SOLUTION MINING RESEARCH INSTITUTE

679 Plank Road
Clifton Park, NY 12065, USA

Telephone: +1 518-579-6587
www.solutionmining.org

Technical Conference Paper

1965 – 2025

Pre-abandonment Mg-salt cavern monitoring for leak-off events

Abel Jan Smit & Peter Fokker

Nedmag, Veendam, Netherlands

SMRI Spring 2025 Technical Conference
27-29 April 2025
Wilhelmshaven, Germany

Solution Mining Research Institute Spring 2025 Conference

Wilhelmshaven, Germany, 27-29 April 2025

Pre-abandonment Mg-salt cavern monitoring for leak-off events

Abel Jan Smit, Peter Fokker

Nedmag, Billitonweg 1, Veendam, Netherlands

Abstract

Nedmag operates a magnesium chloride solution mining plant in Veendam. The eldest well and cavern (Veendam 1 or VE-1) was drilled in 1972 and operated until 1984 and contains about 170,000 m^3 of carnallite-saturated brine in the Zechstein-III 2b/3b formations. The cavern height is about 60 m. The well and cavern have only seen a few operations since 1984, for instance to relieve cavern pressure or to remove the corroded tubulars. The last pressure relieve operation was performed in 2019, after which the cavern and well were left untouched. In the first years the cavern showed a slow cavern pressure increase, mainly the result of (carnallite) salt creep at the ambient (salt and brine) temperature of 70 °C. Thermal heat expansion is most likely irrelevant at this time. Starting 2022 the cavern VE-1 was displaying periodic leak-off behaviour, where every half year the pressure dropped with on average 2-3 bars with an estimated leak-off of 75 to 150 m^3 during a time frame of about 1 month. The compressibility was estimated at 30-40 m^3/bar from a 2019 bleed-off test. After a bleed-off period, the leakage path apparently closes once more and a pressure build-up is seen during 4-6 months. With a leak-off rate of 200 m^3 per year the cavern creep-closure half-time (50% volume reduction) will be more than 500 years, assuming the leak-off rate is proportional with the remaining cavern volume.

It is realised that carnallitic or bischofitic magnesium chloride brine has a higher potential of clogging micro-fractures by cool-crystallisation than sodium chloride brine, so it cannot be guaranteed that the intermittent cavern leak-off is similar to post-abandonment behaviour of halite embedded caverns. A complete steady state brine outflow is however not a given either, given the observed VE-1 data.

Key words: cavern leak-off, fractures, abandonment, magnesium salt, bischofite, carnallite, cavern abandonment, cavern monitoring

1. Introduction

Nedmag operates a magnesium chloride solution mining plant in Veendam, in the north of the Netherlands. The eldest well and cavern (Veendam-1 or VE-1) was drilled in 1972 by Shell, with another 3 wells/caverns (VE-2/3/4) in 1976. Figures 1 and 2 show the subsurface casing shoe positions on a topographic and top salt iso-depth map. More wells were drilled as Billiton Refractories in 1982 (TR-1-6) and 1990 (TR-7/8) and as Nedmag in 2011 (TR-9) and 2022 (VE-5/7). Figure 3 displays an average lithology of area.

