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12-YEAR PRESSURE MONITORING

IN AN IDLE SALT CAVERN

THE 1997-1998 ETREZ ABANDONMENT TEST REVISITED

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ABSTRACT

Twelve years ago, the solution Mining Research Institute awarded a research contract to Gaz de France and Ecole Polytechnique to perform an abandonment test in a salt cavern of the Etrez gas-storage facility. This test was performed during the 1997-1998 period. In the conclusions of the Research Report, it was predicted that cavern pressure would reach a steady-state equilibrium value such that the effects of cavern creep closure and of brine permeation through the cavern wall were balanced exactly. Between 2002 and 2009, wellhead pressures in that cavern were monitored again. During this period, it was observed that, after any sufficiently long period during which the cavern is kept idle (no injection or withdrawal), the cavern pressure reached a constant value exactly equal (within pressure gauge accuracy) to the figure predicted after the 1997-1998 test.

1. INTRODUCTION

The results of a 500-day long abandonment test in a salt cavern supported by the SMRI were published in 2001 [Bérest et al., 2001]. This test was motivated by concerns raised by the long-term behaviour of salt caverns. These caverns eventually will be abandoned: the cavern will be filled with brine, a special plug will be set at the casing seat [Crotogino and Kepplinger, 2006] and cement will be poured in the well. A large "bubble" of saturated brine will be isolated. The long-term evolution of this brine is a serious concern. After cavern plugging, cavern brine pressure will increase, as has been proved by numerous "shut-in pressure tests" performed worldwide. The final value of cavern brine pressure is of utmost importance from the perspective of environmental protection. In some circumstances, brine pressure may reach a figure larger than the geostatic pressure, leading to hydro-fracturing: brine will

flow upward through fractures to shallow water-bearing strata, leading to water pollution, ground subsidence and possible cavern collapse.
In fact, pressure evolution in a closed cavern results from five main factors, as described below.

1.1 Cavern compressibility

Cavern compressibility is the ratio between any rapid change in cavern brine volume (*V*) and cavern brine pressure (*P*). It results from the (adiabatic) elastic compressibility of brine and cavern itself, and is proportional to cavern volume, or $\dot{V} = \beta V \dot{P}$, where $\beta = 4 - 5 \times 10^{-4}/\text{MPa}$ is typical [Bérest et al., 1999].

1.2 Cavern creep closure

In the long term, salt behaves as a (highly) non-linear viscous fluid. The Norton-Hoff law often is assumed, $\dot{\varepsilon} = A(T)\sigma^n$. Salt mass creep leads to cavern shrinkage. The driving force for cavern closure is the gap between geostatic pressure, P_∞, and cavern pressure, or *P*. When cavern shrinks, cavern brine has less room and its pressure builds up.

At the beginning of the process, after cavern plugging, cavern pressure is halmostatic — i.e., it results from the weight of the column of saturated brine that fills the well, or $P = P_h(\text{MPa}) \approx 0.012\, H(\text{meters})$ or P (psi)= 0.52 H (ft), where H is the cavern depth. Geostatic pressure is $P = P_\infty(\text{MPa}) \approx 0.022\, H(\text{meters})$ or P_∞ (psi) = 1.1 H (ft). In these conditions, cavern creep closure rate typically is $Q_{creep}/V = -10^{-5}/\text{yr}$ when $H = 250$ m (750 ft); $Q_{reep}/V = -3 \times 10^{-4}/\text{yr}$ when $H = 1000$ m (3000 ft); and $Q_{creep}/V = -10^{-2}/\text{yr}$ when $H = 2000$ m (6000ft). These figures are indicative and may vary from one site to the other.

The convergence rate is slower when the cavern pressure is higher, and ultimately stops when the cavern pressure becomes geostatic (Figure 1).

