Some aspects of the transient behavior of salt caverns

M. Karimi-Jafari & P. Bérest
LMS, Ecole Polytechnique, Palaiseau, France

B. Brouard
Brouard Consulting, Paris, France

ABSTRACT: The effects of transient creep in salt caverns are discussed. Salt behavior is viscoplastic: following a change in cavern pressure, a slow redistribution of stress takes place. This explains the long duration of any transient phase in a cavern. Stress redistribution also makes fracturing easier when cavern pressure is kept low for a long period of time. "Reverse" creep, a transient mechanical phenomenon that can be observed in the laboratory, also exists in salt caverns and may lead to misinterpretation of Mechanical Integrity Tests.

1 INTRODUCTION

The transient mechanical behavior of *salt samples* has been discussed by several authors (*e.g.*, Lux & Heuserman 1983; Munson & Dawson 1984; Aubertin 1996; Cristescu & Hunsche 1998). When submitted to a rapid applied-load increase, samples experience a period lasting several weeks (or months) during which the strain rate gradually decreases to 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 (Fig.1).

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 cavern fluid pressure. *In situ* "transient" tests are difficult to perform, as measuring small changes in cavern volume or shape is not easy (Bérest *et al.* 2006), and only a small number of such tests have been described in the literature. A few definitions are useful at this step. 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 most often is close to halmostatic. In a natural-gas storage cavern, cavern pressure is lower than halmostatic (and faster volume loss rates can be expected) when the gas stock is smaller. Cavern pressure is said to be "oleostatic" when the well is filled with a light liquid hydrocarbon, a situation sometimes encountered during *in situ* tests.

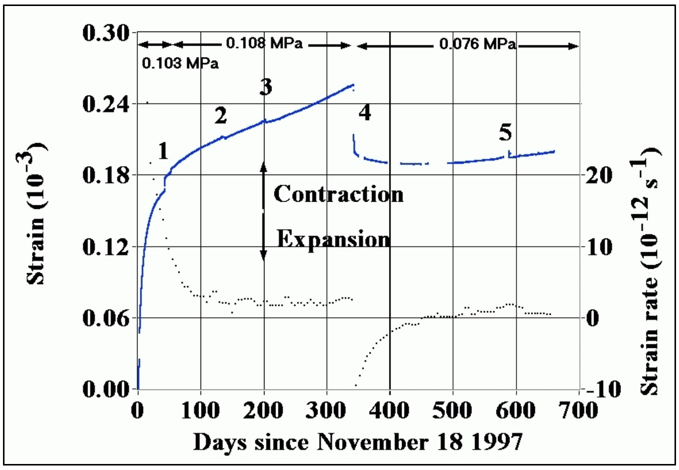

Figure 1. Strain and strain rate as functions of time during a creep test. Reverse creep appears when the applied stress drops from 0.108 MPa to 0.076 MPa (Bérest *et al.* 2005).

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 applied to a rock sample, σ, one considers the difference between the overburden (or geostatic) pressure and the cavern pressure, $P_\infty - P_i$.

A few differences must be noted, however: (1) in a cavern (resp., in a sample), the mechanical loading is more severe when cavern pressure is *lower* (resp., when applied stress is *higher*), (2) any pressure change in a cavern triggers several transient phenomena, of which transient creep is only one, and (3) transient creep in a cavern lasts much longer than in a rock sample.

In this paper, we discuss several aspects of cavern transient mechanical behavior.

2 CAVERN BEHAVIOR FOLLOWING A PRESSURE DROP (GEOMETRICAL VERSUS RHEOLOGICAL TRANSIENT CREEP)

The transient mechanical behavior of a cavern is more complex than the transient mechanical behavior of a 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 a triaxial test is performed on a cylindrical 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 in Figure 2. Computation begins when the cavern is leached out. In the 800-m deep cavern presented in Figure 2, during cavern creation, pressure rapidly decreases from geostatic (the pressure prevailing before the cavern is created) to halmostatic. Later, the cavern pressure is kept constant and equal to halmostatic (a situation approximately met in a liquid-hydrocarbon storage facility or brine-production cavern) and $P_\infty - P_i = 8$ MPa. 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 below in Section 3.3. The volume-loss-rate versus time curve is shown in Figure 2. Note that 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. In general, 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 cylindrical rock sample submitted to a constant mechanical load (see Fig. 2; the applied stress is 8 MPa). Taking into account the transient rheological behavior (Munson-Dawson law) makes volume loss rate slightly slower, but the geometrical transient behavior is by far the most significant effect. In most cases, "steady-state" cavern-volume loss rate underestimates the actual rate.

