DEEP SALT CAVERNS ABANDONMENT

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ABSTRACT: The behaviour of sealed and abandoned deep salt caverns is discussed. In such a cavern brine pressure builds up due to brine thermal expansion and cavern convergence, possibly leading to hydro-fracturing of the rock mass. However brine (micro) permeation through the cavern walls may release brine pressure, leading to a final equilibrium such that brine outflow balances cavern convergence rate. These phenomena are described and the ability to predict long-term evolutions is assessed. To validate these notions, an in situ test was performed.

KEYWORDS: Cavern abandonment, Salt permeability, Salt creep, In situ test.

RESUME : On discute du comportement à long terme de cavernes profondes réalisées dans un massif de sel après que ces cavernes ont été fermées et abandonnées. Dans une telle caverne, la pression de la saumure augmente en raison du réchauffement de la saumure et de la convergence de la caverne. Toutefois la (micro) perméabilité du sel permet une détente partielle de la saumure contenue dans la cavité, et l'apparition d'un équilibre dans lequel la perte de volume par convergence est égale au débit de saumure sortant de la caverne. Ces phénomènes sont décrits et on discute la qualité des prévisions d'évolution. Un essai in situ permet de valider les notions proposées.

MOTS-CLEFS : Abandon des cavernes souterraines, Perméabilité du sel, Fluage du sel, Essai in situ.

1. Introduction

In the past several years there has been concern about the long-term behaviour of deep underground salt caverns after they have been sealed and abandoned. By "deep" we mean caverns whose depths range between 400 and 2000 m and whose horizontal dimensions are significantly smaller than their depth (in such caverns there is no risk of a collapse leading to the creation of a sinkhole). Such deep caverns are leached out from a salt formation. A (typically) 1000-m deep well is cased and cemented to the salt formation. Soft water is injected into a central string and brine is withdrawn from the annular space between the string and the casing. After a year or so a 10,000 to 1,000,000 m^3 cavern is created. In many cases the cavern is later used for hydrocarbon storage (crude oil, LPG or natural gas); however there are several new projects in which caverns are used for disposal of nonhazardous, low level nuclear or industrial wastes, or carbon dioxide. These caverns will be abandoned some day; their long-term behaviour must be predicted (Ghoreychi and Cosenza, 1993; Brassow and Thoms, 2000; Dusseault *et al.*, 2001). The Solution Mining Research Institute which represents companies, consultants and research centers involved in the solution mining industry has set this problem at the center of its research program (Ratigan, 2000).

In most cases, prior to abandonment, the cavern will be filled with brine. Then a special steel plug will be set at casing seat or at a milled "window" above the casing seat, and cement will be poured in the well, isolating a large “bubble” of brine, the evolution of which is the concern of this paper. The brine initial pressure results from the weight of the brine column which filled the well before it was plugged; this pressure is called *halmostatic* and is equal to P_h (MPa) = 0.012 H (m), where H is the average cavern depth. After the cavern is sealed, the brine pressure will build up, as proven by many “shut-in pressure tests” (see for instance, Fokker, 1995; Bérest *et al.*, 2000). Typical build up rates are 3 to 10 MPa/year, but much faster rates can be observed in very deep (say deeper than 2000 m) caverns. The final value of cavern brine pressure is of utmost importance. In a salt formation the natural state of stress in general is isotropic and the geostatic pressure at cavern depth, or H, is P_∞ (MPa) = 0.022 H (m). Several authors (Bérest and Brouard, 1995; Wallner and Paar, 1997) fear that brine pressure eventually reach a figure larger than the geostatic pressure, leading to hydrofracturing, upward brine flow through fractures and pollution of drinkable water. To which point such a scenario can be alleviated by taking into account salt (micro) permeability will be discussed later.

2. Factors contributing to pressure evolution

Behaviour of a sealed cavern is governed by four main phenomena (1) *brine thermal expansion* (2) *salt mass creep* (3) *brine permeation through the cavern walls* (4) *leaks through the casing or casing shoe*. These phenomena result in brine pressure change through *cavern compressibility*. These notions will be developed in the following paragraphs.

2.1. Cavern compressibility

When a certain amount of liquid is injected in a closed cavern or when cavern brine is heated, or when cavern shrinks due to rock mass creep, cavern pressure increases. The relation between the cavern pressure increase rate, or $\dot{P}_i$, and the volume change rate, or Q, is linear during a rapid evolution and the proportionality constant is the cavern compressibility or βV_c:

$$Q = \beta V_c \dot{P}_i \tag{1}$$

Cavern compressibility can be simply measured when injecting brine and measuring the resulting brine pressure build-up. Cavern compressibility is the slope of the curve (injected brine versus brine pressure). An example is provided on Figure 1.