1.3 Brine permeation through the cavern walls

This process is still open to controversy. Brine permeation vanishes to zero (Figure 1) when cavern pressure, P, equals natural pore pressure, P_0. (Pore pressure, or P_0, often is close to halmostatic pressure, or P_h) . Iis generally assumed that brine permeation can be described by Darcy's law. Brine permeation rate or Q_{perm} then is a linear function of the difference $P - P_0$ (Figure 1). Salt permeability is exceedingly small (typically, $K = 10^{-22} - 10^{-19}\,\mathrm{m}^2$). However, even these low figures can lead to a significant brine pressure release.

1.4 Brine thermal expansion

The temperature history of cavern fluids during cavern operation generally is complex [Karimi-Jafari et al., 2007]; in most cases, when a cavern is abandoned, brine temperature is smaller than geothermal temperature at cavern depth. Heat transfer from the rock mass to the cavern leads to brine warming. However, brine thermal expansion is hampered in a closed cavern, and brine pressure builds up. The thermal expansion coefficient of brine is $\alpha \approx 4.4\times10^{-4}/°\mathrm{C}$, and a 1°C increase in brine temperature generates a pressure build-up of $\alpha/\beta \approx 1\,\mathrm{MPa}$. After some time, however, thermal equilibrium is reached, and expansion no longer takes place. The characteristic time for conductive heat transfer is $t_c = V^{2/3}/4k$, where k = 100 m^2/yr is salt thermal diffusivity. For instance, in a cavern with V = 8000 m^3, the characteristic time is $t_c \approx 1\,\mathrm{yr}$, and it can be considered that thermal equilibrium is reached in a cavern after it has been kept idle (no liquid injection/withdrawal) during a period, say, of 5-6 years.

1.5 Brine leaks

Leaks through the casing or the casing shoe are known to have occurred in some underground storage environments. The existence of such leaks — which are likely to vanish after the well of an abandoned cavern has been properly plugged — would lead to severe misinterpretation of a cavern abandonment test (Salt permeability would be overestimated.) if casing leakage and brine permeation were not distinguished.

1.6 Brine pressure evolution

How these factors combine depends on the specific conditions at each site. When thermal expansion can be disregarded (which often is correct in a small cavern kept idle during a long period of time) cavern pressure slowly converges to an equilibrium pressure such that creep closure rate exactly equals brine permeation rate through cavern walls (Figure 1). From a mathematical point of view, brine pressure rate or $\dot{P}$ is proportional to the difference between cavern closure rate (Q_{creep}) and brine permeation rate (Q_{perm}):

$$\beta V\dot{P} = Q_{creep}\left[P_\infty - P\right] - Q_{perm}\left[P - P_0\right]$$

The two functions Q_{creep} and Q_{perm} can be computed when, for instance, Norton-Hoff law and Darcy's law are assumed.

