ÉVOLUTION DE LA PRESSION DANS UNE CAVERNE FERMÉE REMPLIE DE FLUIDE

PRESSURE EVOLUTION IN A FLUID-FILLED SEALED CAVERN

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RÉSUMÉ : Dans une cavité souterraine lessivée dans une formation salifère, la pression de la saumure contenue évolue après fermeture de la cavité sous l'effet du fluage du sel, du réchauffement de la saumure et de la perméation de la saumure dans le massif. On s'est efforcé de quantifier ces effets pour prévoir la pression d'équilibre finale. Un essai d'un an et demi a permis de vérifier le modèle retenu ; l'écart avec la précision est dans doute à attribuer à la perméabilité en grand du massif, le paramètre le plus difficile à évaluer.

ABSTRACT: In an underground cavern leached out from a salt formation, cavern brine pressure builds up after the cavern is sealed, due to salt mass creep, brine warning and brine seepage through the rock mass. These effects have been quantified to predict the equilibrium pressure reached at the end of the process. An 18-month-long test allowed to validate the prediction. The observed discrepancy may be attributed to large-scale permeability assessment which is especially difficult.

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Key Words: Creep; Heat Transfer; Permeability; Abandoned caverns; Rock salt.

1. INTRODUCTION

Thousands of deep (300 m to 2000 m) and large (10,000 m^3 to 1,000,000 m^3) caverns have been leached out from salt formations. They are used for hydrocarbon storage. They will be abandoned some day: the access well will be plugged, isolating a large bubble of saturated brine. The later evolution of such a bubble raises serious concerns for environmental protection. We will prove that brine pressure builds up in a closed cavern. The final value of this pressure is of utmost importance: in salt formations, the natural state of stress is generally assumed to be isotropic, the geostatic pressure being P_∞ (MPa) = 0.022 H (meters) at cavern depth. If brine pressure reaches a figure significantly larger than geostatic pressure, then hydrofracturing will take place: brine will flow upward through fractures, to shallow water-bearing strata, leading to water pollution, cavern collapse and subsidence. Consequences will be more severe when the cavern contains wastes (Tomasko et al., 1997).

In the following we will discuss the different factors contributing to pressure build up (or pressure release) in a closed salt cavern, then we will describe an in situ test designed to validate the main conclusions of the theoretical discussion and comment the discrepancies between predicted and observed pressure evolution.

2. MAIN PHENOMENA

2.1. Cavern creep

The role of cavern creep in brine pressure build up in a closed cavern has been early identified by many authors, (Wallner, 1986; Van Sambeek, 1990; Wallner & Paar, 1997, among others). The mechanical behavior of salt exhibits a fascinating complexity; however experts do agree on several features of importance to the problem under discussion: (i) in the long term, salt behaves as a fluid in the sense that it flows even under small deviatoric stresses; (ii) creep rate is a highly non-linear function of applied deviatoric stress and test temperature. These main features are captured by the following expression of the steady-state axial strain rate ($\dot{\varepsilon}>0$) observed when a uniaxial compressive stress ($\sigma > 0$) is applied on a cylindrical salt sample.

$$\dot{\varepsilon} = A\exp(-Q/RT)\,\sigma^{n} \qquad (1)$$

Where *A, n, Q/R* are three parameters and *T* is the (absolute) temperature. The exponent *n* ranges from 3 to 6, and *Q/R* ranges from 4000 K to 10,000 K. A compilation of data published in the literature can be found in Brouard & Bérest, 1998. This uniaxial expression can be generalized in a 3D formulation:

$$\underline{\underline{\dot{\varepsilon}}} = A\exp(-Q/RT)\,\frac{1}{n+1}\,\frac{\partial\left(\sqrt{3J_2}\right)^{n+1}}{\partial \underline{\underline{\sigma}}} \qquad (2)$$