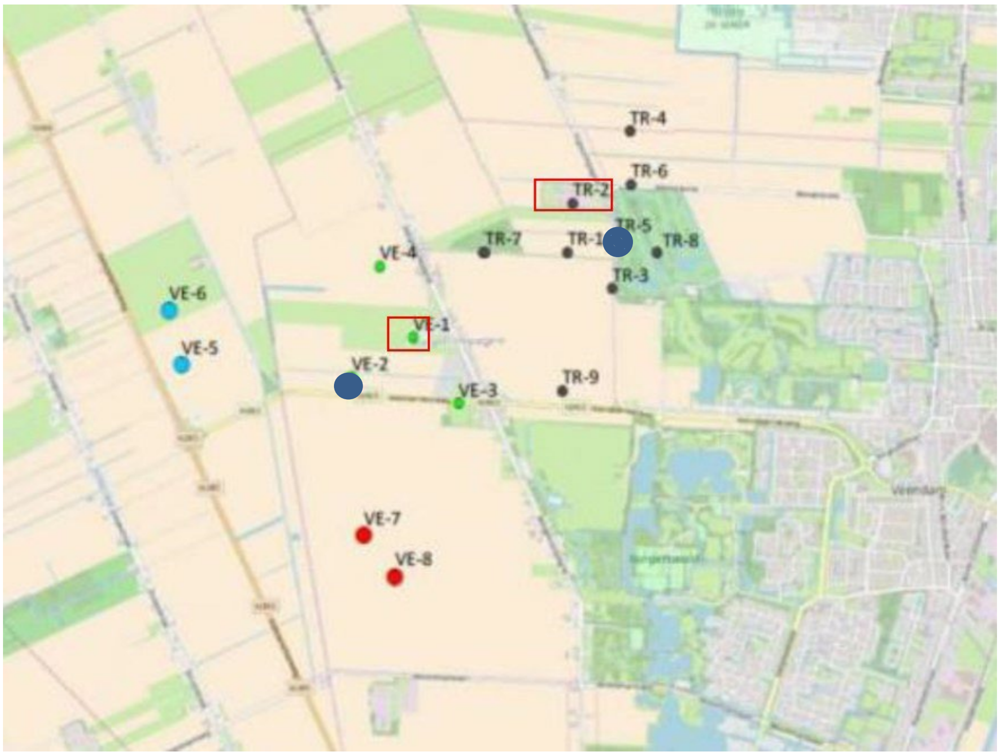

Figure 1. Subsurface positions of casing shoes of wells VE-1 to VE-8 and TR-1 to TR-9, drilled from 2 wellhead centres (red squares). In the East is the town of Veendam. VE-6 & -8 have not yet been drilled. The crossed out wells (VE-2 and TR-5) have been plugged with cement.

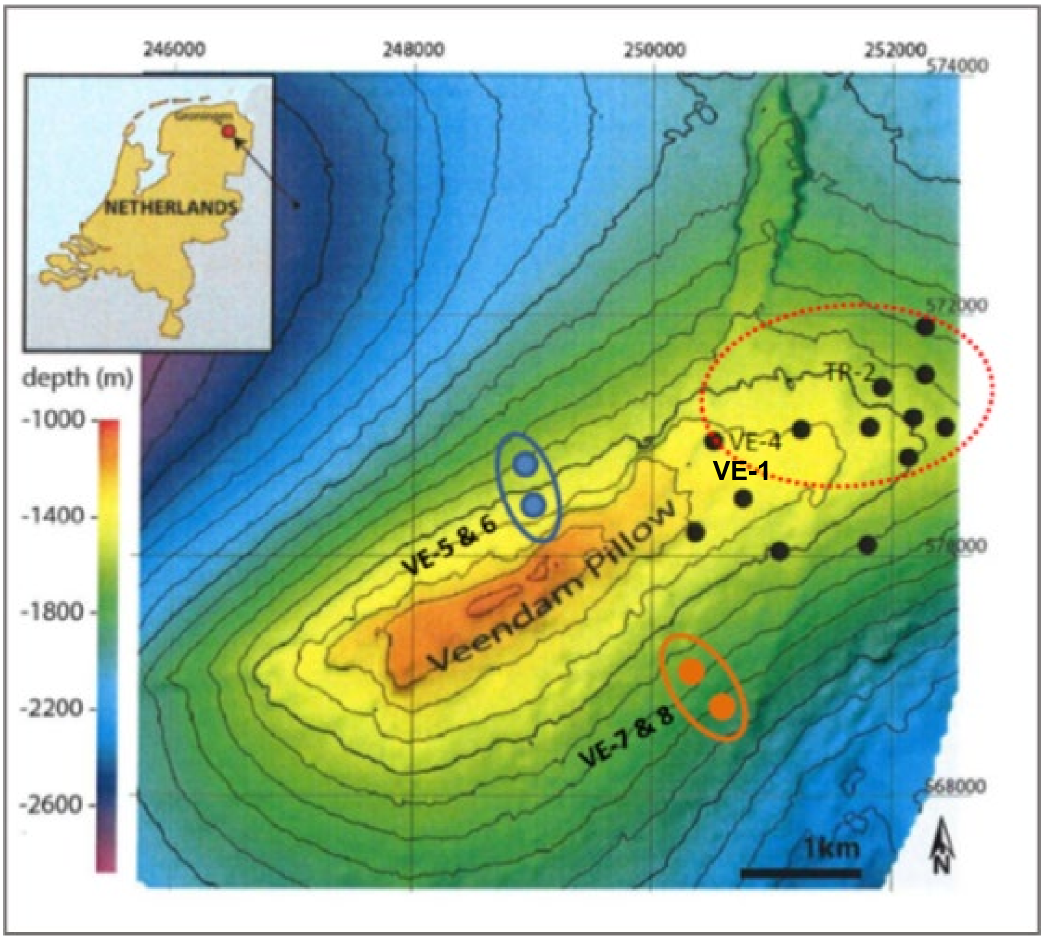

Figure 2. Subsurface positions of casing shoes of wells plotted on a contour map of the top salt. The top of the magnesium layers (ZE-III-3b) is on average 100 meters deeper.

