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SOME ASPECTS OF THE TRANSIENT BEHAVIOUR OF SALT CAVERNS

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1 INTRODUCTION

The transient mechanical behavior of *salt samples* has been discussed by several authors (e.g., Lux and Heuserman, 1983; Munson and Dawson, 1984; Aubertin, 1996; Cristescu and Hunsche, 1998). When submitted to a rapid applied load increase, samples experience a several week- (or month-) long period during which the strain rate gradually decreases to ultimately reach the steady-state rate. Conversely, when submitted to a rapid load decrease (stress drop), samples sometimes experience "reverse creep", or increase in sample height, over a couple of weeks or more.

Less attention has been paid to the transient behavior of *salt caverns* — i.e., the change in cavern volume or (closed) cavern pressure following a rapid change in the cavern fluid pressure. *In situ* "transient" tests are difficult to perform, as measuring small changes in cavern volume is not an easy task (Bérest et al., 2006), and a small number of such tests have been described in the literature (Clerc-Renaud and Dubois, 1980; Hugout, 1988; Denzau and Rudolph, 1997). In this paper, discussion centers on the transient effects of a cavern pressure increase, as they are important in such contexts as mechanical integrity testing, hydro-fracturing and cavern abandonment.

2 THE MECHANICAL BEHAVIOR OF SALT-ROCK SAMPLES

Many laboratory studies have been devoted to the mechanical behavior of salt. Most authors agree on several main features: the overall strain rate, ε, of a sample submitted after time $t = 0$ to a constant load σ is the sum of elastic, steady-state and transient parts (Figure 1).

The elastic part is small; it is described by a linear relation between $\dot{\varepsilon}$ and $\dot{\sigma}$. The steady-state part is characterized by a constant strain rate reached after some days or weeks when constant mechanical loading is applied. The transient part describes the rock behavior before steady state is reached. Any change in applied loading triggers transient creep.

Rock failure is reached when

(a) a sample is submitted to a (small) tensile stress; or

(b) a sample is submitted to a (relatively high) compressive state of stress.

It generally is accepted that short-term failure criterion can be described by a relation such as

$$\sqrt{J_2} - \alpha I_1 = 0$$

where J_2 is the second invariant of the deviatoric stress tensor, and I_1 is the mean stress. However, failure is reached more easily when the two largest compressive main stresses are larger than the mean stress, a situation often met at a cavern wall. Before short-term failure is reached, the sample experiences dilatancy (volume increase). Several authors suggest that the onset of dilatancy characterizes the long-term strength of the rock.

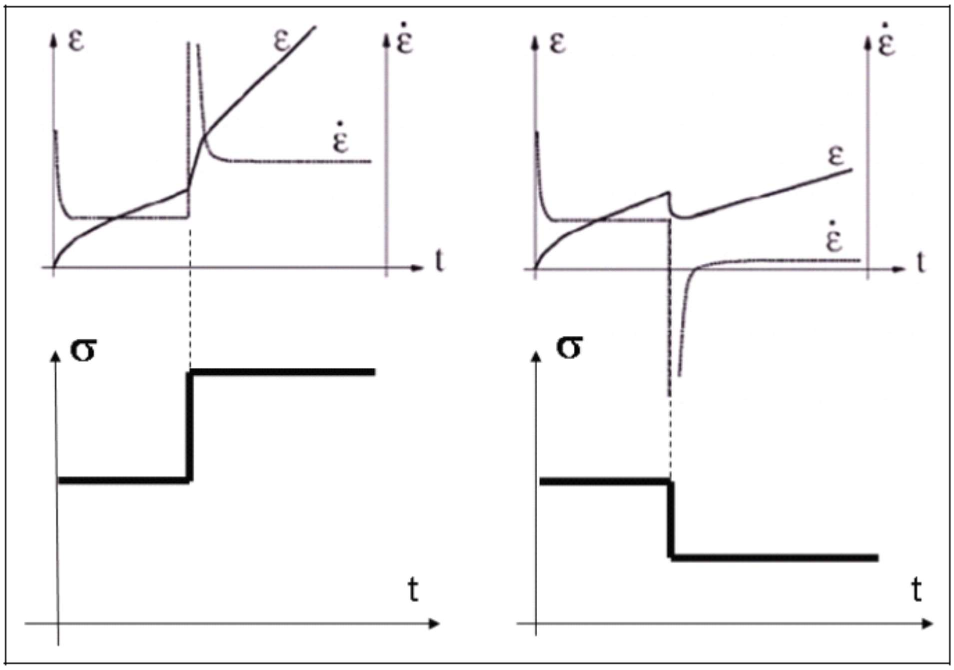

Figure 1 Strain and strain rate as functions of time during a creep test: Cases of load increase (left) and load decrease (right) are considered. A stress drop (right) may trigger reverse creep. (The +sample height increases for a time, even if the stress applied to the sample is compressive.)

3 MECHANICAL BEHAVIOR OF SALT CAVERNS

The general outline for the mechanical behavior of caverns is similar to that for a rock sample when, instead of sample strain-rate $\dot{\varepsilon}$, one considers the cavern volume loss (or increase) rate, $\dot{V}/V$ and, instead of the mechanical load, σ applied to a rock sample, one considers the difference between the overburden (or geostatic) pressure and the cavern pressure, or $P_\infty - P_i$. Note that, in a cavern, the mechanical loading is more severe when cavern pressure is *lower*.

Cavern pressure is said to be "halmostatic" when the central string is filled with saturated brine and zero pressure is applied on that central string at the wellhead. In a brine well, or in a liquid or liquefied storage cavern, cavern pressure is most often close to halmostatic. In a natural-gas storage cavern, cavern pressure is lower than halmostatic (and large volume loss rates can be expected) when the gas stock is smaller.

However, a few differences between the behavior of a sample and the behavior of a cavern must be addressed.

- The elastic behavior of a cavern immediately following any change in cavern pressure is influenced both by the mechanical properties of the rock formation *and* by the shape of the cavern.

- Steady-state behavior ($\dot{V}/V$ is constant.) is reached when the cavern pressure is kept constant for years; steady-state behavior (as is elastic behavior) is influenced both by the mechanical properties of the rock formation *and* by shape of the cavern.