Using this formulation, a closed-form solution can be obtained for the idealized case of a perfectly spherical cavern that, over a long period of time, is subjected to an internal pressure (P_i) smaller than the geostatic pressure (P_∞) at cavern depth. Relative volume rate change is:

$$\frac{\dot{V}}{V} = -\frac{3}{2}\left[\frac{3}{2n}\left(P_\infty - P_i\right)\right]^{n} A\exp\left(-\frac{Q}{RT}\right) \qquad (3)$$

$$\text{or } \dot{V}/V = -3B(T)\left(P_\infty - P_i\right)^{n}$$

An immediate consequence is that, as long as $P_\infty > P_i$, the cavern shrinks, leading to cavern pressure build up in a closed cavern. A typical value of the initial shrinkage rate for a 1000 m deep cavern is $\dot{V}/V = -3\times10^{-4}$ year^{-1}, when P_i is equal to the so called “halmostatic” pressure, or P_h, i.e. the pressure resulting from the weight of a saturated brine (density 1200 kg.m^{-3}) column filling the well from the surface to the cavern, or P_i (MPa) = P_h = 0.012 H (meters). Such a shrinkage rate leads to a pressure build up of $\dot{P}_i = \dot{V}/(\beta V)$, where β is the cavern compressibility factor. In a standard cavern $\beta = 4\times10^{-4}$ MPa^{-1} (Bérest et al., 1999) and $\dot{P}_i = 0.75$ MPa year^{-1}. Of course pressure build up progressively leads to smaller creep rates when the difference $P_\infty - P_i$ becomes smaller. Pressure evolution is described by a differential equation which can be easily solved; equilibrium- i.e., exact balance between brine average pressure and geostatic average pressure at cavern depth – will not be reached for several centuries, as Wallner & Paar (1997) also verified through numerical computations. Formula (3) points out the influence of cavern depth (*H*); when *H* increases, both temperature (*T*) and gravity loading ($P_\infty - P_i$) increase, resulting in a much faster initial pressure build – up rate in a deep closed cavern (Bérest & Brouard, 1997).

2.2. Brine thermal expansion

The importance of brine thermal expansion has been outlined by Bérest et al., 1979, Hugout, 1988, Ehgartner & Linn, 1994. Salt caverns are leached using soft water pumped from shallow aquifers whose temperature is smaller than the temperature of rock salt at cavern depth. At the end of leaching, there exists a significant gap between initial cavern brine temperature (T_0) and rock temperature (T_∞) (say, 25°C = $T_\infty - T_0$ at a 1000 m depth). Later on, when the cavern remains idle, this gap ($T_\infty - T_i$) will slowly resorb with time due to heat conduction through the rock to the cavern, and heat convection in the cavern which stirs up brine.
Appropriate heat-transfer equations are:

$$\partial T/\partial t = k\Delta T \quad ; \quad \int_\Omega \rho_b C_b \dot{T}_i \, d\Omega = \int_{\partial\Omega} \tilde{K}\, \partial T/\partial n \, da \qquad (4)$$

The first equation holds inside the rock mass; k is salt thermal diffusivity, or k = 100 m^2 $year^{-1}$; the second equation is the boundary condition at cavern wall ($\tilde{K}$ is the thermal conductivity of salt, $\tilde{K}$ = 3 W m^{-1} K^{-1}, and ρ_b C_b = 4.8×10^6 J m^{-3} K^{-1} is the volumetric heat capacity of brine). Back-of-the envelope estimations can be reached through dimensional analysis. The equations (4) provide two characteristic times, for instance $t_c = V^{2/3}/(4k)$ and $t_c' = k\ t_c\ \rho_b\ C_b/\tilde{K}$, whose values are not significantly different. Then temperature evolution can be written $T_\infty - T_i(t) = (T_\infty - T_0)\ \varphi\ (t/t_c)$, where $\varphi(0) = 1$ and $\varphi(\infty) = 0$. In the case of a spherical cavern, t_c [years] = $V^{2/3}$ [m^2]/400 is the time after which approximately 75% of the initial gap has been resorbed, $T_\infty - T_i(t_c) = (T_\infty - T_0)/4$. This time is large ($t_c$ = 1 year for a V = 8000 m^3 cavern). The average temperature change rate is
$\dot{T}_i = 0.75\ (T_\infty - T_0)/t_c$ during the 0–t_c period. Brine thermal expansion coefficient is approximately
α = 4.4×10^{-4} °C^{-1}; in a closed cavern a 1°C temperature increase leads to a 1-MPa pressure build up, $\dot{P}_i = \alpha \dot{T}_i / \beta$; in other words, the initial rate is 18 MPa $year^{-1}$ in a 8000-m^3 cavern and 1.2 MPa $year^{-1}$ in a 500,000 – m^3 cavern. In most cases pressure build up due to thermal expansion predominantly governs the behavior of a closed cavern and the above mentioned effect of salt creep is smaller; outstanding exceptions are found in the case of very deep caverns (You et al., 1994) or creep prone evaporitic layers (Fokker, 1995). However, in sharp contrast with creep effects, these thermal expansion effects can be avoided by waiting a sufficient amount of time before closing the cavern.

