CONCLUSIONS AND RECOMMENDATIONS OF THE OVER-PRESSURED CAVERNS AND LEAKAGE MECHANISMS PROJECT (KEM-17)

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1. INTRODUCTION

When decommissioned, brine caverns leached out from geological salt formations will be plugged and abandoned. The long-term behavior of these brine-filled caverns has raised concerns. Dozens of tests proved that brine pressure increases in a shut-in cavern, due to creep closure and brine warming. It has been feared that, when cavern pressure becomes higher than the minimum principal stress in the salt surrounding the cavern, brine will flow out of the cavern, possibly leading to potable water pollution and additional subsidence.

The goals for this project for the Kennisprogramma Effecten Mijnbouw are to improve knowledge of the processes that occur when brine pressure in the cavern (locally) exceeds the minimum stress in the salt surrounding the cavern especially, at cavern roof.

In the salt-solution mining engineering community, there is a long-standing controversy about the processes when brine pressure in a deep salt cavern reaches values close to the minimum principal stress in the rock formation. One opinion is that it is difficult to prevent hydraulic fracturing, localized brine flow and major loss of containment. The other opinion is that as long as the pressure build-up rate is moderate, leak-off by diffuse permeation occurs , and hydraulic fracturing can be excluded.

We critically review the scientific and technical tools available – and required – to abandon safely brine-filled salt caverns. This project presents a review of existing salt engineering, materials science, and geoscience literature relevant to the prediction of the evolution of abandoned, overpressured, brine filled solution mining caverns.

The problem was approached at three different scales: the scale of the grains in the salt formation where microscale studies shed light on the complex relationship between stress, strain, and permeability; the cavern scale, where *in situ* tests can provide data and challenge predictions; and the salt dome scale, where large scale computations and geoscience knowledge provide information on the virgin state stress distribution in the salt body. Conclusions are provided at the end of each individual report. The objective of this introduction is to provide the reader with a synthesis of these.

Stresses are the driving force for permeability evolution in rock salt. In cavern engineering, it is usually assumed that the virgin state of stress in a salt formation is isotropic. However, both micro scale and salt dome scale arguments show that differential stresses up to several MPa can be present, more so in zones of heterogeneities, anhydrite inclusions and zones of active deformation. Such a far-field anisotropy of stress has significant effects on the evolution of caverns, during operation and after abandonment. For a given site, numerical computations allow assessing such initial deviatoric stresses, including their uncertainties.

For a given virgin state of stress, cavern shape and pressure history in the cavern, it is possible to compute the evolution of stress, strain and microstructure around the cavern, provided that a relevant constitutive law has been formulated. Abundant literature, based on laboratory test results, was dedicated to constitutive laws. However, in addition to temperature and stresses, microfabric and brine content play a significant role – a topic often neglected. It is widely recognized now that extrapolation of experimentally-derived constitutive equations to small stresses can only be done on a basis of microphysics. Together with dislocation creep – the governing mechanism when deviatoric stresses are large – solution-precipitation creep, recrystallization and healing play a key role when deviatoric stresses are small.

Cavern-scale computations also prove that, opposite to the case of a rock mass whose behavior is elastic (i.e., reversible), the viscoplastic rock mass in which a salt cavern is leached out experiences a slow stress redistribution generated by the relatively low pressure applied at cavern wall during operation. When cavern pressure increases – for instance, after plugging and abandonment – the state of stress in the rock mass, during a long period of time, remains strongly influenced by this earlier redistribution. In particular, even when cavern pressure is significantly lower than geostatic pressure, the minimum principal stress at cavern can be less compressive than brine pressure, and tensile effective stresses (i.e., brine pressure is larger than the least compressive stress) are present at cavern wall.

Virgin salt permeability is exceedingly low (however, it varies from one site to the other) and, from an engineering perspective, the tectonically relaxed, recrystallized, pure rock salt of much of the Zechstein has no connected grain boundary porosity and can be considered as practically impermeable in virgin state. However, deformation experienced by the cavern walls during operation leads to a change in grain boundary structure: a small amount of brine penetrates the grain boundaries, leading to slow dilatation and permeation. Shut-in tests performed in salt caverns or boreholes confirm this notion: when brine pressure increases in a salt cavern, a certain threshold exists, significantly below geostatic pressure, above which a significant increase in apparent compressibility is observed – a clear sign of permeability increase. In addition, a review of existing experimental and modeling work on permeation suggests that, after abandonment, permeation by high-pressure brine will be localized (preferential fingering) and the brine will reach the overlying formations faster than that predicted by current models. The evolution of abandoned cavern where permeation is localized has not been studied by numerical models, so new models are needed to predict the evolution. The limit between a significant permeability increase and hydro-fracturing remains unclear.

For more than thirty years, abandonment (i.e., shut-in) tests have been performed at Etzel, Stassfurt, Bernburg, Stade-Süd (Germany), Barradeel (the Netherlands), Etrez, Gellenoncourt, Carresse, Tersanne (France) and Mont Belvieu (Texas). All experts (and the SMRI) agree on the following: brine pressure evolution in an abandoned cavern results from three main phenomena: brine warming, which often is the pre-eminent phenomenon at early times, and vanishes in the long term; creep closure, a decreasing function of cavern pressure; and brine permeation through the cavern walls, which is an increasing function of cavern pressure. Brine warming may generate a transient period during which brine pressure is larger than geostatic pressure; this phenomenon can be avoided when cavern plugging is delayed – in many cases, for several years or even decades. When thermal expansion can be neglected, an equilibrium pressure is reached such that brine permeation rate exactly equals cavern creep closure.

