KEM Innovation/Research Question (max. 4 pages + annex)

TITLE *Over-pressured salt solution mining caverns and possible leakage mechanisms*

Objective

The overall goal for SodM is to be able to predict the occurrence of cavern instability and uncontrolled subsidence (including sinkholes) and to define and supervise cavern risk management protocols ensuring cavern instability and uncontrolled subsidence risks stay at acceptable levels during operation and after abandonment.

The specific goals for this KEM project are to improve knowledge on the processes that occur when brine pressure in the cavern (locally) exceeds the minimum stress in the cavern roof or wall. Currently two end-member processes and an intermediate process are described in the literature and discussed during conferences: permeation, hydraulic fracturing and preferential fingering.

1. Permeation (or percolation): laboratory experiments (<reference>) have shown that brine can be squeezed along salt grain boundaries. It is thought that this permeation process can slowly take place over a large area of for example a cavern roof[1].
2. Hydraulic fracturing: from the petroleum industry we know rocks can be hydraulically fractured when a fluid exceeds the minimum stress. The hydraulic fracture can lead to a very local and rapid leakage of brine from the cavern.
3. Preferential fingering: it is hypothesized that an intermediate process may occur where fluid leaks through a local, preferential, semi-stable pathway (<reference>).

We know that the end-members permeation and hydraulic fracture do exist under certain conditions. The specific sub-goals are:

1. To improve knowledge of the micro-mechanisms to determine under what conditions which process takes place/is dominant.
2. To understand how the processes are influenced by local pressure, stress, temperature and salt properties. Also how do local/cavern-scale/salt-dome scale heterogeneities in these parameters affect which process is dominant or the rate of the processes themselves?

State of the art, background

Different views

In the salt mining community there is discussion about the dominant mechanism of leakage from caverns. The visions of what occurs when brine pressure reaches the local minimum stress range from:

- It is difficult to exclude that hydraulic fracturing does not occur[2].
- As long as the pressure build-up of the flow rate of infiltrated brine into the rock mass will be moderate, hydraulic fracturing can be excluded. Often the approximate equalisation of the brine temperature with the salt temperature is mentioned as requirement[3].
- Both the pressure increase created by cavern convergence and by temperature increase of the brine can be accommodated by permeation. There is no indication for macro-fracturing. It is not necessary and not practical to wait for temperature equilibration[4].

Pressure increase

The brine pressure in the cavern is increased by two mechanisms: warming up of the brine and cavern convergence. How large the influence of these two processes is depends on the depth of the cavern, the cavern shape and volume, and the temperature differences between the brine and surrounding salt.

Brine-thermal expansion

Caverns are often leached with water from a river, lake or shallow aquifer with significantly lower temperature. The time it takes for the brine to heat up depends on the shape and volume of the cavern, the thermal diffusion of the surrounding salt and the type of fluid in the cavern. The period of brine warming ranges from about a decade for relatively small caverns (100.000 m3) to a century for very large brine filled caverns[4]. A rule of thumb for the pressure increase in a shut-in salt cavern is that 1°C rise of brine temperature causes 1 MPa brine pressure increase[5].

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[1] K.H. Lux et al. (2006) Long-term behaviour of sealed brine-filled cavities in rock salt mass – A new approach for physical modelling and numerical simulations., SMRI Fall Conference, Rapid City, South Dakota, USA, October 2006.

[2] P. Beréste (2017) Issues concerning the abandonment of deep brine-filled caverns - Oral presentation. SMRI Fall 2017 Technical conference, 24-27 September 2017, Münster, Germany.

[3] F. Crotogino et al., (1997) Bibliography for cavern abandonment. SMRI Research and development project report.

[4] A. Duquesnoy (2017) Issues concerning the abandonment of deep brine-filled caverns – Discussion paper (revised). SMRI Fall 2017 Technical Conference, 24-27 September 2017, Münster, Germany.

[5] P. Berést et al., (2006) In situ mechanical tests in salt caverns. Spring 2006 Conference 30 April-3 May, Brussels, Belgium.

Cavern convergence

All solution-mined caverns become slowly smaller in volume due to salt creep. The driving force for the salt creep is the difference in between the stresses in the salt and the pressure of the brine. For deeper caverns the salt creep rate is generally higher due to the larger difference between salt stress and brine pressure. Also the higher temperature at depth increases the creep rate of salt[5]. Also the type of salt can have a large effect on the creep rate, with for example potash (KCl), Bischofite ($MgCl_2 \cdot 6H_2O$) and Carnallite ($KCl.MgCl_2 \cdot 6(H2O)$) creeping much faster than halite (NaCl). Cavern convergence rates for shallow caverns have been reported as low as 0.03 %/year to more than 10 %/year for low pressure gas storage caverns[5].

Permeation

Permeation is the slow time-dependent brine infiltration into salt roofs[6]. While normally the salt is gas and fluid tight, secondary migration paths can be created along grain boundaries when brine pressure gets close to minimum principal stress. This depends on the type of salt and state of stress. The direction of propagation of these micro-fractures is significantly influence by the local stress field and rock fabric. The progress rate of the brine front is a function of cavern convergence, brine compressibility, secondary porosity and the pressure difference between brine and the minimum principal stress of the formation. From this the secondary porosity and permeability of the salt can be determined. When the brine front reaches a permeable formation at hydrostatic pressure, there is a relatively large pressure gradient and brine can flow from the cavern through the micro-fractures into the permeable layer. This flow may continue at an equilibrium rate or decrease if the cavern pressure declines and the secondary porosity in the salt closes.