2.3. Permeability

The two former mechanisms contributing to pressure build up in a closed cavern have been early identified. The effect of rock mass permeability, which tends to release brine pressure, has long remained controversial. For every standard engineering purpose, rock salt can be considered as an impermeable rock. Thoroughful experiments performed at the WIPP site in small horizontal drill holes (Dale & Hurtado, 1997) provided permeabilities values as small as K = 10^{-21} m^2 for undisturbed salt. A one-year-long test, performed in a 1000 m deep well by Durup, 1998, gave
K = 6×10^{-20} m^2. How small these figures are is clearly illustrated by the case of a spherical cavern, radius R, in which brine pressure is P_i. If natural pore brine pressure is $P_0 < P_i$, steady state brine seepage rate will be:

$$Q_b/V = 3K(P_i - P_0)/(\eta R^2) \qquad (5)$$

For instance, $P_i - P_0$ = 5 MPa, R = 12.5 m (V = 8000 m^3), η = 1.2×10^{-3} Pa.s and K = 10^{-20} m^2 leads to Q_b/V = 0.25×10^{-4} $year^{-1}$, or Q_b = 0.2 m^3 $year^{-1}$. This figure is quite small, when compared to earlier estimations of cavern creep effect ($\dot{V}/V$ = - 3×10^{-4} $year^{-1}$ at a 1000 m depth) or thermal expansion effect ($\alpha \dot{T}_i$ = 8×10^{-3} year^{-1} in a 8000-m^3 cavern), and explains why an initial drastic pressure build up is observed during any "shut-in" test (during such a test, well head is closed and pressure evolution versus time is observed, Bérest et al., 1998). However, when long-term behavior is considered, the general pictures changes: thermal expansion can be disregarded, pressure builds up leads to smaller creep rate and larger seepage. An equilibrium state, characterized by exact balance between brine seepage and cavern shrinkage can take place. This equilibrium pressure can be significantly smaller than geostatic pressure, alleviating any fracture risk. This notion has been introduced by Bérest, 1990 and Ghoreychi & Cosenza, 1993. A test whose objective was to validate this notion will be presented in the following.

2.4. Cavern pressure evolution

The long-term evolution of a sealed brine-filled cavern can be as a whole described by the following equation:

$$\beta \dot{P}_i = -3K\,(P(t) - P_0)/(\eta R^2) + B(T_\infty)\left(P_\infty - P(t)\right)^n + \left(36/R^2\right)^{(1/3)} \alpha k (T_\infty - T_0)\varphi'(t/t_c)/(R^2) \quad (6)$$

where (3), (5) have been used; at the initial closure time, $P_i\ (0) = P_h$. The influence of cavern size (R) and cavern depth ($P_\infty - P_h$, T_∞) clearly appears in (6). It is easy to tune the parameters of this differential equation to fit any real evolution observed during a shut-in test. Clearly, the asymptotic value of brine pressure P_{eq}, reached when $t = \infty$, is defined by the equation.