- The transient behavior of a cavern is more complex than the transient behavior of a sample; in general, its effects last much longer than in a rock sample. In fact, one must distinguish between the "rheological" transient behavior (as observed during a laboratory test) and the "geometrical" transient behavior of a cavern — when cavern pressure changes, the non-uniform stress field around the cavern slowly changes from its initial distribution to its final steady-state distribution, an effect that does not exist when an uniaxial test is performed on a rock sample. These two transient effects combine in a cavern: the geometrical transient behavior is responsible for the long duration of the transient phase in a cavern. This is illustrated by Figure 2. Computation begins when the cavern is leached out. In the 800-m deep cavern presented in Figure 2, during cavern creation, pressure decreases from geostatic (the pressure prevailing before the cavern is created) to halmostatic (the pressure resulting from the weight of a brine column filling the well). Later, the cavern pressure is kept constant and equal to halmostatic (a situation approximately met in a liquid-hydrocarbon storage or brine-production cavern). Two constitutive laws are considered: (a) the Norton Hoff law, in which only steady-state constitutive behavior is taken into account; and (b) the Munson-Dawson (modified) law, in which, in addition to steady-state rheological behavior, transient rheological behavior is taken into account. Parameter values are the same as those defined in Section 4.3. The volume-loss-rate versus time curve is shown on Figure 2: even when no rheological behavior is taken into account (Norton-Hoff law), a transient period lasting several decades can be observed before steady-state cavern behavior is reached. (In fact, it is not reached before 100 years; more generally, the transient period is longer when the *n*-exponent in the Norton-Hoff law is larger). This is in sharp contrast to the behavior of a rock sample submitted to a constant mechanical load. Taking into account the transient rheological behavior (Munson-Dawson law) slightly accelerates the cavern transient behavior, especially during the 5 first years after cavern creation; however, the geometrical transient behavior is by far the most significant effect.

- Transient "reverse" creep (i.e., cavern volume *increase*) is observed after a rapid pressure buildup (as performed, for example, at the beginning of an MIT test). It is discussed in more details in Paragraph 4.

- Cavern failure is a complex phenomenon that depends on cavern shape, insoluble distribution in the rock mass, cavern size etc.[Over-brining often results in very large caverns with roofs that cannot bear the weight of the overburden; for instance Buffet (1998) describes the case of an immerged pump being lowered in a shallow cavern to provoke deliberate collapse of a cavern whose long-term stability could not be guaranteed. A somewhat similar case history was described by Jeanneau, (2005)]. Cavern failure is more likely to occur when cavern pressure is much lower than overburden pressure, a situation sometimes encountered in deep natural-gas storage caverns. However, in addition to low pressure, a rapid pressure decrease rate is considered to be influential. In general, no tensile stress appears in a salt cavern, except when cavern fluid pressure is quite low and when the cavern roof is flat or the cavern shape is irregular (Blocks may fall). When a cavern is submitted to a fluid pressure higher than geostatic (hydro-fracturing), fluid pressure is higher than the minimal stress at cavern wall, and fracturing (or drastic increase in salt permeability at cavern wall) may take place.

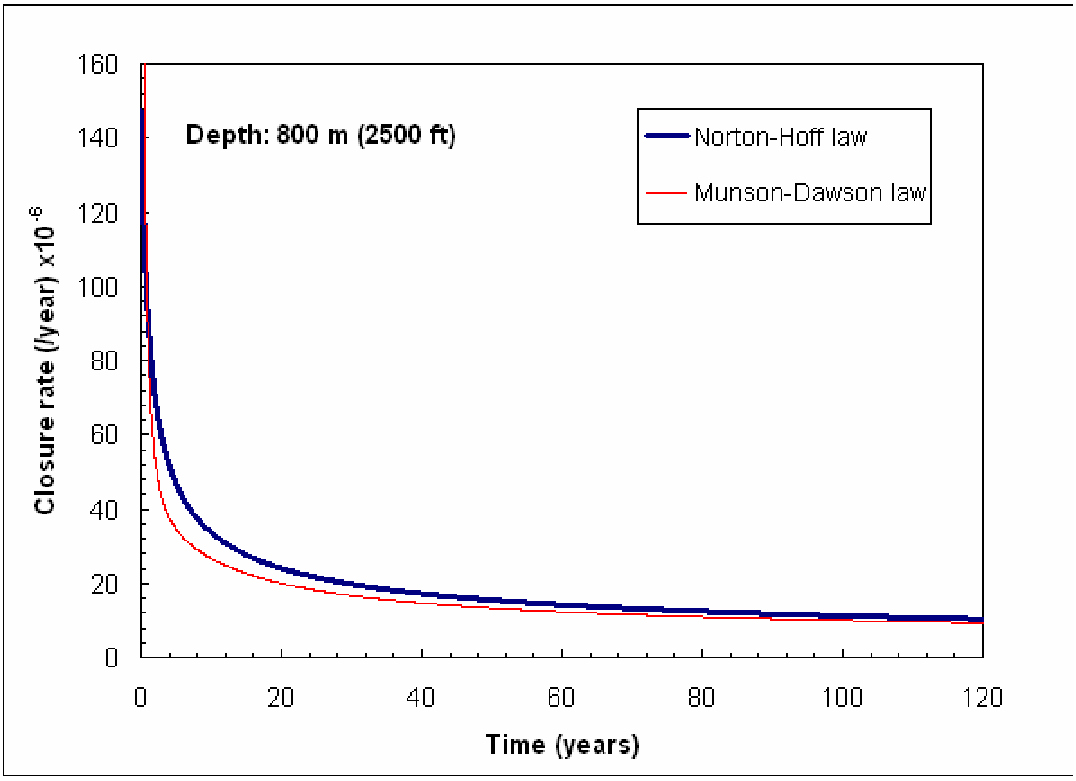

Figure 2. Closure rate as a function of time in a brine production cavern

In this paper, we focus on the behavior of a cavern following an increase in cavern pressure. Two cases will be considered:

(1) the transient behavior of a cavern in the days following a rapid pressure increase (reverse creep), a situation typically met during a Mechanical Integrity Test.

(2) the behavior of a cavern following a pressure increase large enough to generate fracturing (or a drastic increase in rock permeability), a situation met during a hydro-fracturing test or possibly during a cavern abandonment test.

4 CAVERN TRANSIENT EXPANSION (DOES "REVERSE" CAVERN CREEP EXIST?)

4.1 *In Situ* Evidence

Two "hydrocarbon-outflow" tests and a cyclic test tend to prove that cavern volume increases after cavern pressure was increased rapidly.

An example of such a test was described by Hugout (1988) for a cavern that was part of the Etrez site (Ain, France), operated by Gaz de France. It was 950 m deep with a volume of 8000 m^3. Before the test, the central string was filled with saturated brine and the annular space was filled with a light hydrocarbon, A brine flow from the central string was observed. When hydrocarbon was vented, the pressure drop was 3 MPa and the air/brine interface in the central string dropped by several hundred of meters. The test measured the hydrocarbon outflow rate. For several days, the hydrocarbon outflow rate was quite large due to the roles played by transient creep and additional dissolution (Figure 3). After a couple of weeks, the hydrocarbon outflow rate became more or less constant (and much larger than the outflow rate should be in a brine outflow test —clear evidence of the non-linear effect of cavity pressure on cavern closure rate.) When halmostatic pressure was restored on day 254 (The hydrocarbon-filled annulus was closed during this last phase.), brine outflow from the central tubing was negative, strongly suggesting cavern volume transient increase, or “reverse” creep. A complete discussion of this test can be found in Van Sambeek et al. (2005).