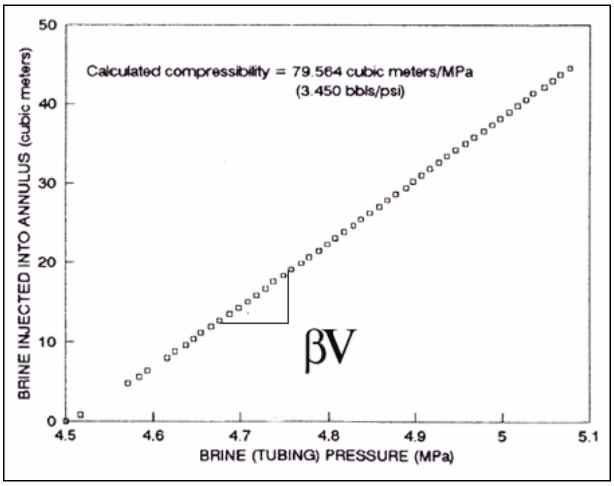

Figure 1 - Measurement of cavern compressibility [After Thiel, 1993].

Cavern compressibility, or βV_c, is proportional to cavern volume, or V_c. The compressibility factor, or β, is the sum of the cavern brine compressibility factor ($2.57\cdot10^{-4}$ MPa^{-1} is typical) and the cavern compressibility factor, which depends upon both rock-salt elastic properties and cavern shape. A typical value of the cavern compressibility factor is $1.4\cdot10^{-4}$ MPa^{-1}, making $\beta = 4\cdot10^{-4}$ MPa^{-1}; however larger values are sometimes met, for instance when the cavern is somewhat flat (Bérest *et al.*, 1999). In fact "instantaneous" compressibility and "long-term" compressibility must be distinguished. The above mentioned figures stand for a rapid test; when long term behaviour is considered, such phenomena as additional dissolution make the "long-term" compressibility larger (brine concentration at saturation, or the amount of brine that can be dissolved in a given mass of water, is a function of pressure and temperature; any pressure increase results in a (delayed) additional dissolution; as brine volume is smaller than the sum of the volumes of the water and the salt, the brine pressure increase is followed by a slight delayed pressure decrease of the initial pressure increase by 4 to 5 %, Van Sambeek *et al.*, 2005; this phenomenon cannot be observed during a short test).

2.2. Brine thermal expansion

In many cases, brine thermal expansion is by far the prominent factor explaining brine pressure build-up in a closed cavern. Its effects slowly reduce with time, but, in a big cavern, they can be effective during several decades.

The temperature of rock increases with depth, a typical value being T_R = 45°C at a depth of H = 1000 m, but caverns are leached out using soft water pumped from a river, lake or shallow aquifer whose temperature is cooler. Brine temperature at the end of leaching, or T_i^o, is close to the soft water temperature and significantly smaller than rock temperature. When the cavern remains idle, after leaching is completed, the initial temperature difference, or $T_R - T_i^o$, slowly resorbs with time, due to heat conduction in the rock mass and heat convection in the cavern brine. Appropriate heat-transfer equations can be written as follows:

$$\begin{cases} \dfrac{\partial T}{\partial t} = k_{salt}^{th} \Delta T \\ \int_{\Omega} \rho_b C_b \dot{T}_i d\Omega = \int_{\partial\Omega} K_{salt}^{th} \left(\partial T / \partial n \right) da \\ T_i(t) = T_{wall} \\ T(t=0) = T_R \text{ and } T_i(t=0) = T_i^o \end{cases} \tag{2}$$

The temperature in the rock mass is T; brine temperature is T_i. The first equation holds inside the rock-salt mass (k_{salt}^{th} is the thermal diffusivity of salt, $k_{salt}^{th} \approx 3\cdot10^{-6}\ \text{m}^2/\text{s}$) ; the second equation is the boundary condition at cavern wall ($K_{salt}^{th} = k_{salt}^{th} \rho_{salt} C_{salt}$ is the thermal conductivity of rock-salt, K_{salt}^{th} = 6 W/m/°C is typical, and $\rho_b\, C_b = 4.8\cdot10^{-6}$ J/m^3/°C is the volumetric heat capacity of brine). The third equation stipulates that rock temperature at cavern wall is equal to the average brine temperature in the cavern, or T_i, which is roughly uniform, a reasonable assumption as thermal convection stirs brine cavern effectively. The last equation describes the initial temperature distribution in the rock formation.

