Deep salt-cavern abandonment

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ABSTRACT: When a salt cavern is sealed and abandoned, its pressure slowly changes due to various mechanical, hydraulic, thermal and chemical effects. These effects are described in this paper. Several of them can be predicted accurately. It is suggested that an abandonment test be performed before sealing a cavern in order to assess each effect separately, a prerequisite for credible long-term prediction.

1 INTRODUCTION

Over the past several years, there has been growing concern about the long-term behavior 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 much smaller than their depth. (There is no risk of a collapse leading to the creation of a sinkhole in such caverns.) Many authors have contributed to this topic; several of them are referenced in the following. The Solution Mining Research Institute (SMRI), 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, 2003).

Prior to abandoning a storage cavern, hydrocarbons are withdrawn from it, and it afterward is filled with brine. (Brine production caverns obviously are filled with brine.) Cavern pressure at that point is halmostatic — i.e. it results from the weight of the brine column filling the well from the surface to the cavern, or P_h (MPa) = 0.012 H (m), where H is the cavern depth. A special steel plug is set above or below the casing seat, and cement is poured into the well, isolating a brine "bubble" whose long-term evolution must be predicted. Many "shut-in pressure" tests performed on closed caverns have proven that brine pressure increases in sealed caverns (see, for instance, Fokker 1995; Bérest *et al.* 2000). Typical initial 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 salt formations, the natural state of stress resulting from overburden weight generally is assumed to be isotropic — i.e. the geostatic pressure is P_∞ (MPa) = 0.022 H (m). (This assumption, however, must be verified on a case-by-case basis.) When the cavern pressure is larger than geostatic, hydro-fracturing is likely: brine may flow upward through fractures to shallow water-bearing strata, leading to water pollution, the consequences of which must be assessed for each site-specific situation.

2 FACTORS CONTRIBUTING TO PRESSURE EVOLUTION

2.1 *Introduction*

The behavior 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; and (4) leaks through the casing or casing shoe. These lead to cavern volume or brine volume changes:

$$\dot{V}_c / V_c = \beta_c \dot{P} - \alpha_c \dot{\bar{T}}_R - Q_{creep} / V_c \tag{1}$$

$$\dot{V}_b / V_b = -\beta_b \dot{P} + \alpha_b \dot{T} - Q_{leak} / V_b - Q_{perm} / V_b \tag{2}$$

where V_c is the cavern volume, V_b is the cavern brine volume, P is cavern brine pressure, T is cavern brine temperature, $\bar{T}_R$ is the average rock temperature change (more precisely defined in Section 2.5), Q_{creep} is the viscoplastic cavern volume change rate, Q_{leak} is the leak rate through the casing or casing shoe, Q_{perm} is the brine seepage rate through the rock mass; and $\alpha_b, \beta_b, \alpha_c, \beta_c$ are thermo-elastic coefficients that will be discussed later.

Other phenomena play a minor role. For instance, the amount of salt that can be dissolved in a given mass of water is an increasing function of pressure and temperature: an increase in P or T leads to additional dissolution. Salt dissolution is an endothermic reaction, and the volume of saturated brine is smaller than the sum of the volumes of its components (salt and water). From this, any increase in P or T is followed by a slightly delayed decrease (by a few percent of the initial change; precise figures are discussed in Van Sambeek *et al.* 2005). In other words, the "instantaneous" thermoelastic coefficients $(\alpha_b, \beta_b, \alpha_c, \beta_c)$ must be modified accordingly when slow processes are considered.

In a closed cavern, $V_b = V_c = V$ and Equations (1) and (2) result in

$$(\beta_c + \beta_b)\dot{P} = \alpha_b \dot{T} + \alpha_c \dot{\bar{T}}_R + \left(Q_{creep} - Q_{leak} - Q_{perm}\right)/V \qquad (3)$$

In the long term (several centuries) $\dot{T}$, $\dot{T}_R$ and $\dot{P}$ vanish to zero and there exists an "equilibrium pressure" such that $Q_{creep} = Q_{leak} + Q_{perm}$ (Q_{leak} is likely to be small). One aim of an in situ test is to predict "equilibrium pressure" value. For this reason the various terms in (3) must be assessed; they are discussed in the following paragraphs.

