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Long-term behavior of salt caverns

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ABSTRACT: Four in-situ tests performed in salt caverns in France and Germany are described. The main objective of these tests was to increase our understanding of the long-term behavior of abandoned caverns. It is proven that, in the long term, when cavern brine has reached thermal equilibrium with the rock mass, pressure evolution is governed by cavern creep closure and brine micro-permeation through the cavern walls. An equilibrium pressure is reached when the closure rate exactly equals the permeation rate. In the shallow caverns described in this paper, equilibrium pressure is significantly lower than geostatic pressure, ruling out any risk of fracture onset at the cavern roof. Interpretation of these tests allows salt permeability to be back-calculated.

1. INTRODUCTION

1.1. Cavern Abandonment

Thousands of caverns have been leached out worldwide. Their volumes range from 10,000 m^3 to several millions m^3. Many of the caverns are used to store gas or oil. These caverns eventually will be abandoned. At that time, they will be filled with brine, and a cement plug will be set in the borehole, isolating a large “bubble” of brine — the long-term behavior of which is the subject of this paper. The Solution Mining Research Institute (SMRI), which comprises most companies, consultants and academics interested in salt caverns, has set this topic at the center of its research program for many years and supported several of the tests described in this paper [1,2].

There has been concern that, in a sealed and abandoned cavern, cavern brine pressure increases to geostatic pressure (and above), leading to fracture creation at the cavern roof [3], brine seepage to overlying strata, and possible pollution of potable water. In fact, it will be proven that, in many cases, brine pressure reaches an equilibrium pressure significantly smaller than geostatic pressure, alleviating any risk of fracture creation.

It is commonly accepted that pressure evolution in a closed and abandoned cavern is governed by four main factors:

(1) cavern creep closure,
(2) brine thermal expansion,
(3) brine permeation through the cavern walls, and
(4) brine leaks through the borehole or the plug.

It can be assumed that brine leaks are small when a tight plug is set in the borehole. While the effects of brine thermal expansion can be dramatic, they are not perennial. Before abandonment, cavern brine often is colder than the rock mass. Heat is transferred from the rock mass to the cavern through thermal conduction. This process is slow: the characteristic time for heat conduction is $t_c = V^{2/3}/4k$, where the cavern volume is V, and $k = 100$ m²/yr is the thermal diffusivity of salt. After a period of several t_c, the initial temperature gap is reduced by 75%, typically. When, for example, $V = 64{,}000\ \text{m}^3$, $t_c = 4$ years. In a closed cavern, temperature increase results in a dramatic brine pressure increase, $\beta\dot{P} - \alpha_b\dot{T} = 0$, where β is the cavern compressibility coefficient [4] and α_b is the thermal expansion coefficient of brine.

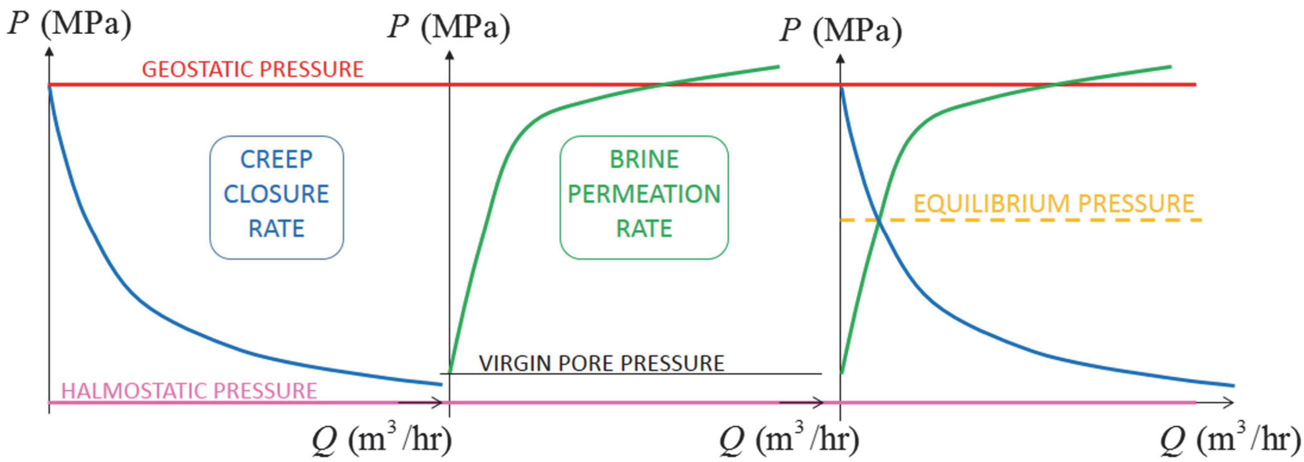

Fig. 1. Cavern creep closure, brine permeation and equilibrium pressure.