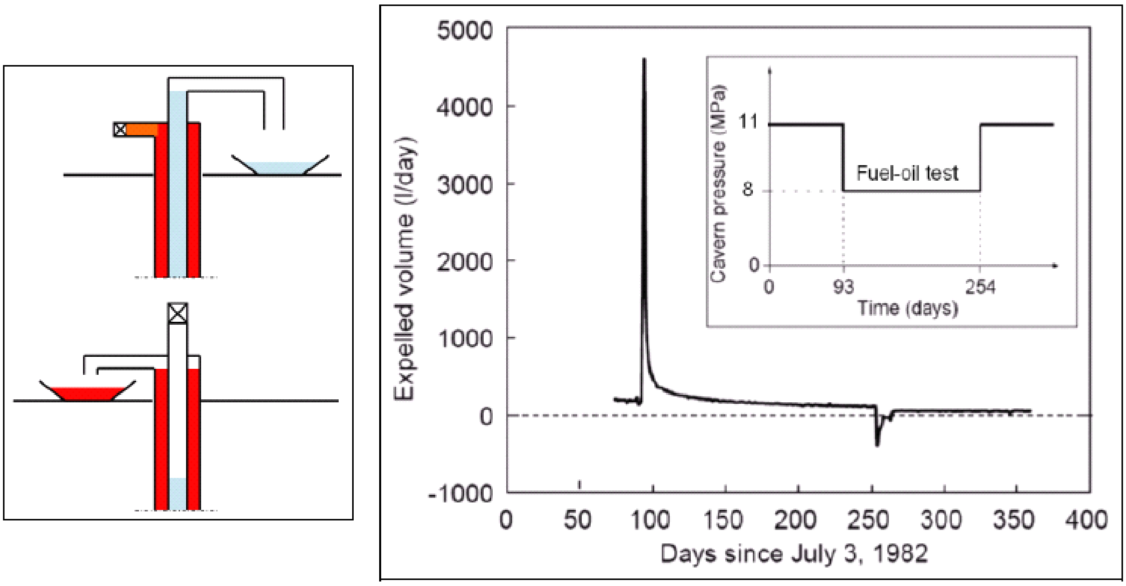

Figure 3 **Hydrocarbon Outflow Test: From day 93 to day 254, the cavern pressure was lowered below halmostatic, resulting in large transient hydrocarbon flow, followed by a more-or-less steady-state hydrocarbon flow. The hydrocarbon flow rate is larger than the brine flow rate before the pressure change on day 93 or the brine flow rate after the initial pressure had been restored on day 254 (Hugout, 1988).**

A similar test has been described by Clerc-Renaud and Dubois (1980) for a cavern belonging to the Manosque site (South Eastern France), operated by Geostock. This cavern was 569- to 864-m deep with a volume of 235,000 m^3. The cavern was filled partly with oil (oil volume of 185,000 m^3). The wellhead oil pressure was 550 psi before the test; the wellhead brine pressure was zero. The wellhead oil pressure was released (PQ on Figure 4) by opening a valve that isolated the annular space from the central string. Oil outflow was measured for 2000 hours (QR on Figure 4), after which brine was injected in the central tube to increase the wellhead oil pressure by 550 psi (RS on Figure 4). Brine outflow then was measured for 2000 hours (ST on Figure 4). Fast convergence rates following a pressure decrease (phase QR) and “reverse” convergence following a pressure increase (phase ST) were observed. This test is interpreted in more detail in Section 3.3.

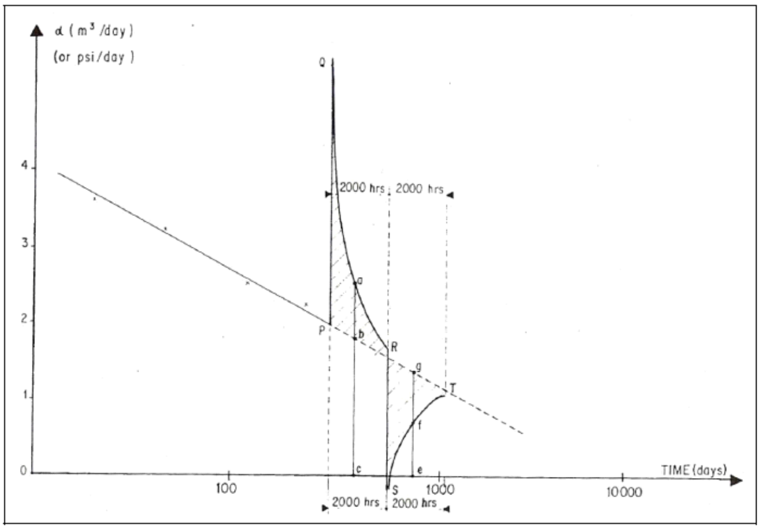

Figure 4 Oil Outflow Test (Clerc-Renaud and Dubois, 1980).

Denzau and Rudolph (1997) describe an imaginative method for assessing the effect of pressure cycles on gas-cavern convergence. The test was performed on a 380,000-m^3 cavern after 6% of the brine volume had been displaced by gas. The volume-depth function in the cavern roof (where the brine/gas interface was to be located) was established precisely via sonar surveys conducted before the test. During the test, the evolution of the interface location was measured through γ-γ logs and through a pressure-temperature gauge lowered down the well. Four pressure cycles were applied during the 180-day test period.

Pressure changes (between minimum and maximum pressures) were larger than 10 MPa. Measurement of the interface displacements allows cavern convergence to be back-calculated as a function of time. When the gas pressure was low, the cavern-volume loss rate was faster, resulting in a faster gas/brine interface rise. It was observed that the convergence rate was most severe during the first cycle; conversely, pressure build-up during each injection phase led to a slight increase in cavern volume — i.e., *in situ* "reverse" creep.

4.2 Difficulties in Interpreting *In Situ* Tests

During the three *in situ* tests described above, "reverse" creep apparently was observed. However, interpreting the results of any *in situ* test is difficult, because, together with transient (reverse) creep, the rapid pressure increase at the beginning of a test triggers several other transient phenomena (described below). According to the Le Chatelier (or Braun) principle, these test-triggered phenomena tend to restore the pre-existing (smaller) pressure in a closed cavern and may lead to an overestimation of the effects of (reverse) creep.