The exact temperature evolution in an actual cavern can easily be predicted through numerical computations. Back-of-the envelope estimations can be reached simply: dimensional analysis proves that heat transfer in the rock mass is governed by one characteristic time,

$t_c = R^2 / \pi k_{salt}^{th}$, where R is defined by $V_c = 4\pi R^3 / 3$, or $t_c(\text{years}) \approx V_c^{2/3}(\text{m}^2)/800$. The second equation of (2) provides a second characteristic time, or $t'_c = t_c / \chi$, $\chi = \rho_b C_b / \rho_{salt} C_{salt}$, which is of the same order of magnitude as t_c. In the case of a roughly spherical cavern, $2t_c$ is the time after which approximately 75% of the initial temperature difference has been resorbed. When V_c = 8,000 m^3, $2t_c \approx 1$ year; when V_c = 512,000 m^3, $2t_c \approx$ 16 years. The average temperature change rate (from leaching completion time to twice the characteristic time) is $\dot{T}_i =$ 0.75 $(T_R - T_i^o)/2t_c$ - i.e., when $T_R - T_i^o = 25°\text{C}$, $\dot{T}_i$ = 18°C/year in a 8,000 m^3 cavern and $\dot{T}_i$ = 1.2°C/year in a 500,000 m^3 cavern.
In a opened cavern, a temperature increase leads to thermal expansion and brine outflow at ground level, $Q_{th} = \alpha_b V_c \dot{T}_i$, where α_b is the brine thermal expansion coefficient, $\alpha_b \approx 4.4 \cdot 10^{-4}/°\text{C}$. In a closed cavern temperature increase leads to pressure build up:

$$\dot{P}_i = (\alpha_b / \beta) \dot{T}_i \tag{3}$$

The ratio α_b / β is close to 1 MPa/°C: when an initial temperature difference of 25°C is resorbed, after a time equal to several times t_c, the related pressure build up should be 25 MPa, far exceeding the initial difference between geostatic and halmostatic pressure which is P_∞ - P_h (MPa) = 0.01 H (m), or 10 MPa at a 1,000-m depth, and possibly leading to salt fracture. How fast this difference is resorbed depends on cavern size; the initial rate is 18 MPa/year (but rapidly decreasing) in a 8,000 m^3 cavern and 1.2 MPa/year in a 500,000 m^3 cavern. An example is provided in Figure 2. The three caverns (A, B, C) were leached out at the same time in the same salt formation and are at comparable depth. For technical reasons, leaching was stopped for a couple of weeks and advantage was taken of this stop to perform shut-in pressure tests. As-observed, pressure build-up rates were 4 MPa/year, 5.9 MPa/year and 10 MPa/year on the 346,000 m^3, 147,000 m^3 and 48,600 m^3 caverns, respectively, clearly highlighting the influence of cavern size on pressure build-up rate.

2.3. Salt mass creep

All solution-mined caverns converge as they gradually, and quite slowly, shrink. The driving force is the difference between the geostatic pressure (P_∞) and the cavity internal pressure (P_i). At this step a few comments on the mechanical behavior of salt are helpful. Most experts agree on the main features of steady-state rock-salt behaviour:

a) In the long term, rock-salt flows even under very small deviatoric stresses.
b) Creep rate is a highly non-linear function of applied deviatoric stress and temperature.
c) Steady-state creep is reached after several weeks or months when a constant load is applied to a sample; it is characterized by a constant creep rate.
d) Transient creep is triggered by any change in the state of stress; it is characterized by high initial rates (following a deviatoric stress increase) that slowly reduces to reach steady-state creep.
e) When deviatoric stress is large, salt experiences damage and dilatancy: its permeability drastically increases. The same occurs when salt is in contact with brine whose pressure is higher than the minimum principal stress (Fokker, 1995).

Main features of steady-state creep are captured by the following simple model (Norton-Hoff power law):

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

Where J_2 is the second invariant of the deviatoric stress tensor; A, n, Q/R are model parameters.