Typical values of these parameters are $\beta = 4\text{-}5\times10^{-4}$/MPa and $\alpha_b = 4.4\times10^{-4}$/°C: a 1°C brine temperature increase results in an approximate 1 MPa pressure increase, which is a large value, as the initial temperature gap may be several dozen °C. However, thermal equilibrium is reached after several decades, and this effect then is no longer taken into account.

When both brine leaks and brine warming can be neglected, brine pressure evolution results from two factors: cavern creep closure and brine permeation through the cavern walls.

1.2. Cavern Creep Closure

An abundant literature [5] has been dedicated to salt creep. It is generally accepted that the steady-state creep rate can be described by a power law, $\dot{\varepsilon} = A\exp(-Q/RT)\sigma^n$, where the exponent of the power law is in the range $n = 3$ to 6. As a result, steady-state creep closure rate, or $Q_{cr}/V|^{ss}$, where V is the cavern volume and Q_{cr} the volume loss rate, is a non-linear function of the gap between the geostatic pressure, P_∞, and the mean cavern pressure, or P. The geostatic pressure is approximately proportional to the mean cavern depth, or $H: P_\infty(H) = \gamma_R H$, where $\gamma_R = 0.022$ MPa/m. For instance, for an idealized cylindrical cavern:

$$Q_{cr}/V|^{ss} = -\sqrt{3}^{\,n+1} A\exp\left(-\frac{Q}{RT}\right)\left(\frac{P_\infty - P}{n}\right)^n \qquad (1)$$

In fact, steady-state creep is reached after a very long period of time as, when cavern pressure changes, the redistribution of stresses in the rock mass ("geometrical transient behavior") is quite slow. In addition, when the gap $P_\infty - P$ is small (smaller, say, than a few MPa), it is suspected that the exponent of the power law is $n \approx 1$ as, in this low deviatoric-stress domain, the mechanisms responsible for creep are not the same as in the large-stress domain [6]. Steady-state creep rate as a function of cavern pressure is shown schematically in Fig. 1 (left). P_h is the halmostatic pressure — i.e., the cavern pressure when the well is filled with saturated brine and the wellhead is open, or $P_h = \gamma_b H$, where $\gamma_b = 0.012$ MPa/m.

When cavern pressure is halmostatic, the creep closure rate strongly depends on cavern depth: typical values are

$Q_{cr}/V|^{ss} = 10^{-5}$/yr for $H = 250$ m

$Q_{cr}/V|^{ss} = 3\times10^{-4}$/yr for $H = 1000$ m, and

$Q_{cr}/V|^{ss} = 10^{-2}$/yr for $H = 2000$ m.

1.3. Permeation through Cavern Walls

Brine permeation through cavern walls is exceedingly slow, as the permeability of rock salt belongs to the range $K =10^{-21} - 10^{-19}$ m^2. However, permeability is larger in a borehole than in a sample, and larger in a cavern than in a borehole, following a law common to all crystalline rocks first described by Brace [7]. Permeation can be described by Darcy's law [8]. However, when the gap between geostatic pressure and brine pressure is low, it is believed that permeability drastically increases due to the onset of micro-fracturing. Figure 1 (center) illustrates this notion; "virgin pore pressure", or P_p, is the virgin pressure of brine in the salt pores and Q_{perm} is the brine outflow through the cavern walls. In many cases, $P_p \approx P_h$. In Gulf Coast domes, however, $P_p > P_h$ often is found.

Comparison of the two curves (Fig. 1, right) proves that they cut at a point such that the creep closure rate exactly equals the brine permeation rate; pressure value is the "equilibrium pressure", or P_{eq}.