2.2 *Cavern compressibility*

Cavern compressibility, $\beta V = (\beta_c + \beta_b)V$, is proportional to the cavern (or brine) volume. Compressibility factor β is the sum of the brine compressibility factor (β_b = 2.57 x 10^{-4} MPa^{-1} holds for a rapid injection; the "long-term" figure is β_b = 2.7 x 10^{-4} MPa^{-1}, see above) and the cavern compressibility factor, or β_c, which depends upon both rock-salt elastic properties and cavern shape. A typical value of the cavern compressibility factor is β_c = 1.3 x 10^{-4} MPa^{-1}, which makes $\beta = 4\times10^{-4}$ MPa^{-1}; however, larger values are sometimes encountered — for instance, when the cavern is somewhat flat (Bérest *et al.* 1999).

Cavern compressibility can be measured simply when injecting brine and measuring the resulting brine pressure build-up. Cavern compressibility is the slope of the curve (injected brine *vs* brine pressure). However, mistakes can be made easily: when injecting (or withdrawing) fluids into (or from) a cavern, one may modify the composition or temperature of the fluids in the well. The relation between wellhead pressure and cavern pressure is modified accordingly, leading to possible misinterpretation.

2.3 *Leaks*

As will be seen later, the permeability of rock salt is exceedingly small in most cases. The real problem is usually the "piping"— that is, the cemented well that connects the cavern to the ground surface. Although 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 often is considered that the maximum allowable leak rate during such a test is $Q_{leak} = 160\ \mathrm{m^3/year}$ (Thiel 1993). Smaller apparent-leak rates often are measured during actual tests and Van Sambeek *et al.* (2005) proved that actual tests often overestimate the actual leak. It can be assumed that such a leak, which is effective when a cavern is in operation, will be made much smaller — or even nil — had the casing been plugged and filled with cement before cavern abandonment. For this reason, it is important to measure accurately leaks that occur during an abandonment test. The leak detection system is based on the density difference between brine and oil densities. ("Green" oil often is used during *in situ* tests). The system is similar to that described by Diamond *et al.* (1993) for brine production wells. The annular space is filled with oil to down below the last casing shoe; the central tubing also contains a small amount of oil (see Fig. 1). Let Q be a cavern or *brine* volume change rate; it generates the same pressure drop (when $Q<0$) or build-up ($Q>0$) rates in the cavern ($\dot{P}_c$), as well as in both the tubing ($\dot{P}_{tub}^{wh}$) and the annular space ($\dot{P}_{ann}^{wh}$) at the wellhead:

$$\dot{P}_{tub}^{wh} = \dot{P}_{ann}^{wh} = \dot{P}_c = Q/\beta V \qquad (4)$$

The two curves (annular-space pressure *vs* time) and (central-tubing pressure *vs* time) are perfectly parallel (right-hand picture in Fig.1).

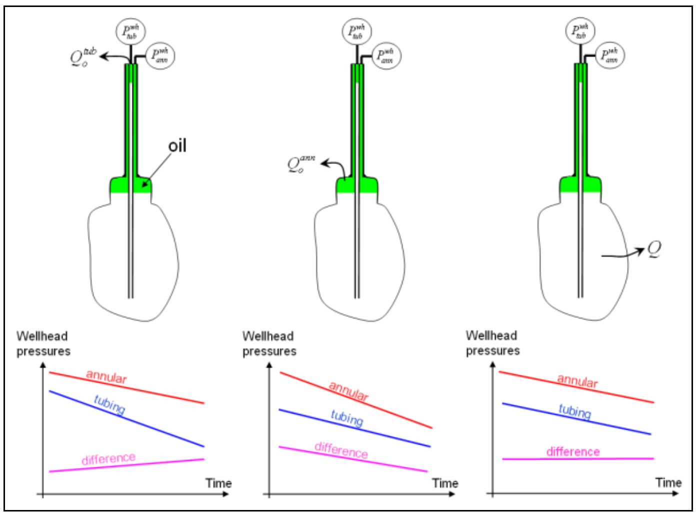

Figure 1. Principle of the oil-leak detection system.