Cavern VE-1 has not been used for solution mining since 1984 and has been standing idle for more than 40 years, with only short periods of pressure bleed-off and hydraulic workovers (to remove the injection and production tubing). Contrary to all other caverns, the VE-1 cavern was developed solely in the carnallite ($MgKCl_3.6H_2O$) layers of the ZE-III-2b/3b, hence neglecting the present main target ZE-III-1b, that usually contains bischofite ($MgCl_2.6H_2O$) that renders higher $MgCl_2$ concentrations in the brine and lower concentrations of KCl, NaCl and $MgSO_4$. With a brine volume of 170,000 m^3 (including some estimated 50,000 m^3 of brine trapped in sump material), the cavern is the smallest Nedmag cavern, except for the brand-new wells (and caverns) VE-5 and VE-7 that have started development in 2023.

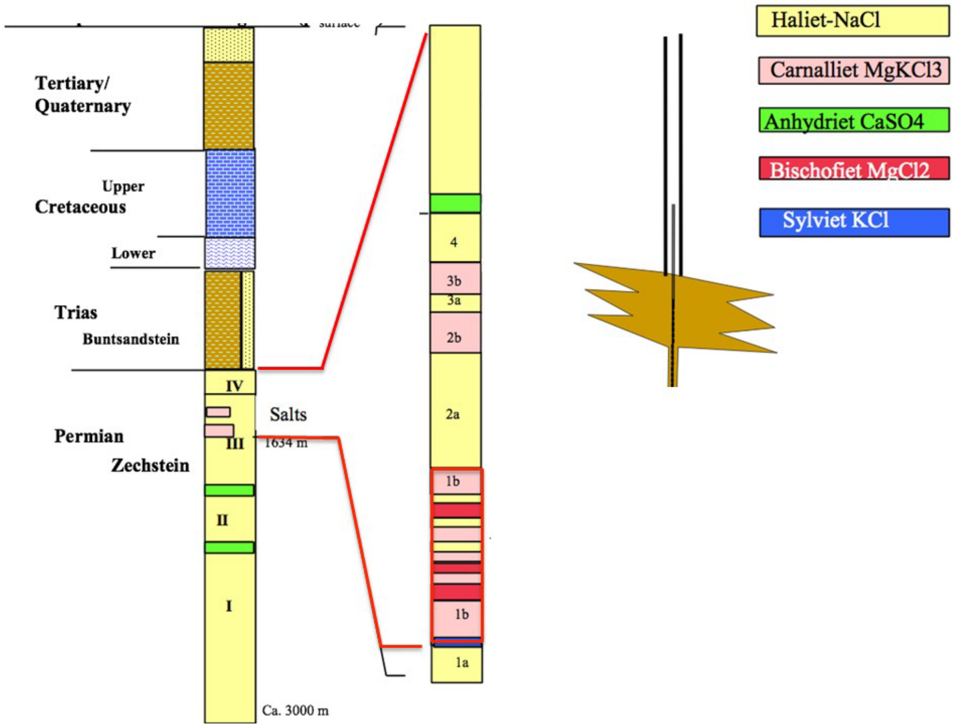

Figure 3. Lithology in Veendam Salt pillow area. VE-1 cavern exists in 2b/3b carnallite only.

It is assumed that after 40 years of near stand-still the brine in cavern VE-1 is fully saturated to carnallite and in thermal equilibrium with the original salt temperature of about 70 °C. The well is on a schedule to be plug-and-abandoned somewhere around 2030, unless there is a further monitoring requirement.

2. Monitoring of leak off

Since 2020, VE-1 was fully shut-in, allowing pressure build-up and potential indications of bleed-off by micro-permeation or fracturing. The general perception is that post-abandonment permeation via (intra-crystal) micro-cracks results in a slow and steady brine flow at brine pressures that are almost equal to the ambient salt roof stresses, close to lithostatic. As displayed in Figure 4, VE-1 shows periodic leak-off moments that indicates re-opening and re-closing of a small fracture that bleeds of brine to either the overburden or neighbouring caverns. The leak-off is too small and too slow to be observed (by simultaneous pressure changes) in the much larger neighbouring caverns, assuming leakage would go there.