The cavern-closure and brine-permeation rates can be written

$$\begin{cases} \dfrac{Q_{cr}}{V}(P) = -A\exp\left(-\dfrac{Q}{RT}\right)\left[P_\infty(H)-P\right]^n \varphi(\Omega) \\ \dfrac{Q_{perm}}{V}(P) = \dfrac{K}{\mu(T)}\dfrac{P-P_p}{V^{2/3}}\psi(\Omega) \end{cases} \quad (2)$$

where P is the brine pressure at average cavern depth, and $\varphi=\varphi(\Omega)$ and $\psi=\psi(\Omega)$ are two functions of cavern shape Ω — not the *size* of the cavern). Equilibrium pressure is reached when

$$Q_{cr}\left(P_{eq}\right)+Q_{perm}\left(P_{eq}\right)=0 \quad (3)$$

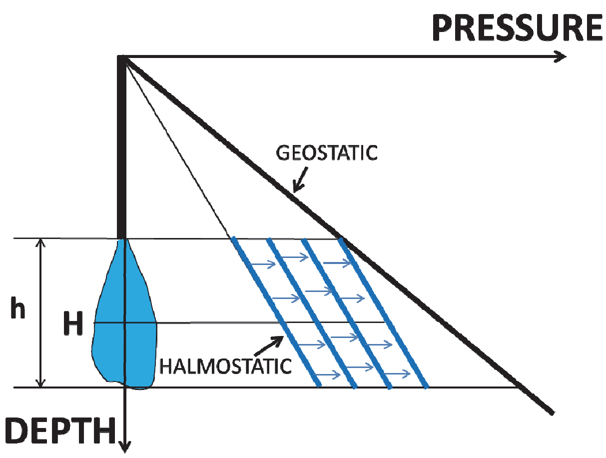

Fig. 2. Geostatic pressure is first reached at the cavern top.

In principle, when the equilibrium pressure is lower than the geostatic pressure, $P_{eq} < P_\infty$, no fracturing can take place. More precisely, in this inequality, both P_{eq} and P_∞ are computed at the mean cavern depth; in fact, the condition must be written for the cavern roof (Fig. 2), or $P_{eq} - \gamma_b h/2 < P_\infty - \gamma_R h/2$ [9]. In the following, the simple condition $P_{eq} < P_\infty$ is accepted (assuming small cavern height, h small).

Determining the equilibrium pressure is important from a practical point of view as well as from a more fundamental perspective: it provides information on the creep law and on the large-scale permeability of salt, a quantity which is often underestimated by laboratory tests.

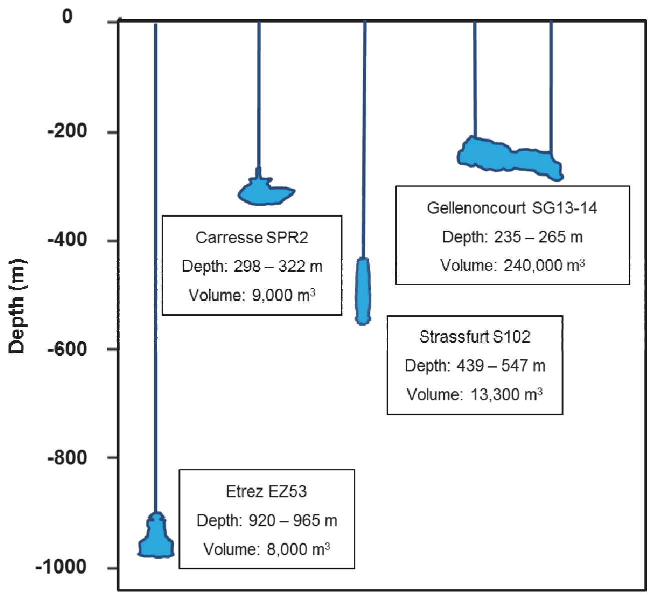

Fig. 3. Four caverns in which equilibrium pressure was measured.

Equilibrium pressure can be assessed through a trial-and-error method (described in the next Section). Four such tests are described (Fig. 3). Note that, when possible after such a test, it is useful to monitor cavern pressure over a long period of time to confirm the value of equilibrium pressure.

2. ETREZ EZ53 (A 17-YEAR LONG TEST)

2.1. Test Design

The EZ53 cavern was leached out in 1982 from a Stampian bedded-salt formation at Etrez, France, where Storengy operates a gas storage. After a cavern with volume $V = 7500-8000\ m^3$ was created, economic conditions changed, and the cavern was kept idle; no hydrocarbon was stored. Well completion included a 842-m deep, 9-⅝" last-cemented casing and a 929-m deep, 7" string.

In 1997, it was decided to perform a test [10] to assess the validity of the notion of long-term equilibrium pressure. This test was supported by the SMRI.

Temperature logs were performed in February and March 1996, and clearly proved that, in this small cavern which had been kept idle since 1982, thermal equilibrium had been reached.