A green oil leak from the central tubing (Q_o^{tub}) through the wellhead produces the same pressure drop both in the central tubing and in cavern — i.e. $\dot{P}_{ann}^{wh} = \dot{P}_c = -Q_o^{tub}/\beta V$. However, brine density ($\rho_b \approx 1200\ \mathrm{kg/m^3}$) is larger than the density of green oil ($\rho_o \approx 810\ \mathrm{kg/m^3}$): thus, a green oil leak yields to both an upward vertical displacement of the oil/brine interface and an additional pressure drop in the central tubing, $\dot{P}_{tub}^{wh} = \dot{P}_{ann}^{wh} - (\rho_b - \rho_o)\, g\, Q_0^{tub} / S_{tub}$, where S_{tub} is the cross-sectional area of the central tubing.

A green oil leak from the annular space (Q_o^{ann}) through the casing, casing shoe or at the wellhead acts in the reverse: the pressure drop rate in the tubing is simply $\dot{P}_{tub}^{wh} = \dot{P}_c = -Q_o^{ann} / \beta V$; in the annular space, it is $\dot{P}_{ann}^{wh} = \dot{P}_{tub} - (\rho_b - \rho_o)\, g\, Q_o^{ann} / S_{ann}$.

This system has proven to be extremely effective. It can detect leak rates smaller than 0.1 *l*/day, and even smaller leaks (0.01 *l*/day) when the pressure-difference evolutions are corrected from the effects of daily and annual ground-temperature fluctuations (Brouard Consulting *et al.* 2006).

2.4 *Brine thermal expansion*

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

The pristine temperature of rock increases with depth, a typical value being $T_R^\infty(H)$ = 45°C at a depth of H =1000 m, but caverns are leached out using soft water pumped from a river, lake or shallow aquifers that have cooler temperatures. Brine temperature at the end of leaching, T^0, is close to the soft-water temperature and significantly lower than the rock temperature, which is $T_R(\underline{x},t) < T_R^\infty$. When the cavern remains idle after leaching is completed, the initial temperature difference slowly resorbs with time, due to heat conduction in the rock mass and heat convection in the cavern. However, the injections and withdrawals of fluids during the operational life of a cavern yield additional temperature changes. The average brine temperature in a cavern, T, is almost uniform, as has been proven by temperature logs: thermal convection stirs brine cavern effectively. Appropriate heat-transfer equations can be written as follows:

$$\partial T_R / \partial t = k_{salt}^{th} \Delta T_R \tag{5}$$

$$\left[\rho_b C_b \dot{T} - \alpha_b T \dot{P}\right] V = \int_{\partial\Omega} K_{salt}^{th}\, \partial T_R / \partial n \cdot da \tag{6}$$

$$T(t) = T_R\,(\text{wall}) \tag{7}$$

$$T_R\,(\underline{x}, t=0) = T_R^0(\underline{x}) \text{ and } T\,(t=0) = T^0 \tag{8}$$