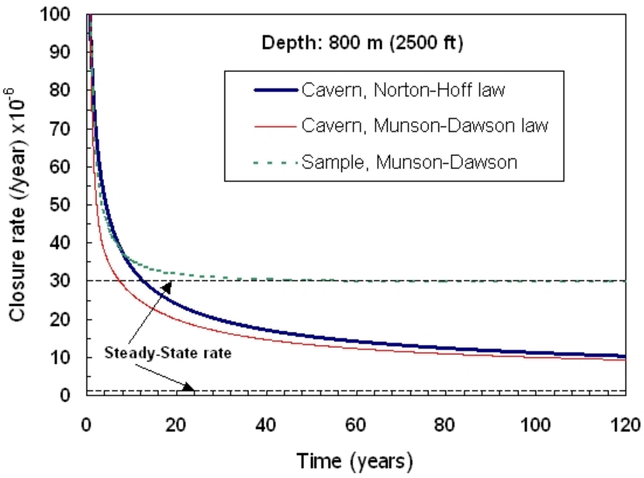

Figure 2. Closure rate as a function of time in a brine production cavern.

3 CAVERN TRANSIENT EXPANSION

The following sections describe "reverse creep" as it affects salt caverns. Several *in situ* tests are described (Section 3.1). These tests are difficult to interpret (Section 3.2); the Manosque test was selected to fit constitutive laws against field data (Section 3.3).

3.1 *Outflow measurement test*

Before an *in situ* test is conducted, cavern pressure is kept halmostatic, and the brine outflow rate from the cavern is measured. At the beginning of the test, cavern pressure is lowered to oleostatic: the well is filled with a light liquid hydrocarbon and opened at ground level, and the hydrocarbon outflow rate is measured over several weeks. (In some cases, the well is shut, and the flow rate of the liquid that must be injected or withdrawn to keep wellhead pressure constant is measured.) At the end of the test, the halmostatic pressure is restored, and the brine outflow rate is measured again. Such tests have been performed by Hugout at Etrez (1988 — a re-interpretation of this test can be found in van Sambeek *et al.*, 2005), by Brouard *et al.* (2004) and by Clerc-Renaud & Dubois (1980), who performed a test in a cavern at the Manosque site (Southeastern France), operated by Géostock. 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, and the wellhead brine pressure was zero. Slowly decreasing brine outflow was observed (Fig. 3); it was generated by the warming of cavern oil and brine and, to a lesser extent, by cavern creep closure. The wellhead oil pressure was released (PQ on Fig. 3) by opening a valve that isolated the

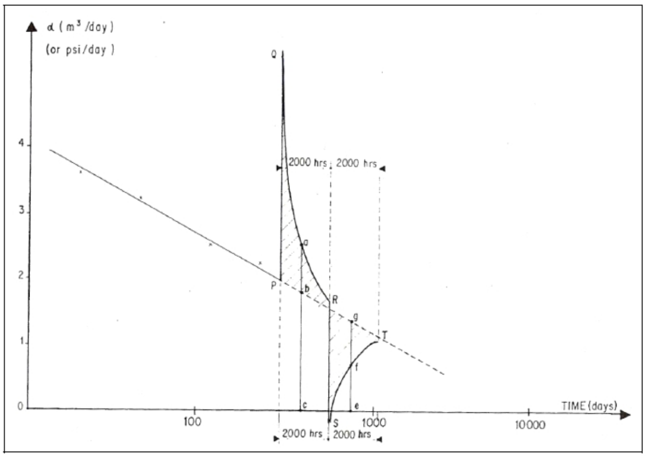

Figure 3. Oil Outflow Test (Clerc-Renaud & Dubois 1980).

annular space from the central string. Oil outflow then was measured for 2000 hours (QR on Fig. 3), after which brine was injected in the central tube to increase the wellhead oil pressure by 550 psi (RS on Fig. 3). Brine outflow then was measured for 2000 hours (ST on Fig. 3). Fast convergence rates following a pressure decrease (phase QR) and "reverse" convergence rates following a pressure increase (phase ST) were observed.