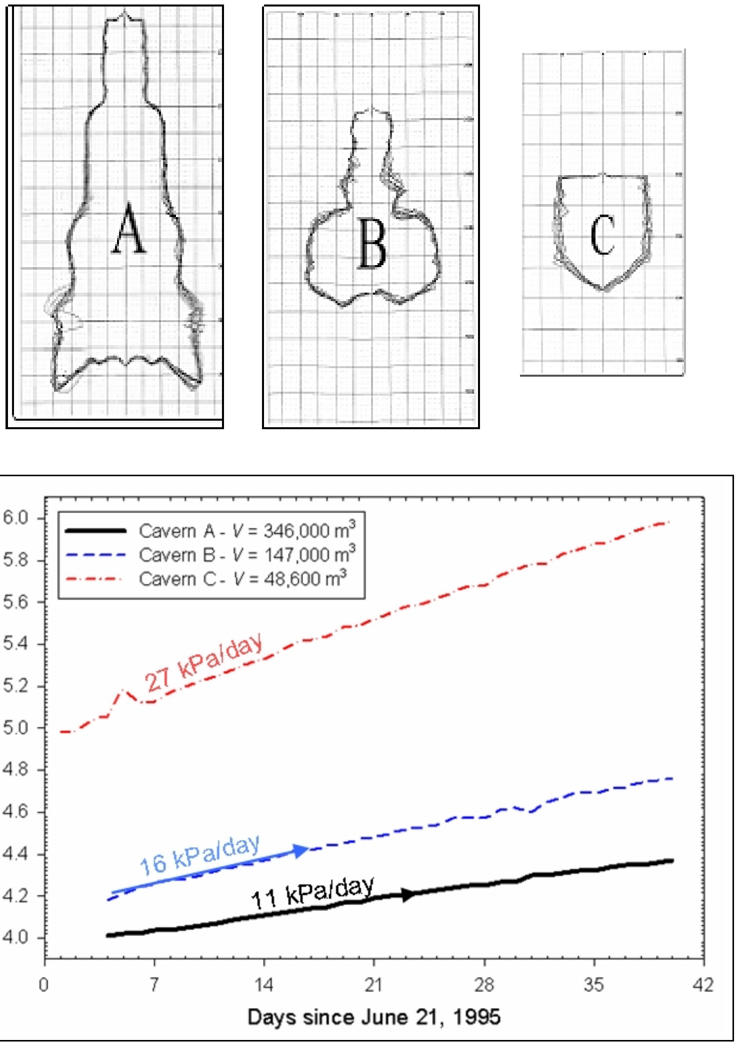

Figure 2 – Pressure Build-Up Due to Brine Thermal Expansion in a Small, Big, and Medium Size Cavern.

Values of these parameters were collected by Bérest and Brouard, 1998: for 12 different salts, the constant n is in the range n = 3-6, illustrating the highly non-linear effect of the applied stress on the strain rate, and Q/R ranges from 4,000 to 10,000 K. Several authors suggest constitutive laws which take into account transient creep. Here again, numerical computations allow to assess cavern convergence (i.e., loss of volume) as a function of time and cavern pressure history. The steady-state formulation (4) allows to obtain a closed-form solution for the idealized case of a perfectly spherical cavern that, over a long period of time, is submitted to an internal pressure (P_i) smaller than the natural geostatic pressure (P_∞) at cavern depth (H). In this solution the long-term deviatoric stress is much smaller (when $n > 1$) than in the corresponding elastic solution and the volume change rate is:

$$\dot{V}_c \big/ V_c = -\frac{3}{2}\left[\frac{3}{2n}\left(P_\infty - P_i\right)\right]^n A \exp\left(-\frac{Q}{RT_R}\right) = A^*(P_\infty - P_i)^n \qquad (5)$$

An immediate consequence of this solution is that, as long as the cavern brine pressure is smaller than the geostatic pressure, the cavern shrinks, leading to cavern pressure build-up ($\dot{P}_i > 0$) in a closed cavern.

$$\dot{P}_i = \left(1/\beta\right)\dot{V}_c / V_c \qquad (6)$$

A typical value of the initial shrinkage rate (when cavern depth is H = 1000 m and pressure is still close to halmostatic) is $\dot{V}_c/V_c$ = -3·10^{-4} year^{-1}, although there are large variations according to site-specific salt properties and cavern shape. Such a shrinkage rate in a closed cavern will lead to a pressure build-up rate of $\dot{P}_i = (1/\beta)\dot{V}_c/V_c$ = 0.75 MPa/year when β = 4·10^{-4} MPa^{-1}. Two comments must be made:

1. Pressure build-up progressively leads to smaller creep rates, because the difference $P_\infty - P_i$ between geostatic pressure and brine pressure reduces with time (it reduces even faster when brine thermal expansion is taken into account).
2. In most cases, and at least in a freshly leached out cavern, the contribution of cavern shrinkage to pressure build-up is much smaller than brine's (see Paragraph 2.2). It is only in a very deep cavern (H = 2000 m) that cavern shrinkage due to salt creep governs cavern pressure evolution. The reason is two-fold: the initial difference between geostatic pressure and brine pressure is proportional to cavern depth, $P_\infty - P_i = 0.01\,H,$ making the cavern convergence rate proportional to H^n; rock temperature, or T_R, is increasing with depth and the cavern convergence rate is proportional to $\exp(-Q/RT_R)$.