The first equation holds inside the rock salt mass (k_{salt}^{th} is the thermal diffusivity of salt, $k_{salt}^{th} \approx 3\times10^{-6}$ m²/s); the second equation is the boundary condition at the 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 x 10^6 J/m^3/°C is the volumetric heat capacity of brine). The term $\alpha_b T \dot{P}$ is small and can be disregarded, as $\dot{P}/\dot{T} \approx \alpha_b/\beta$ and $\alpha_b^2 T / \beta \rho_b C_b \approx 0.03$ (This term is significant only when short-term thermal effects of a rapid pressure build-up are considered.) The third equation stipulates that the rock temperature at the cavern wall, T_{wall}, is equal to the brine temperature. The last equation describes the temperature distribution in the cavern and in the rock formation when cavern sealing is performed (t = 0). In most cases, this quantity is poorly known, as the thermal history of the rock during the cavern's operational life often is complex. Brouard Consulting *et al.* (2006) suggest measuring cavern temperature to assess both cavern temperature and the rate of temperature increase. Temperature evolution can be measured by a temperature gauge set in the cavern for several weeks (However in a large cavern, brine warming is an exceedingly slow process and measuring temperature evolution may prove to be very difficult; in most cases a resolution as small one thousands of a degree Celsius and no gauge drift are needed.) This allows back-calculation of an "equivalent" thermal history — i.e. fictitious initial instant $t_0 < 0$ and initial temperature $T_R^0(\underline{x}, t_0) = T_R^0$ (T_R^0 is *uniform* throughout the entire rock mass.) are computed; they are such that the temperature and temperature rate at t = 0 are the same as the measured figures. This procedure provides good predictions of later temperature evolutions.

2.5 *Cavern thermal expansion/contraction*

In sharp contrast to brine expansion, cavern expansion cannot be described simply by a relation between rock temperature change and cavern volume change. For a given cavern shape, the following thermo-elastic problem must be solved: no body forces; no traction applied at the cavern wall; and thermal strain distributed in the rock mass, $\varepsilon_{th} = \alpha_{salt}(T_R - T_R^\infty)$, where α_{salt} = 4 x 10^{-5} °C^{-1}. In the case of an idealized spherical or cylindrical cavern, the resulting coefficient α_c is zero (see, for instance, Boley & Weiner 1997).

2.6 *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 cavity internal pressure, P. At this step, a few comments on the mechanical behavior of salt are helpful.

1 In the long term, rock salt flows even under very small deviatoric stresses.

2 Creep rate is a highly non-linear function of applied deviatoric stress and temperature.

3 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.

4 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 reduce to reach steady-state creep.

5 When deviatoric stress is large (compared to the mean stress), salt may experience damage and dilatancy, and its permeability drastically increases. The same occurs when salt is in contact with brine which has pressure that is higher than the minimum principal stress (Fokker 1995).

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

$$\dot{\varepsilon}^{ij} = \dot{\varepsilon}_e^{ij} + \dot{\varepsilon}_{ss}^{ij} \tag{9}$$

$$\dot{\varepsilon}_{ss}^{ij} = A\exp\left(\frac{-Q}{RT}\right)\frac{1}{n+1}\frac{\partial}{\partial\sigma_{ij}}\left[\left(\sqrt{3J_2}\right)^{n+1}\right] \tag{10}$$

$$E\dot{\varepsilon}_e^{ij} = (1+\nu)\dot{\sigma}_{ij} - \nu\dot{\sigma}_{kk}\delta_{ij} + \alpha_{salt}\dot{T}\delta_{ij} \tag{11}$$

where J_2 is the second invariant of the deviatoric stress tensor; E, ν, α_{salt}, A, n, Q/R are model parameters.

Several authors suggest constitutive laws that take into account transient creep. A complete set of equations can write:

$$\dot{\varepsilon}^{ij} = \dot{\varepsilon}_e^{ij} + F\dot{\varepsilon}_{ss}^{ij} \tag{12}$$

$$\dot{\sigma}_{ij,j} = 0 \tag{13}$$

$$\sigma_{ij}(\underline{x}=\infty,t)n_j = -P_\infty n_j \tag{14}$$

$$\sigma_{ij}\left(\text{wall},t\right)n_j = -P\left(t\right)n_j \tag{15}$$

where F is a multiplying factor (introduced by Munson & Dawson (1986) to account for transient creep). The second relation is the equilibrium condition, and (14) and (15) are the boundary conditions. Numerical computation allows cavern convergence (i.e. loss of volume) to be assessed as a function of time and cavern pressure history.

