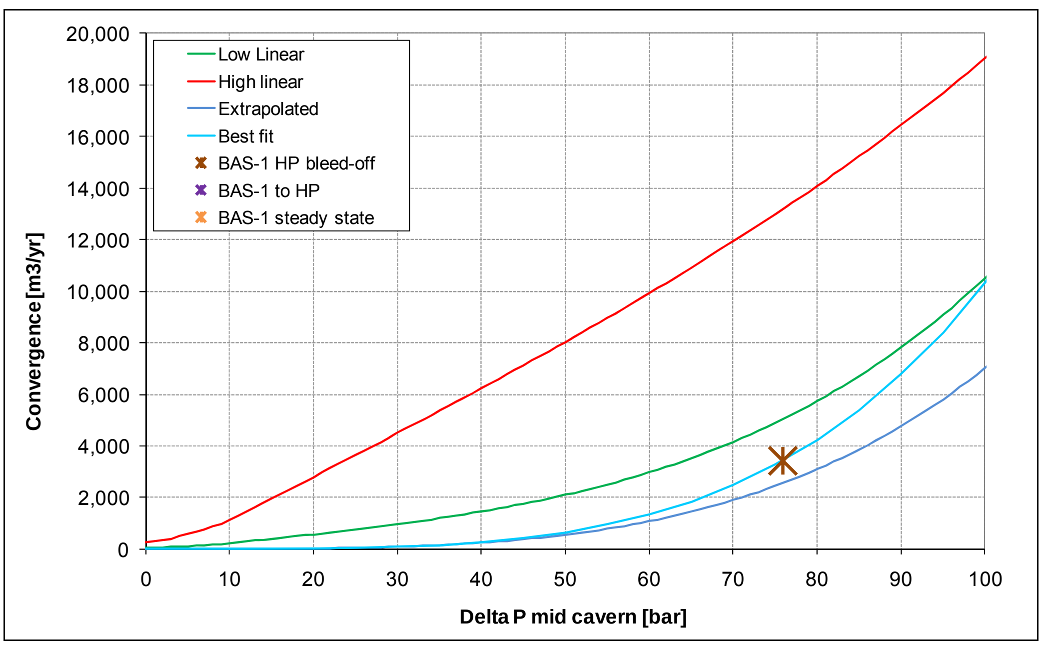


Figure 7 Convergence rate at low pressures differentials.

3.4 Permeation

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 impermeable **[Lorenz, 1981]**. Very low permeability's in the range of 10^{-22} to 10^{-19} m^2 are mentioned in literature. Generally slightly increased permeability in the horizontal direction is found for bedded salt deposits **[Berest, 1995; Lorenz, 1981; Stormont, 1991]**. The virtual absence of permeability is the reason that gas can be trapped under salt layers and that caverns in salt layers are commonly used for the storage of gas. Despite this absence of permeability water drips and seepage are sometimes observed in salt mines and caverns [**Lorenz, 1981; Stormont, 1991]**. Also hydrocarbon inclusions in both primary and secondary porosity in salt have been observed in nature **[Burliga, 2010].**

Around the BAS-2 cavern about 96% of the salt layer consists of Halite. The other 4% consists of Claystone, other salts and Anhydrite. Three Anhydrite layers thicker than 5 cm have been identified by examination of the cores of BAS-1 **[Kohleder, 1994, 1995]**. As discussed in paragraph 2.4 it is not certain that these layers also exist in the current active BAS-3 interval. Such inclusions may have a higher 'base' permeability than halite and are generally stiffer than halite and therefore unable to follow the halite creep. The permeability may have increased because of disturbances due to the flow of salt along the stiffer inclusions. The overall effect on permeability of the salt mass in the FRISIA case is thought to be limited in view of the limited amount of inclusions.

Increased permeability also occurs if the brine pressure approaches and exceeds the minimum rock stress by the creation of micro fractures along the crystal boundaries. The micro fractures form migration paths for the brine. Generally at the roof of the cavern, as the first place where the brine pressure will approach the minimum rock stress, this phenomenon can occur **[Kenter, 1990]**. Salt permeability as a function of effective differential stress, being the difference between the minimum rock stress and the cavern pressure, is illustrated in Figure 8. None of these specific models is used in our modelling, but we have used the concept of the LMS criterion, which allows for slightly enhanced permeability for negative effective stress values . In our model the cavern pressure is constantly kept in a permeating state and cavern volume reduction due to creep leads directly to volume permeating into the above laying salt layer. Figure 9 shows the pressure gradients of the brine and virgin halite rock. It can be seen that the pressure difference between the brine and the virgin halite rock is smallest at the cavern roof.

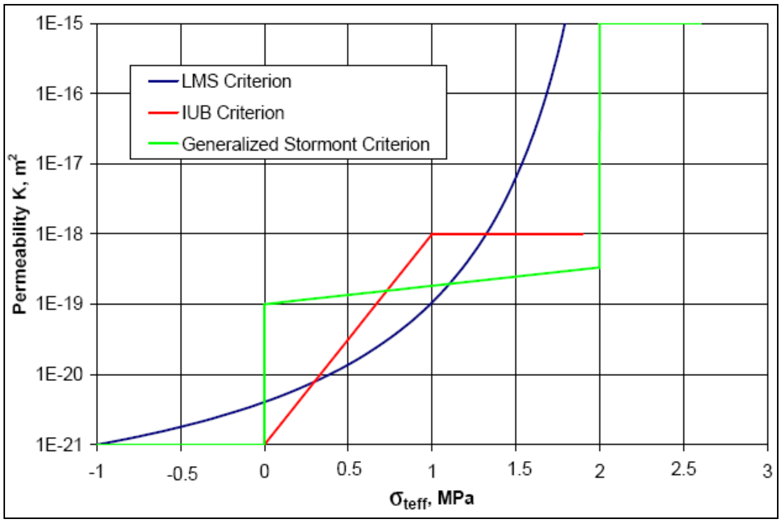


Figure 8 Various secondary permeability criteria. [ROKAHR 2002].

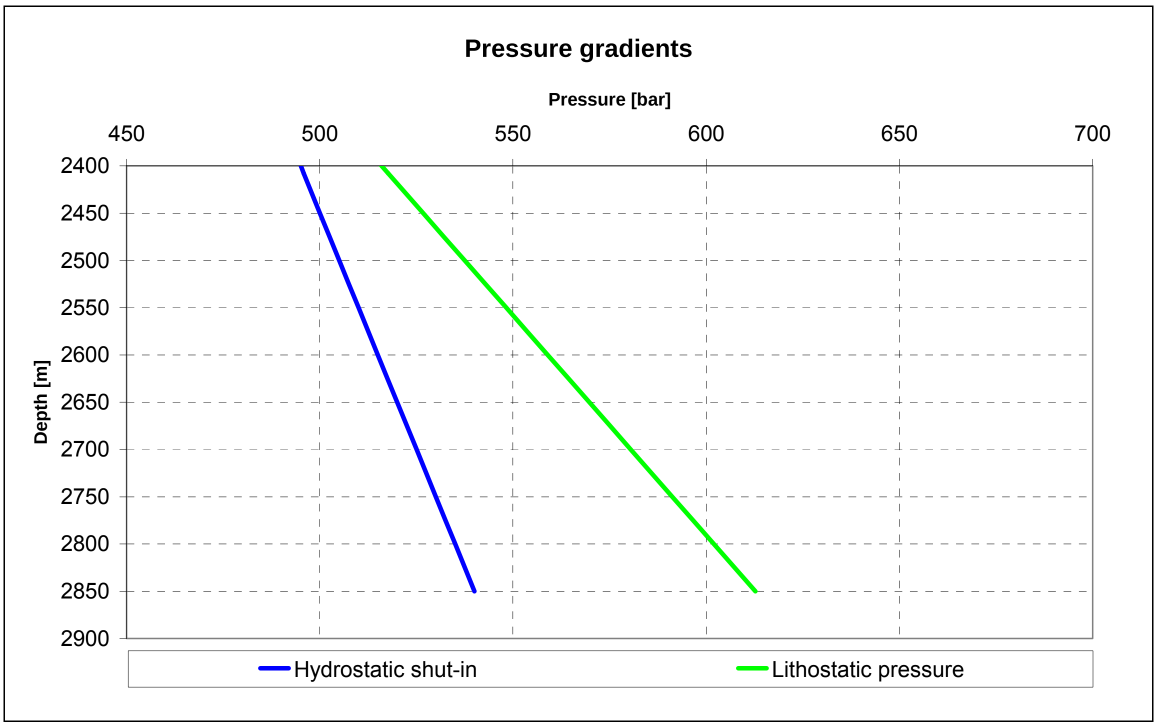


Figure 9 Expected pressure gradients 5 year after shut-in.

The stress field in undisturbed salt sequences is approximately uniform. This is because creep cancels out stress differentials over the long term. The minimum rock stress in salt therefore equates approximately to the pressure exerted by the overlying rock column, the 'lithostatic' pressure. The minimum rock stress in stiff and brittle formations is generally lower than the lithostatic pressure, because compression of the rock matrix due to the principle stress (generally the vertical stress) is only partially transmitted in directions perpendicular to the principle stress (Poisson effect).

During the active mining phase, the stress field around the cavern changes significantly from the virgin lithostatic conditions. Due to the low pressure in the cavity, the stress in the salt around the cavern will vary from brine pressure at the cavern wall to nearly undisturbed lithostatic pressure several hundreds of meters from the cavern. This stress differential causes the salt creep. After the active mining phase the pressures gradually return to the virgin conditions, apart from localised effects caused by the remaining cavity filled with high pressure brine. The pressure conditions around the cavern during its full life have been modelled **[Pruiksma, 2005, 2007 & 2009]**, using the high, low and non linear creep models. In the high creep variant, the pressure differentials in the salt mass around the cavern disappear in several years, while in the non linear variant the process takes several hundreds of years.

The stress fields in the bottom and roof deserve special attention. In the FRISIA situation, the caverns are close to stiff formations at the bottom (Anhydrite, Shale and Sandstones). Although the differential between the active brine pressure and lithostatic pressure is largest at the bottom of the cavern, only a limited contribution of salt creep can come from the bottom section. This will change over the active life of the cavern when the active interval moves up, leaving a ‘tail’ of sump material.

The FRISIA caverns are overlain by massive salt sequences which, in principle, should be expected to contribute to the salt creep via the top of the cavern. Particularly important is the situation at the end of the active mining period, when the top of the cavern approaches the Carnallitite interval (with 40 -50 m of halite roof remaining). The temperature of the salt in the overlying sequence is lower, which would result in a lower creep rate for the halite than for the rest of the cavern; however the overlying Carnallitite may be more mobile than rock salt. The presence of the Anhydrite bank will have a reducing effect on the squeeze rate. Increased rock stress due to arching effects above the cavern will counteract the creep, the overall effect being that no or very little salt flow appears to take place via the roof. This is evidenced by the absence of damage to the last cemented casings in any of the four caverns and the absence of thickening of the Canallitite interval based on time lapsed log results. A further reason for little creep activity in the cavern roof, suggested in discussions by TNO, is the buoyancy behaviour of the brine filled cavity, see below.

The overall picture is that the salt predominantly flows from the sides to the caverns and that the minimum stress in the salt, early after the active mining period is expected to be significantly below lithostatic pressure laterally around the cavern. As the cavern pressure rises and the pressure sink around the cavern fills by creep, the minimum stress in the salt will gradually return to lithostatic conditions.

In the Deltares report **[Pruiksma, 2005]**, calculations have been made to model the salt stress recovery to original lithostatic conditions after cavern abandonment. These calculations have been made for BAS-2 but can be used to give an impression of the BAS-3 situation. The high and low linear creep variants have been modelled. It can be seen that the pressure sink is compensated more rapidly with the high linear variant. This suggests that for a non-linear (or less than low linear) variant the process will be slower. The simulations only cover the first half year after shut-in, with following results:

- For the high linear variant the line with 1 MPa pressure difference between modelled and original horizontal stress has come to about 50 m distance to the cavern wall.
- For the low linear variant the line with 1 MPa pressure difference between modelled and original horizontal stress has come to over 250 m distance to the cavern wall.

The driving force for permeation is salt creep at the lowest section of the cavern, where the pressure deficit (lithostatic pressure minus brine pressure) and the salt temperature, hence salt mobility are highest.

During the BAS-2 high pressure shut-in monitoring period it was observed that the recorded temperature build-up and associated calculated thermal expansion should have led to more pressure build-up than was actually recorded. It was therefore concluded that there is a permeating mechanism in the salt that allows for the gentle leak-off of fluids. This is in line with laboratory observations that the salt permeability increases when the brine pressure approaches the minimum stress in the salt.

Permeation will start at the location where the minimum stress is lowest. Inclusions of stiffer non halite material will form preferential permeation paths. In the beginning permeation is expected at the upper sides of the cavern, leading to accelerated filling of the pressure sink laterally around the cavern. Eventually the brine pressure will be closest to the minimum stress at the roof. The roof will then dominate the permeation process. As the brine pressure in the top of the cavern approaches lithostatic, the stresses due to arching disappear. The stabilisation of pressure observed in BAS-2, suggests that this situation has been reached at a brine pressure of ca 20 bar below the estimated lithostatic pressure (based on a lithostatic gradient of 2.15bar/10m). Intermediate bleed-down/pressure tests during the 6 year monitoring period in BAS-2 have indicated that the cavern has been in a permeating condition soon after shut-in **[van Heekeren, 2010]**; no evidence was found of formation breakdown and fracturing.

The permeation process at near lithostatic conditions is described by **[Kenter, 1990]** as an intermittent process where permeability channels open up and then close when the fluid migrates. At lithostatic conditions, the capacity of the rock matrix to accept fluid is limited. The invasion of fluids will result in compression of the surrounding rock matrix. However at lithostatic conditions there is little or no margin available for compression.