In shallow caverns, equilibrium pressure is typically much smaller than geostatic pressure; brine slowly seeps to the salt formation; the cavern can be abandoned safely. In deep caverns, equilibrium pressure is much closer to geostatic pressure; in situ tests are more difficult to perform as, for safety reasons, mining authorities require that cavern pressure remains below the maximum admissible pressure accepted during mining operations. Tests performed in deep caverns do not form conclusive evidence that high-pressure caverns can be safely abandoned.

These notions are illustrated by Figure 1. Microscale studies and in situ tests both suggest that the permeation rate – vs – cavern pressure curve is non-linear when pressure is above a certain threshold. They also prove that the creep closure rate – vs – cavern pressure curve is still poorly known in the small deviatoric stresses domain: creep closure rate is suspected to be faster than what can be extrapolated from low cavern pressures. The notion of “geostatic pressure” is blurred by several considerations. Dome scale studies show that in the far-field the state of stresses may be anisotropic; computations prove that the resulting deviatoric stresses are amplified at cavern wall. Impurities, and in particular anhydrite fingers, can also modify the state of stress and the fracture criterion at cavern wall. In a high elongated cavern, no equilibrium such that brine pressure exactly equals rock pressure is possible (“Wallner’s margin”). For deep caverns, it is less certain that seeping brine will remain confined into the salt formation. When assessing the consequences of brine seepage for subsidence and potable waters, a much larger domain, including the over- and under-lying geological formations, must be considered. Caverns built near the boundary of the salt formation, or close to heterogeneities in the salt formation, require special attention.

In summary then, using the present state of engineering practice, it is not possible to say with sufficient reliability if a deep abandoned cavern will evolve by localized brine flow, hydraulic fracturing and major loss of containment, or with a pressure build-up that is is moderate with leak-off by diffuse permeation and no hydraulicfracturing.

We see a clear opportunity to improve predictions of the evolution of abandoned caverns, by integrating existing knowledge in the geoscience and materials science with engineering practice, at the micro, cavern, and salt-dome scale.

The consortium strongly recommends that further researches be performed to get a better understanding of the notions for which uncertainties remain. In particular, the required integration level between engineering and materials science domains has not been reached yet.

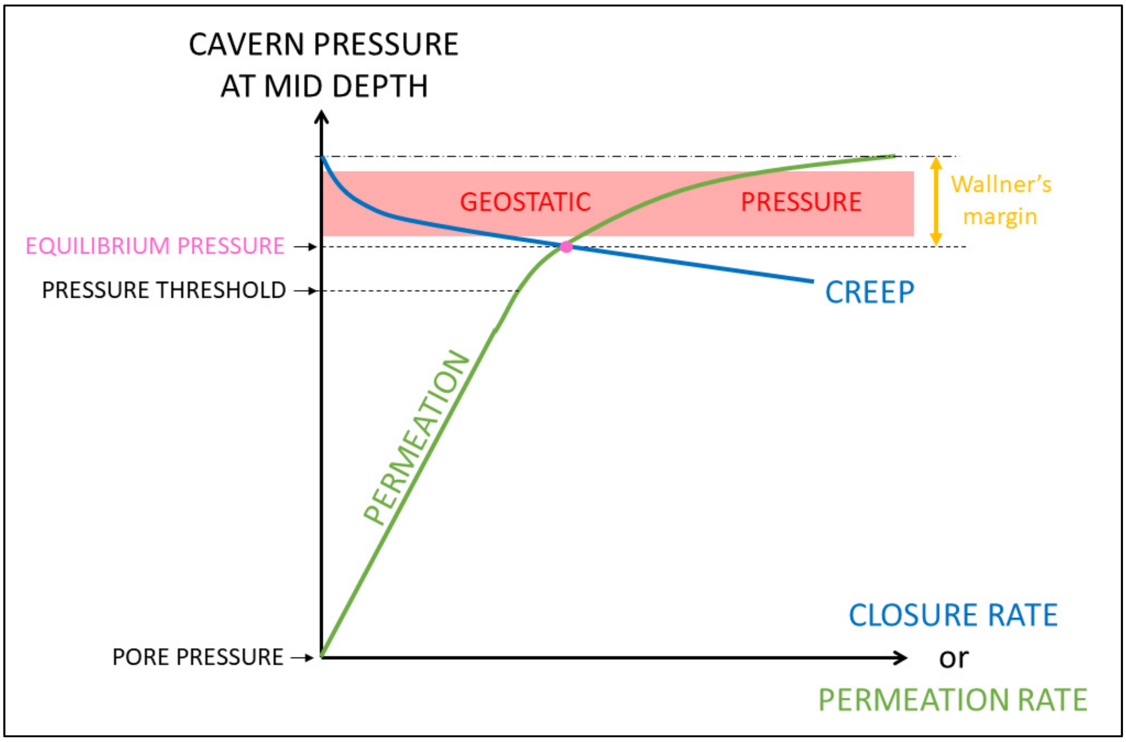

Figure 1. Brine permeation rate (green curve) and creep closure rate (blue curve) as a function of cavern brine pressure. Permeation rate increases when cavern pressure increases. For low cavern pressure, the relation is linear (Darcy-like brine flow). However, above a certain pressure threshold, permeability increase is non linear, as proved by an increase in apparent compressibility. Creep closure rate increases when cavern pressure decreases, a relation often described through a power law. In fact, it is suspected that in the low deviatoric stress domain, i.e. when cavern pressure is close to geostatic, creep mechanisms are different and the relation is linear.