$$3K\,(P_{eq} - P_0)/(\eta R^2) = B\,(P_\infty - P_{eq})^n \quad (7)$$

which depends on two parameters only (say, $B\eta(P_\infty\text{-}P_h)^{n+1}R^2/(3K)$ and n). It is important, prior to any in situ testing, to assess the quality and trustworthiness of the selected assumptions. Thermal evolution prediction (third term of (6) right hand side) is generally fairly good. The reason is that thermal conductivity $\tilde{K}$, in sharp contrast with intrinsic permeability K, does not vary to a large extent from one rock to another. Mechanical evolution prediction (second term of (6).) is at least qualitatively satisfactory; parameters (n and B) determination is open to discussion. Brine seepage (first term of (6).) prediction is much more arguable; in such a low-permeability medium, even use of Darcy law can be questioned and the introduction of the permeability coefficient K/η must be considered as a tentative definition of an "equivalent" or "average" permeability rather than the mathematical consequence of a well-stated phenomenon (Bérest et al., 2001).

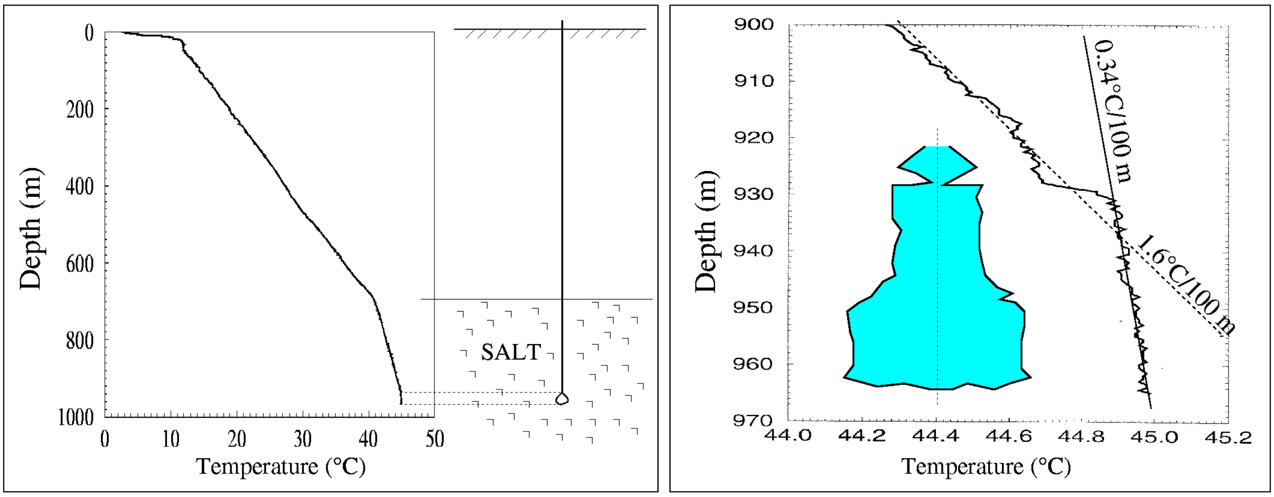

Figure 1 : Geothermal profile in the Ez53 cavern and well (February 1996). Note that brine temperature in the cavern is quite homogeneous, due to natural free convection.

3. VALIDATION

3.1. Test preparation

We are interested in the combined long-term effects of creep and percolation; test conditions must be selected to minimize the effects of thermal expansion. The Ez53 cavern of the Gaz de France storage site in Etrez (Figure 1) met these conditions. It was leached out in Spring 1982 (i.e., 15 years before the tests). Its volume is small ($V \cong 7500$ m^3); the characteristic time of heat transfer is t_c = one year. Cavern brine temperature measurements in 1982-1983 proved that 65 % of the initial temperature gap had already been resorbed after 250 days (Hugout, 1988). Temperature profiles were performed in 1996 and prove that thermal equilibrium was reached at that time (Figure 1).

The average cavern depth is 950 meters; at such depth, moderate creep rates can be expected. Brine outflow from the opened cavern was measured before the test: cavern convergence rate was 3×10^{-4} per year (Brouard, 1998). This figure is consistent with results of laboratory creep performed on Etrez salt by Charpentier, 1988, and discussed by Pouya, 1991.