It should be noted that, in addition to these three "outflow measurement" tests, hundreds of *in situ* tests that triggered reverse creep were performed worldwide: any Mechanical Integrity Test (MIT), which involves a rapid pressure build-up followed by an observation period lasting several days can be considered as a "reverse creep" test.

3.2 *Difficulties in interpreting in situ tests*

During the *in situ* tests described above, transient creep apparently was observed, as the fluid outflow rate experienced a drastic change after pressure decreased or increased. However, precise interpretation is difficult as, together with transient mechanical behavior, any rapid pressure change triggers several other transient phenomena. According to the Le Chatelier (or Braun) principle, these test-triggered phenomena tend to restore the pre-existing pressure in a closed cavern and may lead to an overestimation of the effects of creep. The three main such phenomena (other than transient creep) are (1) additional dissolution (Any change in cavern pressure leads to a change in brine saturation: following a rapid pressure build-up, salt is dissolved, more room is available for cavern brine, and cavern pressure drops accordingly.), (2) transient brine permeation (The permeability of salt is exceedingly small; however, a rapid pressure increase generates fast transient permeation over a couple of days.), and (3) adiabatic pressure build-up (A rapid pressure increase results in a small increase in brine or oil temperature that is followed by cooling and contraction of the liquid and, ultimately, by pressure decrease). They are described in more detail in Van Sambeek *et al.* (2005). These must be taken into account, as their effects are identical to those of transient creep. Most often, however, they especially are active for 2-3 days immediately following the change in cavern pressure. While they are significant during an MIT, they often can be neglected when a test lasting several weeks is considered.

3.3 *Constitutive behavior*

Two constitutive laws were considered: (1) the Munson-Dawson modified (M-D) law, and (2) the Lemaitre-Menzel-Schreiner (L-M-S) law. They do not include "reverse" creep [Munson *et al.* (1996) proposed an advanced version of the M-D law that does take reverse creep into account; this version is not considered here.]. These two laws are described below.

The *Lemaitre-Menzel-Schreiner (L-M-S)* law is used widely in France and can be described as follows:

$$\dot{\varepsilon}_{ij}^{vp} = \frac{\partial}{\partial t}(\zeta)^{\alpha} \frac{\partial}{\partial \sigma^{ij}}\left(\sqrt{3J_2}\right) \tag{1}$$

$$\dot{\zeta} = \left(\frac{\sqrt{3J_2}}{K}\right)^{\frac{\beta}{\alpha}} \tag{2}$$

The (modified) *Munson-Dawson* (*M-D*) law is a generalization of the Norton-Hoff law that takes into account the transient behavior of rock salt. The Norton-Hoff law captures the main features of steady-state salt behavior in the range of stresses and temperatures commonly encountered in salt caverns:

$$\dot{\varepsilon}^{ij} = \dot{\varepsilon}_e^{ij} + \dot{\varepsilon}_{ss}^{ij} \tag{3}$$

$$\dot{\varepsilon}_{ss}^{ij} = A\,exp\left(-\frac{Q}{RT}\right)\frac{1}{n+1}\frac{\partial}{\partial \sigma_{ij}}\left[\left(\sqrt{3J_2}\right)^{n+1}\right] \tag{4}$$

$$\dot{\varepsilon}_e^{ij} = \frac{1+\nu}{E}\dot{\sigma}^{ij} - \frac{\nu}{E}\dot{\sigma}^{kk}\delta^{ij} \tag{5}$$

Munson and Dawson introduced a multiplier (F) and an internal variable (ζ) to describe salt transient behavior:

$$\dot{\varepsilon}^{ij} = \dot{\varepsilon}_e^{ij} + F\dot{\varepsilon}_{ss}^{ij} \quad \begin{array}{ll} F = e^{\Delta(1-\varsigma/\varepsilon_t^*)^2} & \text{when } \varsigma \le \varepsilon_t^* \\ F = e^{-\delta(1-\varsigma/\varepsilon_t^*)^2} & \text{when } \varsigma \ge \varepsilon_t^* \end{array} \tag{6}$$