2.4. Leaks

As will be seen later, rock salt permeability in most cases is exceedingly small. The real problem is usually the "piping", that is, the cemented well that connects the cavern to the ground surface. While correct and robust well designs prevent most leakages, full scale testing is necessary to ensure that acceptable tightness exists. Tightness tests are performed before commissioning a cavern (and from time to time during cavern operation). It is often considered that the maximum allowable leak rate during such a test is Q_{leak} = 1000 bbls/year (Thiel, 1993) or 160 m^3/year, a relatively high figure (in a 100,000 m^3 cavern, when cavern compressibility is β = 4·10^{-4} /MPa, the pressure drop rate generated by such a leak is $\dot{P}_i = -Q_{leak}/\beta V_c = -4$ MPa/year, a figure larger than cavern convergence rate due to salt creep.) However it can be assumed that such a leak, which is effective when the cavern is in operation, will be made much smaller or even nil when the casing would have been plugged and filled with cement before cavern abandonment.

2.5. Salt permeability

For every standard engineering purpose, rock salt can be considered as an impermeable rock. Its matrix hydraulic conductivity is small and no fractures exist in a massive salt formation. The generally small permeability numbers resulting from laboratory tests are scattered ($K_{salt}^{hyd} = 10^{-21}$ m^2 to 10^{-18} m^2). Few in situ tests have been performed. A 1-year-long test, performed in a well and supported by the SMRI (Durup, 1994) gave $K_{salt}^{hyd} = 6\cdot 10^{-20}$ m^2. Such figures are extremely small (hydrogeology textbooks generally define an impermeable rock as a one whose permeability is smaller than $K_{salt}^{hyd} = 10^{-17}$ m^2.) When short-term use of salt caverns is considered, salt cavern are extremely safe from the perspective of product confinement. However when very long-term behaviour is considered, the general picture changes. When brine warming becomes negligible, even tiny losses of fluids, due to high cavern stiffness, can significantly lessen the effect of cavern creep and prevent cavern pressure from reaching high levels. To be more specific, consider the case of a spherical cavern with radius R, excavated in a salt mass with permeability K_{salt}^{hyd}, cavern brine pressure P_i and natural pore brine pressure P_o (The existence of a pore brine pressure uniform throughout the rock salt mass is arguable, as salt porosity is small – often smaller than 1% - and pore connectivity is likely to be poor. However the (few) in situ tests performed in salt mines or salt caverns prove that the notion of a pore pressure is consistent with test results. It is often assumed that pore pressure is equal to halmostatic pressure. However tests performed at the WIPP site proved that pore pressure was higher than expected (Dale and Hurtado, 1997) and more recently several observations made at a storage site (de Laguerie *et al*., 2004) strongly suggest that pore pressure in this specific site was smaller than halmostatic. However for simplicity we assume in the following that $P_o = P_h$.) If μ_b is the brine dynamic viscosity ($\mu_b = 1.4 \cdot 10^{-3}$ Pa.s) then, assuming Darcy law, steady-state brine seepage rate from a closed cavern is:

$$Q_{perm} / V_c = 3K_{salt}^{hyd} \left(P_i - P_o\right) / \left(\mu_b R^2\right) \tag{7}$$

This rate is quite small (for instance, $P_i - P_o = 7$ MPa, R = 12.5 m and $K_{salt}^{hyd} = 10^{-20}$ m^2 leads to $Q_{perm} =$ 0.25 m^3/year) but it can balance creep rate, especially when cavern brine pressure is high.

2.6. Pressure evolution in a closed cavern

Pressure evolution in a closed cavern result from the effects of brine thermal expansion, cavern convergence due to salt creep, brine permeation through the cavern wall and (possible) leaks. The following equation captures these four effects:

$$\begin{cases} \beta \dot{P}_i = \alpha_b \dot{T}_i \left[t/t_c\right] + A^* \left(P_\infty - P_i\right)^n - 3K_{salt}^{hyd} \left(P_i - P_o\right) / \left(\mu_b R^2\right) - Q_{leak} / V_c \\ P_i \ \left(t = 0\right) = P_o = P_h \end{cases} \tag{8}$$

We assumed that pore pressure is halmostatic ($P_o = P_h$). For simplicity, leaks through the casing in a sealed cavern will be supposed to be negligible ($Q_{leak} = 0$). Note that (8) only holds when a slow evolution is considered, as *steady-state* formulations of cavern convergence rate and brine outflow rate are taken into account. $\dot{T}_i$ becomes negligible after a period of time larger than several times t_c (keep in mind that t_c can be several decades long in a large cavern). In other words, equation (7) proves that after a long period of time, brine pressure rate ($\dot{P}_i$) vanishes and cavern pressure reaches an equilibrium value, or P_{eq}, such that:

$$A^* \left(P_\infty - P_{eq}\right)^n = 3K_{salt}^{hyd} \left(P_{eq} - P_o\right) \tag{9}$$

And $P_o < P_{eq} < P_\infty$: the equilibrium pressure is smaller than geostatic and larger than halmostatic. This equilibrium pressure is reached when cavern volume loss rate exactly balances brine outflow from the cavern.