Permeation at near lithostatic pressure conditions is therefore visualised as follows. The salt mass is not uniformly homogeneous. Laminations, weaker crystal boundaries and impurities will form weak spots that will be preferential points for fluid migration. The entry of fluid increases the pressure at the weak spot and thus inhibits the entry of more fluid. The fluid then occupies newly created pore space, referred to as secondary porosity. The 'next weakest point' is then affected by fluid migration, resulting in a process that spreads the fluid in a cone above the roof and leaves a rock mass with secondary brine filled porosity.

The amount of secondary porosity created by permeation in near lithostatic conditions is difficult to establish. IFG advises a value of 0.2% and a value of 1% is used in the report by **[Lux 2010]**. A value of 0.2 is used in this study's base case to stay on the conservative side.

Permeation is likely to be hampered due to the presence of predominantly horizontally orientated anhydrite layers in the salt sections and the re-crystallisation of salts that are deposited due to the reduction in temperature on the way up. Fluids will therefore have the tendency to spread sideways.

Our permeation model assumes that the permeation is high enough to allow for the thermal expansion and volume creep to permeate away without fracturing. This is a valid assumption because the biggest permeation rate has already been incurred in the first years of the shut-in of BAS-2 when the combined effect of creep and thermal expansion was highest. Observations of the BAS-2 cavern in this period, including a echo survey, did not show any signs of rapid loss of brine volume; major fracturing can therefore be excluded. Deliberate pump in tests elsewhere in the industry have confirmed that fracturing is not to be expected**. [Staudmeister & Rokahr, 1998]**

The temperature build-up rate of the BAS-3 cavern compared to the monitored BAS-2 cavern, and therefore the thermal expansion rate will be lower due to the larger volume of BAS-3. This is compensated by the higher creep rate associated with the larger volume of BAS-3.

Therefore the permeation rate for the BAS-3 cavern is expected to be in the same range as for the BAS-2 cavern. The bigger roof area of BAS-3 will therefore result in a lower permeation rate per square metre of roof area.

Permeation processes studied by [Lux, 2010]

has made a history match of the first 6 years of abandonment of BAS-2 and from this a simulation of the abandonment of BAS-3. Although his model is still very conservative it shows a time frame before salt reaches the top of the salt layer that is more than a factor 10 longer than the base case model presented in this report. For details on his work please refer to his report.

3.5 Other migration paths

On first sight, the well itself may be viewed as a potential weak path to formations with lower pressures. However the primary cementations of the currently existing cavern wells give no rise to concern. Also in the active mining period the salt around the casing will have had the tendency to close around the casing due to creep. For this reason the last cemented casing, 14” in BAS-3, has been designed for full collapse pressure caused by lithostatic pressure outside in the salt and the lowest possible inner pressure (diesel column).

Temperature logs in BAS-2 during the monitoring period do not give evidence of brine flow outside the 13 3/8” casing. Hence the well is not considered a likely weak path. The top-down annular cementation of the 10 3/4" – 13 3/8” annulus of BAS-2 has proven to be tight over the last 5 years.

The inner bore of the well will be closed off with mechanical devices and cement covering the entire Zechstein section, an interval around the intermediate casing shoe and an interval close to surface, consistent with all requirements specified in the Dutch mining law & regulations (Ref: Mijnbouwbesluit Afd. 5.1, 5.3; Mijnbouwregeling Afd. 8.5, www.sodm.nl). The inner bore of the well is therefore not regarded as viable migration path, if the abandonment of the well is executed in a technically competent manner.

A sketch of the technical abandonment of BAS-3 is as follows:

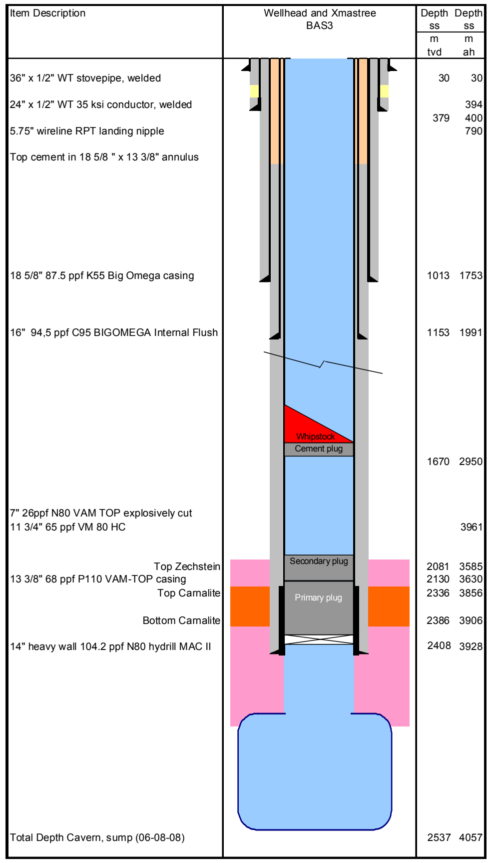


Figure 10 Sketch of the technical abandonment, including first preparations for a sidetrack

The technical abandonment of BAS-3 will be subject of a separate submission as an operational program to SodM, following the outline shown in the sketch.

It is regarded as extremely unlikely that the wellbore and cement will represent a weak point in the formation, and hence it is not expected to be the preferred migration path.

3.6 Impact of the Carnallitite layer

(NG Consultants) has studied the consequences of possible contact between NaCl brine and the Carnallitite layer **[Grueschow, 2010]**. The Carnallitite layer consists of a sequence of Halite (NaCl), Kieserite ($Mg(SO_4)*H_2O$), Sylvite (KCl), Carnallite($KMgCl_3*6(H_2O)$) and insoluble (e.g. Clays & Anhydrite) layers. The Carnallitite has never been cored by FRISIA; therefore the composition is derived from gamma ray and density logs that have been compared with typical sequences commonly found in the Zechstein in North-West Europe. NG has identified two scenarios for these typical Carnallitite compositions. According to NG there may be Carnallite layers in the Carnallitite representing up to 55% of the Carnallite thickness but the average Carnallite content is estimated at 30%.

The figures below show the volume balances for the 55% and 30% scenarios when 1 m^3 of brine migrates through the Carnallitite, this can either be by permeation or direct contact with NaCl brine due to gradual scaling of the cavern roof. It can be seen that, depending on the Carnallite content, the conversion process can vary significantly. For modelling purposes we use the average 30% type Carnallitite for the base case and do a sensitivity run for the 55% type Carnallitite.

For the 55% Carnallitite variety this means that if 1 cubic meter of brine permeates into the Carnallitite 2.06 cubic meter of rock is affected and converted into a total of 3.18 cubic meters of bulked insolubles with carnallitic brine in the pores and free carnallitic brine. This is 0.12 cubic meters net volume increase.

For the 30% Carnallitite variety this means that if 1 cubic meter of brine permeates into the Carnallitite 3.53 cubic meter of rock is affected and converted into a total of 4.68 cubic meters of bulked insolubles with carnallitic brine in the pores and free carnallitic brine. This is 0.15 cubic meters net volume increase.

Volumenbilanz: Quinäres System; 85°C; 55% iger Carnallitit	m³	Schütt-volumen m³	Poren-volumen m³	"Freie" Lösung m³
Lösemittel (NaCl Solevolumen)	1,00			
aufgelöstes Carnallitgestein	2,06			
Kieserite: 10 %				
Carnallite: 55 %				
Sylvite: 0 %				
Halite: 28 %				
Insolubles: 7 %				
Summe	3,06			
Gleichgewichtslösung	2,09			1,65
Primärer Kieserit	0,14	0,20	0,06	
Primär+ Zersetzungs-Sylvin	0,22	0,30	0,09	
Primär und Kristallisierter Halit	0,64	0,90	0,26	
Unlösliches (Ton, Anhydrit)	0,10	0,14	0,04	
Summe	3,18	1,54	0,44	

Figure 11 Volume balance when 1 m³ of brine comes in contact with 55% Carnallitite.

Volumenbilanz: Quinäres System; 85°C; 30% iger Carnallitit	m³	Schütt-volumen m³	Poren-volumen m³	"Freie" Lösung m³
Lösemittel (NaCl Solevolumen)	1,00			
aufgelöstes Carnallitgestein	3,53			
Kieserite: 10 %				
Carnallite: 30 %				
Sylvite: 0 %				
Halite: 53 %				
Insolubles: 7 %				
Summe	4,53			
Gleichgewichtslösung	2,09			1,05
Primärer Kieserit	0,27	0,38	0,11	
Primär+ Zersetzungs-Sylvin	0,22	0,30	0,09	
Primär und Kristallisierter Halit	1,92	2,69	0,77	
Unlösliches (Ton, Anhydrit)	0,18	0,25	0,07	
Summe	4,68	3,63	1,04	

Figure 12 Volume balance when 1 m³ of brine comes in contact with 30% Carnallitite.

The consequences of the Carnallite layer on the permeation process and therefore permeation rate and subsidence will be discussed in paragraph 5.6.

3.7 Containment and confinement

A sequence of containment and confinement zones were identified above the Zechstein **[Barge, 2003]**. Several horizons are available to store the volumes of brine permeated from the caverns, thus avoiding that brine would migrate to the surface.

The fluids that will leak off from a sealed off cavern, and do not become trapped in newly created secondary porosity in the salt sections, will eventually migrate to and flow into a more permeable containment horizon above the salt section. A confinement zone will prevent further migration to shallower levels, unless the pressure increase in the containment horizon exceeds the strength of the overlying confinement horizon leading to failure of the containment horizon and flow into the next higher confinement zone. The strata above the cavern and their function in the leak off process are shown as follows:

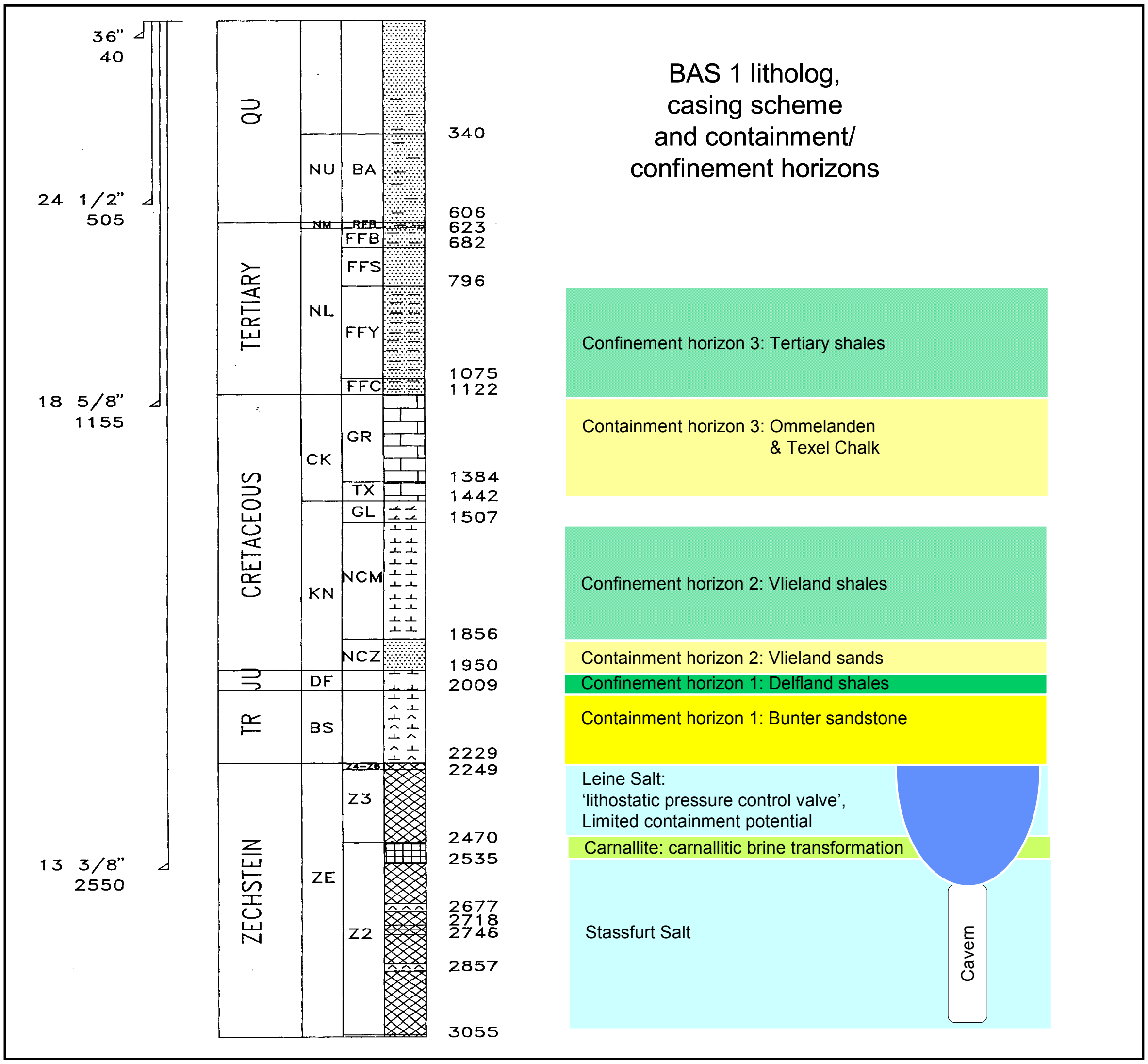


Figure 13 Overview of geological strata above BAS-1 showing containment and confinement horizons.

In the geological situation for the FRISIA caverns, the risk for contamination of fresh water horizons or brine break-out to surface due to leaked off brine is judged to be practically negligible.

Should gas be present in a containment zone, the containment zone is likely to be able to absorb more brine with less pressure increase due to the compressibility of the gas, presenting a lower risk for failure of the confinement horizon and uncontrolled migration of gas to shallower strata. However for the current FRISIA caverns there is no gas in any of the identified confinement horizons. Hence the risk of uncontrolled gas migration due to permeation or fracturing damage to the confinement ('cap rock') horizons is judged to be nil.

