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Technical Note

Twelve-year monitoring of the idle Etrez salt cavern

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1. Introduction

In 2001, a paper describing a salt-cavern abandonment test was published in this journal [1]. This test was motivated by concerns raised by the long-term behaviour of abandoned salt caverns, which are leached out from salt formations, having depths ranging from 200 to 2000 m and typical volumes from 10,000 to 1,000,000 m^3. Thousands of such caverns have been created, and are used for brine production and/or hydrocarbon storage. These caverns eventually will be abandoned: the cavern will be filled with brine, a special plug will be set at the casing seat, 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 [2,3]. 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 hydrofracturing: brine will flow upward through fractures to shallow water-bearing strata, leading to water pollution, ground subsidence and possible cavern collapse.

Pressure evolution in a closed cavern results from four main factors: cavern creep closure, brine thermal expansion, brine permeation through the cavern walls and brine leaks.

1.1. Cavern creep closure

Salt-mass creep leads to cavern shrinkage; 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 which fills the well, or $P=P_h=\rho_b gH$ or $P_h\,(\text{MPa})\approx 0.012H\,(\text{m})$, where H is the cavern depth and $\rho_\text{b}=1200\ \text{kg/m}^3$ is the density of saturated brine. In these conditions, cavern volume loss rate typically is $\dot{V}/V=-10^{-5}/\text{yr}$ when $H=250$ m, $\dot{V}/V=-3\times10^{-4}/\text{yr}$ when $H=1000$ m and $\dot{V}/V=-10^{-2}/\text{yr}$ when $H=2000$ m (these values are indicative and may vary from one site to the other). The compressibility factor of a brine-filled cavern typically is $\beta=4\times10^{-4}/\text{MPa}$ [4], and the build-up rate of cavern pressure due to cavern creep closure is $\dot{P}=-\dot{V}/\beta V$.The volume loss rate is slower when the cavern pressure is higher, and ultimately stops when cavern pressure becomes geostatic, or $P=P_\infty=\rho_R gH\approx 0.022$ H (meters). Rock density is assumed to be $\rho_R=2200\ \text{kg/m}^3$.

1.2. Brine thermal expansion

The temperature history of cavern fluids during cavern operation generally is complex; in most cases, when a cavern is abandoned, brine temperature is lower than the geothermal temperature at cavern depth. Heat transfer from the rock mass to the cavern leads to brine warming. This process is faster in a smaller cavern; however the thermal expansion of brine is hampered in a closed cavern, and brine pressure builds up. The thermal expansion coefficient of brine is $\alpha\approx4.4\times10^{-4}/^\circ\text{C}$, and a 1 °C increase in brine temperature generates a pressure build-up of $\alpha/\beta\approx1$ MPa.

1.3. Brine permeation through the cavern walls

This process is exceedingly slow, as the permeability of salt is small (typically, $K=10^{-22}-10^{-19}\ \text{m}^2$). However, as cavern brine is a relatively stiff body, permeation can lead to a significant release of brine pressure, which is faster in a smaller cavern. In the following, brine permeation will be described through Darcy's

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law. This description is the simplest possible. Some authors believe that rock salt is liquid-tight and gas-tight in its primary state, and that the origin of the non-zero permeability measured during laboratory tests may be due to damage during test sampling and preparation, or to undetected tiny leaks from the testing equipment. For these authors, the permeability observed in the vicinity of a cavern is a *secondary* permeability, i.e., induced by the stresses changes generated by cavern creation and operation in the vicinity of the cavern contour, or salt mass convergence in sealed brine-filled cavity [5,6]. To a certain extent, these different views may be explained by differences in salt compositions. Bedded salt formations often contain a large amount of insolubles (clay, anhydrite) which might be more permeable than salt itself. In the case of Etrez salt formation, the insoluble amount is 10%.

1.4. Brine leaks

Brine leaks can occur through the casing or the casing shoe. For this reason, casing tightness is checked thoroughly during the life span of storage caverns. The existence of such leaks, which are likely to vanish after the well of an abandoned cavern is plugged, could lead to severe misinterpretation of a cavern abandonment test (salt permeability would be overestimated) if casing leakage and brine permeation were not distinguished.

The manner in which these factors combine depends on the specific conditions at each site.

2. The 1997–1998 test

An abandonment test was performed from March 1997 to October 1998 in a 950-m deep cavern of the Etrez gas storage site, operated by GDF Suez, in Ain, France. The cavern volume was 7500–8000 m^3. This cavern had been leached out from a bedded salt formation in 1982 and had been kept idle for 15 years. In such a small cavern, brine warming is relatively fast (the initial temperature gap, which was more than 15 °C, was divided by a factor of four after 1 year; see Section 3.2). Temperature logs performed in February and March 1996 [1] clearly proved that thermal equilibrium was reached at that time.