The leak-off starts at a well-head pressure between 137 and 139 bar, after which the pressure slowly drops to about 136 bar in a time frame a few weeks, after which pressure build-up resumes during 4 to 6 months. The casing is filled with water, so a 136 bar wellhead pressure translates to 273 bar at 1368 m (True Vertical) casing shoe depth. The estimated original lithostatic stress level at an estimated (lower-end) overburden density of 2.15 g/cc amounts to 294 bar, 21 bars higher than the initiation pressure (fracture reopen pressure) of the last leak-off cycle. This is in agreement with the computed reduced salt roof stresses by decades of low pressure mining in the neighbouring cavern cluster, where overburden stress-arching reduced the vertical and horizontal stresses in the salt roof by an estimated 50-70 bar (Smit et al. 2019). Figure 5 is a horizontal stress display in the top salt showing locally decreased salt stresses around the cavern cluster. This stress reduction effect radiates out towards cavern VE-1.

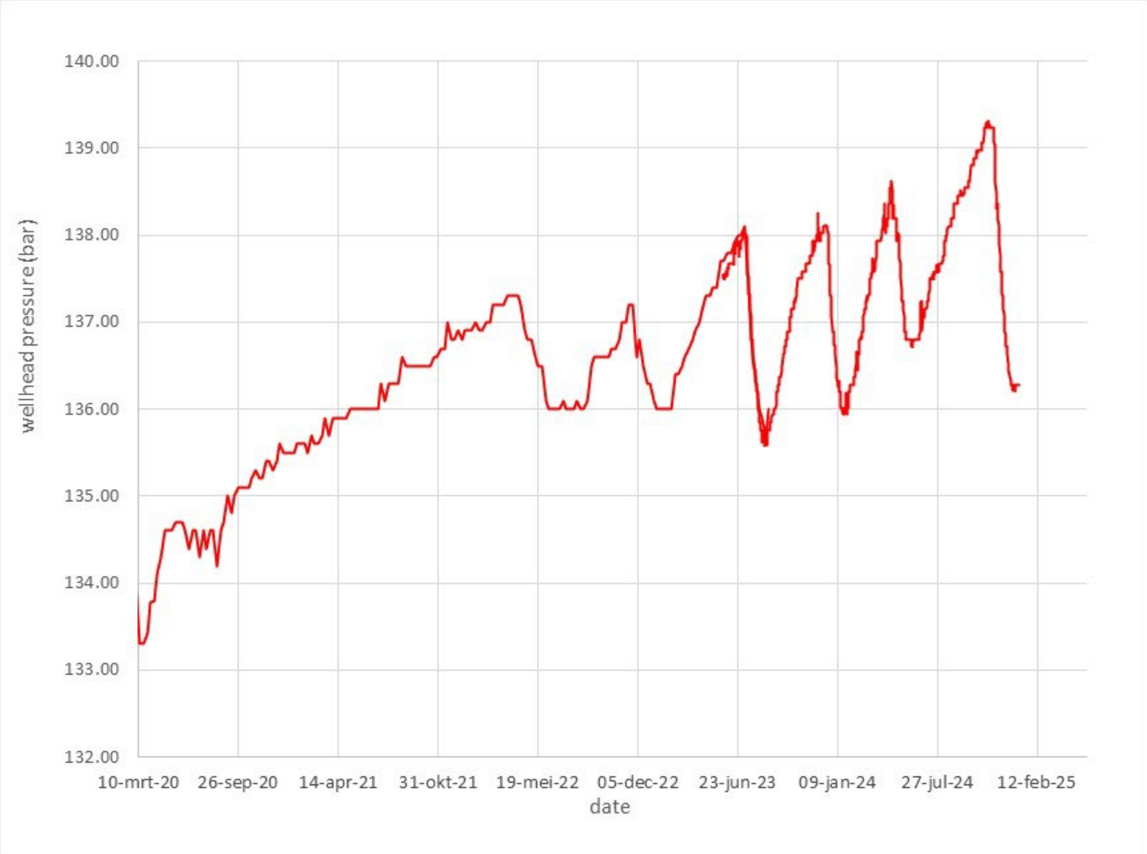

Figure 4. Natural bleed-off pressure cycles of VE-1 in 2022-2025

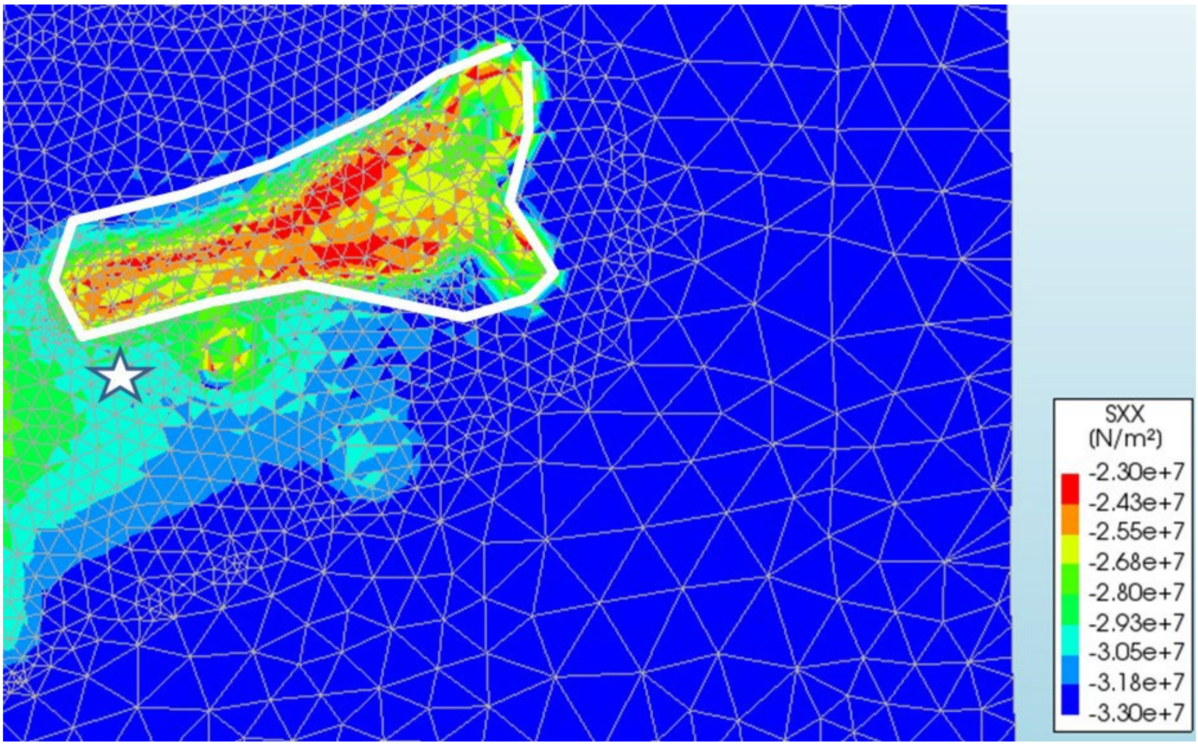

Figure 5: Finite Element computation of the horizontal (Northing) stresses prior to 2018 at the top of the salt roof. In the middle, the red area shows a reduced stress due to long term salt creep and stress arching of the cavern cluster (outlined as estimate), indicating a stress drop of up to 60 bar since the start of solution mining in the 1980's. The star is the approximate position of VE-1, where a salt roof stress reduction of about 20 bar was computed.

3. Fracture closure (in salt)

It is assumed that a fracture in salt -either in carnallite or halite- closes (or almost closes), once the fluid pressure in the fracture has dropped a few bars below the normal stress on the fracture, certainly if the percolating brine is saturated towards the salt of the fracture walls and no dissolution occurs of the fracture walls. In the VE-1 case it is likely that the brine either leaks via the halite roof towards the Bunter formation or (more likely) via the 2b/3b carnallite layers towards the cavern cluster (see figure 6), most likely nearby the casing shoe of VE-4. Carnallite has a tensile strength of about 2 bars with respect to halite tensile strength of about 20 bars. Fracture closure was also seen in 2018 after a (at that moment unexpected) brine leakage incident from the cavern cluster (see also chapter 5).