Nearby and updip from the brine caverns gas is being produced from the Ommelanden Chalk, this layer is depicted in Figure 13 as the third confinement horizon. The gas in this layer is contained by the tertiary shales and has been tight over a period of millions of years. Brine being less mobile than gas will almost certainly be trapped in this confinement zone

3.8 Buoyancy of the cavern

As salt in the FRISIA case behaves as a (very) thick fluid, the cavern will have a tendency to float up, not unlike an oil droplet in water, but with totally different viscosity parameters. The effects of buoyancy of caverns have hardly been described in open literature; the only reference we could find was **[Verruijt, 2006]**. This effect is mainly analysed for foundation calculations in construction projects.

Fluid dynamic modelling did not provide realistic results, probably due to the use of unrealistic flow parameters. In nature brine inclusions are found in salt sequences that have remained stable over geological times. If any floating up occurs, it is thought to be a very slow process on a geological time scale that is stopped when the cavern reaches the stiff overlying anhydrite layer that does not allow for this movement.

The buoyancy of the cavern contents would result in a stress increase in the roof, resisting flow of salt towards the cavern from above in the active mining phase. At near lithostatic cavern fluid pressures, the stresses in the roof induced by buoyancy would lower the minimum stress available to resist permeation. This might be the reason why the maximum cavern pressure does not fully reach the lithostatic value; a feature generally observed and reported about in literature.

For the BAS-2 cavern the buoyancy related stress could be up to 20 bar. This is of the same magnitude as the observed pressure difference between the current near-stabilised cavern pressure and the estimated lithostatic pressure at the 13 3/8" casing shoe. It should be mentioned however that this difference between equilibrium and lithostatic pressure can also be explained by the uncertainty in the calculation of the lithostatic pressure. The value selected for our base case accommodates the buoyancy related stress reduction and we analyse the sensitivity to variations in lithostatic pressure.

3.9 Instability of the cavern roof

It is known that cavern roofs may be subject to degradation by scaling off due to stress differences, softening due to permeation and the like. Initially the roof will find its most stable shape, given the stress conditions and geological features like competent anhydrite layers.

If the roof degradation does not stop, in the general case, the cavity will develop upwards, depositing a tail of decompacted residue formed by the material falling from the roof. The volume increase due to decompaction or bulking will eventually occupy the original free volume of the cavity and stop further upward migration. In the FRISIA case the migrating cavity will meet the overlying Carnallitite and Anhydrite banks; this is discussed under the roof breakthrough scenario for BAS-3.

Instability is related to the rock stresses and the span of the roof. If the cavern pressure increases, the stresses in the roof due to presence of the cavity will decrease. However softening of the roof material due to continued permeation may negatively affect the competence of the roof material. The end result and timeframe of possible degradation are difficult to forecast.

Echo surveys of BAS-2 did not show noticeable roof degradation between 2004 and 2010 and it is expected that if any degradation will take place, it will be a very slow process.

The roof of BAS-3 showed instability with a cavern diameter of ca 100 m and developed a spherical shape during active mining, in spite of the use of large volumes of diesel in an attempt to stabilise the roof. Also the volume of the cavern was purposely reduced to promote roof stability. Towards the end of the active mining period the roof showed stabilisation. The cavern pressure has risen since Q2 2010; this will have a further stabilising effect. It can however not be excluded that the roof will degrade over time and come in contact with the overlying Carnallitite. We have therefore modelled a roof breakthrough scenario for BAS-3, see paragraph 4.5.

In case of roof breakthrough and direct contact of the cavern with the carnallitite, massive amounts of insoluble debris will be created by the conversion of sodium chloride brine to carnallitic brine. This process is expected to fill the entire cavity with bulked debris with fluid stored in the pores of the debris. In view of the near lithostatic pressure conditions, the loading of the debris ‘grain bed’ will be relatively low, this will the stop creep and compaction. The anhydrite bank overlying the Carnallitite will present a barrier for roof degradation and almost certainly stop the upward migration of the cavity. As the bulked insoluble material will be supported by the lithostatically pressurized pore fluids, the load on the grain bed will be limited and therefore eventually stop convergence, as depicted in Figure 4.

4 Modelling

In order to predict the behaviour of the caverns after abandonment, a model was developed that allows rapid evaluation of variables involved. A base case was defined representing to the experience and opinion of the authors the most likely conditions. Several variables were tested to identify best and worst case outcomes.

The squeeze behaviour of a cavern in FRISIA conditions is strongly dependent on depth. Using a single cavern at average conditions will not be representative for the squeeze behaviour of the bottom section of the cavern, where the 'engine' will be strongest. The model therefore distinguishes four 'cuts' in the open cavern section and one cut representing the sump, allowing appropriate pressure conditions to be used for the behaviour of each cut.

4.1 Variables

The diagram below shows the main variables of the model. The variables at the blue side influence the creep here referred to as the 'engine' for permeation, at the yellow side the subsidence variable and at the green side the factors influencing the permeation behaviour.

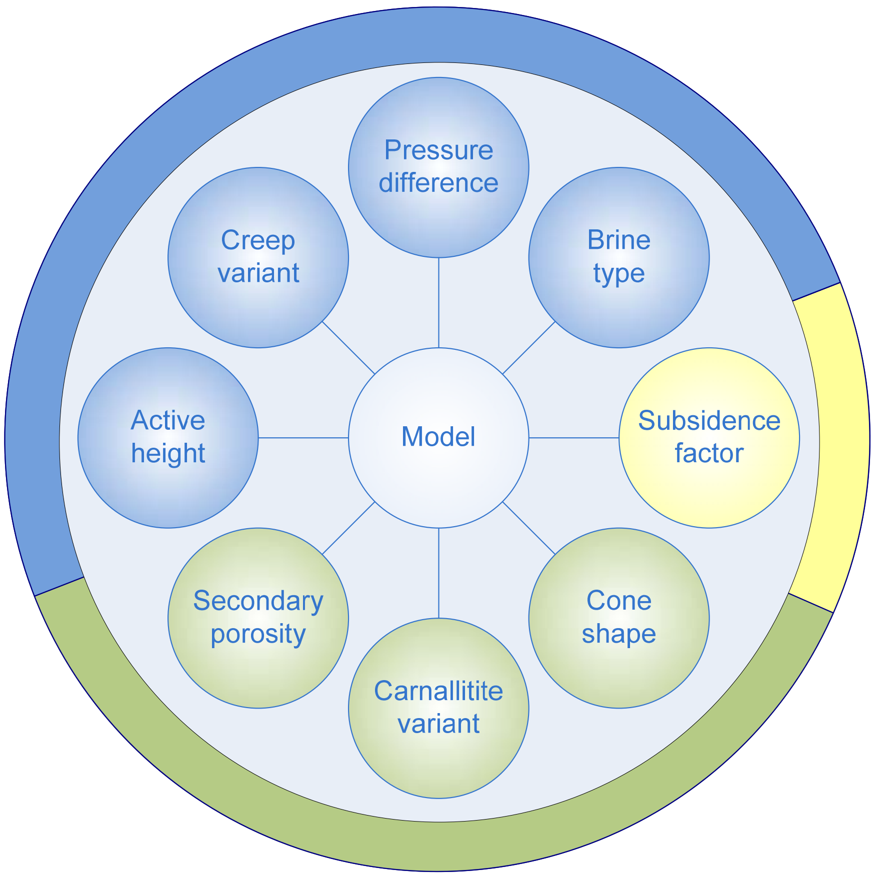


Figure 14 Representation of the model variables.

A base case was developed for the model. This base case represents to the opinion of the authors and reviewers a realistic 'engineered expectation'. A range of sensitivities were then tested with the model to quantify deviations from the expected conditions. An overview of the base case and sensitivity analysis is shown in the following table:

Table 6 Base case values and the respective modelled sensitivities.

Factor	Base case	Sensitivities
Creep variant	Non-linear	Low and high linear creep variants
Pressure difference	Bas-2 experience.	From 0 to more than BAS-2 experience
Sump	Cavern only	Cavern and sump
Brine type	NaCl	Carnallitic (only roof breakthrough scenario)
Subsidence factor	BAS-3 experience	Mature (BAS-1&2) bowl parameters
Secondary salt porosity	0,2 %	0% and 2%
Carnallitite variant	30%	55%
Cone shape	45° from cavern roof	From 0° from cavern roof (chimney) to 90°

Permeation 'engine'

The factors discussed here influence the time that it takes to squeeze out the cavern volume.

Subsidence

This factor influences the effect of convergence on subsidence.

Permeation

These factors influence the capability of the salt to store the permeating volume and the chemical reactions that influence the permeating volume.

4.2 Subsidence

Initially permeation leads to displacement of volume from the original cavern into the overlying salt sequences in a principally near-constant volume system consisting of the cavern, its immediate surroundings, the permeation cone and a vertical column above. If no volume reduction takes place in the underground, there will be no surface subsidence.

Permeated fluid that is stored in newly created porosity, also called secondary porosity created by expansion of the rock at near lithostatic conditions, will not cause subsidence. This effect is included in the model.

Only if fluid escapes from the system, e.g. by flow into permeable (containment) zones, the volume of the system will decrease and subsidence will occur. In the subsidence prediction we have assumed that all fluid leaving the caverns will lead directly to subsidence; this is a worst case approach. In the operational phase a ratio of 1.1 cm subsidence per 100,000 m3 of convergence (subsurface volume loss) has been observed. This ratio is also used in the subsidence prediction.

The subsidence effects are also related to the creep behaviour of the salt. If linear creep is strong, salt will continue to flow to the cavern at low differential pressure. This allows salt to flow from large distances from the pressure sink created by active mining, causing uplift near the centre of the sink and slight subsidence further away. This uplift is also referred to as rebound and can have a magnitude of several cm **[Breunese, 2003]**. The overall effect of linear creep will be that the pressure sink will fill relatively quickly and that the subsidence at the centre of the bowl will wholly or partially be compensated by rebound. Current observations however indicate that linear creep effects will be relatively weak. Rebound has therefore been ignored in our model.

4.3 Model description

The model calculates the creep behaviour of 4 cuts and the sump, as depicted in the following figure 15. The model used has been presented in section 3.3.

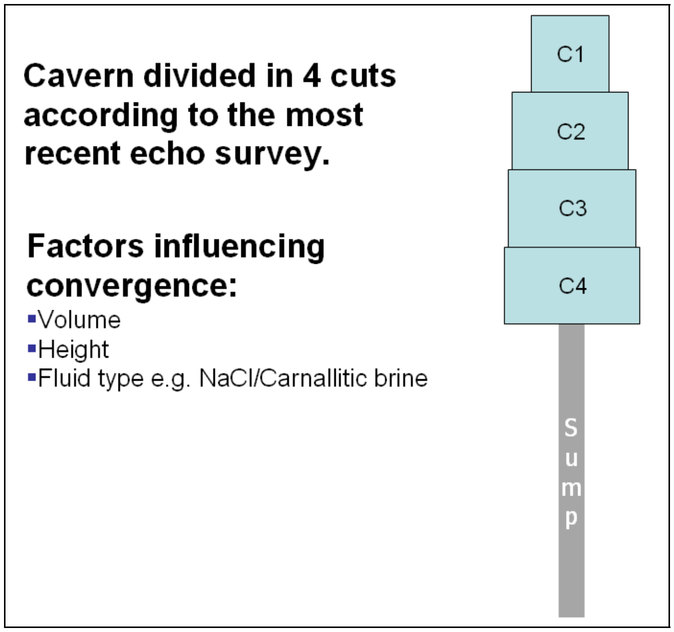


Figure 15 Model setup, partitioning into cuts according to last BAS-3 echo survey

The abandonment process is modelled numerically with time steps of 1 year. At each time step the volume of a cut is calculated from the previous year's volume of the cut minus the squeeze in the cut from the previous year. This new cut volume combined with the pressure differential for the cut determines the new squeeze rate. According to the selected squeeze function. To get the total cavern volume and squeeze rate the individual amounts of all cuts are summed.

The permeation volume through the cavern roof is equal to the squeeze volume in each year. The first part of the brine leaving the cavern is stored in the secondary porosity of the roof halite above the cavern. The available storage room is determined by the defined permeation cone angle and secondary porosity.

When the total permeated brine volume equals the storage volume in the halite roof the rest of the NaCl brine leaving the cavern is converted to carnallitic brine and insolubles according to the ratio of the carnallitite type that is modelled. This conversion is coupled with a brine volume increase. The carnallitic brine permeates further and is first stored in the anhydrite layer. This layer can store some volume due to lateral compression. When the anhydrite layer is filled, the brine will continue to permeate into the secondary porosity of the top halite layer. This layer has a capacity that is determined by the same secondary porosity and permeation cone angle as for the roof Halite. When this volume is filled with the carnallitic brine, the brine will continue to permeate and migrate into the overburden.

The fraction of the brine that migrates into the overburden and can be attributed to sodium chloride brine leaving the original cavern is assumed to lead to surface subsidence according to the subsidence bowl parameters. This is done by correcting the outflow in the overburden with the carnallitic brine conversion factor.

An essential assumption in the model is that the pressure in the cavern is transduced into the overlying salt rock up to the overburden. As long as the engine in the cavern is active no pressure equilibrium in the overlying rocksalt will occur, the result is permanent brine permeation into the rock salt and overburden until the cavern is closed. This concept is very conservative.

4.4 Base case without roof breakthrough

The base case that we have developed is developed in the previous chapters. This base case should be considered as a realistic 'engineered expectation'. In the next chapter sensitivity runs of the variables are shown and the argumentation for the base case parameter will be discussed.

Figure 16 & Figure 17 how the modelling results for the long and short term cavern volume development per cut. Figure 18 & Figure 19 show the development of the permeation rate and the predicted subsidence. Listed below the figure are the variables as used in the run.