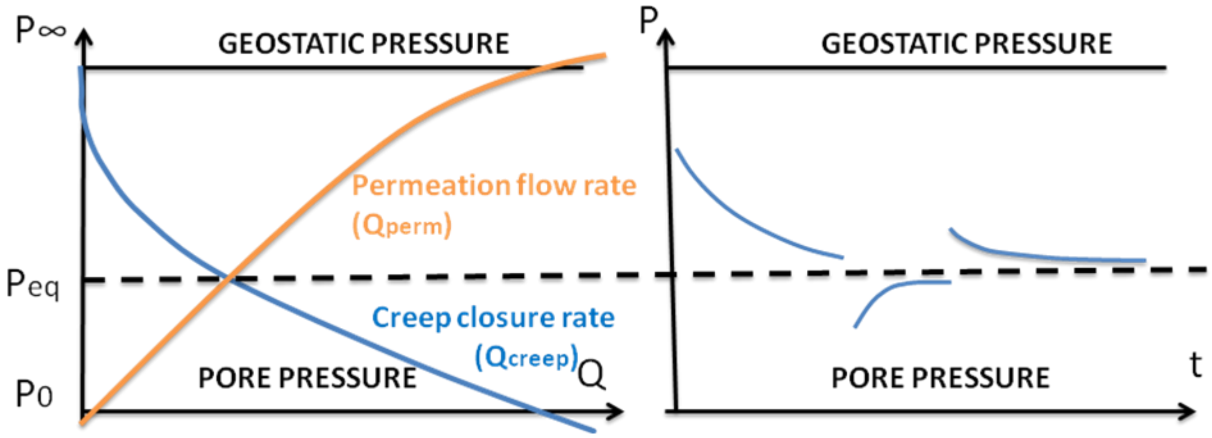

Fig. 1. Equilibrium pressure (left) and abandonment test (right)

It is found that equilibrium is reached ($P = P_{eq}$) when $Q_{creep} = Q_{perm}$ — i.e., when cavern creep-closure rate exactly equals brine permeation rate (Figure 1, left). The objective of an abandonment test is to assess equilibrium pressure and to verify that it is significantly smaller than geostatic pressure. An abandonment test (Figure 1, right) is performed following a trial-and-error method: when cavern pressure is higher (resp., lower) than equilibrium pressure, cavern pressure as a function of time consistently decreases (resp., increases). One significant advantage of this method is that, when transient effects are neglected, it provides both lower and upper bounds for the equilibrium pressure.

2 THE 1997-1998 ABANDONMENT TEST

An abandonment test was performed in the EZ53 salt cavern of the gas storage site operated by GDF SUEZ at Etrez in southeastern France. This cavern had been leached out in July 1982. It is 950-m (3000 ft) deep, and its volume is $V = 8000$ m^3 or 50,000 bbls. Access to the cavern is through a 842-m-long 9-⅝" casing cemented to the rock formation; a 929-m-long 7" string is set in the well [Bérest et al., 2001].

2.1 Brine thermal expansion and Brine leaks

When the test began in 1997, the cavern had been idle for 15 years, and it was assumed that, after such a long period, thermal equilibrium in this relatively small cavern had been reached (see Section 1.4). A temperature gauge lowered in the cavern in February 1986 proved that the cavern brine temperature equalled the geothermal temperature of the rock formation (45°C at a 950-m depth). Thus, brine thermal expansion could be disregarded.

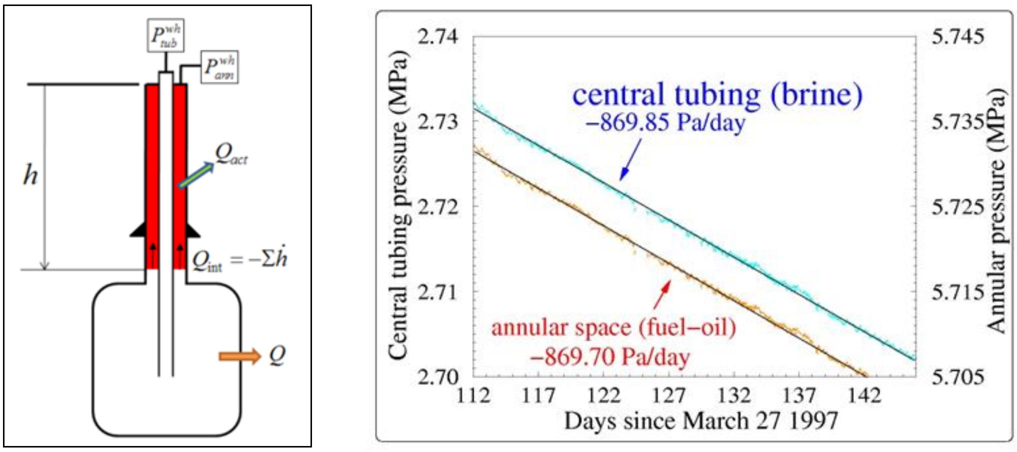

Fig. 2. Wellhead pressure evolution day 112 to day 142.