$$\dot{\varsigma} = (F-1)\,\dot{\varepsilon}_{ss}, \quad \dot{\varepsilon}_{ss} = A\,exp\left(-\frac{Q}{RT}\right)\left(\sqrt{3J_2}\right)^n \tag{7}$$

$$\varepsilon_t^* = K_0 e^{cT} \sigma^m \text{ and } \Delta = \alpha_w + \beta_w Log_{10}(\sigma/\mu) \quad (8)$$

$$\delta = \delta_o,\ \mu = E/2(1+\nu),\ \sigma = \sqrt{3J_2} \quad (9)$$

Parameters of these two constitutive laws first were fitted against the as-observed oil outflow during the 2000-hour long QR phase of the Manosque test (day 485 to day 585). An excellent fit (see Fig. 4) was obtained when the following values of the parameters were selected:

$\beta = 3.3,\ \alpha = 0.13, K = 1.5$ MPa (L-M-S law);

$A\exp(-Q/RT) = 2 \cdot 10^{-11}$ MPa^4/day,

$n = 4,\ K_o = 1.2 \cdot 10^{-10},\ c = 0.0315$ /K, $m = 3$,

$\alpha_w = 15,\ \beta_w = 0,\ \delta = 0.58$ (M-D law).

Note that the Lemaitre and Munson-Dawson laws give similar results: the two curves are identical. The two set of parameters then were used to "predict" the flow rate during the ST phase, when brine was injected into or withdrawn from the central tubing to keep the wellhead pressure as constant as possible. The L-M-S and M-D laws were not able to capture the effect of the pressure increase on day 585. This is no surprise, as those two laws do not include "reverse" creep.

In order to better take into account "reverse" creep, the Munson-Dawson law was modified slightly to become the BBK Transient law, as follows:

$$F = 1 - \left(1 - \varsigma / \varepsilon_t^*\right)^p / (1-k)^p \text{ when } \varsigma > \varepsilon_t^* \quad (10)$$

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

A good fit was reached against the measured flow during ST phase (Fig. 4) when the following values of the parameters were selected: $p = 2.4,\ k = 1.1$.

3.4 *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. Examples can be found in Karimi *et al.* (2005).

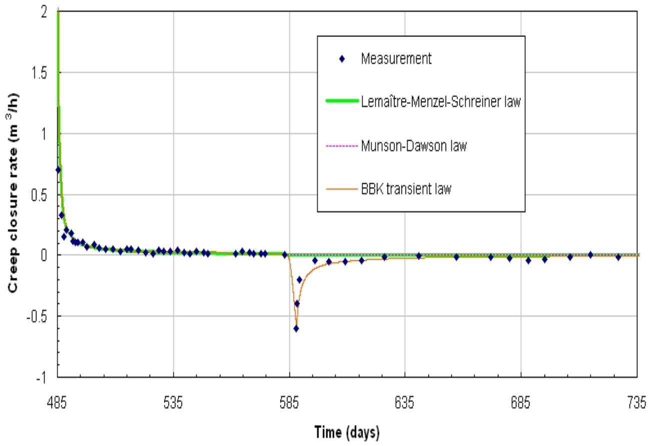

Figure 4. Three constitutive laws are fitted against as-observed oil flow during the days 485 to 585 to predict brine flow during days 585 to 735. (The M-D and L-M-S curves are identical.)

4 HYDRO-FRACTURING

Here, we discuss the effects of a pressure build-up large enough to lead to rock fracturing (or a drastic increase in salt permeability). The elastic case is considered first (Sections 4.1 and 4.2). New features appear when the viscoplastic case is considered (Section 4.3). The case of a full-size cavern and field evidence are discussed in Section 4.4 and 4.5.

4.1 *Introduction*

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. It generally is accepted that fracturing at a borehole well is reached when the fluid pressure, P, is larger than the least compressive stress, σ_m (Compressive stresses are negative.), 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)], or $P + \sigma_m > T$. The fracturing pressure often is called the breakdown pressure, P_c. The shut-in pressure, P_{si}, is the fluid pressure reached a certain period of time after the well was shut-in; it is smaller than the breakdown pressure and generally is considered as being more representative of the minimum *in situ* stress. For a rock-salt mass, it often is assumed that the natural 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.) In such a case, the least compressive stress at the borehole wall during a fracturing test is the tangential stress, $\sigma_m = \sigma_{\theta\theta}$. Several cases must be distinguished according to the period during which fracturing is performed.