Values of the parameters A, n, Q/R (as measured during laboratory experiments) were collected by Brouard & Bérest (1998): for 12 different salts, constant n is in the range n = 3-6, illustrating the highly non-linear effect of applied stress on the strain rate, and Q/R ranges from 4000 to 10,000 K. It must be noted, however, that, especially in the case of bedded salt formations containing a fair amount of insolubles, laboratory test results often are scattered.

2.7 *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 low permeability numbers resulting from laboratory tests are scattered ($K_{salt}^{hyd} = 10^{-21}$ m^2 to 10^{-18} m^2.) Some authors believe that *in situ* (virgin) permeability is null (Lux *et al.* 2006). *In situ* tests were performed in bedded salt formations. A 1-year-long test performed in a well at Etrez site and supported by the SMRI (Durup 1994) gave $K_{salt}^{hyd} = 6\times10^{-20}$ m^2. Another SMRI-supported abandonment test at the same site, (Bérest *et al.* 2001) gave $K_{salt}^{hyd} = 2\times10^{-19}$ m^2. Such figures are extremely low. From the perspective of product confinement, when short-term use is considered, salt caverns are extremely safe. However, when very long-term behavior is considered, the general picture changes. When brine warming becomes negligible, due to high cavern stiffness, even tiny fluid loss, can lessen the effect of cavern creep significantly and prevent cavern pressure from reaching high levels. The set of equations relevant to the hydro-mechanical behavior of salt can be written as

$$\frac{1}{M}\frac{\partial p}{\partial t} + btr\dot{\varepsilon} = \frac{K_{salt}^{hyd}}{\mu_b}\Delta p \tag{16}$$

$$p\left(\text{wall},t\right) = P\left(\text{wall},t\right) \tag{17}$$

$$p\left(\underline{x}=\infty,t\right) = p^0 \tag{18}$$

where M is the Biot's modulus, p is pore pressure, b is the Biot's coefficient, μ_b is dynamic viscosity of brine ($\mu_b = 1.4\times10^{-3}$ Pa.s is typical), p^0 is the initial pore pressure (The existence of a uniform brine pore pressure throughout the rock salt mass is arguable, as salt porosity, or ϕ, is low— often lower than 1% — and pore connectivity is likely to be poor. However, the (few) *in situ* tests performed in salt mines or salt caverns have proven that the notion of a pore pressure is consistent with test results. It often is assumed that pore pressure is equal to halmostatic pressure, but tests performed at the WIPP site have proven that pore pressure is higher than expected (Dale & Hurtado 1997). More recently, several observations made at a storage site (de Laguérie *et al*. 2004) strongly suggest that pore pressure in this specific site was lower than halmostatic.) In fact, all these assertions are controversial, as the applicability of the notions elaborated in the context of reservoir engineering to almost impermeable rocks is questionable. Biot's modulus is defined by $1/M = \phi/K^{fl} + (b-\phi)/K^s$ where $\phi = 10^{-2}$, $1/K^{fl} = \beta_b = 2.7 \times 10^{-4}$ MPa^{-1} and K^s = 25 GPa are typical. Cosenza *et al.* (1999), following McTigue (1986) suggest $b = 0.1$, leading to $1/M = 6.3 \times 10^{-6}$ MPa^{-1}. It often is assumed that, in (16), $btr\dot{\varepsilon}$ can be disregarded, making the hydraulic problem uncoupled. In fact, there are many reasons to believe that coupling is strong because salt permeability is influenced by the state of stress (Lux 2006; Rokhar *et al*. 2003).

Parameters of the hydraulic behavior of rock salt are difficult to measure in the laboratory; furthermore, scale effects are suspected to be significant, and *in situ* tests are preferred. It is much simpler to measure salt permeability (and diffusivity) in a borehole than in a full-size cavern, where multiple effects intermingle (In a borehole, the ratio of surface to volume is larger than it is in a cavern by two orders of magnitude, and the effect of permeation on pressure evolution is made larger accordingly. Examples of this are discussed in Brouard *et al.* (2001) or Doe & Osnes (2006).