Possible leaks also were a concern. On March 20, before the test began, a light, liquid hydrocarbon column was lowered in the 7"×9-⅝" annular space to develop a brine-hydrocarbon interface at a depth of h = 864.5-m. Brine density was $\rho_b = 1200\ \text{kg/m}^3$, and hydrocarbon density was $\rho_o = 850\ \text{kg/m}^3$. Any hydrocarbon leak, Q_{act}, through the cemented casing or through the casing shoe, resulted in an interface rise by $\dot{h} = Q_{act}/\Sigma$, where Σ is the cross-sectional area of the annular space and, consequently, in a change by $\dot{P}^{wh}_{ann} - \dot{P}^{wh}_{tub} = (\rho_b - \rho_o)g\dot{h}$ in the difference between the string pressure P^{wh}_{tub} and the annular space pressure P^{wh}_{ann} as measured at the wellhead. This change can easily be measured and even tiny leaks can be detected.

Figure 2 presents both pressure variations, as measured from day 112 (after test began) to day 150. They are measured through pressure gauges whose accuracy is 1 kPa (7 psi). The rate of pressure difference change is almost nil, precluding any significant leakage. (Small fluctuations can be observed; these are due to the effects of daily ground-level temperature and pressure fluctuations and to the effects of Earth tides). Later, on day 293, a rapid increase in pressure difference took place — clear evidence of a hydrocarbon leak. The cumulated differential pressure increased to 21 kPa after 23 days: the interface rose by 6 m in this period, and 124 litres of hydrocarbon were lost. On day 315, the leak was fixed. (The leak was through the wellhead; it was detected on pressures evolution curves before being observed in the field.) Except for this period, there was no leak from the well, and only two phenomena played significant roles in pressure evolution: cavern creep closure and brine permeation.

2.2 Test results

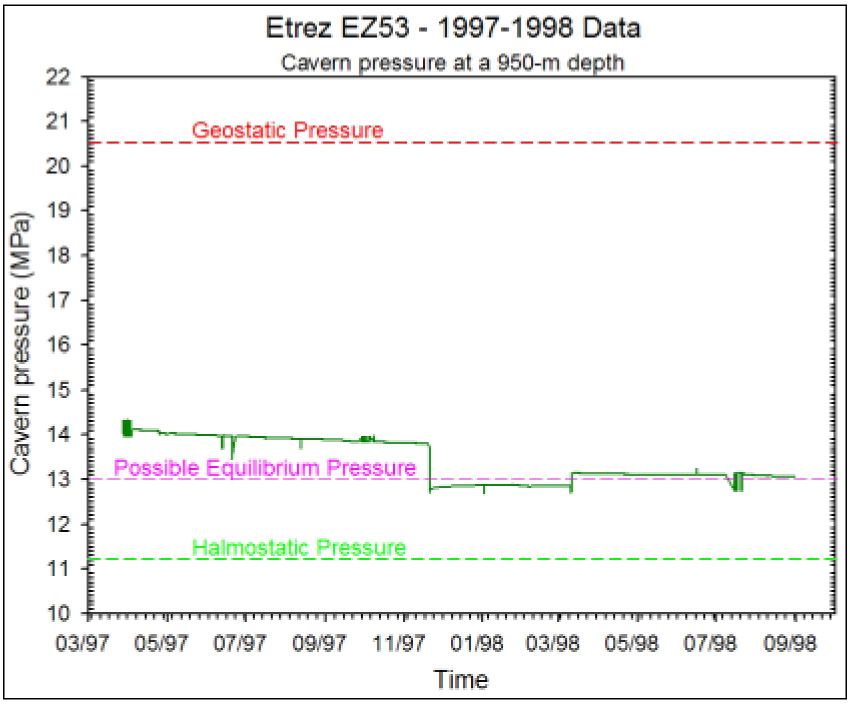

Fig. 3. The 1997-1998 Abandonment test.