3. Assessing the value of long-term predictions

Our goal is to predict the long-term evolution of a sealed and abandoned cavern. The cavern may be filled with pure brine or with some chemical or radioactive wastes, and the meaning of “long-term” is not the same in these three examples. We assume in the following that we want to be able to make accurate quantitative predictions about a period of, say, 3 centuries and to make qualitative predictions when longer periods of time are considered. The quality of the assumptions made above – all contributing to pressure history in a closed cavern – must be assessed.

Cavern compressibility was measured in dozens of caverns (it is a fundamental pre-requisite to any interpretation of a cavern tightness test, a mandatory test for most caverns) and values of β = 4 to 5

10^{-4} MPa^{-1} are generally reported. No smaller figures have been found (brine compressibility is a lower bound for cavern compressibility). It was said that “long-term” cavern compressibility is slightly higher than “short-term” cavern compressibility, but the difference is small. Larger figures are met in flat caverns, or when the cavern contains an even small amount of gas, which is much more compressible than brine. However larger compressibility values make pressure build-up rate slower, a significant advantage in the context of cavern abandonment.

Brine thermal expansion is a well described phenomenon; the various constants such as $\alpha_b, K_{salt}^{th}, k_{salt}^{th}$ are well known and their range of variation from one site to another is small. The system of equations (2) is robust (it leads to excellent temperature evolution predictions because conduction is the only heat transfer process in an impermeable rock, and because thermal convection in the cavern, which stirs brine and makes its temperature uniform through the cavern, is generated by the natural geothermal gradient, a perennial source of energy). Furthermore, brine expansion rate vanishes to zero when very long term evolutions are considered.

Salt creep has been extensively studied. No other rock has given rise to such a comprehensive set of laboratory experiments, motivated, to large extent, by the specific needs of nuclear waste storage¸ see for instance the proceedings of the five Conferences on the Mechanical Behaviour of Salt (Hardy and Langer, 1984 and 1988, Hardy *et al*., 1996, Aubertin and Hardy, 1998, Cristescu *et al*., 2002). Dedicated numerical models, able to accommodate sophisticated constitutive laws, have been written. However, actual cavern convergence data are rough, scarce, and somewhat inaccurate (Bérest, 2005a); they make validation of sophisticated models uncertain. It was said that the constants in mechanical constitutive laws vary to large extent from one site to another, in sharp contrast, for instance, with the constants in the thermal model. Laboratory experiments generally have been performed on rock samples submitted to relatively large deviatoric stresses; it has been argued (Bérest *et al*., 2005b) that the constitutive laws inferred from these tests do not apply to the much smaller deviatoric stresses that will be encountered in the vicinity of an abandoned cavern experiencing high cavern brine pressure (creep rates should be much faster than is expected from standard laboratory results).

Salt permeability is by far the most uncertain factor in long-term cavern behaviour. The concept of a homogeneous isotropic permeability (i.e., a uniform value of K_{salt}^{hyd} through the whole salt mass) is probably incorrect. Bedded salt contains a fair amount of impurities and it can be suspected that their permeability is much larger than the permeability of pure salt. Salt permeability is strongly influenced by the state of stress, and several authors believe that most of the (small) permeability observed during in situ tests in salt caverns is induced by cavern creation and operation (more precisely, either by tensile or high deviatoric stresses developed at the cavern wall, when the cavern fluid pressure is very high or very small, respectively.)

Uncertainties remain, and the present state of knowledge does not allow to perform blind predictions (i.e., predictions based on laboratory measurements). In situ tests must be performed before decommissioning a cavern. Such a test is described in Paragraph 4. Note that, as far as possible, in situ tests must not be used to back-calculate model parameters but rather to check that model parameters, which are to be independently determined, were accurately assessed before the test.