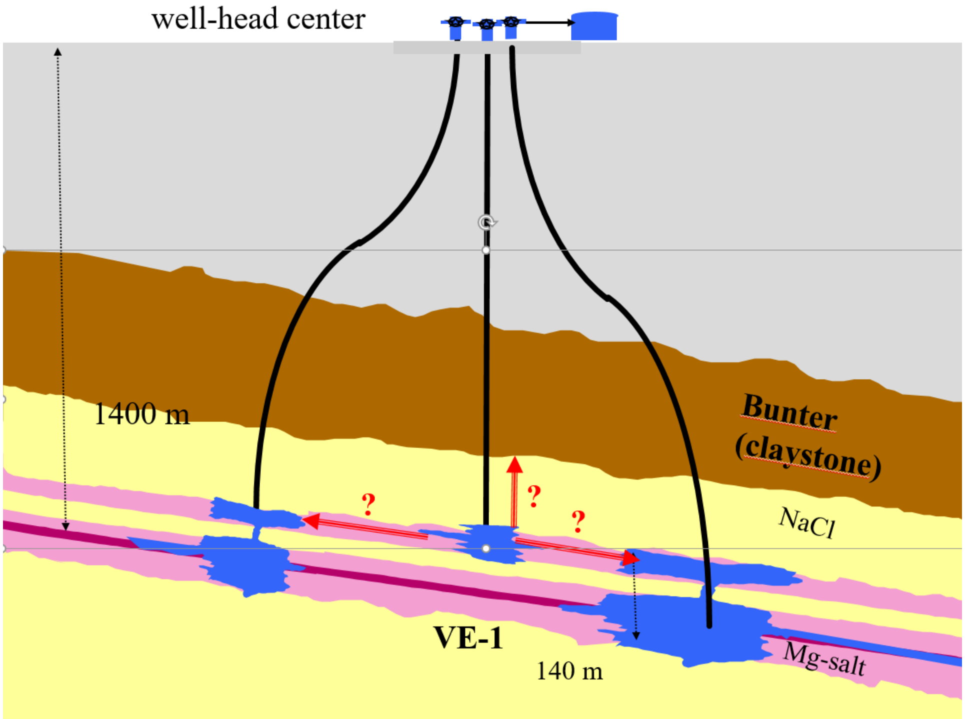

Figure 6. Potential leak paths of VE-1 brine to neighbouring cavern via the carnallite layers or to the Bunter (claystone) formation via the halite roof.

4. Estimating Bleed off volumes

The compressibility of VE-1 was estimated at 30-40 m^3/bar from a 2019 bleed-off test, so the estimated leak-off per cycle is 75 to 150 m^3. After a bleed-off period, the leakage path apparently closes once more and a pressure build-up is seen during 4-6 months. With a leak-off rate of 200 m^3 per year the cavern creep-closure half-time (50% volume reduction) will be about 600 years, assuming the leak-off rate is proportional with the remaining total brine volume of 170,000 m^3 or 400 years if we assume that only the 110,000 m^3 free brine volume is steering the bleed-off and not the brine that is more or less trapped in the porosity of the sump material that will take order of magnitude longer to escape.

In theory the cavern volume can be reduced to a lower brine volume by allowing brine to flow out at much lower cavern pressures. For a small cavern in carnallite, this will be a very slow process if bleed off is governed by creep only (so without compressibility components). The estimated bleed-off is about 4000-7000 m^3 per year (with most likely 2-3 bleed off cycles towards near-halmostatic pressures per year). The well is currently not fitted with tubings and high pressure lines for brine production and counter current flushing with water (to remove carnallite that will deposit on the tubings or casing wall due to cooling crystallisation).

In reality and for operational reasons, VE-1 will most likely be partially bled-off in pressure and volume, prior to setting a final cement plug near the casing shoe. This bleed-off in one month or so (elastic and partially salt creep related) is expected to reduce the cavern size by some 5000 m^3 (according to historic data). This is included in the plot of Figure 7. This is Nedmag's current preferred option.