4.2 *Elastic behavior*

When elastic behavior is considered (an assumption which is correct only during a short period of time after the well is drilled), stress distribution in the rock mass is:

$$\sigma_{rr} + P_\infty = (P_\infty - P)(a/r)^2 \quad (3)$$

$$\sigma_{\theta\theta} + P_\infty = (P_\infty - P)(a/r)^2 \quad (4)$$

$$\sigma_{zz} + P_\infty = 0 \quad (5)$$

where a is the borehole radius. When $P > P_\infty$, the least compressive stress is $\sigma_{\theta\theta}$, and fracturing is reached when:

$$P > P_c = P_\infty + T/2 \quad (6)$$

Hydro-fracturing tests in a salt formation most often are interpreted according to this simple formula (see Rummel *et al.* 1996; Schmidt1993; Staudtmeister & Schmidt 2000; Doe & Osnes 2006). However, as stated by Rummel *et al.* (1996), the shut-in pressure profile (a measure for the minimum principal stress) is "derived from the final refrac cycle to guarantee fractures had propagated away from the borehole and had adjusted to the far field stress" (p.1), a comment whose significance is highlighted in the following paragraphs.

4.3 *The effect of stress distribution at the borehole wall*

In the case of rock salt, as was pointed out first by Wawersik & 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, $P = P_h$, and stress redistribution, from the initial "elastic" distribution to the final "steady-state creep" distribution, takes place slowly. In this process, the tangential stress becomes significantly larger (Compressive stresses are negative.) than it had been when the stress distribution was "elastic". When pressure is increased rapidly in a well (as it is during a hydro-fracturing test), the incremental stress increase is elastic, and the tangential stress often becomes smaller than brine pressure before the brine pressure becomes geostatic, in sharp contrast with what occurs during a standard hydro-fracturing test in an elastic medium. A simple analysis can be performed when Norton-Hoff constitutive behavior is adopted. Assume that the brine pressure in the well was kept halmostatic, $P = P_h$, during a period long enough to reach mechanical steady-state, or

$$\sigma_{rr} + P_\infty = (P_\infty - P_h)(a/r)^{2/n} \quad (7)$$

$$\sigma_{\theta\theta} + P_\infty = (P_\infty - P_h)(1 - 2/n)(a/r)^{2/n} \quad (8)$$

$$\sigma_{zz} + P_\infty = (P_\infty - P_h)(1 - 1/n)(a/r)^{2/n} \quad (9)$$

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

$$\sigma_{\theta\theta} + P_\infty = (P_\infty - P_h)\left(1 - \frac{2}{n}\right)\left(\frac{a}{r}\right)^{2/n} + (P - P_h)\left(\frac{a}{r}\right)^2 \quad (10)$$

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

$$P > P_\infty + T/2 - (P_\infty - P_h)(1 - 1/n) \quad (11)$$

In other words, *fracturing pressure is significantly smaller when a test is performed long after a borehole is opened.* In fact, in some cases, fracturing will be reached even when the pressure is smaller than geostatic.

4.4 *Hydro-fracturing in salt caverns*

We now consider the somewhat more complex case of a cavern whose pressure was kept constant (say, halmostatic) over many years. At the end of this period, pressure is increased to reach fracturing. Several differences with the borehole case are noted. On one hand, cavern shape is not as simple as borehole shape. (It is not a perfect cylinder.) On the other hand, the pressure build-up rate often is much slower in a cavern. For instance, when a cavern is sealed and abandoned, brine pressure slowly increases due to several phenomena, including cavern creep closure and brine thermal expansion; this process may take years before fracturing pressure is reached. In other words, in sharp contrast with the case of borehole fracturing, stresses are given time to redistribute before fracturing is reached.

A 1000-m deep, 200-m high cavern is considered (see Fig. 5). The cavern was kept idle for 20 years to allow stresses to redistribute.

Then, the pressure is increased slowly, and various pressure build-up rates are considered. (The pressure build-up phase lasts from 1 day to 27 years). Computations stopped when “fracturing” occurred — *i.e.*, when the least principal stress at the cavern wall, σ_m (Compressive stresses are negative.), is such that $\sigma_m + P > 0$. (For simplicity, no tensile strength is taken into account.) The corresponding values of the fracturing gradient are plotted on Figure 5. They are smaller than the geostatic gradient, which is 0.022 MPa/m.