- **Additional Dissolution** — Any change in cavern pressure leads to a change in brine saturation. Following a rapid increase in pressure (p) in a closed cavern, salt is dissolved, more room is available for cavern brine, and cavern pressure drops accordingly. When the additional dissolution process is completed, the final pressure drop in this closed cavern is 0.043 p. Chemical equilibrium is almost reached after 10 days; the pressure decays faster during the first 2-3 days.

- **Transient Brine Permeation** — Any tentative quantification of transient brine permeation through the cavern walls is open to discussion, because, in general, the hydraulic properties of rock salt (permeability, porosity, storativity, Biot's coefficient) are not well known and may vary to a large extent from one site to the other. This effect is significant only for a small cavern excavated from a formation with relatively large permeability (say, $K = 10^{-19}$ m^2).

- **Adiabatic Pressure Build-Up** — A rapid increase in pressure results in a (small) instantaneous increase in brine (or fluid) temperature. When a cavern is filled with brine, the temperature increase is $\Delta T(°C) = 0.029p$ (in MPa). This is followed by a brine cooling process that is faster in a smaller cavern. In a closed cavern, the cooling process results in pressure decrease. In an 8,000-m^3 cavern, the pressure drop resulting from brine cooling one day after cavern pressure was increased by p is 0.002 p.

These three phenomena are described in more detail in Van Sambeek et al. (2005). They must be taken into account when interpreting any *in situ* test. Most often, however, computations prove that cavern creep is the pre-eminent transient phenomenon, except perhaps for 2-3 days immediately following the change in cavern pressure.

4.3 The Manosque Test

This test was described in Section 4.1 (Figure 4). Three different constitutive laws were used: (1) the Munson-Dawson modified (M-D) law; (2) the Lemaitre-Menzel-Schreiner (L-M-S) law, which does not include "reverse" creep [Munson et al.(1996) proposed an advanced version of his constitutive model that does take into account reverse creep; this version is not considered here.]; and (3) the BBK law, which is a slightly modified version of the M-D law that takes "reverse" creep into account. The constitutive laws are described below.

- **Norton-Hoff Law** — This law describes the steady-state elasto-viscoplastic behavior of salt:

$$\dot{\varepsilon}^{ij} = \dot{\varepsilon}_e^{ij} + \dot{\varepsilon}_{ss}^{ij} \qquad \dot{\varepsilon}_{ss}^{ij} = A\,exp\left(-\frac{Q}{RT}\right)\frac{1}{n+1}\frac{\partial}{\partial\sigma_{ij}}\left[\left(\sqrt{3J_2}\right)^{n+1}\right] \quad \ldots \dot{\varepsilon}_e^{ij} = \frac{1+\nu}{E}\dot{\sigma}^{ij} - \frac{\nu}{E}\dot{\sigma}^{kk}\delta^{ij}$$

- **Munson-Dawson Law** — The (modified) Munson-Dawson law is a generalization of the Norton-Hoff law that takes into account the transient behavior of rock salt. It can be described as follows:

$$\dot{\varepsilon}^{ij} = \dot{\varepsilon}_e^{ij} + F\dot{\varepsilon}_{ss}^{ij} \qquad \begin{array}{ll} F = e^{\Delta(1-\varsigma/\varepsilon_t^*)^2} & \text{when } \varsigma \le \varepsilon_t^* \\ F = e^{-\delta(1-\varsigma/\varepsilon_t^*)^2} & \text{when } \varsigma \ge \varepsilon_t^* \end{array}$$

$$\dot{\varsigma} = (F-1)\dot{\varepsilon}_{ss}, \quad \dot{\varepsilon}_{ss} = A\,exp\left(-\frac{Q}{RT}\right)\left(\sqrt{3J_2}\right)^n$$

$$\varepsilon_t^* = K_0 e^{cT}\sigma^m \text{ and } \Delta = \alpha_w + \beta_w Log_{10}(\sigma/\mu) \quad , \delta=\delta_0$$

where $\mu = E / 2(1+\nu)$, and $\sigma = \sqrt{3J_2}$.

In this paper, the following parameter values were selected:

$A \exp(-Q/RT) = 1.1 \times 10^{-13}$ /MPa^4/day

$n = 4$, $K_0 = 1.2 \times 10^{-10}$, $c = 0.0315$, $m = 3$

$\alpha_w = 15$, $\beta_w = 0$, $\delta = 0.58$

- **BBK Transient Law** — The Munson-Dawson law does not take into account "reverse" creep. This law was modified slightly to become the BBK Transient Law, as follows:

$$F = 1 - (1 - \varsigma / \varepsilon_t^*)^p / (1 - k)^p$$

when $\varsigma > \varepsilon_t^*$; reverse creep appears when $\varsigma > k\varepsilon_t^*$, or $F < 0$.

In this paper, the following parameter values were selected: $p = 2.4$, $k = 1.1$.

- **Lemaitre-Menzel-Schreiner Law** — This constitutive law is used widely in France and can be described as follows:

$$\dot{\varepsilon}_{ij}^{vp} = \frac{\partial}{\partial t}(\zeta)^{\alpha} \frac{\partial}{\partial \sigma^{ij}}\left(\sqrt{3J_2}\right)$$

$$\dot{\zeta} = \left(\frac{\sqrt{3J_2}}{K}\right)^{\frac{\beta}{\alpha}}$$

In this paper, the following parameter values were selected: $\beta = 3.3$, $\alpha = 0.13$, K = 1.5 MPa.

The Manosque test was back-calculated. (Results are given on Figures 5 and 6.) Parameters of the three constitutive laws first were fitted against the as-observed oil outflow during the 2000-hour long QR phase (day 485 to day 585). These parameters were used to compute the ST phase, during which brine was injected into or withdrawn from the central tubing to keep the wellhead pressure as constant as possible. Two computations were made.

1. The flow during the ST phase was predicted first, assuming that cavern pressure was constant during this phase. (See Figure 5; the effect of brine and oil thermal expansion, assessed before the test, has been subtracted.) The Lemaitre and Munson-Dawson Laws give similar results: the two curves are identical. They were not able to capture the effect of the pressure increase on day 585.