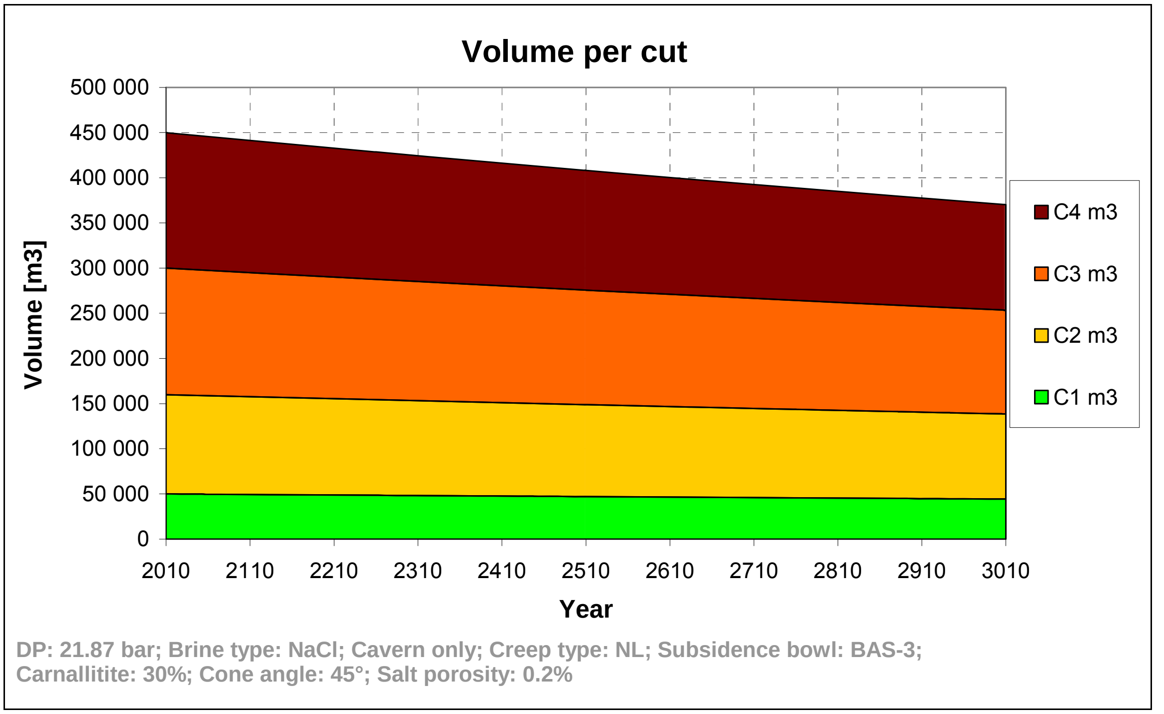


Figure 16 Base case volume development over the first 1000 years.

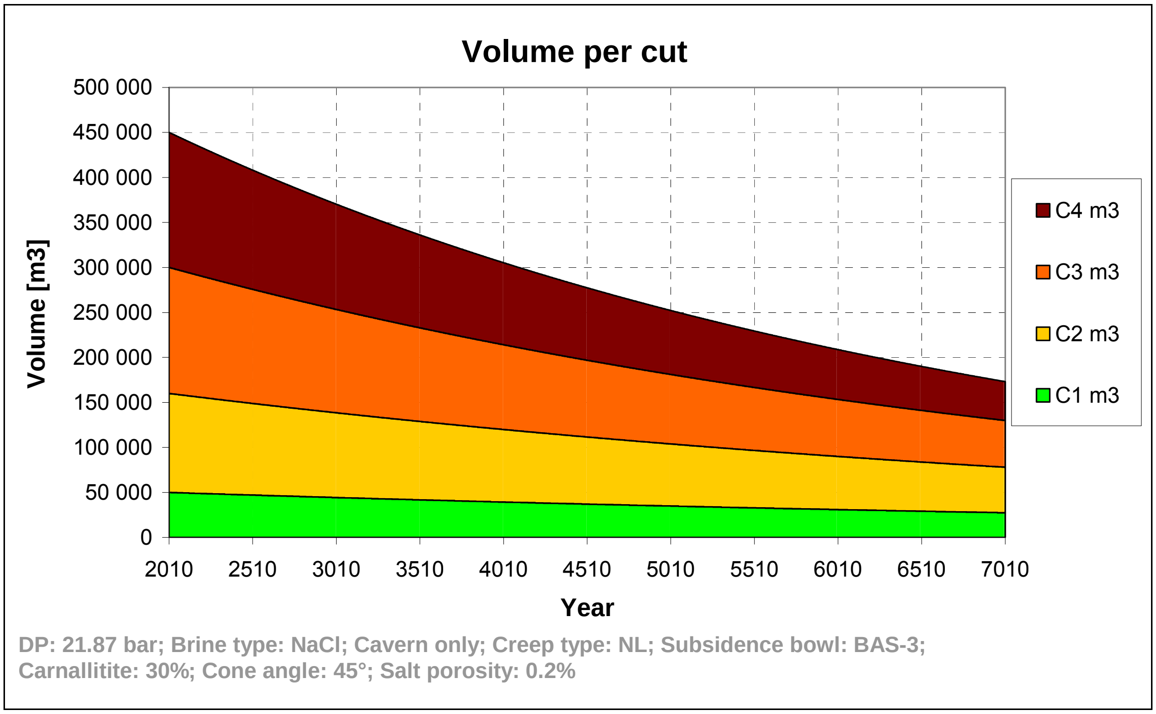


Figure 17 Base case volume development over 5000 years.

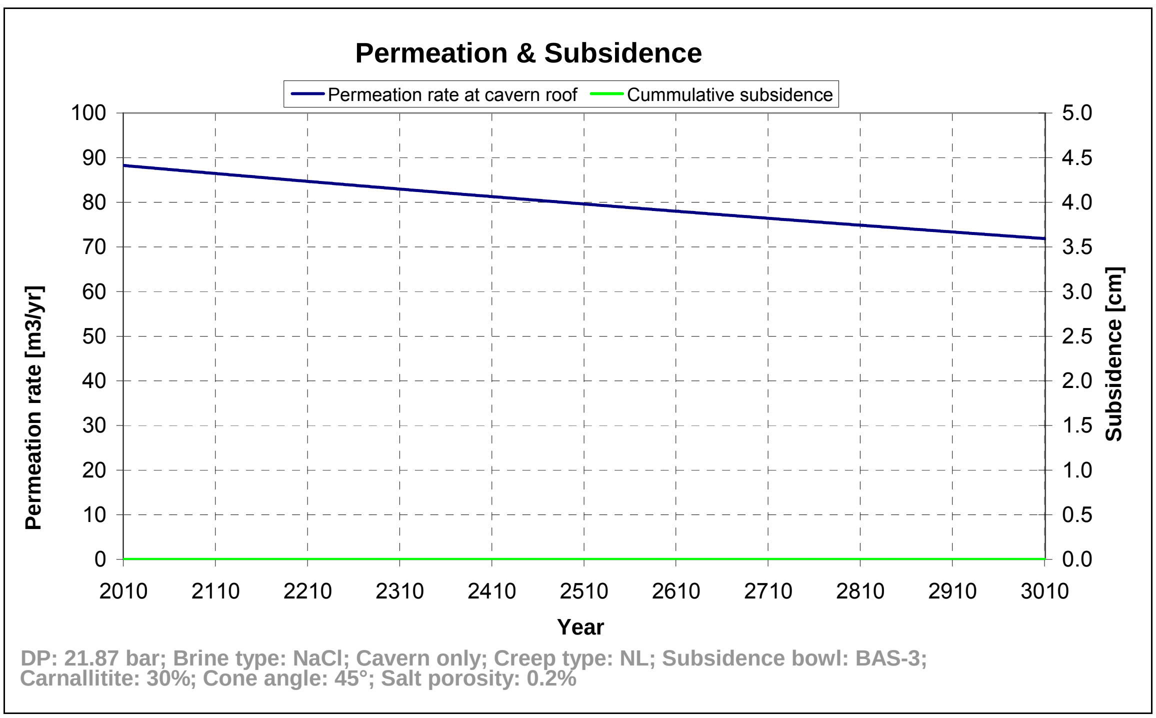


Figure 18 Base case permeation rate and subsidence over the first 1000 years.

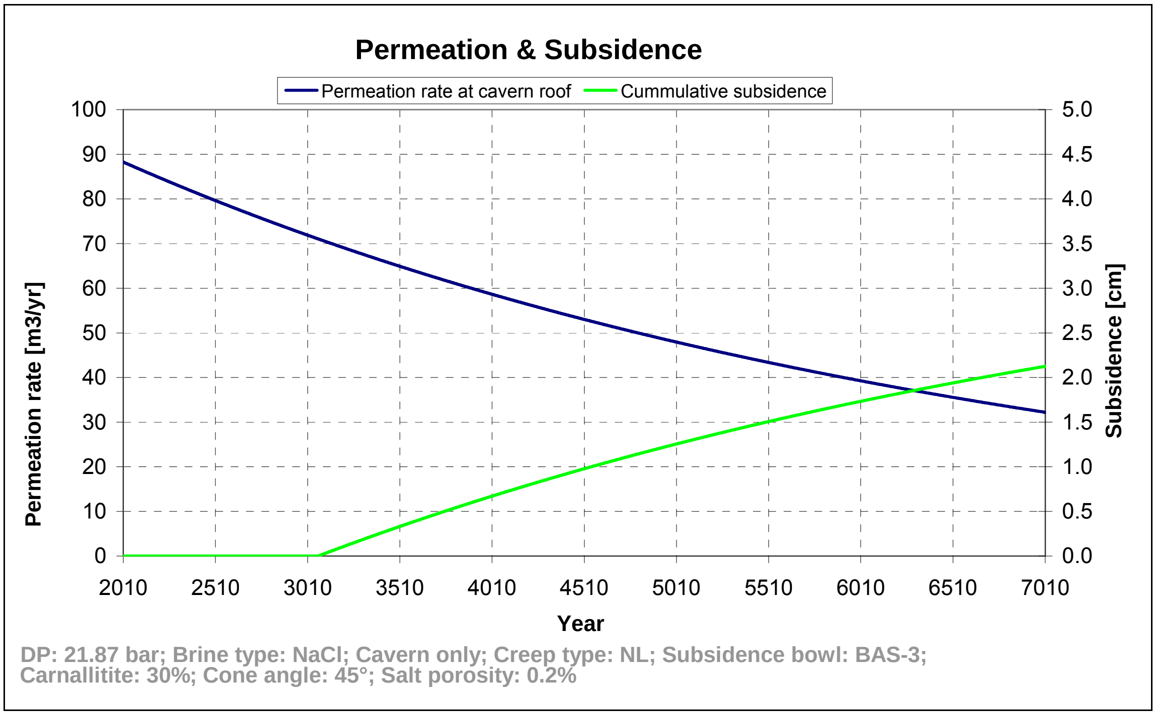


Figure 19 Base case permeation rate and subsidence over 5000 years.

The resulting estimates are considered conservative in view of the underlying assumption that the entire permeation volume lost above the salt section will lead to subsidence, ignoring any storage in secondary porosity above the salt.

4.5 Roof breakthrough case

As discussed in paragraph 2.5 the roof of the BAS-3 cavern with a cavern shape as measured during the last echo measurement in combination with the higher cavern pressures after shut-in is expected to remain stable. If for instance due to continued intensive leaching the shape is changed from more or less spherical to a shape as depicted by picture 0. in Figure 20 instabilities in the roof may develop. This is likely to take the form of a gradual degradation process rather than a sudden collapse scenario.

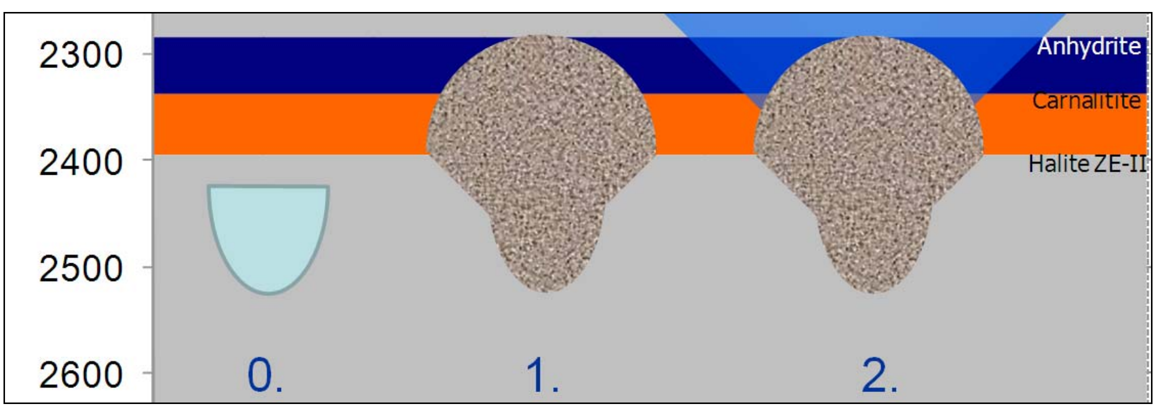


Figure 20 BAS-3 Impression of roof breakthrough scenario cavern development

The gradual degradation of the roof and the conversion of sodium chloride brine to carnallitic brine liberate massive amounts of insoluble debris (Figure 20, picture 1.). The conversion process also leads to an increase in brine volume. The same base case parameters are used as in the permeation scenario. For the 30% Carnallitite case the combination of the aforementioned processes leads to a remaining free brine volume above the bulked insolubles that is half of the original cavern volume. In the 55% case the remaining free volume is almost equal to the original cavern volume.

The free volume is expected to follow the shape of the Carnallite layers and therefore create horizontally oriented slabs of free volume. This will either be followed by a permeation process that is, because of the lack of height and the increased brine density, significantly slower than that of the original cavern or by a process of continued roof degradation until the free volume is choked by the bulking of insoluble material. (Figure 20, 1 and 2) The anhydrite overlying the Canallitite is expected to be relatively resistant to degradation; therefore permeation is expected to be predominant in the beginning. The bulking factor is an important factor in this process. Our base case uses a factor for competent consolidated material that bulks up; this is derived from operational experience and advice from , in addition we have made a raw sensitivity analysis. With a realistic bulking factor of 1.4 the cavern filled by debris can not reach the top of the Zechstein.