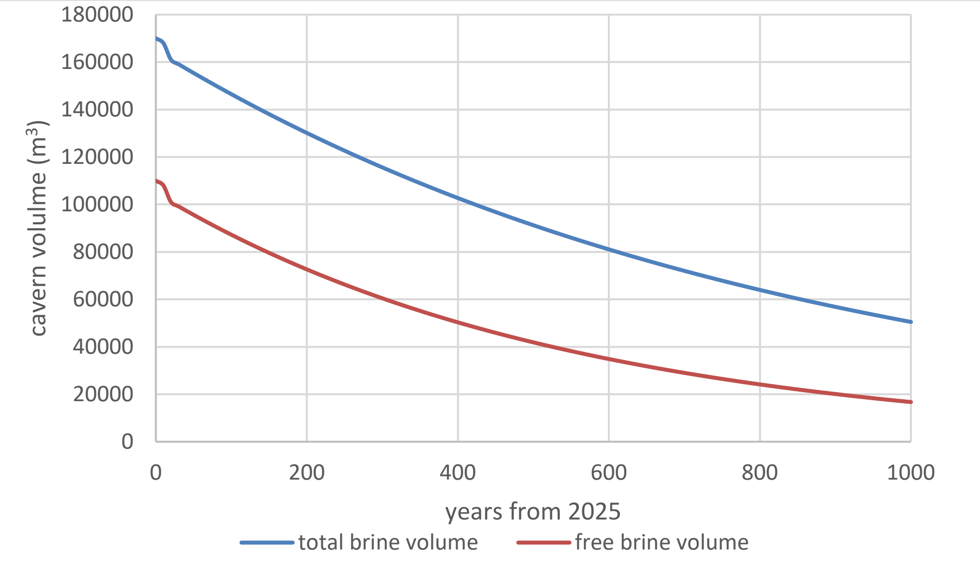

Figure 7. Extrapolated cavern convergence for VE1 including a 5000 m^3 bleed off prior to a plug and abandonment operation.

5. Relation to brine loss incident in 2018

In April 2018 the cavern cluster experienced a sudden pressure drop of 25 bars during a time frame of hours at a cavern pressure of about 50 bars below (1980's XLOT and density estimated) lithostatic stress. This incident is well described in a paper by Smit et al (2019) at the SMRI-Berlin meeting. Due to long term cavern convergence with associated subsidence (to about 50 cm at the time) and stress arching around the cavern cluster, the vertical stresses in the halite layer above the cluster had decreased by some 50-70 bar, where horizontal stresses adjusted due to salt creep towards the vertical stresses. A cavern pressure increase only resets the vertical and horizontal stresses by a small amount, since the subsidence (and general overburden rock deformation) remains. Normally one would expect brine to leak off via the carnallite layer towards a shallower point at the salt cushion, but this area still had higher (original or elevated) vertical and horizontal stresses, by which this route no longer became the route of least resistance. Perhaps the fracture initiation had been delayed by a thin anhydrite layer that separates the ZE-III and ZE-IV halite formations. Such an anhydrite layer has a higher tensile strength, but also higher horizontal stress, since creep effects most likely do not reduce horizontal stresses towards the vertical stresses in a few decades.
In a few weeks to months after the leakage incident, the fracture fully closed and sealed, perhaps assisted by cooling crystallisation of saturated brine, clogging small apertures that remain after a mechanical closure of a fracture.
The cavern cluster pressure has been kept constant since 2018, reducing its effective (free) brine volume of 3.7 million m^3 in June 2018 to 1.6 million m^3 in January 2025 (Figure 8). The bischofite section 1b converges (creep closes) much faster than the carnallite section (2b/3b). At present the volumes are estimated to be about equal. By 2045 (end of present production license -- formally: the approved 2018 extraction plan), most remaining volume is estimated to be in the carnallitic 2b/3b section with some open 0.2 million m^3. In Figure 8 the calculated open brine volume in the 1b and 2b/3b formations are plotted with the cavern convergence rate of both cavern sections. The convergence rate in total are measured from net outflow of cavern brine, but the subdivision of the 2b/3b and 1b sections is a fit, assuming convergence (at constant cavern pressure) is linear to the remaining open volume. The trend is more or less linear, with small effects small pressure fluctuations (1-2 bars), brine purification gypsum slurry injection and off-grade brine injection (for bischofite up-grade purposes) from the new caverns VE5 and VE7.