When permeation rate equals creep closure rate, an equilibrium pressure can be reached as proved by in situ tests performed in various salt formations. In shallow caverns, this equilibrium pressure is much lower than geostatic. In a deep cavern, uncertainties are larger: cavern permeability increases as effective stresses are less and less compressive; fluid-assisted creep closure (rather than dislocation creep) becomes preeminent; the notion of a “geostatic pressure” blurs, as the state of stresses at cavern roof depends on cavern pressure history and far-field virgin stress.

When equilibrium pressure is computed at cavern mid-depth, “Wallner’s margin” must be added to this equilibrium pressure to assess fracturing risk.

2. CONCLUSIONS - MICROSCALE REPORT – RHEOLOGY AND PERMEATION

2.1 Conclusions: Rheology and Deformation mechanisms

The materials science of the rheology and microstructure evolution of rock salt is reasonably understood but this knowledge is not integrated between engineering and materials science domains. Especially deformation at low deviatoric stress and the effect of grain boundary water is not implemented in engineering studies, and microstructural investigations are rare in cavern engineering.

The constitutive laws governing the deformation of rock salt are related to microfabric, fluid distribution, impurities, strain rate, temperature. The study of deformation mechanisms tells us about mechanical properties and fluid transport: power law versus Newtonian creep, grain boundary structure and mobility, connected versus non-connected porosity, permeability versus effective stress. Rock salt contains only small amounts of H_2O, and in the Zechstein (at virgin state after a long geologically quiet period) it is generally present in unconnected grain boundary pores, so that at present pressure solution is not generally active. However, when the effective stress is changed significantly (values of this are not well known) even this small amount dramatically enhances fluid-assisted grain boundary processes such as grain-boundary dilatancy, grain-boundary migration and pressure solution and has a strong effect on rheological and transport properties. Current engineering practice does not use this information.

Reliable modelling of the deformation and fluid transport in rocksalt under the very low strain rates characterizing long term engineering conditions requires **extrapolation of experimentally derived constitutive equations** to deviatoric stresses and strain rates lower than those attainable in the laboratory. This extrapolation must be **based on a modern materials science approach (but is currently not)**, with quantitative understanding of all the microphysical deformation mechanisms operating in the experimentally deformed samples, integrated with studies of natural laboratories where deformation took place under much lower strain rates. The engineering creep laws generally used in the salt mining industry are based on dislocation creep processes quantified in laboratory experiments of necessarily limited duration. However, a large body of evidence clearly demonstrates that grain boundary dissolution-precipitation processes, such as solution-precipitation creep and dynamic recrystallization, commonly play a significant role in natural rock salt and are expected to be common around solution mined caverns too. Currently the salt engineering community is starting to investigate this effect. Therefore, **current predictions of convergence rate are quite uncertain, and this uncertainty can be strongly reduced by using a modern materials science approach to determine rock salt rheology under all relevant conditions.**

In-situ (virgin) deviatoric stress in rock salt as measured by subgrain size piezometry can be as high as several MPa, in areas of active salt movement and in the order of kPa around Anhydrite bodies enclosed in the salt. When tectonics or glacial loading are over, this value relaxes and the in-situ virgin stress tensor becomes closer to isotropic. This is the case in the vast majority of the Zechstein.

We reviewed the microphysics of **grain boundary water-related dynamic recrystallization and solution-precipitation processes** in rock salt, together with the constitutive relations associated with these processes, and we discuss the contribution of these mechanisms around solution mined salt caverns, during their operation and during abandonment. In many current engineering studies, the effects of water-activated grain boundary processes are neglected, and this omission leads to errors in the prediction of displacement rates, especially over the long term. **Geomechanical modelling of the deformations around salt caverns can be significantly improved by using constitutive equations based on microphysical models for dislocation creep in combination with solution-precipitation creep, fluid-assisted recrystallization, and surface energy-driven grain boundary healing, site-specific for the rock salt around the cavern**. Recent development of methods to study microstructures in rock salt include (i) transmitted light microscopy of Gamma- decorated thin sections, (ii) subgrain size paleo-piezometry of polished and chemically etched samples using reflected light microscopy, (iii) micro-CT analysis of grain boundary fluid inclusions, (iv) analysis of grain boundary structure and microchemistry by cryogenic BIB-SEM and (v) X-ray or EBSD orientation imaging.

This toolbox is readily available for engineering studies and the world's top laboratory to carry out these studies is in the Netherlands. There is a growing understanding of deformation mechanisms, constitutive laws and fluid flow in naturally deforming rocksalt (at stresses and strain rates relevant to caverns) by inverting data from a wide range of geological settings. Integrating this knowledge base provides an improved basis for making better predictions of the evolution of abandoned salt caverns. There is a need for additional materials research, especially of the kinetics of transformation of grain boundary fluids, and the role of material variables like composition and impurities.