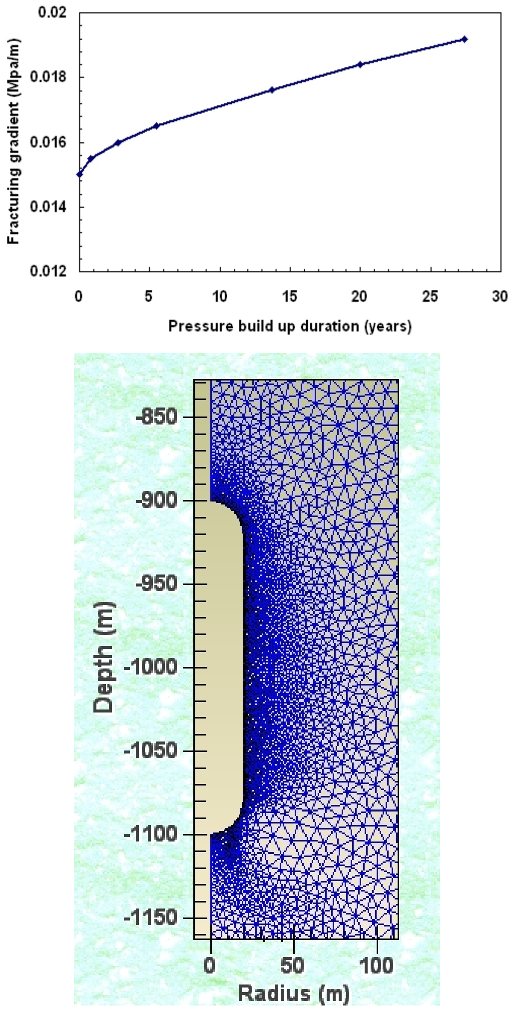

Figure 5. Fracturing gradient (no tensile strength) as a function of pressure build-up duration. (The cavern had been kept idle for 20 years before sealing.)

4.5 *Field Evidence*

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. 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 hydro-fracturing tests. A systematic procedure was used during the test: each pressure build-up phase was followed by an observation period lasting several weeks. During the third step, at which a gradient of 0.0219 MPa/m was to be reached, 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). When injection stopped, the pressure began to drop; after a two-month observation period, extrapolation to a final pressure level of 0.0217 MPa/m appeared plausible. It is noted that the geostatic 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 geostatic pressure gradient ranges between 0.0204 MPa/m and 0.0211 MPa/m (*i.e.*, slightly smaller than the cavern breakdown pressure.) It is suggested here that redistribution of stress in the rock mass, as explained above, may have been influential in the early onset of fracture (or of increased salt permeability).

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 had enough time to take place.) The 200-m high open hole was subjected to a series of stepwise increasing pressures. One objective of the test was to determine the pressure gradient corresponding to the beginning of loss of tightness. This gradient was reached after a pressure build-up of one-year; it was slightly less than 0.024 MPa/m. In this case, the effects of stress redistribution seem to be less significant than in the Etzel case, as fracturing pressure was significantly higher (by 2 MPa) 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.

4.6 *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 is reached 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 somewhat 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,

$$P > P_\infty + T/2 - \left(P_\infty - P_h\right)\left(1 - 1/n\right) \qquad (20)$$

It is clear 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.

5 CONCLUSIONS

The transient mechanical behavior of a cavern has been discussed. It has been proven that: (1) transient behavior lasts much longer in a cavern than in a sample, (2) when submitted to a rapid pressure increase, a cavern experiences "reverse" creep, an effect that can lead to overestimation of the actual leak during an MIT, and (3) when a cavern (or a borehole) is kept idle for a long period of time, a slow redistribution of stresses takes place in the rock mass, and a relatively low pressure increase may lead to fracturing. However, field data remain scarce, and interpretation is difficult. Further investigations are needed, as the consequences of the mechanical behavior of caverns possibly are significant.

6 REFERENCES

Aubertin, M. 1996. On the physical origin and modeling of kinematic and isotropic hardening of salt. In *Proc. 3rd Conf. Mech. Beh. of Salt*: 3-17. Clausthal-Zellerfeld, Germany: Trans. Tech. Pub.