The test began on March 27, 1997 (day 1) and lasted for 540 days. The test (Figure 3) included four phases ("trial-and-error" method). At the beginning of each phase, a different pressure was applied in the cavern. The test ran smoothly except for the period from day 293 to day 315, described above. At the end of the test, the cavern pressure was P = 13.1 MPa and slowly decreasing. It was inferred that the equilibrium pressure at a depth of $H = 950\,\text{m}$ was $P_{950}^{eq} = 13 \pm 0.1\,\text{MPa}$ — i.e., smaller than the geostatic pressure $(P_\infty = 20.5\text{ MPa})$ and larger than the halmostatic pressure $(P_h = 11.2\text{ MPa})$ at cavern depth. It also was inferred that salt-formation permeability was $K \approx 2 \times 10^{-20}\text{ m}^2$ and that cavern-creep closure rate was $\dot{V}/V \approx 2 \times 10^{-4}\,\text{yr}^{-1}$ [Bérest et al., 2001].

3 WAS THE 1997-1998 TEST LONG ENOUGH?

In principle, the results of this test can be considered to be convincing. The physical phenomena that play a role are identified clearly, and the test results provide an upper and lower bound for the "equilibrium pressure". The Solution Mining Research Institute (SMRI) has set the cavern abandonment issue at the centre of its research program [Ratigan, 2003], and SMRI supported the 1997-1998 test. It also supported similar later tests performed at Carresse (France) [Brouard et al., 2006] and Stassfurt (Germany) [Banach and Klafki, 2009] and a test currently performed in deep caverns at Mont Belvieu, Texas. Many papers contributed to the discussion [Wallner and Paar, 1997;

Rokhar et al., 2000; Rokhar et al., 2003; Cosenza and Ghoreychi, 1993] over the years, and many companies performed abandonment tests following the same methodology [Brückner et al., 2006; Hévin et al., 2007; Brückner and Wekenborg, 2006; Van Heekeren et al., 2009]. These efforts provide some confidence in the selected approach. However, the Etrez test lasted 540 days, and one could question whether the evolution observed during that period of time can be extrapolated to much longer periods. A pragmatic approach was considered suitable: recording pressure evolution several years after the initial test was over should provide additional insight and help build confidence in the test results.