Deformation **at the walls of brine filled caverns** is usually modeled assuming that the salt is initially impermeable, and if it deforms in the non-dilatant field it will remain impermeable, so that the brine only acts as a confining pressure. This can however better be compared with "unjacketed" triaxial tests, and it is likely that deformation leads to change in grain boundary structure, where a small amount of brine penetrates the grain boundaries, establishing a pore pressure which slowly reduces the effective stress at the cavern walls, leading to slow dilatancy and permeation, even under conditions which would traditionally be evaluated as non-dilatant. Calculated deviatoric stresses around producing brine filled caverns can be of the order of 10 MPa, leading to considerable strains, **dynamic recrystallisation and change in grain size and grain boundary structure - during abandonment and relaxation of deviatoric stress this will have a much weaker rheology than predicted based on dislocation creep alone**. More work is needed to implement this knowledge to predict these changes at the cavern walls.

We note here that these conclusions are formulated for brine-filled caverns, and may be different for caverns filled with compressed air, oil, natural gas or hydrogen.

2.2 Recommendations, Rheology and Deformation mechanisms

Based on this literature review, it is clear that the constitutive equations used to model the mechanical response of solution mining caverns can be much improved, especially for the conditions which cannot be accessed by laboratory experiments.

We recommend the use of constitutive laws which are supported by microphysical materials science evidence, to arrive at much improved and less uncertain predictions of convergence, incorporating state variables for changing of grainsize, grain boundary structure, and the corresponding microphysical deformation mechanisms.

Measurement and microphysical understanding of the conditions and kinetics of grain boundary structure transitions in rock salt to model cyclic rheology are not completely understood – more work is recommended.

We recommend more materials science-based investigations of the changes in the properties of the rock salt at the cavern wall, during operation and during abandonment.

Materials science studies of rheology, AND microstructure of salt cores from cavern intervals to provide much improved constitutive equations for calculating deformation during solution mining and during abandonment, withe site-specific predictions of rheology to much improve predictions for cavern abandonment.

Development of a knowledge base of microstructure and mechanical properties for a series of rock salt samples, to allow better extrapolation and the development of microstructure-based rock salt rheology predictions.

2.3 Conclusions: microscale permeation mechanisms of salt rocks

Rock salt is known as the best subsurface seal for fluids, based on three key properties. First, the near-isotropic stress state provides resistance to hydrofracturing. Second, in-situ permeability in pure, equilibrated rock salt in nature is very low, as porosity is unconnected are very small. Third, plastic deformation of halite in nature is ductile and therefore non-dilatant. Fourth, fractures can be healed by ductile flow and solution-precipitation processes.

Under suitable conditions, however, all rock salt can lose their subsurface sealing capacity. For engineering (short-term) applications, it has been established that if the fluid pressure is several MPa higher than the minimum principal stress in the salt, rapid propagation of fluids through hydraulic fractures will initiate. The exact pressure for this depends on the rock salt, on material parameters like grainsize and anhydrite layers.

In-situ permeability of undisturbed halite can be very low at 10-^{21} m^{2}, but higher permeabilities also have been reported. This allows rock salt to seal fluids and fluid pressure cells over geologic time. The main controlling microphysical parameter here is the structure of grain boundary porosity which can be unconnected by fluid assisted healing processes, or connected by dilatancy or the presence of second phases. Grain size will play an important role in both cases.

In pure, very low permeability rock salt, infiltration rate increases rapidly with the difference between fluid pressure and minimum principal stress: the available results suggest that if this difference is more than about 2 MPa, the flow is so rapid that it can be considered a hydraulic fracture.

It has been shown in both laboratory experiments and in-situ tests that **brine (and oil) can migrate through salt along diffusely dilatant salt-grain boundaries if the fluid pressure is higher than the minimum principal stress but not high enough to cause hydraulic fractures**. It is not well known what the effect of a deviatoric stress in the rock salt is on the conditions of permeation. Some models argue that in an abandoned salt cavern's roof, this permeation process is slow, permeating a large volume of rock salt and creating a volume of dilated salt that both hosts significant brine and changes its permeability by nonlinear effective pressure-dependent dilatancy. However, considering the nonlinear nature of this effective pressure-dependent dilatancy in a heterogeneous rock-salt mass, others argue that this process is unstable and will lead to preferential fingering — or even fracturing — and a fluid pathway with a much smaller volume. This is especially true, as brine density is smaller than rock density: when head losses are small, the gap between brine pressure and geostatic pressure in the dilated zone is larger when this zone moves upward, making the process potentially unstable. In our opinion all available evidence points to this second process, when the fluid overpressure is small. In abandoned caverns, this can lead to localized and rapid leakage of brine from the cavern. **Large scale diffuse dilatancy and permeation is very unlikely to occur after abandonment.**

Controlling parameters of the process are salt microfabric, the state of stress and the amount of fluid pressure. The infiltration along fronts that are irregular even in the laboratory scale has been studied in bulk experiments and in solution-mined cavities, and first-order trends in the evolution of dilatant porosity and permeability of the salt were measured. However, **the microphysics of this process is not well understood and more materials-science based work is needed to establish the likely long-term processes. It has been shown that dilatant (permeated) rock salt can undergo complex dilation-compaction, recrystallization, crystal plasticity, and pressure solution; therefore, a number of potential feedback processes are present.**

The conditions in an abandoned cavern roof under which (localized) permeation or hydraulic fracturing will occur are not sufficiently understood given the lack of microphysical understanding, the empirical nature of the results and the need to extrapolate.