Figure 21 below shows the volume of affected rock above the cavern due to roof collapse as a function of the bulking factor. When less consolidated material (the extreme being loose sand sequences) bulks up, significantly lower bulking factors may occur because resorting of the grains will lead to a limited increase of pore volume. A much lower bulking factor of 1.1 may be expected if poorly consolidated material above a shallow cavern bulks up, however this situation is considered to be unrepresentative for the conditions above the deep FRISIA caverns.

It can be seen that in the 55% Carnallitite case more rock above the cavern is affected. The rock volume from the cavern up to the top of the salt section, considering a cone with a 45 degree angle from the cavern roof, is about 47 million m^3. For both cases the affected rock mass is limited to the salt section for the complete range of bulking factors.

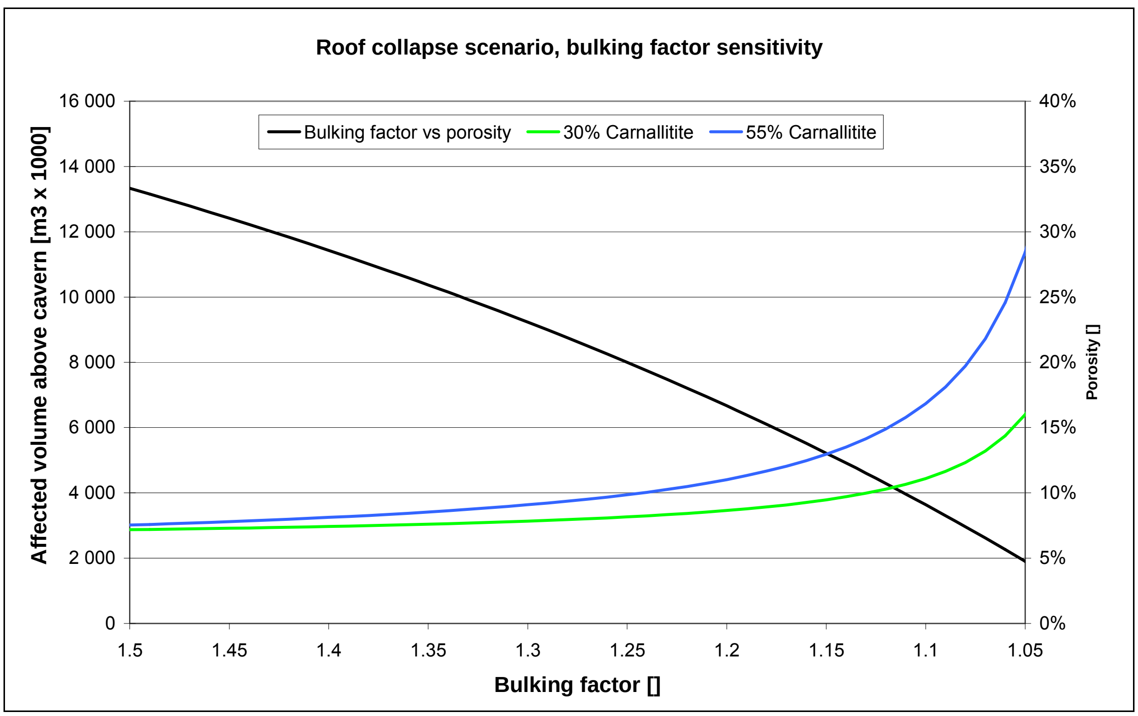


Figure 21 Sensitivity to bulking factor

In the end situation there will be a cavity filled with bulked material. Subsidence will occur if this bulked material is compacted and the pore fluids permeate into the overburden. The high fluid pressures will support the grains of the bulked material. This process will, if existing, therefore be significantly slower than the permeation scenario described in the base case. The subsidence will therefore be equal or less than for the base case but on a much longer time scale.

Besides this gentle process we have also considered the unlikely event of a sequence of processes that would induce sudden roof collapse:

If brine permeation into the Carnallite and the resulting volume increase create a pressure condition where at the same time brine (for some reason) can not permeate further it cannot be excluded that instabilities in the cavern roof will occur. Larger fragments will fall out of the roof and open contact will be established between the sodium chloride brine and the Carnallitite. At the contact surfaces sodium chloride will precipitate and Carnallite will dissolve. Again we see this as self slowing process, because the precipitate will restrict the exchange in the Carnallitite with 30% (likely) to 55% (high) Carnallite salt. Most of the material will bulk up and a condition will be created with a less “worst case” outcome than the base case gentle process. The gentle base case with the various sensitivity analyses as described in this report can still be considered as the worst case process.

4.6 Conclusions

- The BAS-3 base case without roof breakthrough represents in the opinion of the authors and reviewers a realistic engineered expectation of what is likely to happen to an abandoned BAS-3 cavern.
- The base case shows a very slow process of migration of the current cavern content at near lithostatic conditions, leading to hardly measurable subsidence of an order of magnitude smaller than the predicted rate of sea level rise or observed autonomous subsidence in the area.
- Roof breakthrough will not likely lead to a worse situation than gradual closure of the cavern without roof breakthrough. The presence of the Carnallitite and Anhydrite banks are expected to stop upward migration of the cavity.

5 Sensitivity analysis

5.1 Creep variants

Although, as discussed in paragraph 3.3, there are a number of arguments that support modelling with the non-linear creep variant as used in the base case we also did runs with a high linear creep variant (HL) and a low linear creep variant (LL). This is done because these variants were used in some of the modelling work done in the past. The results are shown in the diagrams below:

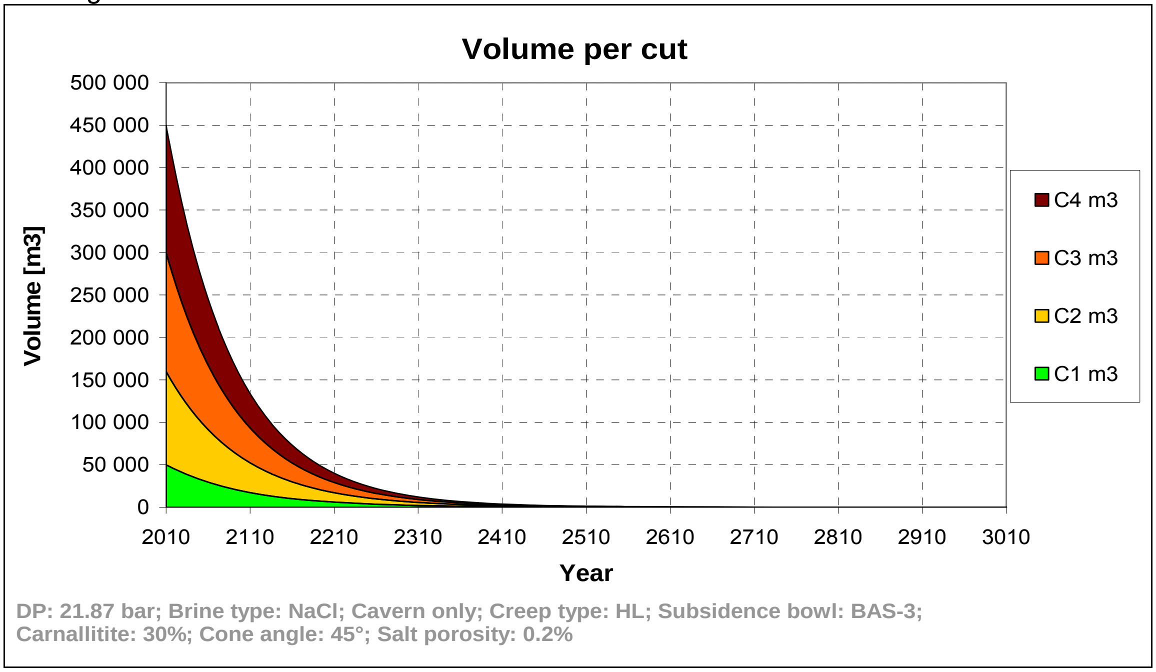


Figure 22 High linear variant volume development during the first 1000 years.

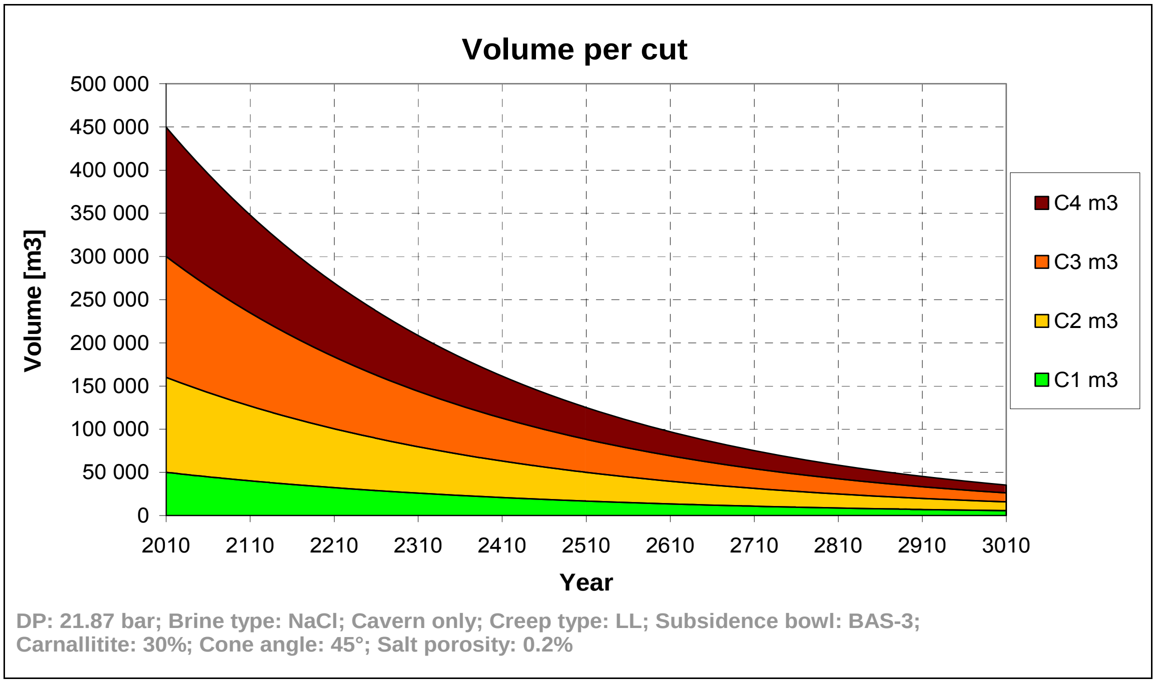


Figure 23 Low linear variant volume development during the first 1000 years.

It can be seen that the time it takes for the cavern volume to be fully permeated into the overlying salt layers is much shorter with the creep variants that include linear creep and that when the linear creep is more pronounced the process is faster. The linear creep term contributes most of the total creep at near lithostatic cavern pressures. In the creep chapter we discussed the different variants and came to the conclusion that the non-linear variant has the closest match with the field data. Another argument was that the expected rebound effect, uplift instead of subsidence, after shut-in for the linear variants is not observed.

Our model does not consider this rebound effect that could more than compensate the modelled subsidence after shut-in. The model forecasts the following permeation rates and subsidence – ignoring uplift effects- for the HL and LL creep variants:

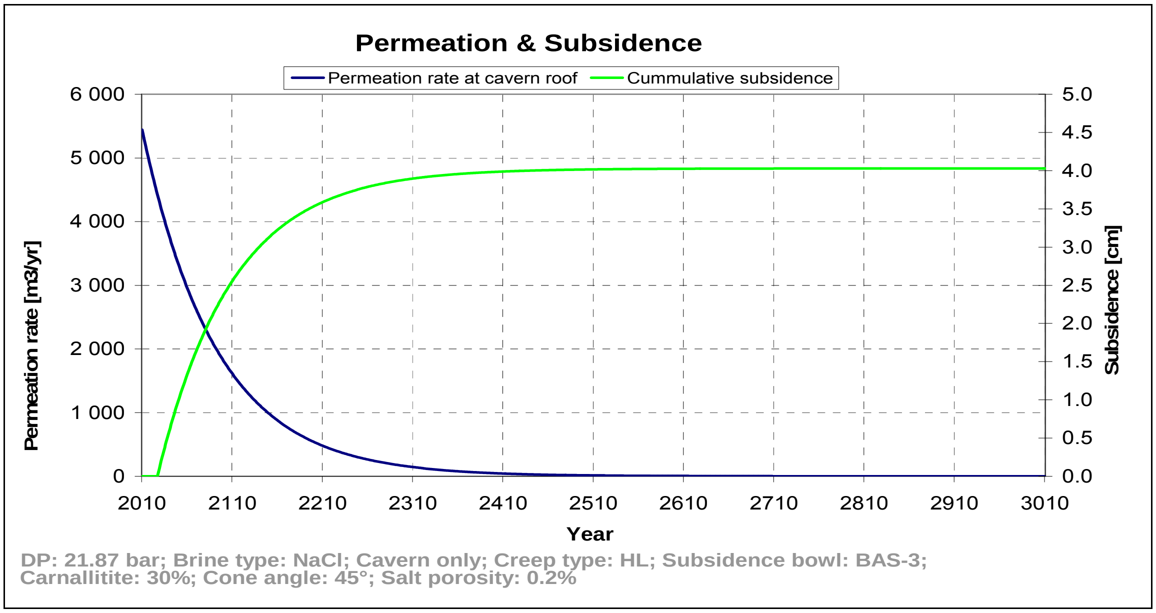


Figure 24 High linear variant permeation rate and subsidence over the first 1000 years, without taking a rebound effect into account.