It was feared that some leakage might take place through the casing shoe, especially when cavern pressure is high, and a simple system was designed to assess well leaks. The $9^5/_8''$ cemented casing shoe is 842-m deep, and the 7″ string shoe is 929-m deep (Fig. 1). An 864.5 m high fuel-oil column was lowered in the annular space; the rest of the cavern was filled with saturated brine (except for a fuel-oil column, a few meter high, at the top of the string). Any fuel-oil leak generates a rise of the brine/fuel-oil interface in the annular space. Because fuel-oil (ρ_O=850 kg/m^3) is less dense than brine (ρ_b=1200 kg/m^3), any interface rise generates a change in the difference between annular space pressure and string pressure, as measured at the wellhead. When the interface rise is δh=1 m, this drop is $\delta P=(\rho_b-\rho_O)g\delta h \approx$ 3.5 kPa, a value which can easily be measured when accurate pressure gauges are used. In fact, during the 1997–1998 test, it was proven that the pressure difference rate was slower than $\dot{P}=1\,\text{Pa/day}$, indicating that the fuel-oil leak was null or exceedingly small.

In other words, during this test, two of the four phenomena mentioned above played a significant role: cavern creep closure, and brine permeation. Cavern creep closure leads to an increase in cavern pressure; the increase is faster when cavern pressure is lower. Brine permeation leads to cavern pressure release; the release is slower when cavern pressure is lower. An equilibrium pressure is reached when the effects of these two phenomena are exactly equal – i.e., when the cavern-volume loss rate (due to creep closure) is balanced exactly by the brine outflow rate (due to permeation). The main objective of an abandonment test is to assess this equilibrium pressure and to check that it is significantly lower than the geostatic pressure.

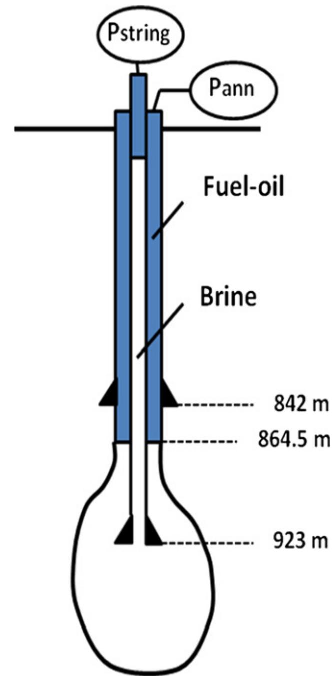

Fig. 1. Schematic layout of the 1997–1998 test.

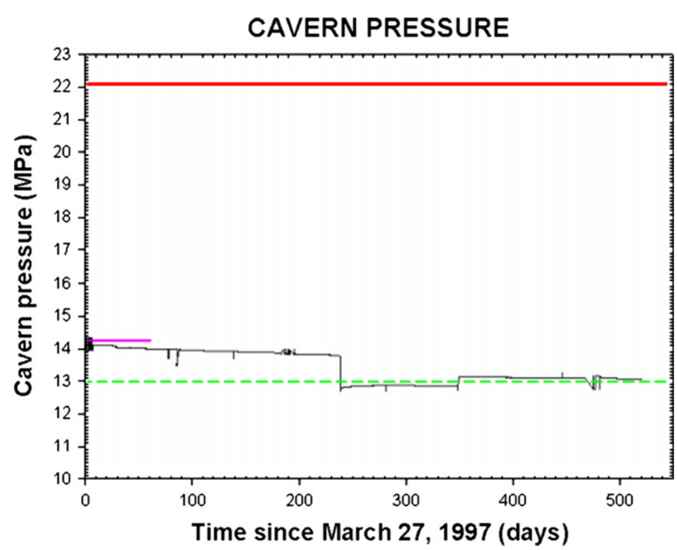

Fig. 2. Cavern pressure evolution from March 1997 to October 1998.

The test consists of a "trial and error" process (Fig. 2) 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 (respectively, decreases) for a sufficiently long period of time, it can be inferred that cavern pressure is lower (respectively, higher) than the equilibrium pressure. In such a case, a higher (respectively, 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.