Measurements point to differences in the rate of infiltration and permeation between homogeneous samples and predict spatially heterogeneous permeation. In heterogeneous samples, permeation is much more heterogeneous, controlled by the distribution of heterogeneities: large Halite crystals, anhydrite layers, etc.

A First look at rock salt core from around Dutch solution mined caverns clearly shows that these heterogeneities are present and important.

In bedded salt, this anisotropy is sub-horizontal, in domal salt this is sub-vertical, suggesting major differences between permeation processes in these two settings.

At present, there is no microstructural information to quantify the grain boundary dilation and healing processes, although the toolbox to study this is readily available.

We also note that **in an abandoned cavern, when brine pressure is increased, the state of stresses in the surrounding salt is quite different from lithostatic. This adds additional uncertainty** to predictions of the allowable brine pressure.

A number of processes are known to create an increase of permeability in initially impermeable or poorly permeable material. The first is microcracking and associated dilatancy, which can take place at high differential stresses or high fluid pressures. Dilatancy in the presence of brine has been shown to be suppressed by pressure solution and recrystallization processes. **However, the conditions relevant to abandonment, with low differential stresses and high fluid pressures, are largely unexplored. These conditions are complex indeed: in the case of permeation, they include the establishment of a pore pressure in rock salt where Terzaghi's law is added to the time-dependent elastoplastic material law.**

In numerical models of infiltration around caverns, it seems that the surrounding salt is assumed to be homogeneous. We propose that if realistic heterogeneous properties are included, infiltration

will be much more localized, tending towards preferential fingering. The evolution of an abandoned cavern which leaks by preferential fingering has not been modelled and is not well understood.

Accurate prediction of the rate and distribution of percolation of fluids into the salt roof of solution mining caverns is a hard problem, requiring understanding of several coupled, nonlinear processes.

Although the main macroscale processes are recognized, further progress will require microphysical understanding of processes and parameters.

In bedded salt, horizontally continuous, impermeable anhydrite layers can form barriers which may allow fluid pressure to rise to more than 2 MPa above the minimum stress. Once these layers fail, the brine will rapidly penetrate the overlying rock salt.

Therefore, permeation of the salt after abandonment is much more heterogeneous than suggested by current models.

At present, there is very little information on the relevant microphysical processes, as the existing permeation studies did not carry out microstructural study of the deformed samples. Salt microstructure is variable and heterogeneous. Including microstructure in abandonment will help to better predict cavern evolution after abandonment.

The available evidence strongly suggests that infiltration will be localized but, further progress will require microphysical understanding of processes and parameters.

2.4 Recommendation, microscale permeation

We recommend materials science-based research to provide a microphysical understanding of the permeation and healing processes:

- Understand microphysical processes of permeation to allow upscaling to constitutive models which can be extrapolated to long time scales and incorporate heterogeneous material
- Develop a standardized microstructure characterisation protocol
- Integrate macro and micro analysis by developing constitutive equations which are implemented in 3D simulation codes to model the full evolution of abandoned cavern.

3. CONCLUSIONS - CAVERN-SCALE REPORT

3.1 Conclusions

[1] The state of stress in a salt formation can be assessed through density logs, frac tests and specialized logs. Interpretation of frac tests raises theoretical problems that have not been solved to date. Fracture tests seem to overestimate the actual stresses by 5-10%. It often is assumed that the state of stress is isotropic (exceptions clearly exist), and that, at a given depth, the geostatic pressure equals the weight of the overburden, $P_\infty = \gamma_R H,$ where *H* is the cavern depth, and γ_R is the average volumetric weight of the overburden; $\gamma_R = 0.022 - 0.023$ MPa/m is typical. Density-based assessment of the vertical stress often is considered supplying data of sufficient quality.

[2] Thousands of caverns have been operated worldwide for brine production or for gas and liquid storage. In the case of gas or oil storage, for which safety and environmental protection concerns are especially important, companies select a maximum admissible pressure that is proportional to casing-shoe depth, $P_{\max} = \gamma_{\max} H$. In most cases, $\gamma_{\max}$ is close to 0.018 MPa/m. Maximum admissible pressure is significantly smaller than computed geostatic pressure. This large factor of safety ($\gamma_R / \gamma_{\max} = 120\%$) is dictated by experience and the special concerns mentioned above. The same maximum admissible pressure applies to brine caverns (in which high pressure is applied for short periods — e.g. when tightness tests are performed). However, a few exceptions can be found, notably at Veendam and Barradeel (in the Netherlands), where fast-creeping salts are leached out at depths larger than 2000 m and the operating pressure is closer to geostatic pressure.