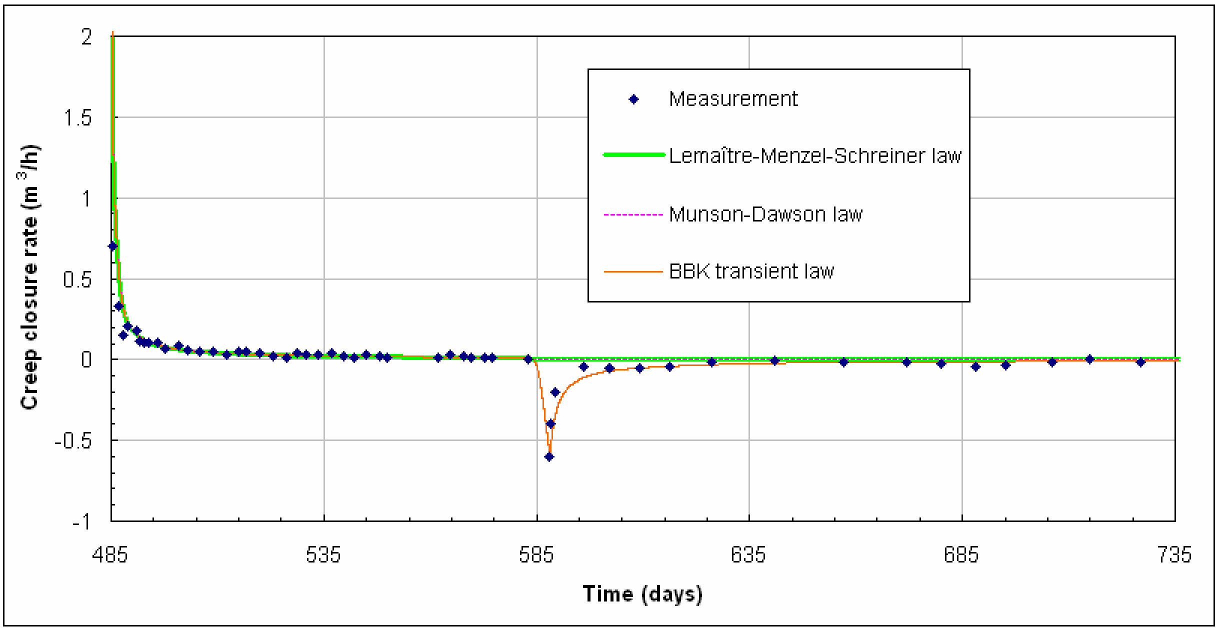

Figure 5. **Three constitutive laws are fitted against as-observed oil flow during the days 485 to 535 to predict brine flow during days 585 to 735. (The M-D and L-M-S curves are identical.)**

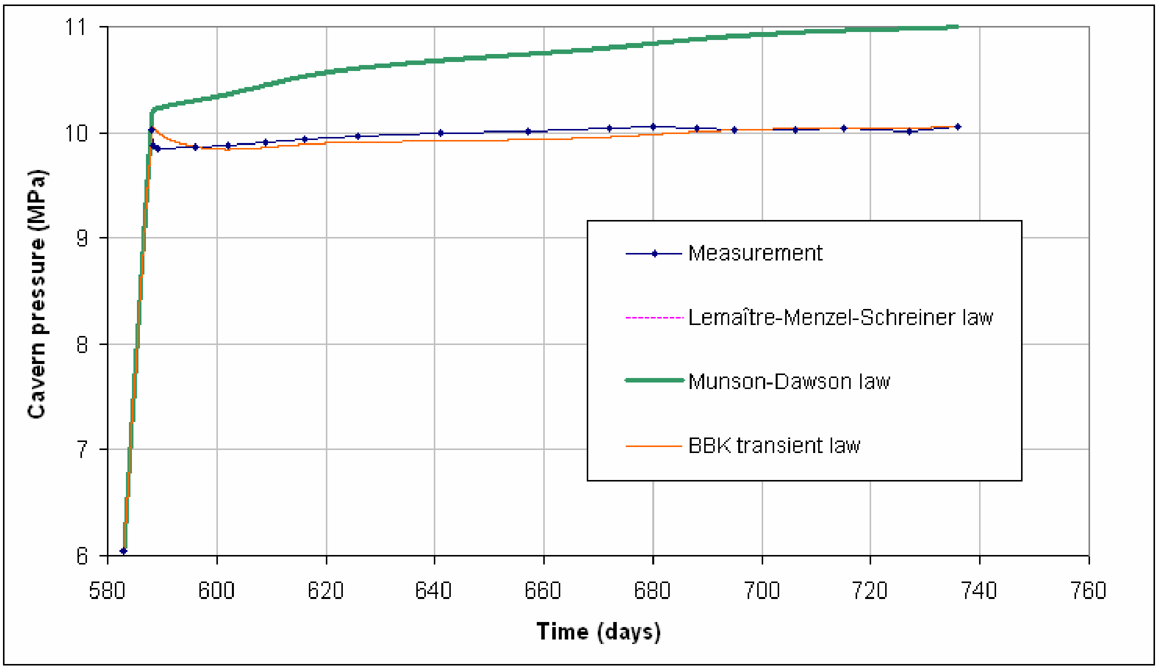

Figure 6. **The as-observed brine flow during the RT phase is fitted against various constitutive models to compute cavern pressure. (The M-D and L-M-S curves are identical.)**

- In fact, the as-observed pressure was not perfectly constant during the ST phase. It was decided to back-calculate the pressure history that fit-best the as-observed brine flow history and to compare it with the as-observed pressure evolution (Figure 6). When using the BBK Law, an excellent fit can be found (except during the 10 first days, when transient phenomena other than transient creep play a significant role; see Section 4.2).

The other two laws provide a poorer fit. This is no surprise, as those two laws do not include “reverse” creep.

4.4 Conclusion

Interpretation of the Manosque test proves, as did interpretation of the Etrez test (Van Sambeek et al., 2005), that, following a rapid increase in cavern pressure, “reverse” creep takes place in a closed cavern. This effect must be taken into account to interpret a Mechanical Integrity Test precisely, as reverse creep makes apparent leaks greater than actual leaks.

5 HYDRO-FRACTURING

Here, we discuss the effects of pressure build-up leading to rock fracturing.

5.1. Elastic Behavior

For a rock-salt mass, it often is assumed that the state of stress at depth is spherical — i.e., the three main stresses are equal, $S_h = S_H = S_v = -P_\infty$ (However, anomalous stress distribution can be found, for example, at the fringe of a salt dome,), and fracturing at a borehole well is reached when fluid pressure, P, is larger than the geostatic pressure, P_∞, by an amount that is related to the “tensile strength” of the rock mass [“a complex material parameter, certainly not an intrinsic material property”(Rummel et al., 1996)]. In fact, this assumption holds when elastic behavior is considered: in this case, stress distribution in the rock mass is $\sigma_{rr} = -P_\infty + (P_\infty - P)a^2/r^2, \sigma_{\theta\theta} = -P_\infty - (P_\infty - P)a^2/r^2$ (where a is the borehole radius), and fracturing is reached when fluid pressure (P) plus the less compressive stress ($\sigma_{\theta\theta}$) is larger than $T, \sigma_{\theta\theta} + P > T$ or

$$P > P_\infty + T/2$$

Such an assumption is correct when a fracturing test is performed shortly after the well has been drilled, as stresses have not yet had enough time to redistribute. An example of this is described in the next section.