4. In situ test in the EZ53 cavern

4.1. Objective of the test

The objective of the test was to verify that pressure build-up in a sealed cavern does not reach geostatic values but, rather, due to the combined effects of salt creep and salt (small) permeability, will vanish when a certain steady-state value of the cavern pressure (larger than halmostatic, but significantly smaller than geostatic) is reached. The cavern selected for the test was the EZ53 cavern of the Gaz de France storage site in Etrez, France. Its volume is small (7500 m^3) and its depth is 950 m. It was leached out in Spring 1982, i.e., 15 years before the test. The test was supported by the SMRI.

4.2. Brine thermal expansion

From Spring 1982 to Winter 1983, the thermal behaviour of the EZ53 cavern was monitored via cavern brine temperature measurements; they confirmed that 65% of the initial temperature difference between the rock mass and the cavern brine has been already resorbed after 250 days, which is consistent with the value of the characteristic time, $t_c \text{ (years)} \approx V_c^{2/3}(\text{m}^2)/800$ = 6 months (see Paragraph 2.2.). Temperature profiles were performed 14 years later, in February and March 1996, a few weeks before the test: they strongly suggested that thermal equilibrium was reached at that time, and that brine thermal expansion could be disregarded.

4.3. Salt creep

The rock salt belonging to the so-called upper layer of the Etrez salt formation, in which the EZ53 cavern had been leached, was studied by Pouya (1991) who fit laboratory data to the Norton-Hoff constitutive law described in Paragraph 2.3 and suggests the following parametric values: A = 0.64 MPa^{-n}, Q/R = 4100 K, n = 3.1. With these figures a simple estimation of cavern convergence rate in a 950-m deep cavern can be reached, see Formula (4); it is $\dot{V}_c/V_c$ = - 3 10^{-4} $year^{-1}$. Several weeks before the test, the EZ53 well-head was left opened and Brouard (1998) measured the brine outflow from the cavern. As the cavern had been at rest for most of the time since the end of leaching, and brine thermal expansion was nil, this outflow was considered as representative of steady-state cavern creep. The outflow was 6 liters per day, or $\dot{V}_c/V_c$ = - $3 \cdot 10^{-4}$ $year^{-1}$; this perfect agreement between observed and computed figures must be considered as partly fortuitous, but it does provide some confidence in the estimation of the mechanical behaviour of the cavern.

4.4 Brine permeation

Etrez salt permeability has been studied by Le Guen (1991) who found for some samples an intrinsic permeability of $K_{salt}^{hyd} = 10^{-21}$ m^2. Durup (1994) has performed an in situ permeability test on the EZ58 well, which belongs to the same salt formation as EZ53 and has similar depth. Durup found that pore pressure, P_o, was very close to halmostatic pressure, or $P_o = P_h$, and suggested an average value of $K_{salt}^{hyd} = 6 \cdot 10^{-20}$ m^2 for the 150-m high EZ58 well. This larger figure is consistent with the generally accepted effects of scale on rock permeability; as explained below, still larger values were found when interpreting the EZ53 test, performed in a *cavern* instead of a *well*.

4.5. Leaks

An important difference between a shut-in test and an actual cavern abandonment lays in the fact that during a shut-in test the cavern is closed at the well-head – and not sealed at the bottom of the well. During the test, leaks can occur in the well through the casing, the casing shoe or through the well-head. Such leaks would lead to severe misinterpretation of a sealed cavern long-term behaviour. To assess these leaks, an oil column was lowered down to a depth of 864.5 m (i.e., below the casing shoe depth) in the annular space between the cased and cemented casing and a central string. A small amount of oil was also injected in the central string. Pressure evolutions were measured at the well-head both in the annular space and in the central string. Oil density is smaller than brine density. Any oil leak through the casing (or through the well-head) results in a rise of the oil/brine interface and a difference in the evolution of the two pressure measured at the well-head. This system proved to be quite effective. In fact a leak (on day 315 after the test began) was detected through curve observation before being observed – and repaired – in the field.