[3] Several salt caverns used for hydrocarbon storage experienced product losses and unexpected pressure drops resulting from a casing leak (a dozen cases are known). They are not of direct interest for the present study, as it is assumed that wells will be plugged efficiently before abandonment (at Bryan Mound, poor plugging led to large subsidence). Leaks through cavern walls are much less frequent. The LOOP (oil storage, Clovelly Dome, Louisiana) and Bayou Corne (brine production, Napoleonville Dome, Louisiana) cases are explained by the proximity of the cavern to the flanks of the dome. The severe gas leak at Regina South (Canada) resulted from failure of a thin cavern roof that had poor mechanical qualities. The Mineola (Texas) case, which led to a propane blow-out, is poorly documented. The Spindletop case is puzzling: gas seeped from a gas cavern to a brine cavern, even though the cavern walls were 120-m apart. A horizontal discontinuity in salt composition is suspected, but evidence is scarce. The Veendam case (a severe pressure drop) seems to be related to high cavern pressure, a thin salt roof, and a strongly anisotropic state of stress in the overburden, where a fracture almost certainly developed after a connection was created with the cavern cluster through the salt roof. These examples outline the significance of the geological context and, more specifically, of the hydraulic and mechanical conditions at the boundary of the salt formation.

[4] Prompted by increasing public concerns in environmental protection and several projects in which hazardous products were disposed of in abandoned salt caverns, the abandonment issue was raised in the 1980s. From that time until now, advances have been considerable. In Germany, Wallner (1986) proved that, in the long term, brine overpressure develops at the cavern roof of a tight cavern (the “*Wallner’s margin*”). At that time, rock salt was considered as perfectly tight and, provided that the pressure build-up rate in the cavern was slow enough, it was expected that no

fracturing would take place even when the cavern pressure became significantly higher than geostatic pressure (a gradient of $0.022-0.023$ MPa/m). In fact, the Etzel test (1990-1992) proved that the cavern ceased being tight when the pressure gradient in the cavern was as low as 0.019 MPa/m. The Kenter-Fokker tests performed at the laboratory in a mock-up cavern proved that a significant permeability increase was observed when the effective stress at cavern wall was tensile. In France, Bérest et al. (1979) highlighted the role of brine thermal expansion: years or decades are required before a brine cavern reaches thermal equilibrium with the rock mass — a serious concern when abandoning a cavern, as brine warming in a shut-in cavern typically leads to a pressure increase by 1 MPa/°C. The authors also showed that in a site where deep (2000 m) caverns had been linked by hydrofracturing, the pressure build-up rate is fast when caverns are shut in, leading to re-fracturing after a couple of months. Durup (1990 and 1994) performed long-term permeability tests in a 1000-m deep borehole in a bedded salt formation at Etrez; permeability to brine or gas was small but non-negligible.

A vast majority of authors agreed that evolution of a shut-in cavern is governed by three main phenomena: (1) brine warming, which is independent of cavern pressure; (2) creep closure, which is a decreasing (non-linear) function of cavern pressure and far-field stress field (whose possible anisotropy is important in this context); and (3) brine permeation through the cavern walls, which is an increasing function of cavern pressure. One consequence is that, at least when brine thermal expansion can be neglected and the wellbore is sealed efficiently, an equilibrium pressure is reached when the brine-outflow rate exactly balances the cavern-closure rate. In a shallow cavern (less than 1000-m deep; this figure is somewhat arbitrary), this equilibrium pressure is significantly lower than geostatic pressure, preventing any risk of fractures being created. Tests (several of which were sponsored by the Solution Mining Research Institute) were performed in France at Etrez, Carresse and Gellenoncourt, and, in Germany, at Bernburg and Stassfurt. These tests strongly supported these views. At Etrez, after an 18-month test, a low equilibrium pressure was reached. Fifteen years later, during a new shut-in test, the same equilibrium pressure was reached. It is accepted widely now that, provided thermal equilibrium is reached, shallow caverns can be abandoned safely.

These conclusions hold when the cavern is reasonably tight. At Brian Mound (Louisiana), subsidence was especially large above a large-diameter shallow cavern that did not have hydraulic integrity.

Several tests (Durup's tests at Etrez, the Etzel test and the Barradeel test, mentioned below) also proved that the *apparent* compressibility of a cavern or a wellbore (the volume of brine to be injected in a cavern to increase its pressure by a pressure unit) consistently increases when cavern pressure is larger than a certain threshold that is significantly smaller than geostatic pressure —evidence of an increase in cavern permeability.

In deeper caverns (more than 1000 m), creep closure is faster, and the equilibrium pressure is closer to the geostatic pressure. In many cases, the computed equilibrium pressure is larger than the maximum admissible pressure during operation (see above). The fracturing risk cannot be disregarded, especially when Wallner's margin and residual brine warming are taken into account. An 8-year-long test was performed in four caverns (more than 1000-m deep) at Mont Belvieu, Texas. Brine thermal expansion was still active, and drawing definite conclusions was difficult. At Tersanne, France, a 1400-m deep cavern was shut in 14 years ago; here, again, brine warming is still active and, for safety reasons, the cavern must be vented from time to time: the computed equilibrium pressure is larger than the maximum pressure accepted by the mining authorities. Another test was performed in 2004-2008 at Barradeel, the Netherlands, in a 2500- to 3000-m deep cavern (BAS 2). Pressure increased rapidly in the shut-in cavern and reached a value close to geostatic, after which the pressure increase became very slow. It is highly likely that a significant volume of brine seeped to the rock mass. Issues changed accordingly: the question asked was not "*Can brine seep from the cavern?"* (it did) but, rather, "*Can a hydraulic connection be created between the cavern and a potable water reservoir*?" — a less demanding requirement.