5.2 A Case History

Hydro-fracturing tests may be performed in wells, before washing out takes place, to assess *in situ* stresses. This is especially helpful when the cavern is used later to store natural gas, whose maximum operating pressure must be kept lower than the minimum *in situ* stress.

Rummel et al. (1996) describe an extensive hydraulic-fracturing test program designed to determine the *in situ* stress within the salt at depth at the K6 borehole of the Krummhörn gas-storage facility in Germany. Eleven hydro-frac tests were carried out in the 8.5-in.diameter hole between depths of 1300 m and 1800 m. The analysis yields a well-documented shut-in pressure profile, P_{si} (MPa) = 29.38 + 0.0194 z (m), or a shut-in pressure gradient of dP_{si}/dz = 0.0221 MPa/m, for depths between 1300 m and 1720 m. Rummel et al. state that

> When we consider the characteristic hydro-frac data from all eleven tests conducted between 1305.7 m and 1721.6 m (TVD) we can observe both a systematic increase in breakdown pressure P_c with a break-down gradient P_c/TVD = 0.0255 MPa/m and in shut-in pressure P_{si} with depth with a gradient of

$P_{si}/TVD = 0.0221$ MPa/m. The depth dependence of tensile strength as a material property is less significant with an average value of 6.3 MPa. (p.5)

The authors conclude "The shut-in pressure profile [a measure for the minimum principal stress] is in good agreement with the vertical stress profile derived from various geophysical logs for the overburden density. (p.1)". This profile was "derived from the final refrac cycle to guarantee fractures had propagated away from the borehole and had adjusted to the far field stress", a comment whose significance will appear later. Similar studies were presented by Schmidt (1993) and Staudtmeister and Schmidt (2000).

5.3 The Effect of Stress Redistribution at the Borehole Well

As was pointed out first by Wawersik and Stone (1989), the state of stress in the vicinity of a borehole may be complex, making test interpretation more difficult. When a borehole is kept open for a long time (say, several years), the brine pressure remains halmostatic, and stress redistribution, from the initial "elastic" distribution to the final "steady-state creep" distribution (as explained in Section 3) takes place slowly. In this process, the difference between radial and tangential stresses is made significantly smaller than it had been when the stress distribution was "elastic". When pressure is increased rapidly in a well (as it is during a hydraulic fracturing test), the incremental stress increase is elastic, and the tangential stress becomes smaller than brine pressure before the brine pressure becomes geostatic, in sharp contrast with what happens during a standard hydro-fracturing test in an elastic medium. In other words, *fracturing pressure is significantly smaller when a test is performed long after a borehole is opened.*

5.4. Steady-State Behavior

A simple analysis can be performed when a well was kept idle for a long period before hydro-fracturing is performed. Assume that the brine pressure in the well was kept halmostatic during this period, $P = P_h$. The period was long enough to reach mechanical steady-state, or

$$\sigma_{rr} = -P_\infty + (P_\infty - P_h)(a/r)^{2/n} \qquad \sigma_{\theta\theta} = -P_\infty + (P_\infty - P_h)(1-2/n)(a/r)^{2/n}$$

Now, pressure in the well is increased rapidly. The additional stresses generated by a pressure increase of $(P - P_h)$ can be computed using the elastic solution and

$$\sigma_{\theta\theta} = -P_\infty + (P_\infty - P_h)(1-2/n)(a/r)^{2/n} + (P - P_h)(a/r)^2$$

and fracturing will be reached at the borehole wall ($r = a$) when $\sigma_{\theta\theta} + P > T$, or

$$P > P_\infty + T/2 - (P_\infty - P_h)(1-1/n)$$

That is, *fracturing will occur when a pressure much smaller than that in the "elastic" case is reached.* In fact, in some cases, fracturing will be reached when the pressure is smaller than geostatic. For instance, assume, for simplicity, that the tensile strength is zero, $T = 0$, and the exponent of the Norton-Hoff power law is $n = 4$. In a 1000-m deep well, the geostatic pressure is $P_\infty = 22$ MPa ($P_h = 12$ MPa), and one might expect that fracturing would be reached when the brine pressure is $P = 22$MPa (as $T = 0$). In fact, fracturing will be reached when the brine pressure is $P = 14.5$ MPa — a surprisingly slow figure. However, fracture propagation will be much slower than in the "elastic" case, as the stress distribution deep inside the rock mass is less favorable for fracture propagation.

5.5 Transient Stress Distribution

In the last section, it was assumed that steady-state stress distribution was reached. Similar conclusions can be reached even when stress redistribution has not yet been completed. Figure 7 presents an example of this. A borehole is drilled in a salt formation down to a depth of 800 m, and pressure is kept halmostatic after drilling has been completed. The evolution of tangential stress as a function of time and radius is shown. Assume that, after some time, a hydro-fracturing test is performed. (For simplicity, it is accepted that salt has no tensile strength ($T = 0$) — i.e., hydrofracturing takes place when brine pressure equals the smaller main compressive stress.) Salt is assumed to behave according to Norton-Hoff constitutive behavior.

- For short periods of time (t = 0; in fact, it is assumed that drilling was performed in 12 days), stress distribution is nearly elastic (Stress redistribution due to creep closure has not yet had enough time to have a significant effect.), and the tangential stress is approximately $\sigma_{\theta\theta} = 2P_\infty - P_h$. Hydro-fracturing will take place when brine pressure equals geostatic pressure, $P = P_\infty \approx 17.6$ MPa.

- For long periods of time (t = 27 years), stress distribution is changed significantly; it is closed to steady-state distribution, and fracturing will take place when the brine pressure equals P = 13.1 MPa. In other words, geostatic stress distribution will be underestimated significantly if the effects of stress redistribution are not taken into account.

