

POSSIBLE PRACTICAL MEASURES (KEM-17)

It may be valuable to recommend the following practical measures:

[1] **Perform a pressure observation test (POT)** on any new drilled well into a salt formation before starting mining (Figure 1). This test consists in:

- Filling the wellbore with saturated brine.
- Lowering an inner string to get an annular space.
- Pumping a blanket fluid in the annular space such that the interface between the blanket and the brine is set below the latest cemented casing shoe (LCCS).
- Pressurizing the wellbore to the maximum pressure allowed at LCCS during operations.
- Observing wellhead-pressures decay for a few days/weeks.

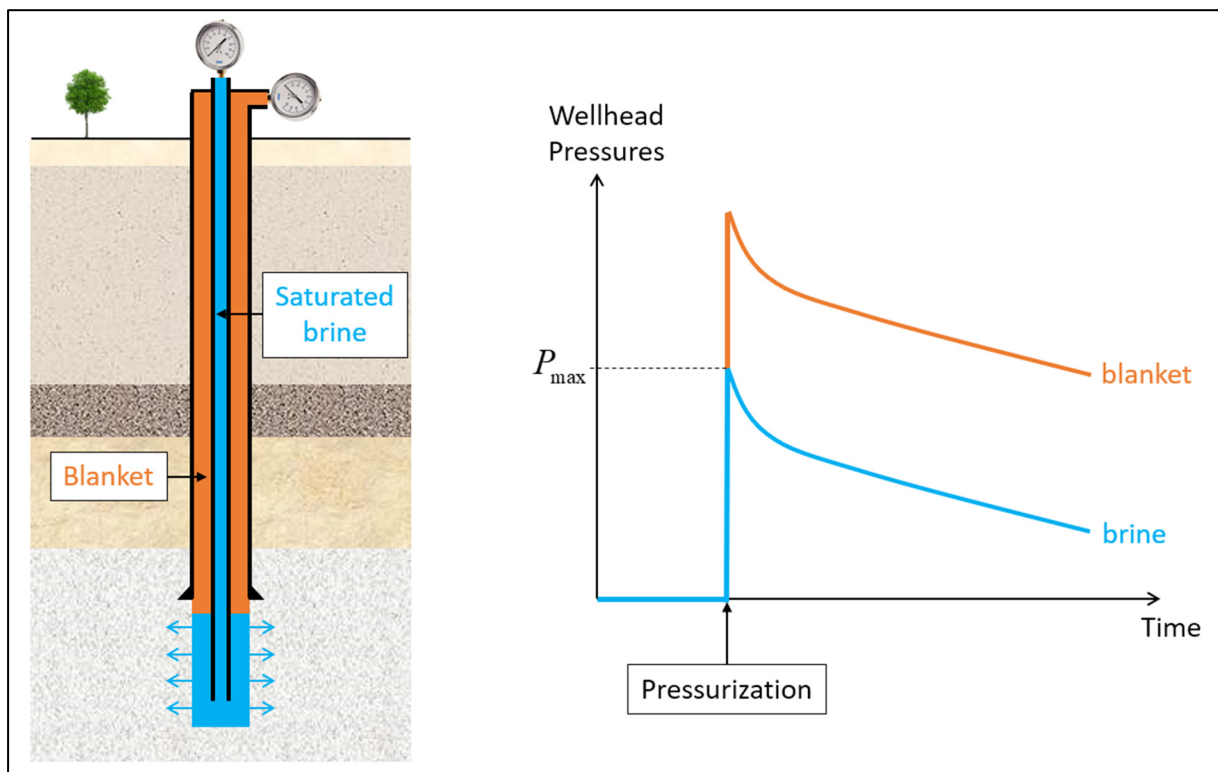


Figure 1 – Pressure observation test to determine average permeability.

There are numerous advantages for this test:

- ✓ Easy and not very expensive for companies. The completion designed for mining/leaching can be used. The duration of the test is only a few days or weeks depending on the average permeability of the salt formation.
- ✓ The integrity of the well, casing collars and casing shoe, is checked through the pressure differential measured at wellhead. If wellhead pressures are not perfectly parallel, a leak can be suspected.
- ✓ In such a configuration, brine permeation is the main phenomenon leading to a pressure decrease, other phenomena like creep closure, thermal equilibrium or salt crystallization are transient and/or negligible. When cavern is created, there is not such an opportunity to measure permeability separately anymore. Average salt-formation permeability, at the scale of the whole salt formation, can then be back-calculated. The obtained value of the permeability will be much more representative of salt actual permeability than a permeability measured at the lab, especially because clean core samples are preferentially tested at the lab and therefore any much permeable interbeds may be disregarded.
- ✓ The salt-formation permeability measured with this in situ test can be used for numerical simulations of cavern abandonment at the same facility.
- ✓ This type of test is mandatory in France (Brouard et al., 2001).