3 ASSESSING THE VALUE OF LONG-TERM PREDICTIONS

Our goal is to predict the long-term evolution of a sealed and abandoned cavern. We assume in the following that we want to be able to make accurate quantitative predictions for a period of about 3 centuries and to make qualitative predictions when longer periods of time are considered. The quality of assumptions made above — all contributing to the pressure history in a closed cavern — must be assessed.

Cavern compressibility was measured in dozens of caverns (It is a fundamental pre-requisite for interpreting cavern tightness tests, a mandatory test for most caverns), and values of $\beta = 4$ to 5×10^{-4} MPa^{-1} are reported generally. No lower figures have been found. (The value for brine compressibility is a lower bound for cavern compressibility.) It has been said that "long-term" cavern compressibility is slightly higher than "short-term" cavern compressibility, but the difference is small. Larger figures are encountered in flat caverns, or when the cavern contains a small amount of gas, which is much more compressible than brine (Bérest *et al.* 1999). However, larger compressibility values make the pressure build-up rate slower, a significant advantage in the context of cavern abandonment (Bérest *et al.* 2006a).

Brine thermal expansion is a well-described phenomenon: the various constants (e.g. $\alpha_b, K_{salt}^{th}, k_{salt}^{th}$) are well known, and their range of variation from one site to another is small. The system of equations (5) to (8) is robust, leading to excellent temperature evolution prediction because conduction is the only heat transfer process in an impermeable rock, and because thermal convection, which stirs brine and makes its temperature uniform throughout the cavern, is generated by the natural geothermal gradient, a perennial driving force. Furthermore, the rate of brine expansion slowly vanishes to zero; in the very long term, its influence is small. The coefficient of cavern thermal expansion, α_c, is null in an idealized, perfectly spherical or cylindrical cavern; it can be computed easily for any cavern shape.

Leaks can be assessed accurately during an *in situ* test when a system such as that described above is used. In tests performed to this date (Bérest *et al.* 2001; Brouard Consulting *et al.* 2006), these leaks were exceedingly small; they are expected to be smaller still after the cavern is sealed.

Salt creep has been studied extensively: see, for example, the proceedings of the five conferences on the Mechanical Behavior of Salt. Dedicated numerical models, able to accommodate sophisticated constitutive laws, have been written to predict the behavior of underground caverns. However, actual cavern convergence data are rough, scarce, and somewhat inaccurate (Bérest *et al.* 2006b), making validation of sophisticated models uncertain. It was noted previously that the constants in mechanical constitutive laws vary to a large extent from one site to another, in sharp contrast to the constants in the thermal model, for example. Laboratory experiments generally have been performed on rock samples submitted to relatively large deviatoric stresses. It has been argued (Bérest *et al.* 2005; Pennock *et al*. 2006) that the constitutive laws inferred from these tests do not apply to the much smaller deviatoric stresses to be encountered at large distance of the cavern or even in the vicinity of an abandoned cavern that experiences high cavern brine pressure. (Creep rates should be much faster than those extrapolated from standard laboratory results).

Salt permeability is by far the most uncertain factor in long-term cavern behavior. The concept of a homogeneous isotropic permeability (i.e. a uniform value of K_{salt}^{hyd} throughout the entire salt mass) is probably incorrect. Bedded salt contains a fair amount of impurities, and it is suspected that its permeability is much higher 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 low, respectively.) For instance, Doe & Osnes (2006) performed tests in Kansas wells, where they found that the wells exhibited composite behavior in which the material near the well had a higher permeability than the material farther away, possibly reflecting a borehole damage zone.