Etrez salt permeability (K) and brine pore pressure (P_o) were not as precisely know. Durup, 1998, had performed an in–situ permeability test on the 150-m-high uncased part of the 1000 m-deep Ez58 well; he suggested a value of $K = 6\times10^{-20}$ m^2 and $P_0 \cong P_h$. Experience proves that several independent measurements are necessary before the order of magnitude of such phenomenon as large scale permeability or creep can be ascertained. Such measurements did exist in the case of thermal or mechanical properties, which had been studied by many authors on various sites; the same could not be said of permeation properties.

When applied to formula (7), the above cited Etrez parameters led to a predicted P_{eq} = 14.1 MPa value of the equilibrium pressure to be observed in the Ez53 cavern.

(Geostatic pressure is P_∞ =20.5 MPa and halmostatic pressure is P_o = 14.1 MPa).

3.2. Testing method

The test basically consists of a “trial and error” process: different pressure levels are tested successively (Figure 2). When the wellhead pressure rate consistently remains negative (resp. positive) for a sufficiently long period of time, it is re-adjusted to a slightly smaller (resp. larger) value, in hopes of triggering a change in sign for the pressure rate. The timing of each step must be thoroughly examined: any pressure change triggers transient effects (e.g., transient creep); each step must be long enough for these transient effects to vanish. Former tests (Hugout, 1988) have proven that these effects were more significant during a period of a dozen of days. During this test, each step was longer than 3 months.

3.3. Casing leakage

Permeation through cavern wall must be discriminated from brine leaks through the casing, casing shoe or wellhead. The latter is known to have occurred in some underground storage environments; this is why casing are tested through tightness tests before commissioning. A typically recommended resolution of such a test is 50 m^3 year^{-1} (Crotogino, 1994), much larger than the absolute values of creep rates or seepage flow considered during the described test. The existence of such leaks could lead to severe misinterpretation of the test. We designed a system to differentiate brine seepage and well leakage based on an idea first proposed by Diamond et al., 1993. Well completion includes a 9”$^{5/8}$ cemented casing and a 7” string; both the annular space and the central 7” string were filled with fuel oil, a light liquid which floats above the saturated cavern brine, a fuel-oil leak generates a fuel-oil/brine interface upward movement in the annular space (casing leak) or in the central tubing (well-head leak), therefore a differential evolution of the two measured well head pressures. This method proved to be extremely accurate (a fuel-oil leak of a few milliliters per day could be detected).