Hydraulic fracturing

Hydraulic fracturing has been used since the fifties to hydraulically connect caverns. Water is injected under high pressure in one well and produced from the other. After some time salt is dissolved around the fracture and pressure communication between the caverns can take place at lower differential pressures. Besides the minimum principal stress also the tensile strength of the salt (few MPa's) has to be overcome.

Research Questions

Further develop knowledge on what happens when the brine pressure reaches and exceeds the (local) minimum stress in the salt? How is the pressure relieved: via permeation/hydraulic fracturing/preferential fingering/other? Below is list of questions regarding the leakage mechanism and influencing parameters on different scales. Most important is understanding the micro-scale. After that the understanding how additional complexity influences the process.

1. Micro-scale:
    a. What are the micro-scale salt-brine interface processes (permeation and hydraulic fracturing or preferential fingering):
        - Depending on initial brine pressure and rate of pressure increase, stress tensor and salt material characteristics such as grainsize, microscopic heterogeneity, mechanical salt properties (Young's modulus, Poisson's ratio) and geochemical properties?
        - At which combination of parameters is permeation a dominant mechanism, at which combination is hydraulic fracturing dominant and/or can an intermediate or mixed mechanisms like preferential fingering occur? To which parameters are the processes most sensitive? What is the inherent parameter uncertainty? Is there a self-strengthening or self-weakening feedback mechanism?

    b. How big a flow of brine can be accommodated by these processes?
    c. What are appropriate models to simulate these processes?

2. Cavern-scale:
    a. How does the pressure built in a cavern depending on:
        - Operational, post-abandonment pressure, built up due to cavern convergence and temperature increase? How to model these processes?
        - The stress field around the cavern? Can there be local sub-lithostatic stress states and where do they occur? What is the effect of potential weak zones such as salt-cement, salt-casing and cement-casing interfaces and salt formation heterogeneity (anhydrite layers and/or other lithologies)?

    b. How (fast) is the pressure built up in time as a function of cavern geometry, volume, stresses, temperature and salt mechanical processes? Are there critical stresses at the salt-brine interface leading to (roof) instability?
    c. A number of caverns in the North of the Netherlands are 600 to 700 meter high. This can create a significant brine overpressure at the top of the cavern and brine "under-pressure" at the bottom. Do these pressure differences influence the leakage mechanism?

3. Salt dome-scale:
    a. How does the stress field (direction and magnitude) in salt dome change from the centre of the dome to the edge and the surrounding sedimentary formations? In the salt dome, how far from the salt dome

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[6] K.H. Lux et al., (2006) Long-term behaviour of sealed brine-filled cavities in rock salt mass. – A new approach for physical modelling and numerical simulation. SMRI Fall 2006 Conference, 1-4 October, Rapid City, South Dakota, USA.

edge could sub-lithostatic stresses be expected? How does geological heterogeneity (salt dome edge and internal structure such as internal shear zones, Zechstein 1,2,3 and anhydrite) affect the internal state of stress in the salt dome. How does the presence of other caverns in the salt dome (with various operational and abandonment pressure regimes) affect the state of stress in the salt dome? How can this be modelled?

b. What are required operating and abandonment conditions to avoid undesired interference between caverns in a salt dome and between caverns and (nearby) salt dome boundary? What is the influence of low pressures on permeation/fracking initiation and velocities? How to assess risks of mining activities close to caverns, such as large scale water injection or extraction? What is the risk of collapse and what are the cavity migration speeds when these conditions are not met?

Deliverables expected

A report with:

1. Literature review of already available knowledge on the mechanisms of brine leakage (permeation/hydraulic fracturing/other) when the brine pressure reaches or exceeds the local minimum stress. Include case studies if available. The questions above under “Research Questions” should be answered as good as possible. With the micro-scale processes being the most important.
2. Criteria for determining when which leakage mechanism (permeation/hydraulic fracturing/other) is dominant and in which cases it cannot be determined. Criteria should be a function of salt properties (mechanical, chemical, grain size, heterogeneities), brine pressure, (local minimum) stress and temperature.
3. Report on state of the art and scope for improvement of the salt mining effect modelling approaches and tools for predicting the short (operational) and long term (post abandonment) behaviour of typical caverns in The Netherlands under different cavern pressure strategies, including permeation, fracturing and brine leakage and salt collapse effects.

A catalogue of required measures by operators and owners of abandoned cavers for different cavern typologies to prohibit any uncontrolled cavern leakage and thereby reduce hydrogeological risks in aquifers and geotechnical risks at the surface.

Timeline

Maximum 200 characters (phases, milestones, end of project dates)

2 years

1. Literature inventory
2. Report on Salt mining effect modelling taking into account permeation and fracking mechanisms (criteria)
3. Best practices/and measure for controlling caverns

Expected use

To be able to take into account interference in licencing and inspection by SodM.

To be used to further elaborate abandonment procedures and guidelines for cavern owners or responsible authoriies.