[5] From a theoretical point of view, it is difficult to predict the effects on subsidence at ground level of a significant brine flow from a cavern to an overlying aquifer layer. The Bryan Mound and Veendam examples strongly suggest that subsidence increases.

[6] The Etzel test prompted several modelling attempts. It is now accepted widely that, after (or even slightly before) the effective tensile stress criterion is reached (one of the two tangential stress at cavern wall is less compressive than brine pressure), the porosity, permeability and mechanical behaviour of rock salt drastically change. As suggested by several authors (Karimi-Jafari et al., Djizanne et al., Smit et al.), these changes may take place long before cavern pressure reaches geostatic pressure, as, in a visco-plastic rock mass, tangential stresses at the cavern wall experience complicated evolutions. Much evidence is available from microscale studies (micro-fracturing takes place at grain boundaries). One must distinguish between a "primary" zone that did not experience damage and, closer to the cavern, a "secondary" zone, in which a strong hydro-mechanical coupling must be taken into account. Computing rock-mass evolution is difficult: the boundary between the primary and secondary zones is unknown *a priori*, and the constitutive law describing the poro-mechanical behaviour of the secondary zone involves many parameters whose acquisition at the laboratory requires considerable effort. The first models were quite simple; substantial advances were made, and sophisticated models are now available. Cavern compressibility has a stabilizing effect (any brine outflow leads to a decrease in cavern pressure); conversely, along an upward-oriented flow path, effective stresses tend to be more tensile at shallower depth — a possible cause of fast upward fracture growth. However, many difficulties remain. It is suspected that boundary evolution is not smooth and that localization/fracturing can take place. Field data are scarce. Despite considerable advances, solution of the evolution problem has not reached a fully stabilized state.

3.2 Recommendations – Cavern scale

The case of large-diameter shallow caverns with no salt roof, which are prone to stoping and, ultimately, to creating a sinkhole, is not discussed here.

[1] When abandoning a cavern, the site-specific composition and sensitivity of the underground environment must be studied. Is subsidence a severe concern? Are potable water resources above or below the cavern field to be protected? Are they protected by a sufficient thickness of impermeable-ductile rocks? Are there large porous and permeable "receptors" able to accommodate large volumes of brine? Are they sensitive to hydro-fracturing when reached by highly pressurized brine? Addressing this would require salt-dome scale numerical models that are coupled

with poro-elasto-plastic model of the overburden to estimate the stress state and orientation at the salt-sediment interface, for reasonable variations in the material parameters.

[2] The thermal status of the cavern must be perfectly known. How large is the gap between brine temperature and rock temperature? How fast is the temperature change rate? How long is the waiting time needed to lower this gap to sufficiently small values?

[3] Information must be gathered on hydraulic (permeability) and mechanical (ability to creep) properties of the salt formation. Together with thermal properties, they allow building of a thermo-hydro-mechanical model able to predict the long-term behaviour of the shut-in cavern and cavern pressure evolution during the monitoring period (see below). This model should take uncertainties in rheological parameters into account. It is advisable to create dome-scale models that take the stress-state of the overburden into account, to monitor the expected stress evolution of the overburden along with the deformation of the cavity. A shut-in test should be performed before abandonment

[4] In shallow caverns (less than 1000 m), when thermal equilibrium is reached, several *in situ* tests performed in various geological conditions strongly suggest that, in the long term, an equilibrium pressure, significantly smaller than geostatic pressure, will be reached. Slow brine rates will permeate to the salt formation. Safe abandonment is possible. A monitoring period (several years and more) is needed before abandoning the cavern to verify that the actual cavern behaviour matches the behaviour predicted by computations.

[5] Deep caverns raise a more difficult problem, as the equilibrium pressure mentioned above is much closer from geostatic pressure. Taking into account Wallner's margin, the residual thermal gap (which is difficult to avoid in a very large cavern), and various uncertainties, it is difficult to be certain that no fracture will take place.

- Filling the cavern with solid residues is so costly a solution that it can only be considered in very specific cases.
- When creep closure is fast enough, allowing the cavern to close completely before abandonment is the simplest option (an outlet must be found for the relatively small brine rate that will be expelled from the cavern over a long period of time). The advantage of such an option is that possible negative consequences are not delayed (subsidence) or even are suppressed (brine seepage to the underground environment).
- When such a solution is not possible (for instance, because subsidence must be minimized), a waiting period must be managed to allow a temperature gap to reach a small value (injecting a small amount of a compressible fluid, e.g. nitrogen, can also be considered) and, as in the case of shallow caverns, a monitoring period must be managed.
- One can also try to prove that the amount of brine that can seep from the cavern through fractures or micro-fractures will remain confined in the salt formation. The recent Barradeel case (Duquesnoy et al., 2019) proves that such a demonstration is difficult.