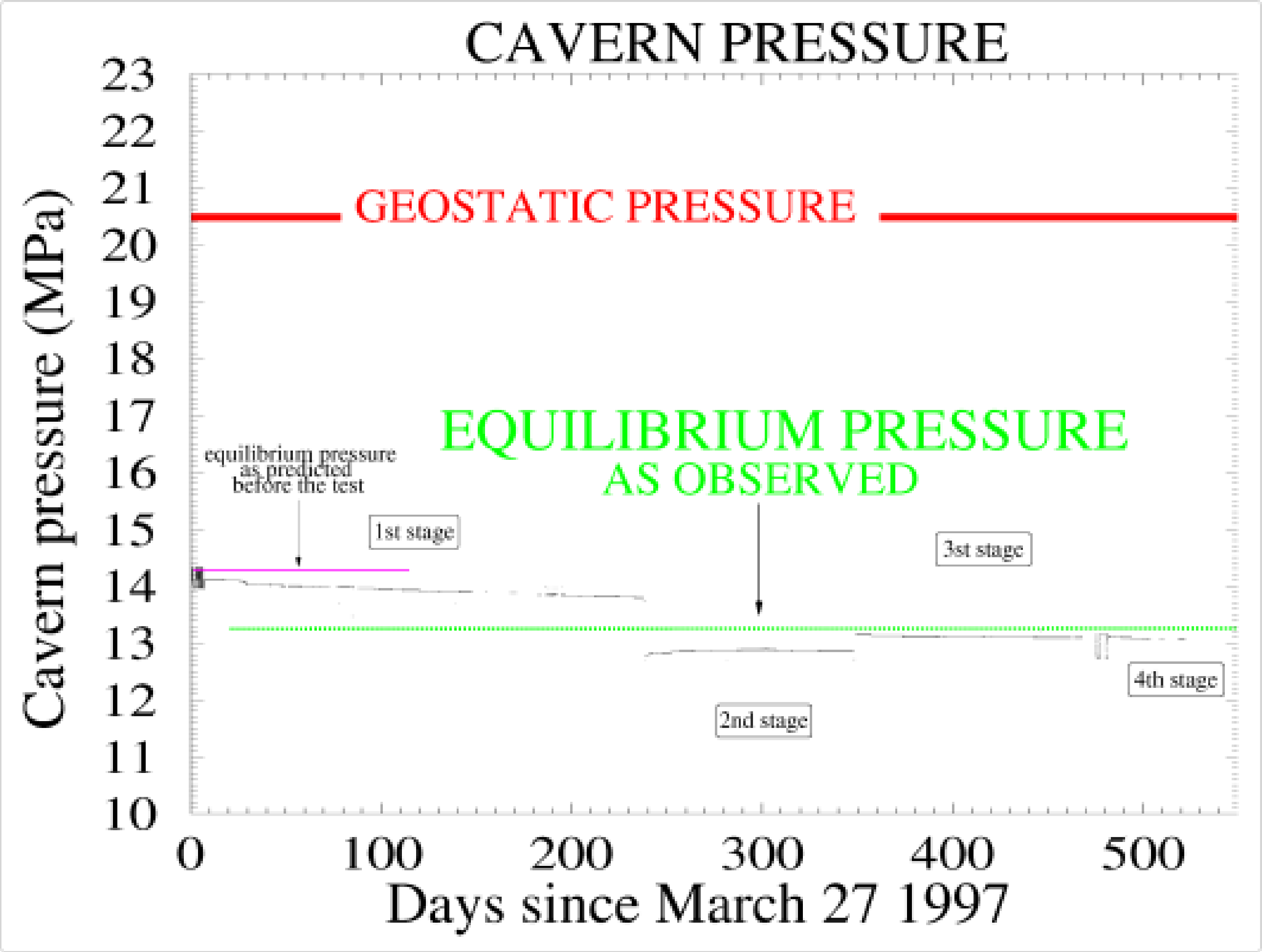

Figure 2 : Cavern pressure evolution during the test.

3.4. Mains results

The test was 540 day long and included four different steps (Figure 2). A fuel-oil leak appeared on day ≅ 295; it was first detected through the method described above and repaired. A full account of the results can be found in Bérest et al., 2001, to be published. From these results it can be inferred that the cavern pressure decreases when higher than $P_i = 13 \pm 0.1$ MPa (permeation prevails over creep) and increases when smaller than this value (creep prevails over permeation); the predicted value was $P_i = 14.3$ MPa. The discrepancy may be due to an initial underestimation of the equivalent permeability of a full-sized cavern. The actual permeability can be back-calculated using (7) which leads to $K = 2\times10^{-19}$ m^2 (instead of $K = 6\times10^{-20}$ m^2 estimated through a well performed test by Durup, 1988). This discrepancy is consistent with the generally accepted effects of scale on rock permeability (Brace, 1980). When equilibrium pressure is met, cavern shrinkage rate and brine seepage rate are of the order of 1.4 m^3 year^{-1} (or 3.3×10^{-11} s^{-1} when compared to overall cavern volume).

4. CONCLUSION

The 18-month-long test performed on the Ez53 cavern proves that brine pressure reaches an equilibrium value in a closed cavern when cavern creep rate (which leads to cavern shrinkage) exactly equals brine seepage toward the rock mass (which reduces the cavern brine volume). This test proves that salt formation permeability can prevent large pressure build up in an abandoned cavern, then avoiding the risk of fracture creation and rapid fluid seepage to shallow aquifers. Observed equilibrium pressure value was quite close to blindly predicted value, providing some confidence in the modelling. The remaining discrepancy must probably be attributed to a poor initial estimation of rock mass permeability, a phenomenon much more difficult to assess than heat transfer or even mechanical behavior.

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