Uncertainties remain, and the present state of knowledge does not allow for blind predictions (i.e. predictions based on laboratory measurements). *In situ* tests must be performed before decommissioning a cavern. 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 determined independently, were assessed accurately before the test. In fact, cavern compressibility, brine thermal expansion and brine leaks can be measured accurately, but the same cannot be said of the rate of cavern creep closure and rock permeability. Orders of magnitude are known (e.g. K_{salt}^{hyd} belongs *a priori* to the range 10^{-22} m^2 to 10^{-18} m^2; the rate of cavern creep closure in an (opened) 1000-m deep cavern typically is $3\text{x}10^{-4}$ year^{-1}, and the actual figure can be faster or lower by one order of magnitude).

4 INTERPRETING ABANDONMENT TESTS

For the reasons explained above, one must try to assess separately the four effects that explain pressure build-up during an abandonment test. Pressure evolution must be observed for a sufficiently long "observation period". The objective of the test is to prove that an accurate prediction can be made. It was said that pressure increase (or decrease) rate, effects of thermal expansion and leaks can be measured accurately or predicted. They simply provide an estimation of the difference between brine permeation effects and cavern-creep closure effects:

$$Q_{creep} - Q_{perm} = (\beta_c + \beta_b) V\dot{P} - (\alpha_c + \alpha_b) V\dot{T} + Q_{leak} \qquad (19)$$

Assessing each of these two effects (Q_{creep} and Q_{perm}) *separately* is more difficult, and assumptions must be made. It generally is assumed that salt permeation is governed by the steady-state Darcy law and that cavern creep closure is governed by steady-state creep — two assumptions that are somewhat arguable. Salt formation permeability and Norton-Hoff parameters then can be back-calculated through an optimization process (Section 5).

However, transient effects also play a significant role and make test interpretation trickier. The test often consists of a trial-and-error process to assess the various effects that take place when the cavern is submitted to different brine pressure levels: the cavern pressure is changed periodically through injection or withdrawal of a liquid [It is important to check that such movements do not result in a change in well fluids density, because the relation between well pressures (which can be measured easily) and cavern pressure (which must be assessed correctly) must be known.] One important drawback of this testing strategy (which allows cavern response to various pressure conditions to be explored) is that any rapid pressure change triggers transient effects that blur the general picture for a time. (For example, after an increase in pressure, "reverse" salt creep seems to take place and cavern volume increases for a time, making cavern convergence negative (Karimi *et al.* 2007). For this reason, the transient evolution of cavern pressure must be computed. In Brouard Consulting *et al.* (2006), a dedicated software program (*LOCAS*, Brouard et al., 2006) is described that takes into account the various transient effects that affect a closed cavern whose pressure is subject to rapid changes.

Fortunately, from the perspective of cavern abandonment, exact assessment is not always necessary. If it can be proven that in the range of cavern pressure experienced during the test, the brine permeation rate is faster than the creep closure rate (i.e. when combined, and when the effect of brine thermal expansion is subtracted, they lead to a pressure drop), it is clear that the cavern equilibrium pressure (achieved after a very long period of time, when the rate of brine permeation exactly balances the rate of cavern creep closure) is smaller than any cavern pressure experienced during the course of testing.

5 OPTIMIZATION PROCESS

Finite-element computations allow fitting mechanical and hydraulic parameters through an iterative comparison between computed cavern pressure and measured cavern pressure. The average pressure difference (in hPa) between computed and measured pressures can be plotted in contour plots as a function of the fitting parameters. In fact, three parameters are considered for optimization: salt permeability, or K_{salt}^{hyd} (Steady-state flow is assumed.); and the two parameters of the Norton-Hoff steady-state law, *n* and $A^* = A\exp(-Q/RT)$. (Q/R and *A* cannot be assessed separately, as temperature changes are too small during the test). Optimization allows K_{salt}^{hyd} to be determined fairly accurately. It proves more difficult to determine A^* and *n*. [Several (A^*, n) couples provide good fits.] The reason for this is that during an abandonment test, cavern pressure experiences relatively small changes. The following example is from Brouard Consulting *et al.* (2006). An *in situ* test (supported by the SMRI) was performed in a small cavern of the propane storage facility operated by