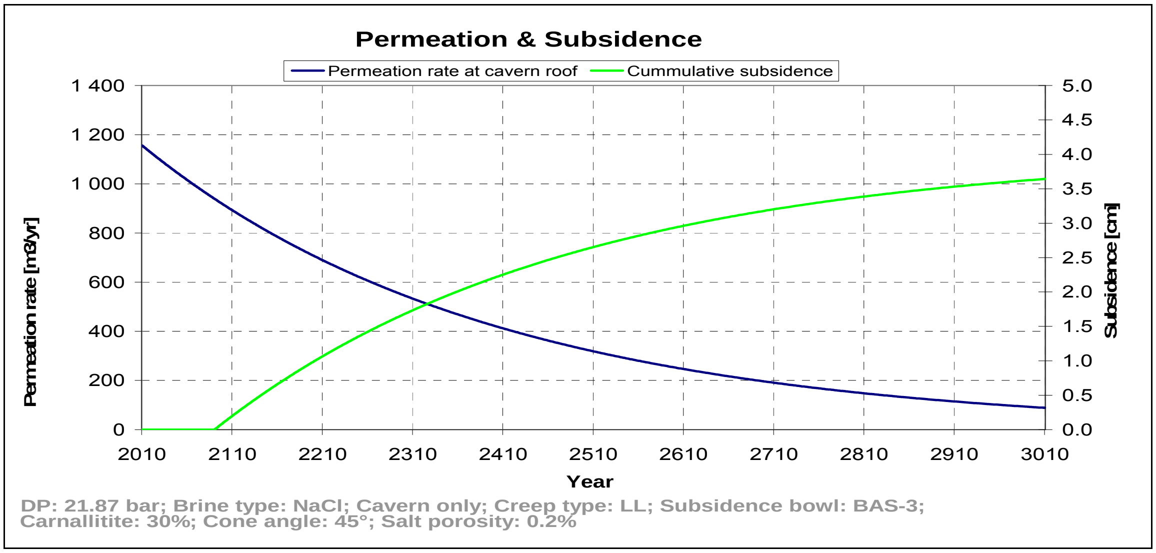


Figure 25 Low linear variant permeation rate and subsidence over the first 1000 years, without taking a rebound effect into account.

It can be seen that the modelled subsidence even in the very conservative high linear case is only about 2.5 cm in the first 100 years. This is hardly measurable considering other autonomous influences on surface subsidence.

5.2 Pressure deficit

As discussed in the previous chapters the creep rate is driven by the difference between the cavern (brine) pressure and lithostatic pressure, referred to as the pressure deficit. Because the cavern pressure is currently lower than originally expected and the lithostatic pressure is subject to discussion as it has never been measured, it was decided to vary it.

It was originally expected that the pressure in the cavern would reach lithostatic pressure at the 13 3/8” shoe soon after shut in. This situation would lead to the lowest pressure deficit lower in the cavern, hence the lowest creep rate and weakest ‘engine’ for permeation. However the BAS-2 cavern pressure seems to have stagnated ca 20 bar below estimated lithostatic pressure at the 13 3/8” shoe, based on an average estimated gradient of the overlying rock column of 2.15 bar/10m. The pressure deficit resulting from this condition has been taken as the Base Case. Deltares **[Pruiksma, 2005, 2007 & 2009]** calculates a somewhat higher lithostatic pressure, based on an average gradient of 2.18 bar/10m, resulting in a higher pressure deficit than the Base case.

To depict the effect of varying the pressure deficit it was chosen to vary the pressure difference at the 13 3/8” shoe to cover the full range of conditions described above, for all three considered creep variants. All other variables are the same as for the base case.

As discussed before, a rebound effect is not considered for the linear creep variants. It can be seen that the non-linear variant reacts increasingly stronger when the pressure difference gets bigger, this is to lesser extend the case for the linear variants due to the linear behaviour at these pressures. For the high linear case the effect of the diminishing cavern volume is stronger than the increasing creep rate showing a slowing down effect of the subsidence.

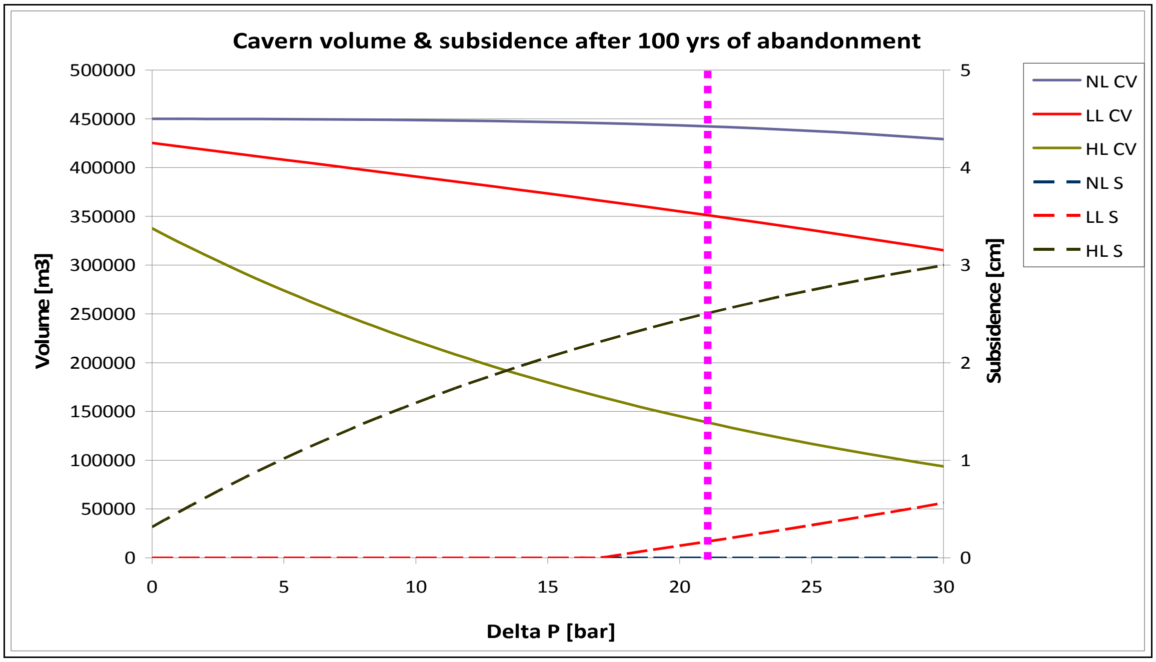


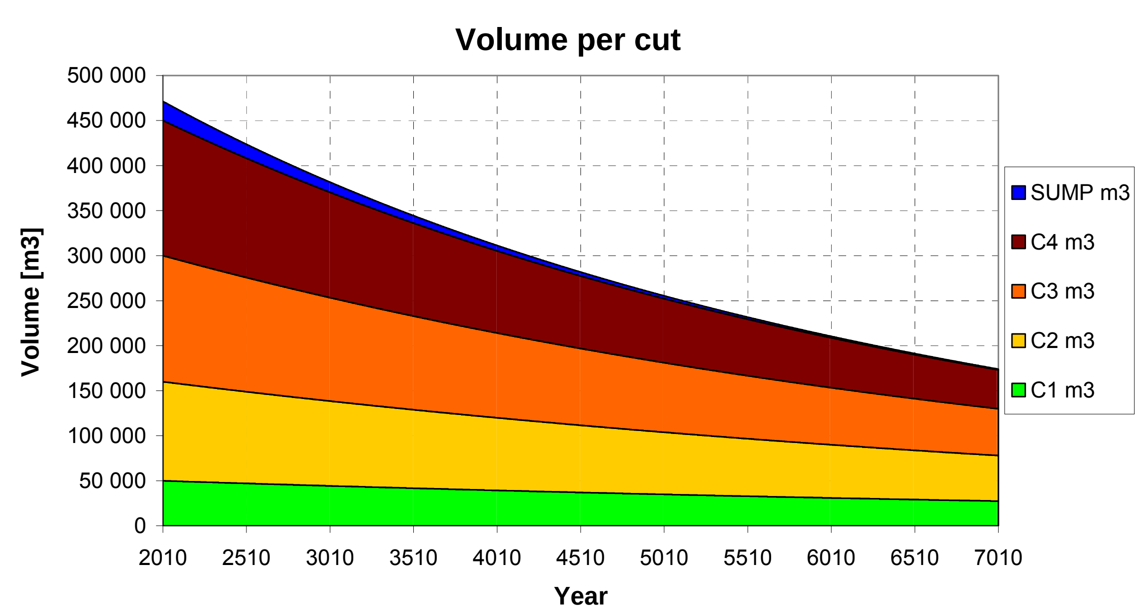
Figure 26 Cavern volume (CV) and subsidence(S) after 100yrs for various pressure differences (lithostatic minus cavern pressure) at the 13 3/8" shoe and the various creep variants for the BAS-3 cavern volume, the continuous lines depict the cavern volume, the dashed lines the subsidence and the pink dotted line the pressure difference used in the base case.

It can be seen in Figure 26 that if the pressure difference between the cavern and lithostatic is 0 at the 13 3/8" shoe there is hardly any volume lost and there is no subsidence for the most likely non-linear creep variant. The maximum modelled subsidence is 3 cm in a 100 years, this is reached if the creep would be high linear and there would be a pressure differential of 30 bars at the 13 3/8" casing shoe. This subsidence is hardly measurable considering other autonomous influences on surface subsidence.

5.3 Sensitivity to sump porosity and compressibility

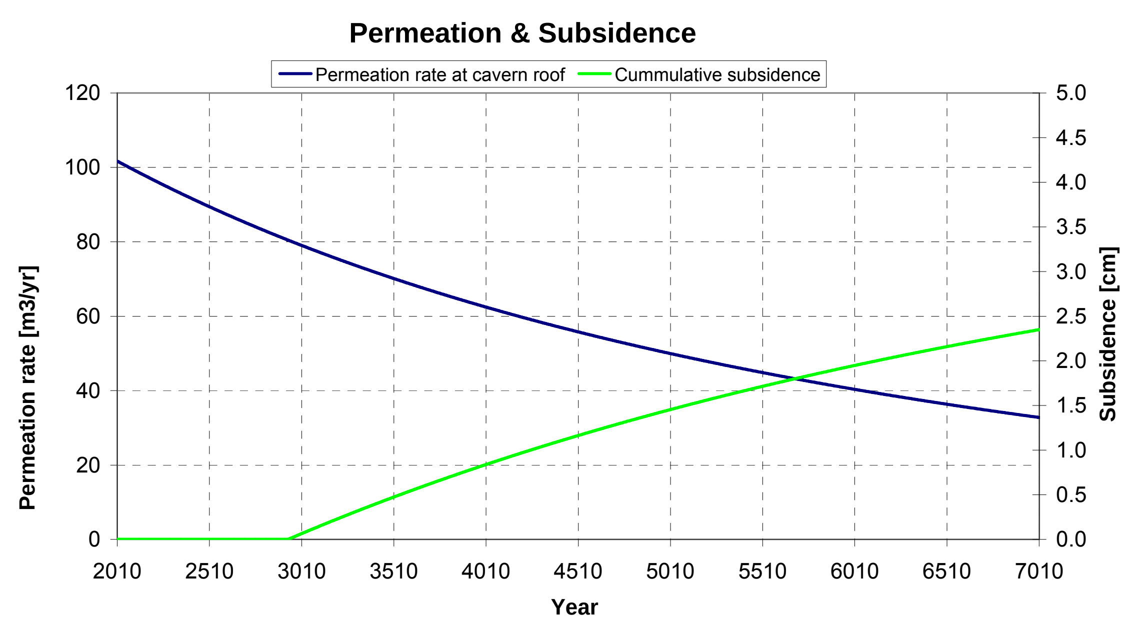
The height of the BAS-3 cavern is well known due to recent wireline activities that could tag the sump. There has however been some discussion about the behaviour of the sump after shut-in. As discussed previously we consider the sump and its porosity as a "Volume mort" in the abandoned condition. Therefore the sump does not affect the behaviour of the cavern in the abandonment phase. In this run we show the effect of an active sump that has an initial porosity of 30% and squeezes totally empty. In practise this implicates the unlikely event of total compaction of the sump or complete salt penetration into the sump pores such as mentioned previously. Due to the large depth of the sump tail compared to the cavern height the pressure differential at the sump is very high leading to a high creep rate compared to the other cuts in the model. This effect on the creep rate is partly compensated by the relatively small volume of the sump pores.

To be on the conservative side we have considered the maximum possible sump volume that could have accumulated during the BAS-3 lifetime and have this volume squeezed tight in the same way an open cavity would do. This is a worst case approach because support of the grains of the sump will probably slow this process down significantly.



DP: 21.87 bar; Brine type: NaCl; With sump; Creep type: NL; Subsidence bowl: BAS-3; Carnallitite: 30%; Cone angle: 45°; Salt porosity: 0.2%

Figure 27 Sensitivity to sump volume development.



DP: 21.87 bar; Brine type: NaCl; With sump; Creep type: NL; Subsidence bowl: BAS-3; Carnallitite: 30%; Cone angle: 45°; Salt porosity: 0.2%

Figure 28 Sensitivity to sump permeation rate and subsidence.

It can be seen in Figure 27 that there is slightly more volume from the start and that this volume is permeated quite rapidly. The permeation rate in the beginning is marginally higher and there will also be a bit more and faster subsidence (Figure 28). The total subsidence increase after 5000 years is negligible with about 0.3 cm.

5.4 Sensitivity to subsidence bowl parameters

The base case uses the current ratio between lost volume in the underground (convergence during the operational phase) and subsidence in the deepest point of the subsidence bowl, i.e. 1.1 cm subsidence/100,000 m^3 loss of underground volume. This is the current value for BAS-3. The BAS-1 & 2 caverns have shown that this parameter can change in time due to widening of the subsidence bowl it has currently dropped slightly below 1.0 cm/100,000 m^3 for the BAS-1&2 caverns. This only has an influence on the subsidence and not on the cavern volume development. The long term subsidence graph can be found in Figure 29.