There are also some possibilities to even improve this test:

- It can be advantageous to perform several pressure steps up to the maximum pressure in order to check the applicability of Darcy's law; i.e., brine permeation into the salt formation is assumed to be a linear function of wellbore pressure. A pressure threshold might be highlighted (see cavern-scale Report); any significant increase -or not- of apparent permeability when wellbore pressure is close to the maximum allowable would be interesting in the perspective of cavern abandonment.
- There is a new well-testing method, called WTLog (Jacques et al., 2019; Manivannan et al., 2019) that allow to derive a permeability log along the whole height of the openhole. A WTLog consists in displacing along the openhole an interface between two liquids whose viscosities are significantly contrasted while keeping some constant brine overpressure at the wellhead. The WTLog was already tested in the configuration of a salt formation at Gellenoncourt and at Marboz sites in France (Manivannan et al., 2018). The configuration is the same as shown in Figure 1 where blanket liquid is a viscous liquid, as for instance a rapeseed oil which is environment friendly and much viscous than brine (70 cp vs 1 cP). This technique would allow to derive a injectivity/permeability log exhibiting possible thin very-permeable layers that would play a significant role in the perspective of cavern abandonment. The vertical resolution of the test depends on its duration, a longer test would provided a better accuracy.

[2] **Perform low-deviatoric stress tests.**

An experimental program (Bérest et al., 2018), supported by the SMRI, proved that, in the 0.2 - 1 MPa deviatoric stress range, creep rate of natural salt sample was much faster – by several orders of magnitude – that the creep rate extrapolated from what is currently observed during standard creep tests performed in the 5 – 20 MPa range at the laboratory (Figure 2). Theoretical considerations suggested that pressure-solution, a mechanism in which grain size and brine content play an eminent role, is especially active in the small stress domain.

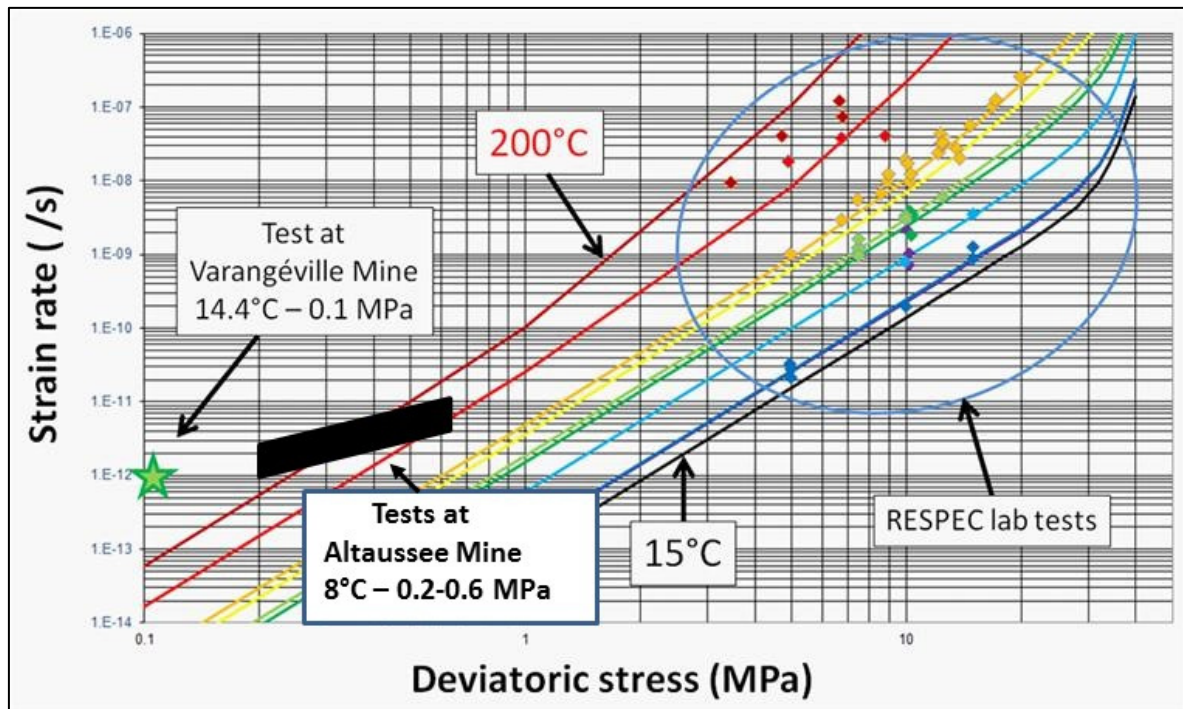


Figure 2 - Steady-state strain rate, as a function of deviatoric stress and temperature, for Avery Island salt (After DeVries, 1988); results of the 2014-2016 SMRI tests in the Altaussee Mine were added.

Such creep tests with deviatoric stresses lower than 5 MPa cannot be performed at the lab because temperature variations are too large; this is the reason why special testing devices were designed and installed at the Altaussee salt mine in Austria where temperature is extremely stable (Photo 1 and Photo 2). Prognosis from micro-scale analysis (Urai and Spiers, 2007) were confirmed by these tests performed on several type of salt.