4.6. Test results

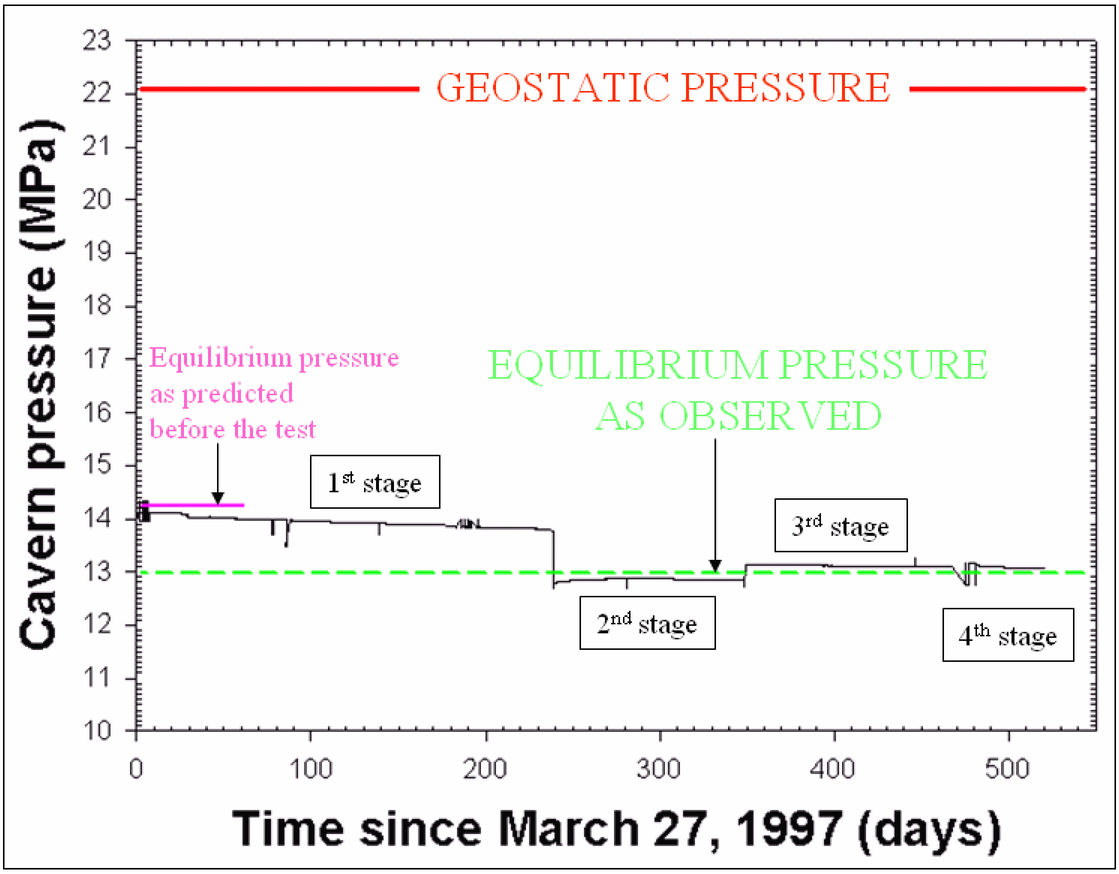

Figure 3 – Cavern evolution during the EZ53 test.

The test basically consists of a “trial and error” process (Figure 3) to approach the expected steady-state pressure. Different pressure levels are tested successively; each level is selected to trigger a change in pressure rate sign, providing upper and lower bounds for the steady-state equilibrium value. The test lasted 540 days and 4 steps were managed. From the test it can be inferred that the equilibrium is $P_{eq} = 13.0 \pm 0.1$ MPa. The equilibrium pressure is much smaller than the geostatic pressure, which is $P_{\infty} = 20.5$ MPa at a 950-m depth, and larger than halmostatic pressure which is $P_h = 11.2$ MPa. A $P_{eq} = 14.3$ MPa figure had been predicted before the test. While EZ53 creep, which had been measured through in situ tests, can be considered to have been reasonably well estimated, it is logical to conclude that cavern permeability must be larger than estimated through earlier well tests; a $K_{salt}^{hyd} = 2 \cdot 10^{-19}$ m^2 value can be back-calculated; the variations in cavern volume and cavern brine volume are then of the order of $Q_{perm} \approx 1.4$ m^3/year. This test proved that in this site an equilibrium pressure did exist and that its value could be relatively well predicted. A similar test was performed in a 700-m deep cavern in another site (Brouard *et al.*, 2004) and two additional tests are currently performed in shallow caverns in France and Germany; these two tests are supported by the SMRI.

5. Conclusions

It was proved that in a sealed cavern brine pressure evolution is governed by brine thermal expansion, cavern convergence due to salt creep and brine permeation through the cavern wall. In a (micro) permeable formation brine pressure will not exceed a figure smaller than a geostatic value – provided that thermal expansion can be disregarded. After a long period of time, a large volume of rock salt around the cavern will be impregnated by brine expelled from the cavern. The final equilibrium pressure can be accurately predicted provided that cavern thermal history, rock salt permeability and rock salt mechanical behaviour are known. An in situ test proved that most phenomena were relatively well described: cavern compressibility and brine thermal evolution can be very accurately measured and computed; cavern convergence can be fairly well predicted; large scale permeability of salt formations can be estimated through an in situ test but remains a partly opened question.

6. References

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