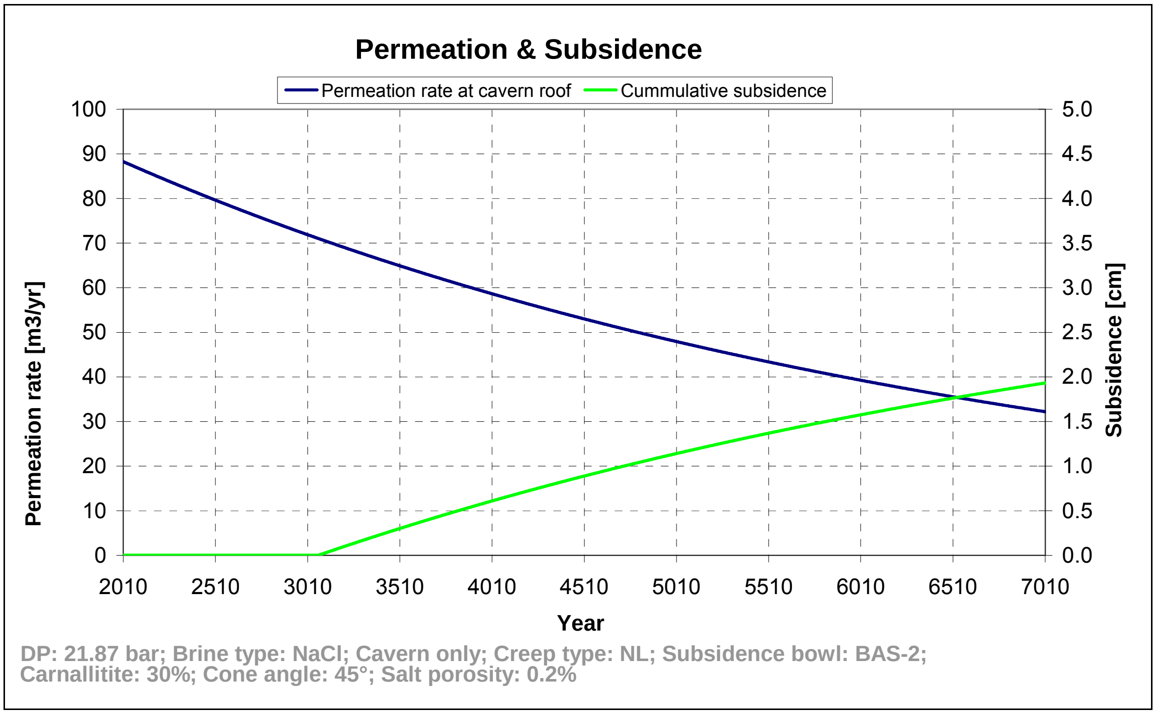


Figure 29 Sensitivity to subsidence bowl parameter.

When compared with Figure 19 it can be seen that the subsidence behaves linearly with the subsidence bowl parameter. The subsidence is 10% lower in Figure 29 with less than 2 cm in 5000 years.

5.5 Sensitivity to secondary porosity and cone angle of the permeation zone

Secondary porosity is created when brine under lithostatic pressure oozes through the lithostatically loaded salt layers above the cavern. This secondary porosity is created in the permeation path of the brine. The newly created pore space leads to a small local expansion, - hence newly created volume – of the salt at near lithostatic pressure conditions. This new volume compensates, apart from compressibility effects in the permeated rock volume, for the volume lost in the cavern or Carnallitite layer and thus to a near constant volume displacement of brine from the cavern into the newly created porosity.

A high secondary porosity therefore provides a lot of new storage volume. The same holds for the permeation cone because the volume of salt with secondary porosity strongly increases with the angle of the cone. The cone can have an angle between 0 degrees, basically a cylinder (representing a permeation chimney as observed by Professor Lux), and 60 degrees (being an estimated ‘realistic’ maximum). For the base case a 45 degree cone is assumed.

It was chosen to model three secondary porosities of 0.02% (worst case), 0.2% (advised by IFG) and 2% (high estimate, uses 1% in the BAS-2 hstory match) for a continuous range of cone shapes between 0 and 60 degrees, assuming that all permeated volume that is not trapped in secondary porosity would lead to subsidence over a period of 5000 years.

As can be seen in figure 27, the difference between the base case (asterisk on red line) and the worst case (green line) is only ca 8 mm after 5000 yrs, hence insignificant.

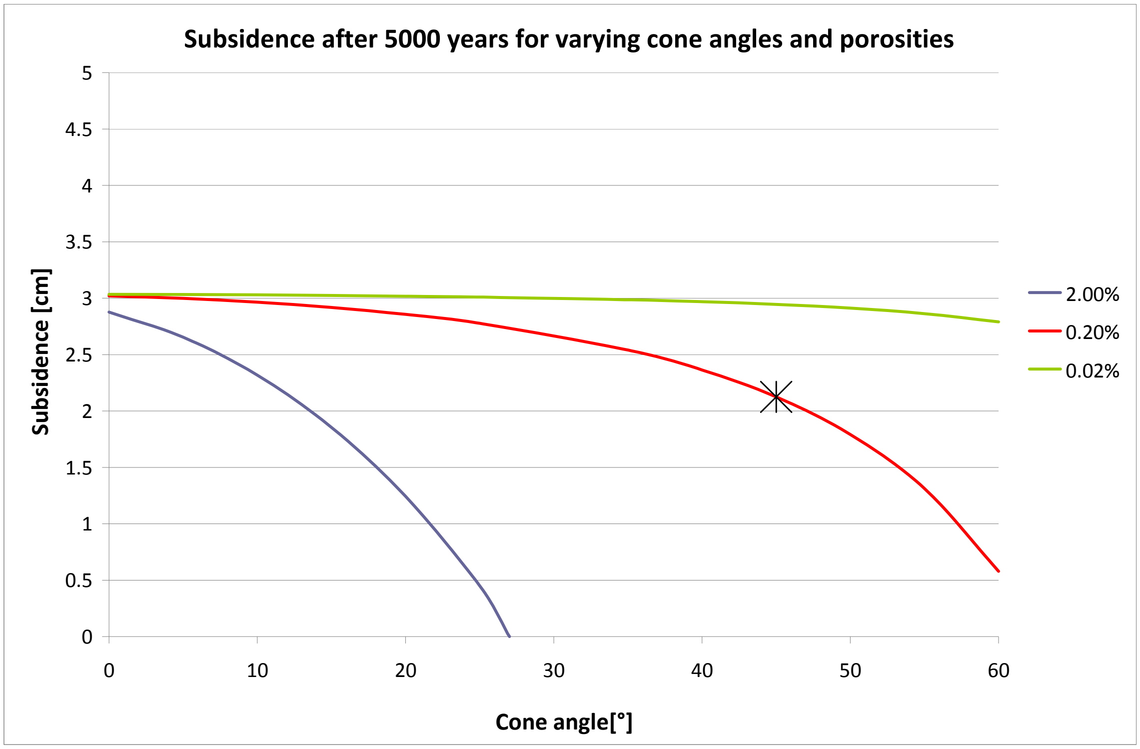


Figure 30 Subsidence sensitivity for storage capacity in the salt as a function of various permeation cone angles and porosities after 5000 years; the base case is marked with an asterisk.

Figure 30 shows that with a low secondary porosity of 0.02% hardly any brine is stored in the salt layer almost independent of the permeation cone angle and therefore leads to the most subsidence. For high secondary porosities of 2% the permeation cone angle starts to play a major role, for the high secondary porosity case all brine is stored in the salt layer even if the permeation cone angle is only 28 degrees, for lower cone angles the subsidence gradually increases with a lower cone angle. For the base case secondary porosity of 0.2% there is some subsidence even with a wide permeation cone, this increases gradually when the permeation cone is narrowed. The maximum subsidence of about 3 cm after 5000 years is represented by the point 0 degrees and 0.02% porosity, this is not the total subsidence that can occur for the base case because there is still some converging cavern volume at that time. If a longer period would be modelled this would increase the subsidence to a maximum of 4.9 cm at infinity.

5.6 Sensitivity for Carnallitite variety

In the model subsidence is caused by volume loss in the cavern interval that is not compensated by the creation of secondary storage in the overlying salt layers. The conversion of the Carnallitite that has been discussed in paragraph 3.6 takes place above the cavern interval. The effect of this conversion to the subsidence is regarded as minimal, the calculated volume increase can even lead to a small uplift. This is disregarded in the model because it is only a small effect. In the case of the 55% carnallitite a substantial amount of free volume is created when the carnallitite is converted, this is expected to create small horizontally orientated accumulations of carnallitic brine that are expected to be squeezed out and permeated on a much longer geological timescale due to the lack of drive from the carnallitic brine that has hardly any active height. The volume loss in the carnallitite area will lead to some additional subsidence. This will take place on such a long timescale that it is also disregarded in this model.

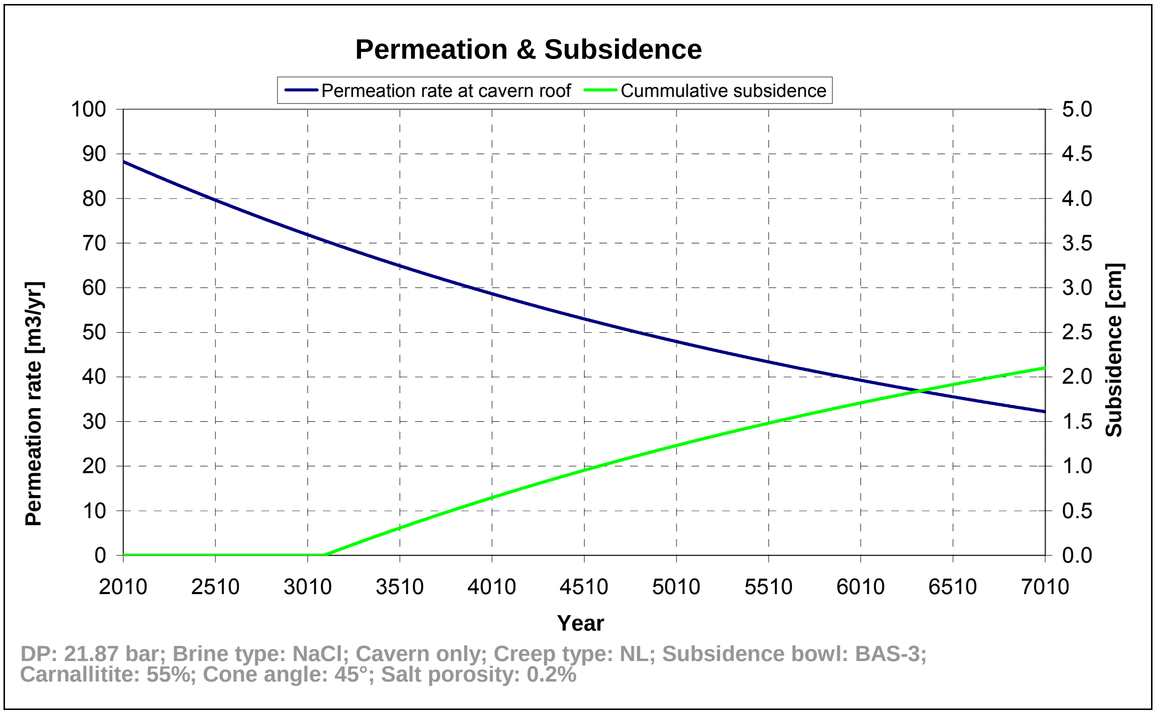


Figure 31 Sensitivity for 55% Carnallitite variety.

No difference in subsidence between the two carnallitite varieties can be seen, in a comparison between Figure 19 (Base case with 30% carnallitite) & Figure 31. Also, no difference in permeation rate from the cavern roof can be seen. However, for the 55% Carnallitite variant there will be a somewhat higher permeation rate into the overburden because of the difference in the carnallitic conversion process that creates a bit more brine volume increase.

5.7 Conclusions

- The sensitivity analysis provides a 3D view of some of the key factors dominating the processes after a fluid filled cavern has been permanently closed off.
- All variants predict a maximum subsidence directly above each cavern of less than 5 cm.
- The closure and subsidence process will be faster, the stronger the linear creep term is. This will be compensated by the expected rebound effect associated with the linear creep mechanism.
- The speed of cavern closure is sensitive to the pressure differential that will establish itself at the shoe of the last cemented casing.
- Even if the porosity of sump completely would close and be squeezed out, relatively minor effects are expected.
- Various assumptions for bowl shape parameters have minor effects on subsidence.

- Our base case uses a low value for secondary porosity. Larger values for porosity will lead to storage of more brine, hence reducing the amount available for continued permeation.
- A higher content of Carnallite in the Carnallitite bank results in more free volume in the Carnallitite bank and a somewhat higher permeation rate into the overburden.
- None of the sensitivities would result in dramatic situations regarding worst case outcomes (chapter 2.3) to the opinion of the authors and reviewers.

6 Risk analysis

6.1 Introduction

The above considerations picture a realistic ‘engineered expectation’ with sensitivities that cover most of the possible spread of variables. Monitoring over a period of 6 years of the ‘hard shut in’ of BAS-2 has shown a gradual restoration of the pressures around the cavern, with permeation taking place, early after shut in, however without any evidence of dramatic events. The subsidence data indicate that the contribution of BAS-2 to subsidence in the area has reduced to negligible and no significant change in cavern volume has been observed during the BAS-2 monitoring period.

The closure and migration process will be faster the stronger the linear creep term is, however this would be compensated by rebound. The overlying sequence incorporates several containment and confinement horizons that will inhibit migration of brine to the surface. After well considered study and consultation of leading specialists, a picture has emerged of a very gradual closure process with nil or very minor subsidence effects over a period of several hundreds to thousands of years.