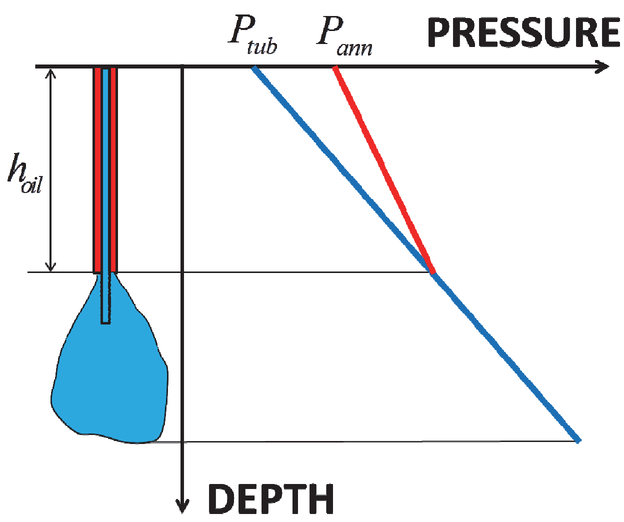

Fig. 4. Pressure distribution in the leak-detection system.

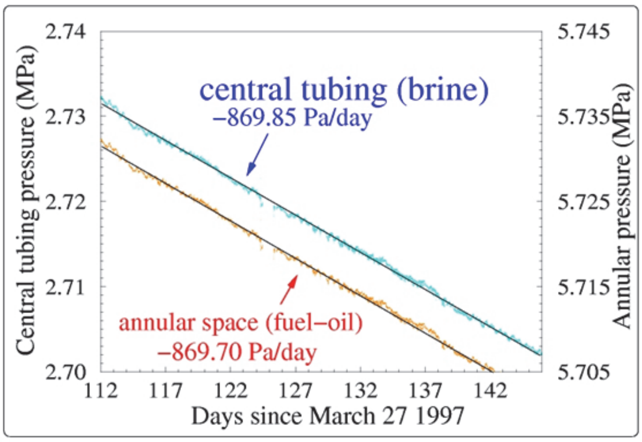

Fig. 5. Comparison between tubing pressure and annular pressure over a one-month period.

It was feared that some leakage might take place through the steel casing or through the casing shoe, especially when cavern pressure was high; consequently, a simple system was designed to assess well leaks. A fuel-oil column (864.5-m high) was lowered in the annular space; the rest of the cavern and the central string were filled with saturated brine (Fig. 4). Any fuel-oil leak generates a rise of the brine/fuel-oil interface in the annular space. Because fuel oil is lighter than brine ($\gamma_{oil} = 8.5$ kPa/m instead of $\gamma_b = 12$ kPa/m.), any interface rise generates a change in the difference between annular space pressure and string pressure as measured at the wellhead, or $\dot{P}_{ann} - \dot{P}_{tub} = (\gamma_b - \gamma_{oil})\dot{h}_{oil}$, where $\gamma_b - \gamma_{oil} = 3.5$ kPa/m. The annular cross-sectional area is 5.7 liters/meter. An interface rise of $\delta h_{oil} = 1$ mm (a 5.7 ml fuel-oil leak) generates a pressure change of $\delta(P_{ann} - P_{tub}) = 3.5$ Pa, a quantity that is easily detectable at ground level when accurate pressure gauges are used. This leak-detection system proved to be extremely effective. Figure 5 shows that, from day 112 to 142 after the beginning of the test, $\dot{P}_{ann} - \dot{P}_{tub} < 1$ Pa/day, making the average interface rise rate slower than 0.3 mm/day.

The test, performed from March 27, 1997 to October 1998, consists of a trial-and-error process (Fig. 6) that includes several phases. At the beginning of each phase, a specific initial pressure value is imposed through brine injection or withdrawal. When the pressure consistently increases (or decreases) for a sufficiently long period of time, it can be inferred that the cavern pressure is lower (or higher) than the equilibrium pressure. In such a case, a higher (or lower) initial pressure is tried at the beginning of the next phase. One significant advantage of this method is that, when transient effects can be neglected, it provides both lower and upper bounds for the equilibrium pressure.