4 THE 2002-2009 TEST

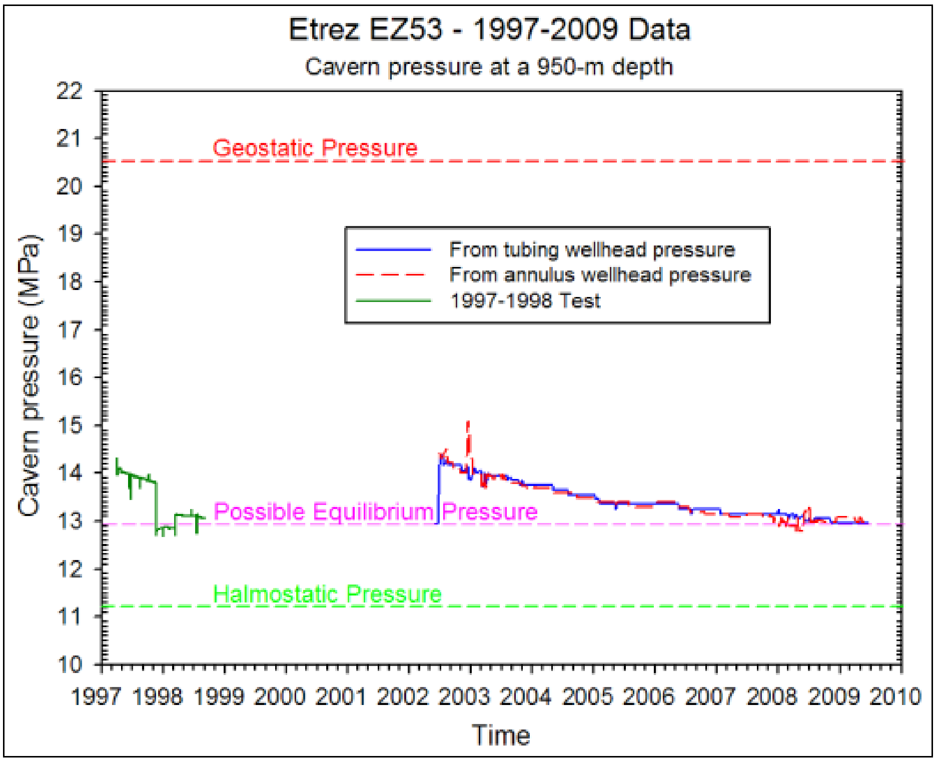

Fig. 4. Cavern pressure evolution in the 1997-2009 period.

4.1 From November 1998 to May 2002

The EZ53 well completion was discussed briefly in Section 2. The well has a 7" central string that is 929-m (H_{tub}) long, and a 842-m long 9-⅝" cemented casing shoe. The internal volume of the string is 19.5 m^3. At the end of the 1997-1998 test, the cavern and the central string are filled with saturated brine except for a 3.5-m liquid hydrocarbon column at the top of the string. The annular space is filled with liquid hydrocarbon to a depth h = 858.5 m. From depth 0 to 32 m, the cross-sectional area of the annular space is 52.4 litres/m; from 30 m to 842 m, it is 14.7 litres/m; and, from 842 m to 890 m (location of the cavern chimney), it is Σ = 5.7 litres/m. The liquid hydrocarbon volume injected in the annular space in 1997 was approximately 14.5 m^3.

No information is available for the period November 1998 to April 2002. On May 24, 2002, recording of the string pressure at the wellhead began again, and weekly recordings were performed. The pressure gauge, with a resolution of 0.1 MPa, is much less accurate than that used during the 1997-1998 test, although 0.05-MPa pressure changes can be detected. Wellhead string pressure from May 24 to June 6 was $P_{tub}^{wh} = 1.75$ MPa, a figure observed consistently during one month. Because the string is filled with saturated brine, cavern pressure can be deemed to be

$$P_{950} = P_{tub}^{wh} + \rho_b gH = 1.75 + 11.2 = 12.95 \text{ MPa}$$

This is a figure that ranges between the upper and lower bounds of the predicted equilibrium pressure.

On June 13, 2002, a pressure gauge was set at the wellhead on the annular space (partly filled with oil). At that point, the wellhead annular pressure was $P_{ann}^{wh} = 4.4$ MPa, from which the value of

$$P_{950}^{'} = P_{ann}^{wh} + \rho_o gh + \rho_b g(H - h) = 12.6 \text{ MPa}$$

can be inferred. This figure is smaller than that inferred from the wellhead string pressure. (Obviously, they should be equal.) Thus, the following two hypotheses must be considered.

1. A liquid hydrocarbon leak occurred during the 1998-2002 period. Such a leak would result in a heavier annular space column, because the brine/hydrocarbon interface rises and hydrocarbon is replaced by saturated brine. This hypothesis is not fully convincing, as the leak was almost zero during the 1997-1998 period.

2. There were uncertainties in pressure measurements and liquid densities. Accuracy of pressure gauges is poor: liquid densities are not constant, but depend on liquid pressure and temperature (which, from the wellhead to the cavern bottom, vary from a couple of MPa to 11 MPa, and from 10 °C to 45 °C, respectively). These result in variations of liquid density by 1% for brine (and more for liquid hydrocarbon).