When cavern pressure is close to geostatic pressure after cavern P&A, low-deviatoric stresses play an important role, therefore, low-deviatoric stress tests are very valuable to derive relevant creep parameters than can be used in the numerical models.

With kind help from C. Spiers, who is a partner in the SMRI program, such a test began a few weeks ago on a Zechstein salt sample cored in a drill hole in the Netherlands.

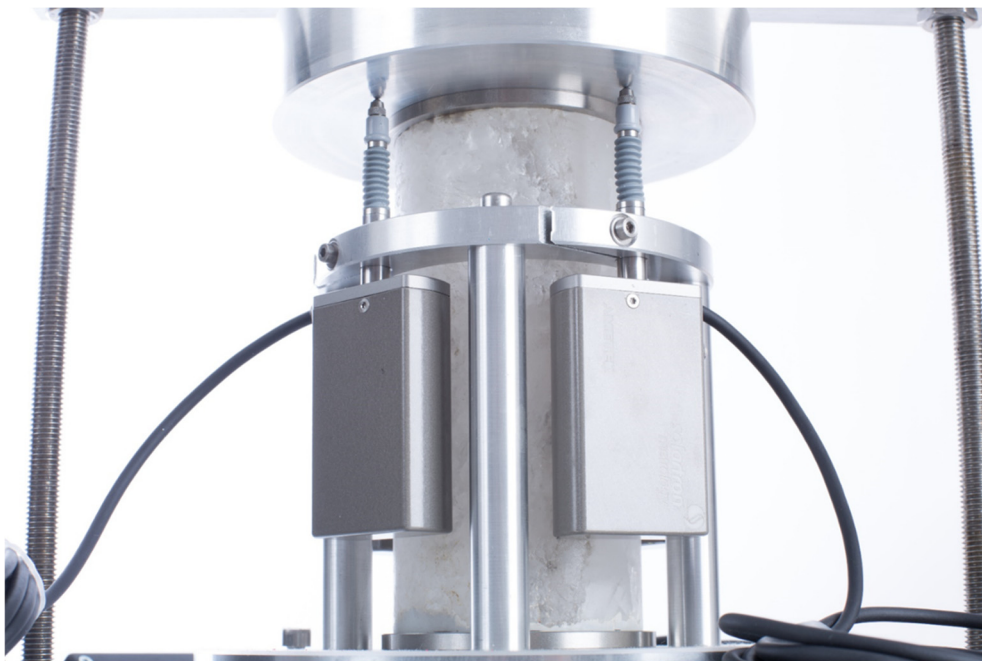


Photo 1 – Testing device.



Photo 2 – Testing devices at the Altaussee salt mine.

[3] Perform a cavern-abandonment test before P&A.

Before plugging and abandoning any cavern it should be mandatory to perform a cavern-abandonment test to determine what is the relevant scenario for the long-term pressure evolution. There are two kinds of possible scenarios:

- If cavern is shallow, say less than 1000-m deep, or if actual permeability at the scale of the salt formation is rather large, say larger than 10^{-20} m^2 , it might be possible to get an equilibrium pressure on the long term such that the pressure at the cavern roof is less than geostatic pressure alleviating any risk of hydrofracturation.
- If no pressure equilibrium is observed at the maximum allowed pressure, then it can be expected that tensile stresses would develop at the cavern roof. In that case, numerical modeling involving low-deviatoric stresses and localized increase of salt permeability must be considered.

If cavern is not at thermal equilibrium during the test, cavern-temperature rate must be determined using a downhole sensor and this effect must be withdrawn from the as-observed pressure evolution.

Such abandonment tests were successfully performed on several shallow caverns (See cavern-scale report). Furthermore, these tests allow to quantify any leak through the wellbore using a blanket/brine set below the LCCS.

[4] **Numerical computations of the long-term cavern evolution.**

After the cavern-abandonment test, it is relevant to perform numerical computations that, on one hand confirm the results of the test and, in the other hand, predict the long-term behaviour of the cavern.

These numerical computations should take into account:

- The actual shape of the cavern according to the latest sonar survey.
- The complete pressure/temperature history of the cavern since its creation in order to estimate, as good as possible, the redistribution of the stresses over a very long period of time.
- A creep law which is well adapted for the long term, and a set of parameters for this law which fits with the loss of volume observed during the life span of the cavern.
- The creep law should embed a mechanism for low-deviatoric stresses with parameters that fit the strain rates observed during the low-deviatoric stress tests (see item [2]).
- A law for the coupling between intrinsic permeability and effective stress. Several simple laws already exist. A threshold may be considered for this law if the Pressure Observation Test (see item [1]) demonstrated that there is no injectivity/permeability below a certain pressure threshold.

The numerical computations should predict the cavern behaviour for a period of one or two century; a prediction over a longer period is probably unrealistic. Attention must be paid on the onset of tensile effective stresses at the cavern roof. Numerical computations should be able to determine the waiting time before plugging and abandoning safely the cavern -whenever possible.

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