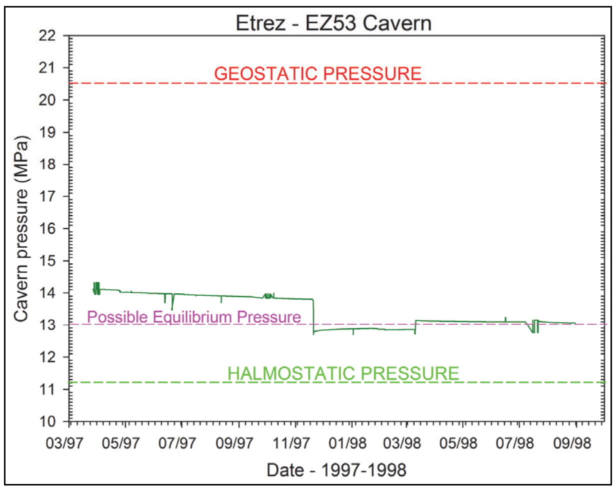

Fig. 6. Cavern pressure evolution from March 1997 to October 1998 during the trial-and-error test.

In addition, an examination of the pressure-vs-time curve allows the main parameters, which govern brine permeation and cavern creep closure, to be back-calculated, as pressure evolution is governed by a simple differential equation:

$$\beta V \dot{P}(t) = Q_{cr}(P) + Q_{perm}(P) \qquad (4)$$

In fact, however, this analysis must be performed carefully, because several transient phenomena must be taken into account; these phenomena are mainly significant after a rapid pressure change [11].

2.2 Results of the 1997-1998 Trial-and-Error Test

In this deep cavern ($H = 950-\text{m deep}$), geostatic pressure at mid-depth is $P_\infty = 20.5$ MPa, and halmostatic pressure is $P_h = 11.2$ MPa. The test began on March 27, 1997 (day 1) and lasted for 540 days. Four initial pressures were tested successively (Fig. 6). The test ran smoothly except for a small leak through the string at the wellhead from day 293 to day 315, which was detected through the system described in Section 2.1 and repaired. At the end of the test, the cavern pressure at a depth of $H = 950$ m was $P = 13.1$ MPa and slowly decreasing. It was inferred that the equilibrium pressure was $P_{eq} = 13 \pm 0.1$ MPa, smaller than the geostatic pressure and larger than the halmostatic pressure.

From a scientific perspective, it must be noted that, when equilibrium pressure and cavern shape are known, the rock-mass average permeability can be back-calculated. Creep parameters of the Etrez salt formation had been measured in the laboratory and during an outflow test. (The well was left open at ground level, and the brine flow rate expelled from the cavern was measured; it was equal to creep closure rate, or $Q_{cr} / V = -3 \times 10^{-4}$/yr [12].) The creep parameters are $A = 0.64$ /MPa^{n}-yr, $Q/R = 4100$ K, and $n = 3.1$. Virgin pore pressure (P_p) had been measured to be equal to halmostatic pressure [8]. In other words, all the parameters that define the equilibrium pressure were relatively well known, except for salt permeability, which was determined through numerical computations to be $K \approx 2 \times 10^{-19}$ m^2. Durup [8] performed a one-year-long permeability test on the 150-m-high EZ58 borehole, located at a couple of hundred meters from EZ53. He proposed $K = 6 \times 10^{-20}$ m^2 for salt permeability. Brouard et al. [13] analyzed the results of six Mechanical Integrity Tests performed on four boreholes of the Etrez site; the values of the permeability back-calculated from these tests ranged from $K = 4.6 \times 10^{-21}$ m^2 to $K = 1.9 \times 10^{-20}$ m^2. Permeability of Etrez salt samples also were measured in the laboratory by Leguen [14], who found $K = 10^{-21}$ m^2. These results are consistent with the generally accepted effects of scale on the permeability of crystalline rocks [7].

2.3. Results of the 2002-2013 Pressure Records

No information for the period from October 1998 to April 2002 is available. On May 24, 2002, recording of the string pressure at the wellhead began again, and weekly recordings were performed [15]. On June 13, 2002, a pressure gauge was set at the wellhead on the annular space (Fig. 7). Computed downhole pressures inferred from string pressure and annular pressure were almost equal (as expected!) and close to the equilibrium pressure observed at the end of the first test.

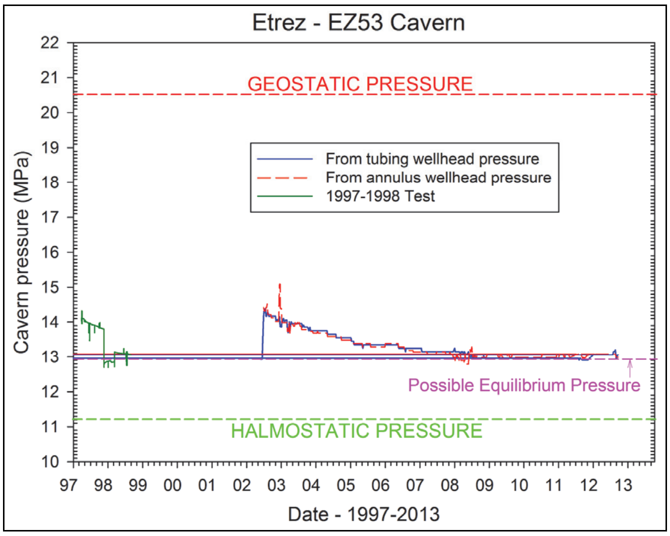

Fig. 7. Cavern pressure evolution during the 1997-2013 period.