Bérest, P., Blum, P.A., Charpentier, J.P., Gharbi, H. & Valès, F. 2005. Very slow creep tests on rock samples. *Int. J. Rock Mech. & Min. Sc*. 42: 569-576.

Bérest, P., Brouard, B., Karimi, M. & Bazargan, B. 2006. *In situ* mechanical tests in salt caverns. In *Proc. SMRI Spring Meeting*, *Brussels*: 92-130.

Brouard, B., Bérest, P., Héas, J.Y., Fourmaintraux, D., de Laguérie, P. & You, Th. 2004. An *in situ* creep test in advance of abandoning a salt cavern. In *Proc. SMRI Fall Meeting, Berlin*: 46-64.

Clerc-Renaud, A. & Dubois, D. 1980. Long-term operation of underground storage in salt. In A. H. Coogan & L. Hauber (eds), *Proc.5th Symp. on Salt:* Vol. II, 3-10. Cleveland: The Northern Ohio Geological Society.

Cristescu, N.D. & Hunsche, U. 1998. *Time Effects in Rock Mechanics.* West Sussex, England: John Wiley & Sons.

Doe, Th. & Osnes, J. 2006. *In situ* stress and permeability tests in the Hutchinson salt and the overlaying shale, Kansas. In *Proc. SMRI Fall Meeting, Rapid City*: 181-213.

Durup, G. 1990. Field tests in Well EZ 58. *SMRI Project Report n°90-00002-S.*

Hugout, B. 1988. Mechanical behavior of salt cavities - *in situ* tests - model for calculating the cavity volume evolution. In *Proc. 2nd Conf. Mech. Beh. of Salt*: 291-310. Clausthal-Zellerfeld, Germany" Trans. Tech. Pub.

Karimi-Jafari M., Bérest, P., Van Sambeek, L. Brouard, B. & Bazargan, B. 2005 Interpretation of Mechanical Integrity Tests In *Proc. SMRI Fall Meeting, Nancy*: 153-173.

Lux, K.H. & Heusermann, S. 1983. Creep tests on rock salt with changing load as a basis for the verification of theoretical material laws. In *Proc. 6th Int. Symp. on Salt*: Vol. I, 417-435. Alexandria, Virginia: The Salt Institute.

Munson, D.E. & Dawson, P.R. 1984. Salt constitutive modeling using mechanism maps. In *Proc. 1st Conf. Mech. Beh. of Salt*: 717-737. Clausthal-Zellerfeld, Germany: Trans. Tech. Pub.

Munson, D.E., De Vries, K.L., Fossum, A.F. & Callahan, G.D. 1996. Extension of the Munson-Dawson model for treating stress drops in salt. In *Proc. 3rd Conf. Mech. Beh. of Salt*: 31-44. Clausthal-Zellerfeld, Germany: Trans. Tech. Pub.

Rokhar, R.B., Hauck, R., Staudtmeister, K. & Zander-Schiebenhöfer D. 2000. The results of the pressure build-up test in the brine filled cavern Etzel K102. In *Proc. SMRI Fall Meeting, San Antonio*: 89-103.

Rummel, F., Benke, K. & Denzau, H. 1996. Hydraulic fracturing stress measurements in the Krummhörn gas storage field, Northwestern Germany. In, *Proc. SMRI Spring Meeting, Houston.*

Schmidt, T. 1993. Fracture tests for determining primary stress conditions in salt deposits provide clues to the rock mechanics of salt caverns. In *Proc. 7th Symp. on Salt*: 135-140. Amsterdam: Elsevier.

Staudtmeister, K. & Schmidt, T. 2000. Comparison of different methods for the estimation of primary stresses in rock salt mass with respect to cavern design. In *Proc. 8th World Salt Symposium*: Vol. I, 331-335. Amsterdam: Elsevier.

Van Sambeek, L.L., Bérest, P. & Brouard, B. 2005. Improvements in Mechanical Integrity Tests for solution-mined caverns used for mineral production or liquid-product storage. *SMRI Research Project Report 2005-1*,142 pages.

Wawersik, W. & Stone, C.M. 1989. A characterization of pressure records in inelastic rock demonstrated by hydraulic fracturing measurements in salt. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr*. 613-627.