KEM Research review, evaluation and interpretation (max. 4 pages + annex)

TITLE: *Over-pressured caverns and leakage mechanisms*

KEM Quality review

The project was commissioned in 2018 to a team led by Dr Benoit Brouard (brouard consulting, France), consisting of Prof. Pierre Bérest (Ecole Polytechnique, France), Prof. Boris Kaus, Dr Tobias Baumann, Dr Anton Popov (Smart Tectonics GmbH) and Prof. Janos Urai, Dr Joyce Schmatz, Dr Job Klaver (Microstructures and pores GmbH). The final report was submitted in November 2019.

The expected deliverables were as follows:

A. A report containing:

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. 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.

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

The problem was approached at three different scales: the scale of the grains in the salt formation, the cavern scale, and the salt dome scale. A detailed individual report was prepared for each of the three components of the research, along with a brief report that summarized the findings and conclusions.

The research team that was assembled consisted of some of the leading experts in the mechanical behavior of rock salt, and in the performance of underground salt caverns. The work carried out in this project was of a high technical quality. The amount of work performed was commensurate with, and perhaps exceeded, the budget and timeframe. The reports were very well written and structured. It can be concluded that the work performed has fulfilled the requirements of the project.

KEM Evaluation of the results

The problem was approached at three different scales, in three separate work packages: at the grain scale, at the cavern scale, and at the salt dome scale.

The first study was a grain-scale study of the relationships and interplay between grain size, grain boundary processes, and permeability. The main relevant conclusion seems to be that it is impermissible to extrapolate creep rates that were measured at moderate deviatoric stresses, down to the lower deviatoric stresses that may be expected in the vicinity of a cavern. It was then asserted in the Final Conclusions that "It is widely recognized now that extrapolation of experimentally-derived constitutive equations to small stresses can only be done on a basis of microphysics." This, and similar, statements were repeated frequently in various places, but no explanation was offered as to how this could be achieved. The researchers finally suggested that further research be done to "understand microphysical processes of permeation to allow upscaling to constitutive models". However, as a general rule in rock physics, microphysical investigations can be useful in helping to frame conceptual models of constitutive behavior, but have rarely led to quantitative constitutive equations.

The second study was a cavern-scale study that examined the stresses that exist around the salt cavern, the pressure increase in the brine due to heat transfer from the salt to the brine, and possible leakage of brine due to either pervasive permeation, or "hydraulic fracturing". Numerous case studies from around the world were reviewed. It was concluded that in "shallow caverns" (<1000 m deep), a safe steady state will be reached in which the decrease in cavern volume due to creep closure is balanced by the outflow of brine due to permeation through the salt. But in deeper caverns, it cannot be ruled out that the brine pressure created by the cavern closure might become large enough to create a hydraulic fracture. Nevertheless, no examples were given of cases in which it can be inferred with any certainty that a hydraulic-fracture-like leakage event occurred, and led to any safety or environmental problems.

The third study, which involved detailed and sophisticated finite element calculations, investigated the *in situ* stress state that would be expected to have evolved over geological time, in various salt structures (flat-lying salt, salt pillows, and a salt wall) in the Netherlands. It was concluded that, depending on the constitutive law that is assumed, varying small degrees of anisotropy in the principal stresses could be expected, generally less than 1 MPa. But the deviatoric stresses caused by the creation of the salt cavern would generally overshadow this small amount of initial anisotropy. For example, consider the classic equation for the initiation of a hydraulic fracture, as given in section 4.2.1.2 of the cavern-scale report: $P_f = 3\sigma_h - \sigma_H$ (neglecting the small tensile strength, *T*). It is clear that small fractional differences between σ_h and σ_H are of second-order importance, compared to the term $2\sigma_h$ that would still be present if $\sigma_h = \sigma_H$.

In a final submitted document, "Possible Practical Measures", some suggestions were given for salt cavern mining and abandonment. The first suggestion was that pressure observation tests (POT) should always be performed before the start of mining, to obtain an estimate of the *in situ* permeability of the salt. Such tests are already required in France. This suggestion seems very reasonable and prudent.