On June 25, 2002, fuel oil was withdrawn from the annular space, brine was injected in the string, and cavern pressure increased. The cavern pressure was inferred from annular space pressure and tubing pressure independently. The two values were consistent and led to a value of $P = 14.2 \pm 0.1$ MPa. Over the summer and fall of 2002, the cavern pressure consistently decreased.

On December 13, 2002, a small amount of fuel oil was injected both in the string and in the annular space to prevent brine freezing. Wellhead pressures increased by 0.1 MPa.

From March 2003 to 2007, pressure evolutions were smooth; both pressures slowly decreased, as they did during the 1997-1998 test (when pressure conditions were similar), and the gap between these two pressures remained roughly constant (strongly suggesting that no oil leak occurred). At the end of 2007, string-pressure readings became difficult, as the gauge clearly was not working properly. A new string gauge was set on June 4, 2008. A small pressure increase, smaller than gauge accuracy, was observed during the 2012-2013 period. It can be concluded that the cavern pressure at a 950-m depth is $P = 13 \pm 0.1$ MPa, a value consistent both with the value predicted at the end of the 1997-1998 test and with that observed in 2002, after the well was kept idle for four years.

3. CARRESSE SPR2 (AN 11-YEAR TEST)

3.1. Test Design

The SPR2 cavern is located in the southwest of France at Carresse, where Total operated a propane storage facility. SPR2 was leached out in the early 1960s in a diapiric structure of the Pyrenean foothills and used for storing liquid propane. The salt formation contains thin salt layers of Triassic age. The amount of insoluble materials, mainly clay and anhydrite, is relatively large (20% to 30%). The propane storage was decommissioned, and propane was withdrawn in 2002. The volume of SPR2 is $V \approx 9000\ \mathrm{m}^3$ (Fig.3). Well completion includes a 286.6-m deep, 9-⅝" last-cemented casing, and a 319.7-m deep, 4" string. The cavern roof and bottom depths are 304.4 m and 321 m, respectively.

In this 310-m deep cavern, the geostatic pressure is $P_\infty = 6.68$ MPa; the halmostatic pressure is $P_h = 3.64$ MPa. SPR2 had been refilled with brine in July 2002. The temperature increase rate of the brine was measured from October 2002 to January 2003; it was $\dot{T} = 0.66$°C/yr. The gap between the rock and brine temperatures was estimated to be 1.8 °C. In April 2005 (one year after the beginning of the test), a leak-detection system (see Section 2.1) was set in the well.

A trial-and-error test, supported by the SMRI, began on June 2004 [16]. However, because thermal equilibrium was not reached, interpretation of the test was more difficult. After December 2005, pressure increased consistently, and no additional injection/withdrawal was performed. It was predicted at that time that a brine temperature increase would slow down and that, after several years, thermal expansion would become small enough to be unable to prevent cavern pressure decrease.

3.2. Further Evolution of Cavern Pressure from 2005 to 2013

Pressure evolution was recorded both in the annular space and in the central tubing from October 2005 (end of the trial-and-error test) to the end of 2012 (see Fig. 8). Pipes were removed at ground level in May 2010, leading to an increase in annular space pressure by 0.17 MPa, but this operation was not documented fully. It was expected that pressure reaches a maximum after several years; in fact, the pressure increase rate consistently decreased, but, 8 years after the October 2005 injection, no maximum was reached. The difference between predicted and observed evolutions is relatively small (see Fig. 8). In the framework of its Abandonment Research Program, the SMRI issued an RFP focused on obtaining a better explanation of this difference. The report by Brouard et al. [17] considered several hypotheses and proved that the discrepancy can be explained by underestimating the geothermal temperature by 0.1°C, a small value.