- One should take care if cavities are built close to the top of a salt structure with a more significant amplitude, close to the lateral salt-sediment, or close to weak/strong layers within the salt such as stronger and dense anhydrite stringers or weak K-Mg-salt layers. For these cases, differential stresses tend to be higher and detailed computations (see salt-dome Report) are recommendable combined with microstructural analysis.

[6] A safety file including geological information, cavern history, *in situ* test results, results of numerical computation, and assessment of abandonment consequences for health and environmental protection should be prepared. It is likely that, in some cases, abandonment should be delayed (for instance, to allow the temperature gap to reach a small value). Monitoring will be mandatory for several years or decades before a final decision can be taken. In some cases, it will be difficult to avoid transferring monitoring and the abandonment decision to the state.

4. CONCLUSIONS OF THE DOME-SCALE REPORT

4.1 Overall summary

We have addressed dome-scale variations in the stress field by summarizing published literature and by describing the results of new, 3D, simulations tuned to three relevant scenarios in the Netherlands. We can summarize the findings as follows:

[1] Based on microstructural observations, differential stress variations of up to several MPa can be expected to occur within salt domes. There is, however, no published work that systematically measured how such stresses vary within larger-scale salt domes. There are some (weak) suggestions that stresses are higher close to shear zones within the salt structures.

[2] In-situ measured stresses from drill-holes seem to suggest smaller values of up to 1 MPa, but results are not entirely conclusive.

[3] The effect of differential stresses may have a significant effect on cavity closure rates, which will generally increase depending on the ratio of the far-field shear stress and pressure difference of the cavity with respect to the surrounding (a parameter that is likely to change during the abandonment phase). Analytical models of hole-closure suggest that the results are highly sensitive to the rheology of the rock salt.

[4] Existing literature suggests that anhydrite stringers within the salt can cause stresses of ~0.1-0.5 MPa, but existing work mostly focusses on stresses around rather than within salt structures.

[5] We, therefore, performed systematic 3D numerical simulations that took a flat-lying salt, salt pillows, and a salt wall into account, as well as internal heterogeneities within the salt, such as a weak K-Mg-layer and higher-density stringers.

[6] We demonstrate that it is now computationally feasible to perform 3D numerical models at a dome-scale to create an uncertainty analysis of the subsurface stress state, taking into account a-priori parameter ranges from microstructural analysis and in situ constraints.

[7] Our simulation results show that differential stresses are generally largest for the salt pillow and salt wall cases and may reach values of up to 0.65 MPa, whereas stress magnitudes are rather < 0.4 MPa for flat-bedded salt cases. Stresses are largest towards the top and sides of the salt structures. Far-field tectonic deformation can enhance stresses, depending on the geometry of salt structures. Yet, for the rather low deformation rates in the Netherlands, this is not a first-order effect.

[8] Stresses can also be enhanced in the vicinity (~500 m) of basement steps and internal heterogeneities. Weak layers within the salt may result in a 'stress-focusing effect' that enhances stresses above the layers, whereas dense anhydrite stringers cause buoyancy related stresses in their vicinity.

[9] The effect of rheology is significant. The largest stress magnitudes are obtained for cases in which pressure-solution is inactive. In low-stress regime, the pressure solution creep is weaker, and hence preferable deformation mechanism, compared to the dislocation creep. The transition between the creep mechanisms is, however, poorly constrained. A particularly important parameter influencing this is the mean grain size. In order to provide more insights for a specific case study, the parametric numerical simulations combined with the microstructural analysis are generally recommended.

[10] The effect of glacial loading changes the stresses immediately after the loading was removed, but has only a minor effect on the present-day stress field within salt domes, particular given the already discussed effects and uncertainties in the material parameters.

4.2 Recommendations

[1] Caverns within flat-bedded salt structures are more likely to experience low differential stresses, provided they are not close to anhydrite stringers or steps in the basement topography.

[2] Yet, more care should be taken if cavities are built close to the top of a salt structure with more significant amplitudes, close to the lateral salt-sediment, or close to weak/strong layers within the salt such as stronger and dense anhydrite stringers or weak K-Mg-salt layers. For these cases, detailed computations are recommendable combined with microstructural analysis.

[3] It is generally advisable to consider a range of creep rheologies in models of cavity closure, including non-linear ones, as the uncertainties in rheology remain large. At this stage, it remains unclear whether closure is mostly sensitive to the rheology of the salt immediately surrounding the cavity or also to the rheology further away. This is a critical point that deserves further studies, as the creation of the cavity may re-activate grain boundaries and therefore induce pressure solution creep which micro-structural observations suggest to be otherwise currently largely inactive in many of the salt structures in the Netherlands. It is advisable to

take dome-scale models into account in this, as a switch in deformation mechanism in parts of the salt structure may induce larger scale flow within the salt (and potentially activate, for example, the sinking of anhydrite stringers).

[4] In order to improve the predictive power of subsidence, subsurface deformation, and stress-state, we suggest that studies of cavity abandonment should employ integrated 4D models of the geological salt structure and its overburden, while taking the cavity construction, operation, and its abandonment phase into account. These models should not only concentrate on deformation within the salt, but also on the stress-state at the salt-host rock interface to allow estimating how this changes as a result of abandonment and evaluate the potential of hydrofracture formation there in case highly pressurized brine escapes the salt.