4.2 From June 2002 to December 2002

On June 25, 2002, liquid hydrocarbon was withdrawn from the annular space, and brine was injected in the tubing to increase cavern pressure. The injected brine was slightly undersaturated, with a density of $\rho_b^{uns} = 1177$ kg/m^3. The annular space was filled with the fully saturated brine from the cavern that displaced the fuel-oil column. The tubing pressure fluctuated from $P_{tub}^{wh} =$ 3.2 to 3.4 MPa, an increase of $\Delta P = 1.45$ to 1.65 MPa when compared to the May 2002 period (see Figure 4). Because the cavern compressibility is $\beta V = 3\ \mathrm{m^3/MPa}$, it can be inferred that the injected brine volume was $\beta V \Delta P \approx 4.5\ \mathrm{m^3}$ (to increase cavern pressure) plus 14.5 m^3 (to withdraw liquid hydrocarbon from the annular space), or 19 m^3. It also can be inferred that the string, whose volume is 19.5 m^3, is filled with unsaturated brine and that the cavern pressure is:

$$P_{950} = P_{tub}^{ann} + \rho_b^{uns} g H_{tub} + \rho_b g (H - H_{tub}) = 14.2 \text{ to } 14.4 \text{ MPa}$$

The annular space pressure during this period is $P_{ann}^{wh} = 3.1$ to 3.2 MPa, from which a cavern pressure ranging from

$$P_{950}^{'} = P_{ann}^{wh} + \rho_b g H = 14.3 \text{ to } 14.4 \text{ MPa}$$

can be inferred; the two figures are consistent (suggesting that the discrepancy observed in June 2002 resulted from poor estimation of liquid hydrocarbon density, the second hypothesis mentioned in Paragraph 4.1).

4.3 From December 2002 to July 2009

On December 13, 2002, a small amount (110 litres) of hydrocarbon was injected in both the string and the annular space to prevent brine freezing. Both wellhead pressures increased by 0.1 MPa, a figure consistent with what is known of cavern compressibility and hydrocarbon density. By mid-December, the annular pressure suddenly increased by 1.1 MPa (see Figure 4). This increase cannot be explained; gauge misreading is suspected, as, by the end of December, the pressure drops to the figure observed before this “pressure crisis”. A similar “pressure crisis” can be observed in March 2003, when both pressures unexpectedly dropped by 0.2 to 0.3 MPa. This pressure drop remains puzzling; both surface temperature and atmospheric pressure fluctuations generate small changes in wellhead pressure (These phenomena clearly were observed during the 1997-1998 test, when pressure gauge resolution was much better.), but these changes typically are 0.01 MPa in magnitude (see Figure 3) and cannot explain the much larger pressure drop observed in March 2003.

From March 2003 to 2007, pressure evolutions were smooth; both pressures slowly decreased (see Figure 4), as they did during the 1997-1998 test when pressure conditions were similar, and the gap between these two pressures remained roughly constant. At the end of 2007, string pressure readings became difficult, as the gauge clearly no longer worked properly. A new string gauge was set on June 4, 2008. From then until July 2009, the string pressure is $P_{tub}^{wh} = 2.0$ MPa, and the annular space pressure is $P_{ann}^{wh} = 1.8 - 1.9$ MPa. It can be concluded from these figures that the cavern pressure is $P_{950} = 13 \pm 0.1$ MPa, which is consistent both with the figure predicted at the end of the 1997-1998 test (see Section 2.2) and with that observed in 2002, after the well was kept idle for four years. It must be kept in mind, however, that a couple of short "pressure crises", a couple of weeks long, were observed during the 2002-2009 observation period. They remain unexplained. Misreading and/or gauge faults are the most likely explanations.

CONCLUSION

A 12-year-long shut-in test was performed on the 950-m (3,000 ft) deep, 8000-m^3 (50,000 bbls) Ez53 cavern of the Etrez cavern field operated by GDF Suez. Pressures were monitored precisely during the 1997-1998 period; less accurate gauges were used during the 2002-2009 period. It is observed that at the end of any period during which the cavern was kept idle (e.g., October 1998, May 2002, July 2009), cavern pressure remained constant at 13.0 ± 0.1 MPa at a depth of 950 m. The notion of a steady-state "equilibrium pressure" in a closed cavern, resulting from the opposing effects of brine permeation and cavern creep closure, has been clearly confirmed.

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