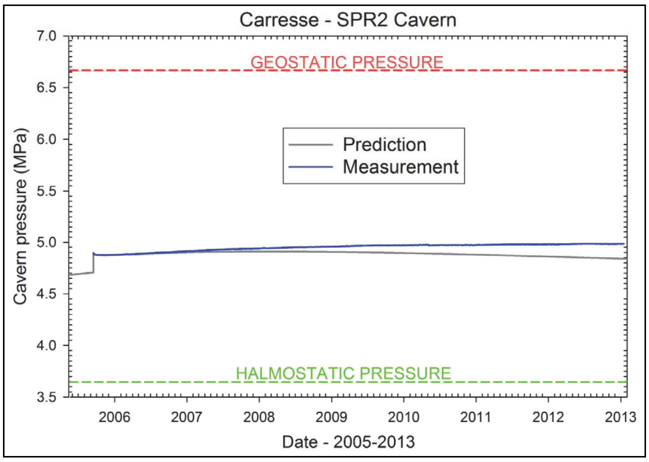

Fig. 8. SPR2 — Comparison between predicted cavern-pressure evolution and measured pressure. (Computed cavern pressures were predicted using the 2004-2006 test results.)

4. GELLENONCOURT SG13-14 (A 3-YEAR TEST)

4.1 Test Design

The Gellenoncourt brine field, operated by CSME since 1965, is located at the eastern (and shallowest) edge of the Keuper bedded-salt formation of Lorraine-Champagne ([18]). The SG13 and SG14 7-inches wells were drilled to a depth of 275 m in May 1975, and operated as brine-production wells from July 1976 to June 1977 (SG13) and from October 1978 to July 1980 (SG14). After some time, the two caverns coalesced, and SG13-SG14 now is composed of two caverns connected by a large link; hydraulically, SG13-14 can be considered as a single cavern (Fig. 3). The cavern volume at the end of the mining operations was inferred from “mass balance” ─ i.e., from the cumulated amounts of injected water and withdrawn brine during mining operations. “Mass balance” suggests that the actual cavern volume might be as large as $V \approx 240{,}000\ \mathrm{m}^3$. The average cavern depth is 250 m.

In the framework of ACSSL (*Abandon de Cavités Salines Stables en Lorraine*), a CSME project, a trial-and-error test began in June 2010 and is currently on-going. The cavern had been kept idle for nearly 30 years by the time the testing campaign began, and the initial gap between geothermal temperature and brine temperature certainly was small. However, the Carresse test example proved that even a tiny temperature gap was able to generate a significant difference between prediction and measurements. A temperature gauge was lowered into the SG13 well at a 247-m depth, and a perfectly constant temperature was recorded from December 2008 to November 2009. In June 2010, cavern temperature was measured again using the same gauge: the recorded temperature was exactly the same as in December 2008. Gauge resolution was tested as follows [19]. It is known that when cavern brine pressure is increased rapidly by ΔP, its temperature adiabatically increases by $\Delta T / \Delta P = \alpha_b T / \rho_b C_b$, where $T = 290$ K is the absolute brine temperature, and $\rho_b C_b = 3.8 \times 10^6$ J/m^3-°C is the volumetric heat capacity of the brine, leading to $\Delta T / \Delta P \approx 0.03$ °C/MPa. At the beginning of the trial-and error test, on June 2010, brine pressure was increased gradually. When pressure increase reached $\Delta P \approx 0.6$ MPa, the gauge temperature abruptly "jumped" by $\Delta T = 0.02$°C, proving that the gauge was sensitive and that its resolution was 0.02 °C.

During the SPR2 and EZ53 tests, it was observed that computation of cavern pressure changes were hampered by the injection/withdrawal of brine, oil or water during the course of the test, as these movements change the density distribution in the wells, and the relation between wellhead pressures and cavern pressure. For this reason, in addition to the temperature gauge, a pressure gauge was set in the well at cavern depth.

4.2 Test Results

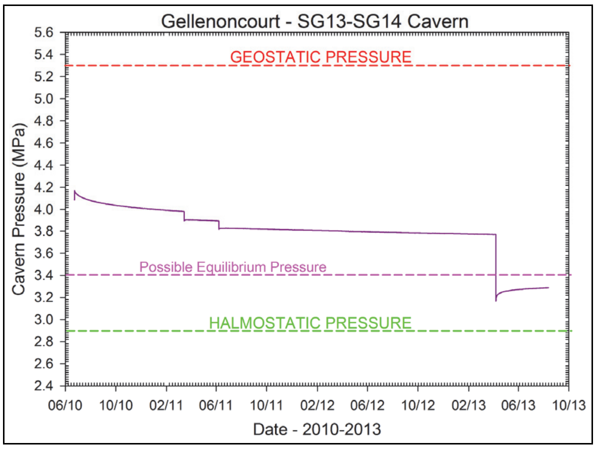

Fig. 9 – SG13-14 pressure evolution from June 2010 to August 2013 during the trial-and-error test.