The second suggestion was to perform creep tests under low deviatoric stresses in an underground mine, where the results will not be contaminated by temperature fluctuations that are unavoidable in the lab. The argument for the need for these tests is heavily based on Figure 2 of the Micro-scale Processes report, which compares measurements made on one salt at "high" deviatoric stress, with measurements made on a different salt at low stresses. Even if this comparison is accepted, it would seem that a smooth curve could be fitted through these two data sets.

The third suggestion was that, before a cavern is plugged and abandoned, a pressure buildup test be performed to assess the pressures that might be expected to be reached after plugging. This suggestion is also sensible.

The fourth suggestion was that numerical computations of the long-term cavern evolution should be performed, using actual cavern shapes, more accurate creep laws, *etc*. Although such calculations would be useful, it is not clear why usable results could not be obtained by simpler analytical models, assuming cylindrical geometries, for example.

The quality of the research in the project is evaluated as excellent. The conclusions and suggestions are right and useful.

KEM interpretation of the outcome

The project has resulted in better insight into the potential causes and their role in leakage at microscale, cavern and scales) of salt caverns in The Netherlands. It was concluded that for closed caverns deeper than 1000 meters leakage risks do exist. However, determining the contribution of the various leakage mechanisms is complex, but can be understood better by executing tests and applying modelling techniques used in the project.

The KEM-17 investigation led to two sensible practical suggestions: that pressure observation tests should be performed before the start of mining, to obtain an estimate of the *in situ* permeability of the salt, and that a "pressure build-up" test be performed before abandonment, to help assess the pressures that might be expected to be reached after the cavern is plugged and sealed. It was also correctly emphasised that accurate constitutive (creep) laws are needed in order to predict cavern closure rates and brine pressure build-ups.

As was mentioned in the final reports, although not strongly emphasised, potential problems with catastrophic leakage events can be avoided by either delaying the final plugging of the cavern until closure has occurred (if the closure rate is high enough for this to be feasible), or periodically venting brine from the cavern after it has been abandoned, to avoid a pressure build-up sufficient to cause fracturing or other types of localised leakage.

As cavern leakage hazards after cavern closure cannot be excluded for, especially, deeper salt caverns in The Netherlands for longer periods, monitoring of fluid and solid mechanical parameters in and around caverns is recommended.

Closure text for the website

The KEM-17 research project "Over-pressured caverns and leakage mechanisms" was commissioned in 2018 to a team led by Dr Benoit Brouard (brouard consulting, France), consisting of Prof. Pierre Bérest (Ecole Polytechnique, France), Prof. Boris Kaus, Dr Tobias Baumann, Dr Anton Popov (Smart Tectonics GmbH) and Prof. Janos Urai, Dr Joyce Schmatz, Dr Job Klaver (Microstructures and pores GmbH). The final report was submitted in November 2019.

The central research question was: What processes (permeation, preferential flow, flow in induced fractures) contribute most likely lead to leakage of brine abandoned cavers and what actions can be taken to minimise the risk of leakage of brine from an operational or abandoned underground salt mine cavern, into the biosphere?

The project has resulted in better insight into the potential causes and their role in leakage at microscale, cavern and scales) of salt caverns in The Netherlands. It was concluded that for closed caverns deeper than 1000 meters leakage risks may exist. However, determining the contribution of the various leakage mechanisms is complex, but can be understood better by executing simple tests and applying modelling techniques used in the project. Some suggestions were made for simple tests that could be performed, at the start and at the end of salt mining, that would provide useful data on the performance of the cavern and the cavern-dome scale research showed valuable modelling capabilities to be used in future.

For the record, the detailed literature review of salt caverns throughout the world was performed, which uncovered few if any cavern leakage events that had caused any threat to people or the environment.

The potential of catastrophic leakage events can be avoided by either (a) delaying the final plugging of the cavern until closure has occurred (in those cases in which the closure rate is high enough for this to be feasible), or periodically venting brine from the cavern after it has been abandoned, to avoid a pressure build-up that might be large enough to cause fracturing or other types of localised leakage.