However due to the unique depth of the FRISIA caverns, limited laboratory research into the prevailing conditions and lack of representative field cases with other operators, one may argue that the ‘unexpected may happen’. The following risk factors could be envisaged:

6.2 Much stronger subsidence than predicted

In spite of a realistic ‘engineered expectation’ and counter evidence in the field, a major fracture could occur leading to faster leak off of brine into one or more containment horizons. Should this happen, the rate of the closure and leak off process will still be controlled by the pressure required for injection into the containment horizon, the dynamic pressure loss over the fracture and the strength of the ‘engine’.

This process is comparable with the former open well workovers on BAS-1 & 2 that showed a gradual decrease in outflow rate until the leaching strings were blocked due to crystallisation of the salt and would still take a minimum of several years. This condition would be worse than would be predicted on the basis of previous laboratory results of . **[Lux, 2006]**

If all free brine is expelled and moved into permeable overlying formations the worst case subsidence potential will be 4 to 5 cm in the BAS 3 case.

The extra subsidence would have to be remediated in the same way as the subsidence incurred during the active mining phase. In terms of risks for the general public and real damage to the environment, this risk factor does not represent unacceptable risks in the view of FRISIA. In this context, it must be noted that an agreement is in place with the Water Authorities that subsidence of 5 cm more than the forecasted maximum will not require additional measures in the field.

Consequences	General	People	Environment	Likelihood: Insignificant	Low	Medium	High	Very high
	Non	No health effect/injury	No impact					
	Insignificant	Slight health effect/injury	Slight impact					
	Minor	Minor health effect/injury	Minor impact					
	Moderate	Major health effect/injury	Localised impact					
	Major	PTD or 1-3 fatalities	Major impact					
	Severe	Multiple fatalities	Massive impact					

Figure 32 Risk matrix much stronger subsidence.

6.3 Creation of sink holes

Upward migration of the cavity due to continued roof degradation will almost certainly be stopped by the overlying Carnallitite and anhydrite banks, if there will be any migration at all. If this is not the case the process will be choked by the bulking of the degraded material.

The bulking factor is the ratio between the density of the bulked material and the virgin rock. The creation of sinkholes can occur above shallow caverns where there is a small difference in density between the often unconsolidated overburden and the final bulked material, and therefore results in a low bulking factor in combination with a thin overburden. This is very much different in the FRISIA case where the overburden is not only very thick but also consists of dense consolidated material. Migration of the cavity through more than 1500 m of consolidated sequences with a high bulking factor is considered impossible. In the opinion of the authors and reviewers, this case can be ignored.

6.4 Uncontrolled surface brine outflow

If in spite of all precautions one of the wells forms a flow path to surface, brine starts flowing to the surface via this well bore. The dynamic pressure drop over the leak path would still be substantial and the flow of brine would be inhibited by salt crystallisation due to temperature loss. Flow of brine along the (cemented) outside of well will meet the containment and confinement horizons; and it is extremely unlikely that external flow would reach surface.

The worst case flow rate during an outflow of brine may be derived from the open flow observed during atmospheric workovers, i.e. a gradual decrease in outflow was observed. This is partially caused by crystallisation due to cooling of the brine. The type of brine would be sodium chloride or carnallitic brine, both non toxic components to humans, but harmful to agricultural activities.

In this worst case collection of brine and processing of the brine in the Harlingen factory would be required. The well should then be re-entered and re-abandoned. If the factory would no longer be available, the brine should be evacuated by pipeline and discharged at a suitable location, until the flow path is closed off. The risk for fatalities in the case of a brine outflow is extremely low.

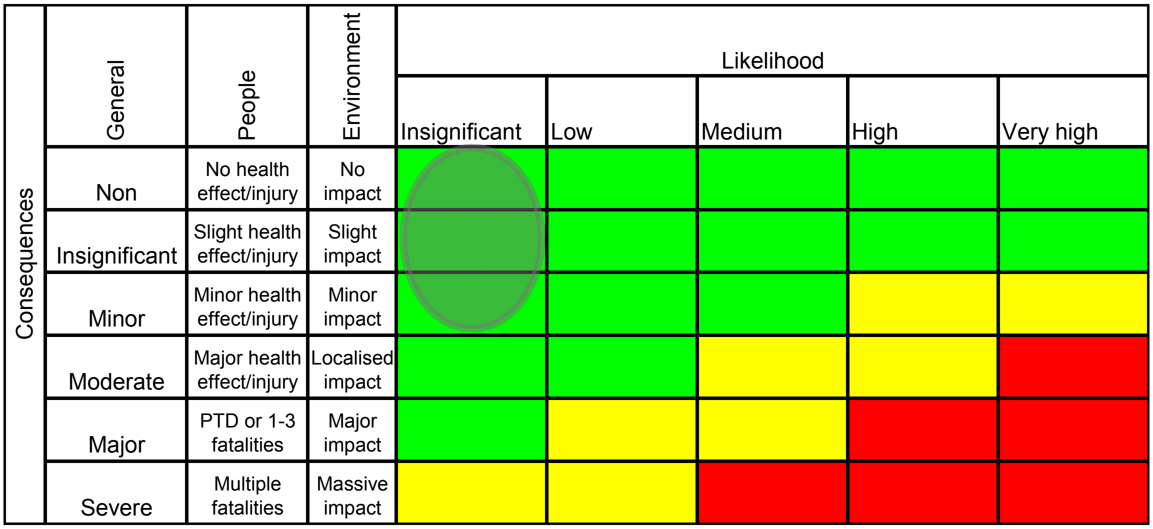


Figure 33 Risk matrix uncontrolled brine outflow.

6.5 Contamination of shallow fresh water horizons

As explained in the foregoing, it will be highly unlikely that brine will pass all three containment and confinement horizons and migrate into shallow fresh water sands. Should this nevertheless happen, the salinity of the groundwater will increase. Should the leak prove to be unstoppable, the groundwater should be pumped off at a higher rate than the leak, to avoid lateral migration of the brine. During analysis of the problem and remedial activity, limited damage may occur to agricultural actvities. Shallow fresh water sands are not being used for the production of drinking water in the area, partly because of the influx of seawater in the subsurface. The density difference between the brine and water will lead to a separation, with the salt water at the bottom.

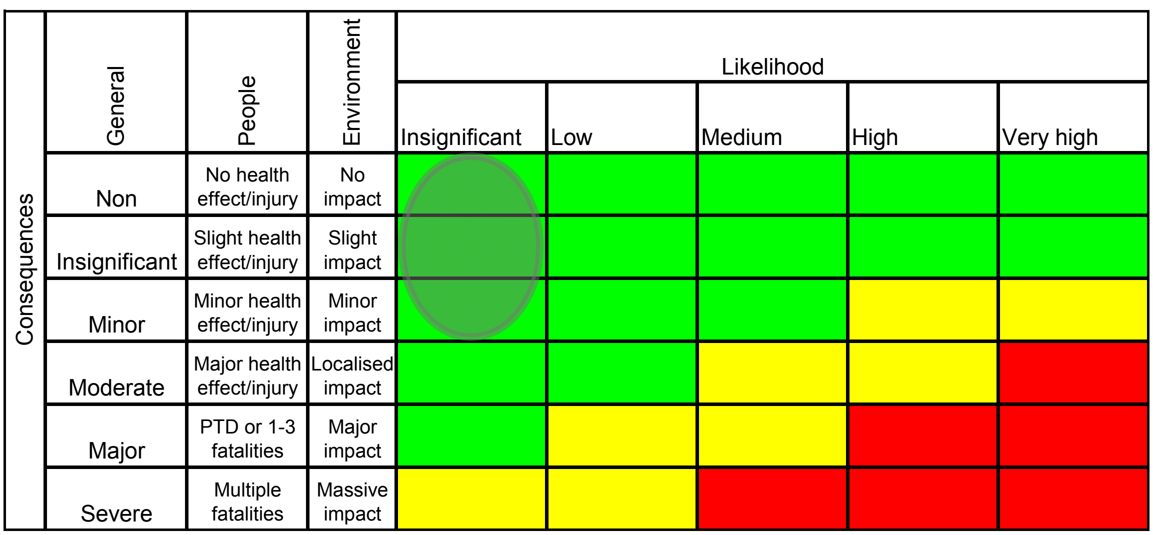


Figure 34 Risk matrix contamination of fresh water zones.

6.6 Sudden shocks/earthquakes

A very gentle process of permeation of the free volume of brine is expected over several hundreds to thousands of years. However pressure accumulation below barriers or sudden collapse of barriers may cause seismic disturbances.

During the active mining period seismometers that could detect seismic events of over 1.7 on the Richter scale **[van Eck, 2006]** did not record any event that could be subscribed to the FRISIA mining activities. For over a year more sensitive seismic measurements are in place, that as yet have not recorded any significant activity attributable to the FRISIA activities. Due to the viscous behaviour the salt itself is not capable of storing energy. Stress differences lead to gradual movement of the salt.

The geology above the salt sequences does not show faults or other potential situations with significant stored energy, hence the risk for sudden shock or earthquakes with damage potential is considered to be nil.

Based on experiences of mine collapses in the German potash industry, a German study **[Leydecker, 2006]** provides a relationship between a collapse area in open, air filled rooms (F in km²) and the local magnitude (ML),

$$ML = 1{,}13 * \log F + 4{,}486$$

The intensity at surface (I_O) directly above the collapsed area can be calculated by,

$$I_0 = 1{,}15 * ML + 1{,}93$$

The so calculated energy is mainly caused by the combination of pillar collapse and roof reaction. With the conservative preconditions of ignoring the cone shaped cavern roof, the brine filling and a choice of maximum diameter of 100 m, the maximum collapse area is ca. 8,000 m². From these equations follows: ML = 2.1 and I_O = 4.4. This intensity can cause vibration noise in windows and pottery. The intensity decreases with increasing distance to the collapse area.

The above calculation represents an absolute worst case. Hence the likelihood and consequences are rated by the authors and reviewers as ‘insignificant’:

Consequences	General	People	Environment	Likelihood				
				Insignificant	Low	Medium	High	Very high
	Non	No health effect/injury	No impact					
	Insignificant	Slight health effect/injury	Slight impact					
	Minor	Minor health effect/injury	Minor impact					
	Moderate	Major health effect/injury	Localised impact					
	Major	PTD or 1-3 fatalities	Major impact					
	Severe	Multiple fatalities	Massive impact					

Figure 35 Risk matrix for sudden shocks/earthquakes.

6.7 Influence of BAS-3 on the newly created “BAS-3 Original” cavern and wellbore

The horizontal distance between BAS-3 Original and BAS-3 Current is comparable to the distance between BAS-1 and BAS-2. No direct hydraulic contact between these caverns has been observed during the shut-in period of BAS-2. Small pressure drops that have been observed in BAS-2 might be explained by a decrease of the local lithostatic pressure due to lower pressures at BAS-1 caused by operational phases. A lower local lithostatic pressure will lead to an increase in permeation rate at lower cavern pressures and therefore a small pressure drop. Contrary to the BAS 1 -2 case, the Bas-3 Original cavern will be situated in a vertically lower position than BAS-3 Current, hence an even smaller influence of BAS-3 Original on the abandoned BAS-3 Current cavern is expected.

As subsidence due to BAS-3 Current virtually stops after the shut in, and the sidetracked BAS-3 Original wellbore passes over BAS-3 Current considerably above the top of the salt, no potentially damaging effects are expected on the wellbore of BAS 3 Original.

6.8 Conclusion risk factors

The above worst case events have been evaluated against a risk matrix commonly used in the industry. This assessment shows that there are no unacceptable risks associated with the proposed hard shut-in and abandonment of FRISIA caverns provided the abandonment is professionally carried out according to the existing legislation.

7 Overall Conclusions

Hard shut-in of the prematurely mined out BAS-3 cavern, has taken place in Q2 2010, and the cavern has to be abandoned in order to be able to sidetrack the well and mine the remaining permitted reserves from a new cavern. With current planning it will be possible to monitor the abandoned BAS-3 cavern for at least one year before closing off the cavern. A separate document will be made with the goals and specifications of the monitoring programme. This report is focussed on the abandonment or the BAS-3 cavern.

Active mining in BAS-2 has been discontinued in 2004 and a 6 year test has been carried out following a ‘hard shut-in’ procedure. With a hard shut-in no volume is bled off from the cavern to compensate for thermal expansion of the brine and convergence of the cavity due to squeeze.

A thorough analysis has been carried out of the processes that can be expected when FRISIA caverns are permanently closed off, locking-in underground free brine volumes of several hundred thousands of m^3, typically up to 500,000 m^3 with a ‘hard shut in’ procedure that implies that no volume is bled off from the cavern to compensate for thermal expansion and cavern convergence.

Experts have been consulted and use has been made of available literature. The processes have been evaluated for the applicable geological situation and analysed with an engineered model. For the analysis, data have been used of cavern BAS-2 that has been shut in with a hard shut in procedure and observed and tested over a period of 6 years.

On the basis of the work done, the authors and reviewers come to a realistic ‘engineered expectation’ of the effects of hard shut-in for FRISIA caverns, showing a gentle process of closure of the underground volume over several hundreds or thousands of years with negligible or minimal subsidence. A sensitivity analysis shows a band of uncertainty around the time scale and migration volumes that does not materially affect the general picture of a gradual process with marginal effects at the surface.

A risk analysis of worst case events that are highly unlikely to happen does not reveal unacceptable risks in the opinion of the authors and reviewers according to an accepted industry risk assessment method. Additional subsidence that may take place in case of an unlikely worst case event is fully covered by an agreement with the Water Board stating that no measures are required and costs are expected if the actual subsidence is 5 cm more than the prognosed maximum **[REF Stuurgroep Franekeradeel – Harlingen, 2009]**. If for some unknown reason the subsidence after shut-in is more than predicted this can still be corrected by adjusting the operational parameters of the newly created BAS-3 original cavern.

It is therefore concluded that hard shut in of FRISIA caverns, without an extensive post mining observation/bleed off period, taking account of considerable uncertainties is the best technical and environmental solution for a responsible and safe abandonment.

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