In the 250-m deep SG13-14 cavern, the halmostatic pressure is $P_h = 2.97$ MPa, and the geostatic pressure is $P_\infty = 5.39$ MPa. Pressure evolution is very slow (Fig. 9). Small amounts of brine were withdrawn periodically in order to reach equilibrium pressure more rapidly. Any pressure drop is followed by a transient period during which pressure increases before decreasing again. (This phenomenon was explained in Section 3.2.) Because it was observed that the cavern pressure consistently decreased, it was decided, in spring 2013, to lower the cavern pressure from $P \approx 3.79$ MPa to $P \approx 3.16$ MPa. After this pressure drop, cavern pressure consistently increases, proving that equilibrium pressure is smaller than 3.75 MPa and larger than 3.2 MPa. A more precise estimate will be available in a couple of years.

5. STASSFURT CAVERN (A 3-YEAR TEST)

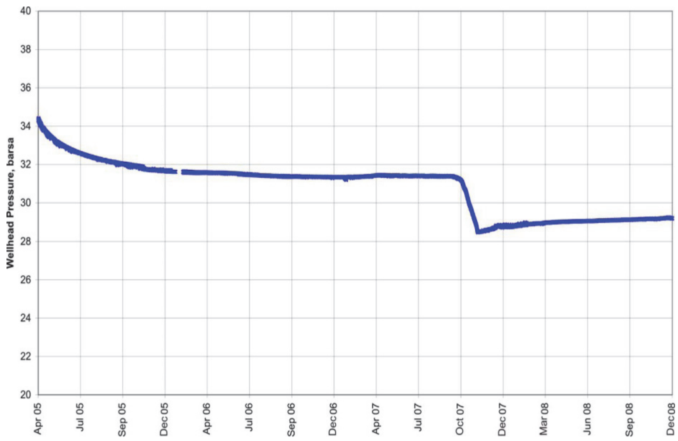

Fig. 10. Wellhead pressure evolution from April 2005 to December 2008 during the trial-and-error test ([20]).

The S102 cavern was leached out in 1973 from an anticlinal salt formation at Stassfurt, Germany. The amount of insolubles is 5-10%. The cavern volume is 13,300 m^3, and the maximum diameter is 15 m (Fig. 3). It had been kept idle from 1973 to 2005, when it was decided to perform a test ([20]). This test was supported by the SMRI. It was reasonable to assume that thermal equilibrium had been reached. No leak-detection system was set (No string had been left in the well.), but it was known from tightness tests that leaks were small.

The test began on April 2005, when the cavern pressure was increased to 95% of the geostatic pressure at roof depth, which is 9.36 MPa (Fig. 10). Pressure consistently decreased to November 7, 2007, when an abnormal pressure drop took place. A leak was found and repaired. After this incident, pressure consistently increased until December 31, 2008, when the test stopped. Data suggest that the equilibrium pressure is $P_{eq} \approx 8.15$ MPa at the cavern roof — i.e., at a 436-m depth (3 MPa at the wellhead).

6. CONCLUSIONS

Trial-and-error tests performed in four different shallow (less than 1000-m deep) caverns proved that when thermal equilibrium is reached in a shut-in cavern, brine pressure reaches an equilibrium pressure when the rate of brine permeation through the rock mass exactly equals the creep closure rate. This equilibrium pressure is significantly smaller than geostatic pressure. This behavior applies to any salt cavern, although the four tested caverns were both shallow and relatively small (less than 240,000 m^3). Creep rate is faster in a deeper cavern, and brine micro-permeation is slower in a larger cavern (as the wall surface/volume ratio is smaller), resulting in a higher equilibrium pressure. For such caverns, additional tests are needed; an example of such tests is described in [21].

The following lessons were learned as a result of these tests.

- The trial-and-error test allows definition of a lower and upper bound for the equilibrium pressure that will be reached over the long term.
- Conclusions are more difficult to draw when thermal equilibrium between geothermal and cavern brine temperatures were not reached before the test began.
- Test interpretation is made easier when the composition of the liquid columns in the borehole experiences no, or small, changes or, still better, when pressure and temperature gauges are set in the cavern (rather than at the wellhead).
- During a trial-and-error test, pressure steps must be long enough to allow the transient phenomena that follow each pressure change to vanish.
- Interpretation is more certain when a leak-detection system is installed in the well.

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