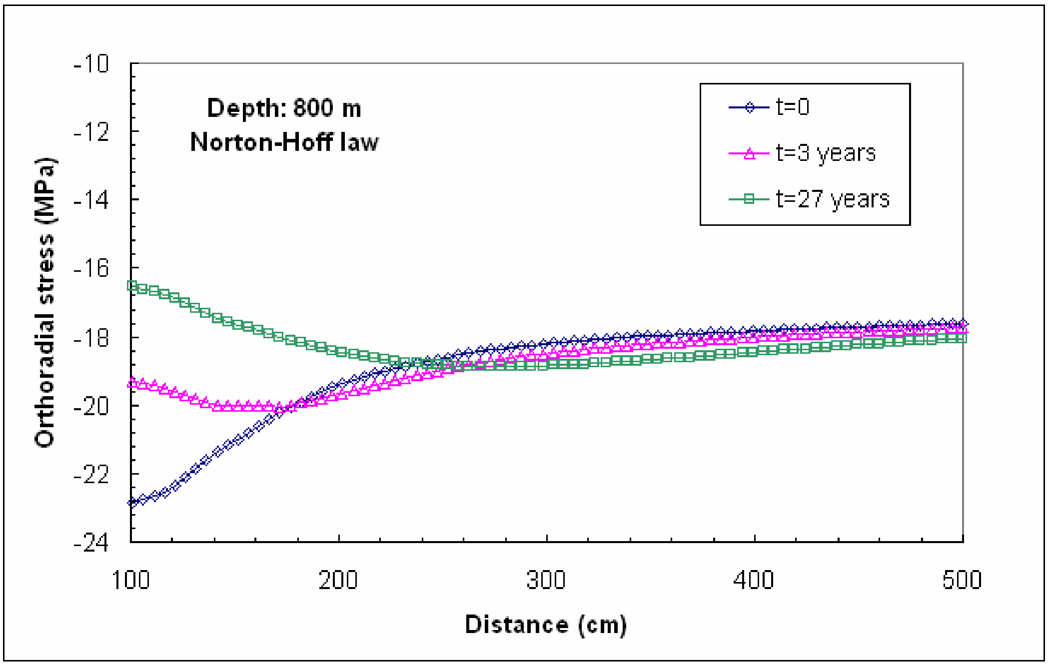

Figure 7. Orthoradial stress distribution as a function of the distance to the borehole wall

- This effect is less pronounced when an intermediate period of time (t = 3 years) is considered, and fracturing will take place when P = 14.6 MPa.

5.6 Hydro-Fracturing in Salt Caverns

We consider now the somewhat more complex case of a cavern. When a cavern is sealed and abandoned, brine pressure slowly increases due to several phenomena, including cavern creep closure and brine thermal expansion. Fracturing of the rock mass must be prevented. A 1000-m deep, 200-m high cavern was considered (cavern shape presented in Figure 8). Two cases are considered. In the first, the cavern was kept idle for 20 years to allow stresses to redistribute.

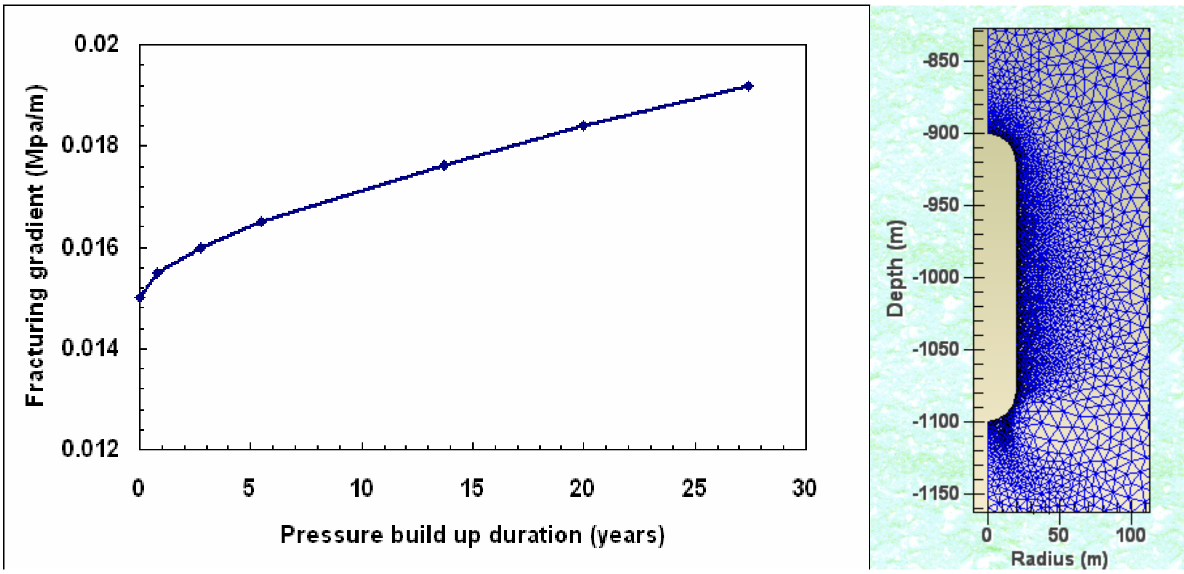

Figure 8. FEM Mesh and fracturing gradient after 20 years (no tensile strength).

Then pressure was increased, and various pressure build-up rates were considered. (The pressure build-up phase lasted from 1 day to 27 years). Computations stopped when "fracturing" occurred — i.e., when the maximal principal stress at cavern wall, σ_{max} (Compressive stresses are negative.), is such that $\sigma_{max} + P > 0$. The corresponding values of fracturing gradient are plotted on Figure 8. In another case, the cavern was kept idle for 5 years before increasing cavern pressure (Figure 9). "Fracturing" pressures are slightly greater for the 5-year waiting period than in the case of the 20-year long waiting period.

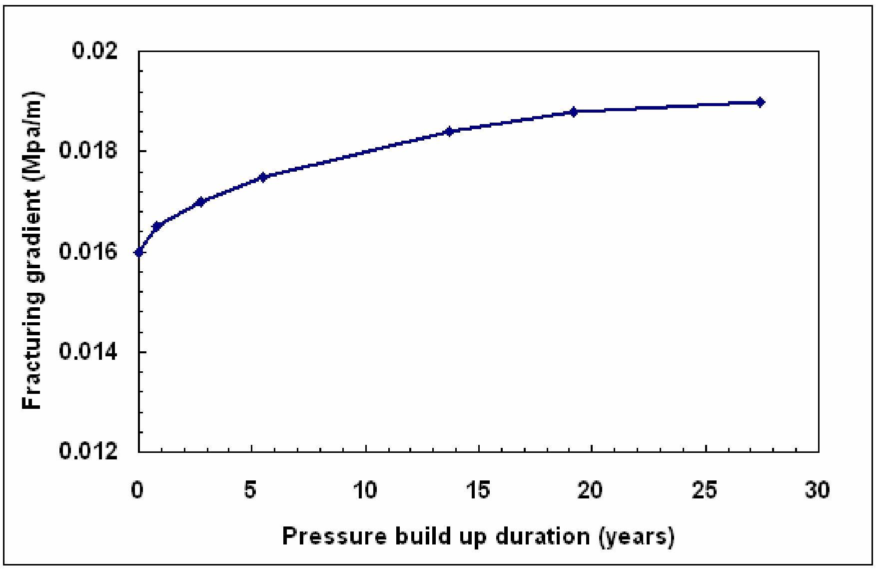

Figure 9. Fracturing gradient after 5 years (no tensile strength).