Total at Carresse, France. Pressure evolution during a part of this test is drawn on Figure 2. Note that the range of cavern pressures experienced during the test is small (P = 4.6 to 4.8 MPa). Optimization was performed for two intervals of time (intervals beginning several months after any large pressure change in order to allow transient effects to dissipate). First, a best fit for salt permeability was sought, and a value of $K_{salt}^{hyd} \approx 4 \times 10^{-20}$ m^2 was found. Assuming that this estimation is correct, the mechanical parameters A^* and n were searched for with a Monte Carlo procedure.

Figure 3 shows the fitting map. Precise determination of A^* and n appears to be difficult (Several couples provide a fairly good fit.), but long-term (one-century) predictions are not deeply affected by the values of A^* and n selected for the computations.

Figure 2. Cavern pressure evolution fitted against Darcy's law and Norton-Hoff's law during two fitting periods.

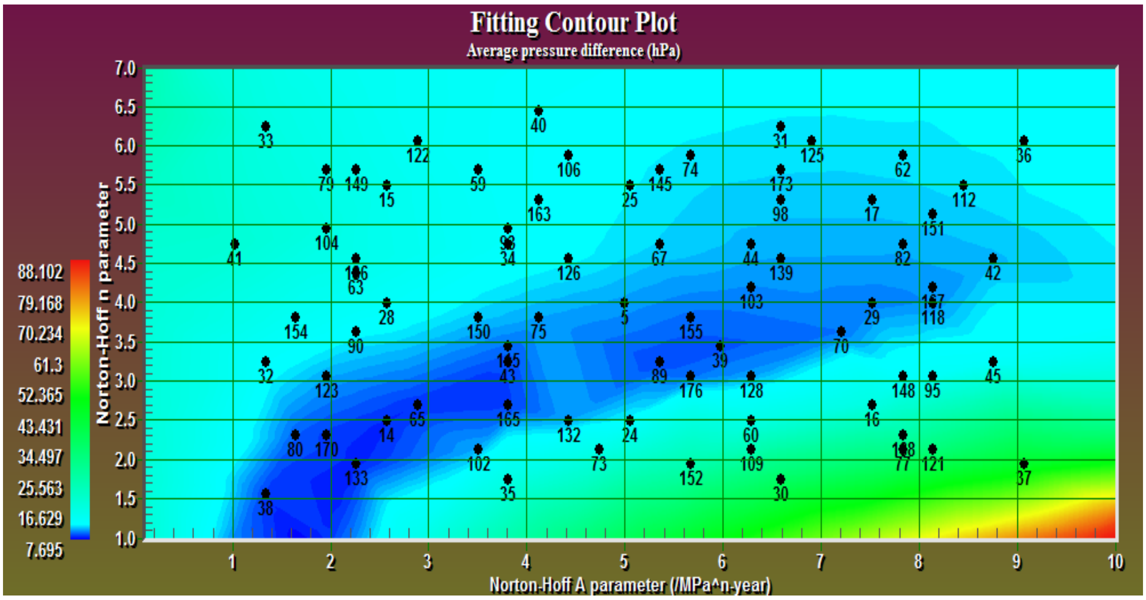

Figure 3. Fitting map in the case of salt permeability of $K_{salt}^{hyd} = 4 \times 10^{-20}$ m^2.

6 CONCLUSIONS

In a sealed cavern, brine pressure evolution is governed by cavern compressibility, brine thermal expansion, leaks, cavern convergence due to salt creep, and brine permeation through the cavern wall. The three first phenomena can be assessed accurately. As far as creep closure and brine permeation are concerned, uncertainties remain. *In situ* testing must be performed for a sufficiently long observation period to allow calibration of the various parameters and to credible long-term predictions.

7 REFERENCES

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