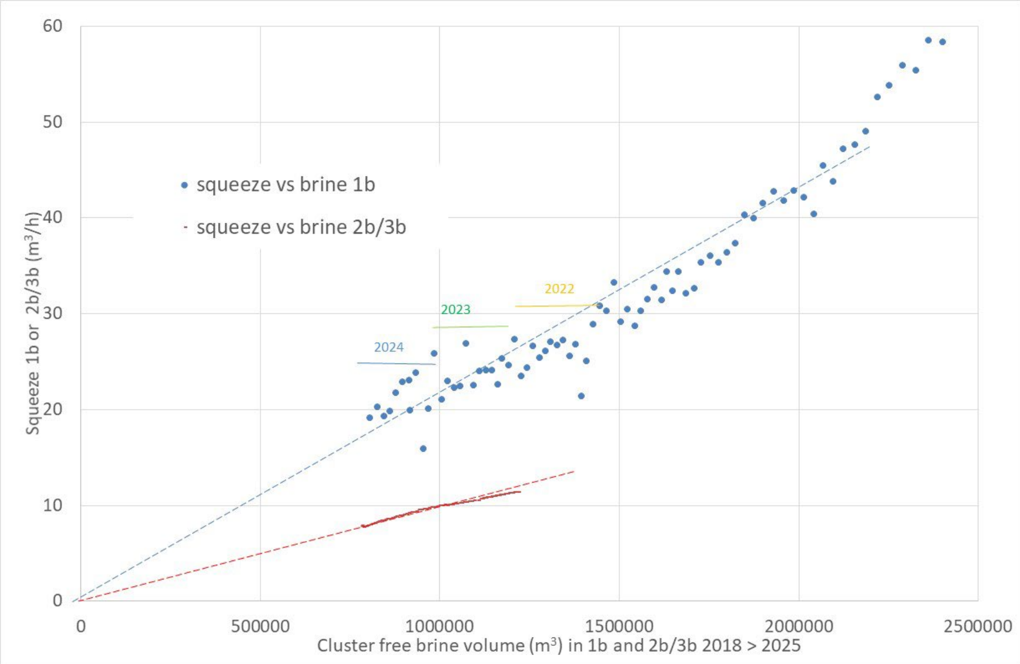

Figure 8. Squeeze rates of brine from the cluster per remaining open brine volume, separated in their assumed source from the bischofite section 1b (blue dot) and the carnallite section 2b/3b (red line). The uttermost left values are the most recent values (Jan 2025).

It is expected that if the cluster would be allowed to pressure up again, a renewed leakage would occur, close to the original fracture closure pressure. Most likely, the same leak-path would reopen, given that full halite (tensile) strength healing is not very likely in a short timeframe and with carnallite veins present. The pressure drop and the outflow from the cavern will be significantly less, the first due to the lower fracture energy and the latter due to the lower pressure drop and the significantly (60-70%) lower cavern compressibility compared to the 2018 situation. Until abandonment of the TR cavern cluster, Nedmag will conduct a cluster pressure regime that prevents a repeat of the 2018 brine loss incident, whilst using the brine expelled by cavern convergence for production purposes.

6. Cavern pre-abandonment planning

Nedmag is planning to reduce cavern volume by cavern convergence (creep closure) as much as practically possible, prior to well and cavern abandonment. Cavern brine can be used for commercial purpose and subsidence can be dealt with in the present day (mainly by adjusting local water tables). Nedmag believes that large magnesium brine volumes in relatively fast creeping salts cannot be contained by simple plug and abandonment for eternity. Even after a period of monitoring and reheating of the brine, brine will leak off to the overburden after abandonment, the rate of which can be estimated. Small volumes of brine that cannot be extracted by reasonable means, will be left behind at cavern abandonment. The associated leakage and subsidence will only realise in centuries to come. The associated amount of soil subsidence after those centuries can be estimated on the basis of the free brine volumes left behind and historic averages of 7-8 mm of the amount of subsidence per 100,000 m^3 cavern convergence (or post abandonment leak-off). These rates are comparable to natural changes in ground level changes due to geological, hydrological or biological (peat rot) effects.

7. Subsidence planning

Most of the subsidence bowl is in an area with no shipping canals or rivers, so surface (canal-) and ground-water tables can be relatively easily controlled by small dams and pumping stations. Nedmag currently expects a subsidence bowl of up to 95 cm by salt mining (i.e. excluding effects from historic gas extraction of the Groningen and Annerveen gas fields), of which 68 cm (since start production in the 1970's) has realised by early 2025. For this level water table measures have been implemented by the water boards. Plans to accommodate the up-to 27 cm to come have been recently approved by the water-board for implementation in 2025-2040.

Conclusions

Post abandonment cavern leakage (by means of micro-fractures) is not necessarily a steady-state process. The monitoring cavern VE-1, that awaits final abandonment, show cyclic pressure build-up and leak-off periods. The Nedmag caverns (and salts) with magnesium chloride salts and brines may not be representative for caverns (and brine) that are completely in a rocksalt domain. The behavior does show that the leak-off is small and controlled, and occurs at cavern pressures that are close to the lithostatic pressures. The convergence and subsidence take (half-time closure) takes centuries to a thousand years for the specific cavern VE-1 and most likely also for other caverns. Leakage of larger caverns or the cavern cluster is perhaps equally slow in time, but more in total volumes, assuming leak-off is linear to the total volume of brine.

Nedmag chooses to allow cavern convergence and subsidence to the maximum technical limit, in order to prevent a repeat of a major brine loss incident and use the brine for production purposes, whilst compensating for most of the subsidence in the present years. At some time in the future, small amounts of brine must be left behind if the brine outflow becomes too low to maintain an active well. This brine will leak off in the centuries to come, but volumes are expected to be limited.

References

A.J. Smit et al.: Sudden pressure drop in Nedmag Cavern cluster. SMRI fall meeting 2019 in Berlin – Germany.