It can be observed that "fracturing" occurs when cavern pressure is smaller than geostatic pressure, a result that may explain the observation made during the Etzel test. (Note that "fracturing" is somewhat of a misnomer here, as no account is taken of the rock "tensile strength".)

5.7 The Etzel Test

Rokhar et al. (2000) describe a test performed in 1990 in the Etzel K102 cavern, a 230,000-m^3 cavern in the cavern field located in the Etzel salt dome, 25 km southwest of Willemshaven, Germany. The cavern roof is 850 m deep, and its height is 662 m. The objective of the test was to induce a fracture at slow pressurization rates. It was hoped that such slow rates would induce a fracture (i.e., breakdown) gradient significantly higher than the fracture gradient reached during standard hydrofracturing tests. A systematic procedure (Figure 10) was used during the test: each pressure build-up phase was followed by an observation period lasting several weeks. The two first gradient steps were 0.019 MPa/m and 0.0205 MPa/m. A slight loss of pressure was observed following the first step, and no loss of pressure was observed following the second step. During the third step, the ratio of the injected-volume rate versus the pressure build-up rate began to increase, clear proof of the onset of a fracture (or of increased, or "secondary", salt permeability). A gradient of 0.0219 MPa/m was reached after 7 weeks; when injection stopped, the pressure began to drop; and after a two-month observation period, extrapolation to a final pressure level of 0.0217 MPa/m appeared plausible. It must be noted that the lithostatic pressure gradient derived from borehole investigations was 0.0241 MPa/m — i.e., far larger than the gradient reached during the third step. (In hindsight, this early estimate was considered too high; additional investigations have proven that the pressure gradient ranges between 0.0204 MPa/m and 0.0211 MPa/m.)

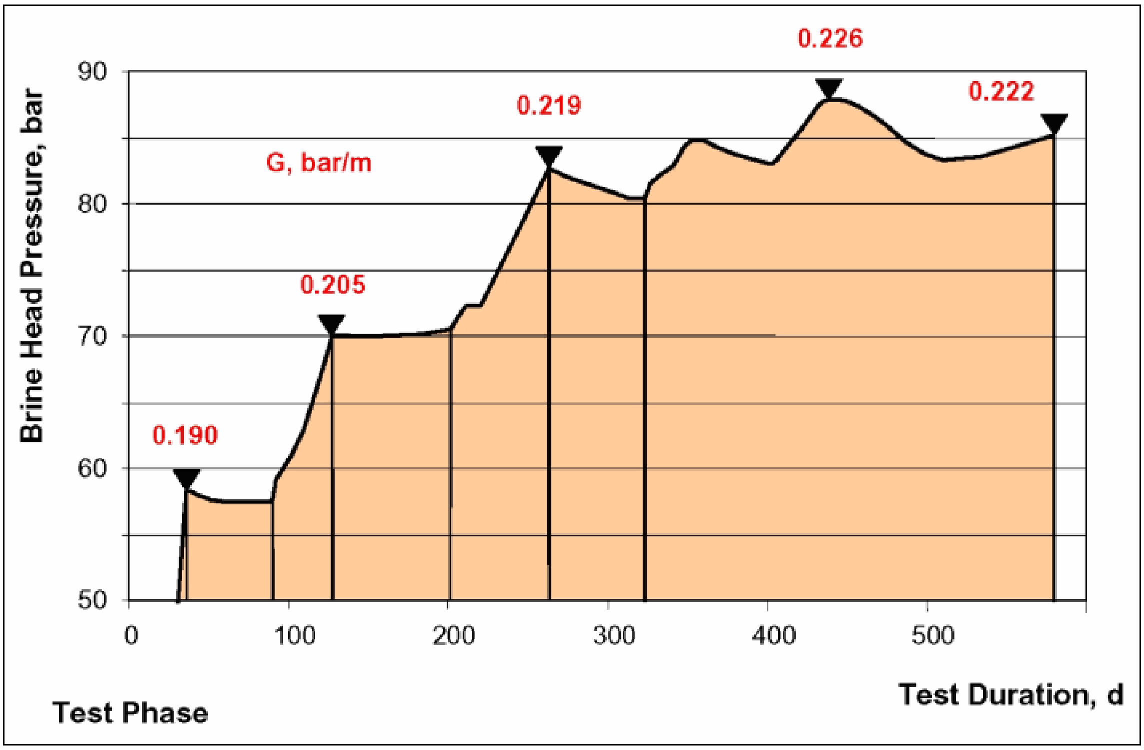

Figure 10 Cavern pressure as a function of time during the Etzel test (after Rokhar et al., 2000)

It is suggested here that re-distribution of stress in the rock mass, as explained above, also may have been influential in the early onset of fracture (or of increased salt permeability), as the cavern had been kept idle for a long period of time before the test.

5.8 The Etrez Test

Durup (1990) performed an SMRI-supported tightness test on the 1000-m deep Ez58 well, six years after the well was drilled (A partial stress redistribution is thought to have taken place). The 200-m high open hole was subjected to a series of stepwise increasing pressures. An objective of the test was to determine the pressure gradient corresponding to the beginning of loss of tightness. This gradient was reached after a one-year long pressure build-up; it was slightly less than 0.024 MPa/m. In this case, the effects of stress redistribution seem to be less significant, as fracturing pressure was significantly higher than geostatic pressure. This difference may be explained by: (a) a shorter "waiting" period, (b) a larger rock tensile strength, and/or (c) a larger overburden density.

5.9 Conclusions

Strong mechanical and mathematical arguments yield the conclusion that fracturing in a well or cavern that has been kept idle for a long period of time will appear at a pressure level much smaller than the figure obtained during a hydro-fracturing test performed soon after the well was drilled. This conclusion may have important consequences, especially when cavern abandonment is considered.

However, field data are equivocal. It must be kept in mind that several uncertainties make the interpretation of *in situ* test results difficult. For example, if the above-mentioned formula for the onset of fracturing is accepted,

$$P > P_\infty + T/2 - (P_\infty - P_h)(1 - 1/n)$$

instead of the "standard" formula

$$P > P_\infty + T/2$$

that large uncertainties may affect the value of the geostatic pressure (P_∞), as mentioned by Rokhar et al. (2000), as well as the value of the tensile strength (T), making any validation of this formula difficult.

Further investigation is needed.

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