The test began on March 27, 1997 (day 1) and lasted for 540 days. Four initial pressures were tested successively. The test ran smoothly except for a small leak through the string at the wellhead from day 293 to day 315. 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 $H=950$ m was $P_{950}^{eq}=13\pm0.1\,\text{MPa}$, smaller than the geostatic pressure ($P_\infty=20.5$ MPa), and larger than the halmostatic pressure ($P_h=11.2$ MPa). It also was inferred that salt-formation permeability was $K\approx 2\times10^{-19}\,\text{m}^2$. The cavern-creep closure rate upon reaching equilibrium pressure – which also is the brine outflow from the cavern – was estimated to be 1.4 m^3/yr or $\dot{V}/V=2\times10^{-4}\,\text{yr}^{-1}$.

3. Was the 1997–1998 test long enough?

In principle, the results of this test can be considered to be convincing. The physical phenomena which 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), which represents companies, consultants and research centres involved in the solution mining industry, has set the cavern abandonment issue at the centre of its research program, and SMRI supported the 1997–1998 test [7]. It also supported similar later tests performed at Carresse (France) [8] and Staβfurt (Germany) [9]. Many papers contributed to the discussion [10,11,12] over the years, and many companies performed abandonment tests following the same methodology [13,14,15,16]. 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. In the months and years following cavern creation, cavern pressure behaviour is governed by thermal, mechanical and hydrogeological *transient* phenomena. Long-term prediction must be based on a correct assessment of the *steady-state* behaviour of the cavern, which may be reached after several decades. Too short a monitoring period may lead to misinterpretation of data.

3.1. Thermal phenomena

In many cases, thermal transient phenomena play a pre-eminent role, as the initial temperature gap can be several dozens of °C, and a 1 °C temperature increase leads to a 1 MPa brine pressure increase (see the Introduction). This is especially true in large caverns, in which brine warming is spread over several decades. Brine warming is governed by heat conduction through the rock mass. A first characteristic time [1] for cavern brine warming is $t_c^{th}=a^2/\pi k_{th}$, where a is a cavern characteristic length (say, its radius) and k_{th}=100 m^2/yr is the thermal diffusivity of rock salt. For the Ez53 cavern, a small cavern, $a^2=150$ m^2, and the thermal characteristic time is $t_c^{th}\approx0.5\,\text{year}$. The second characteristic time, $t_c^{th'}=\rho_bC_bt_c^{th}/\rho_{salt}C_{salt}$,where ρ_bC_b and $\rho_{salt}C_{salt}$ are brine and salt volumetric heat capacity, respectively, is of the same order of magnitude [1]. In 1997, some 15 years after cavern had been created, the Ez53 cavern had reached thermal equilibrium.

3.1.1. Brine permeation and cavern creep closure

When brine warming and brine leakage through the well can be neglected, pressure evolution in a closed cavern mainly results from cavern creep closure and brine permeation through the cavern walls. Several other phenomena play a minor role. Atmospheric pressure and temperature variations generate daily or yearly fluctuations, which are small; when averaged over a long period of time, their effects are nil. Rapid pressure changes trigger adiabatic temperature evolution and additional salt dissolution. Their consequences are transient and become negligible after a couple of weeks. Mechanical and hydrogeological transient responses to a cavern pressure change are longer and must be discussed.

The driving forces for cavern creep closure and brine permeation are the gap between overburden pressure (P_∞) and cavern pressure (P), and the gap between cavern pressure (P) and natural pore pressure (p_0), respectively. During the 1982–1997 period, cavern pressure (at a depth of 950 m) was almost constant and equal to halmostatic pressure, or $P=P_h=11.2$ MPa. During the 1997–2009 period it was close to the predicted equilibrium pressure, $P_{eq}=13$ MPa. These figures must be compared to the overburden pressure, $P_\infty=20.5$ MPa, and to the natural pore pressure, which Durup [17] proved to be close to the halmostatic pressure, or $p_0=P_h=11.2$ MPa. In other words, cavern pressure did not experience large or frequent changes during the 1982–2009 period. However, cavern pressure did experience a large change when the cavern was created, and one must question whether steady-state behaviour actually was reached at the end of the 1997–1998 test.

3.1.2. Brine permeation through the rock mass

When Darcy's law for brine permeation is accepted – a controversial issue, as mentioned in the Introduction – the following equations hold:

$$\frac{\partial p(x_k,t)}{\partial t}=k_{hyd}\Delta p(x_k,t) \tag{1}$$

$$p(x_k,t)=P(t)\quad\text{and}\quad \beta V\dot{P}(t)=-Q=\int_{\partial\Omega}-\frac{K}{\mu}\frac{\partial p(x_k,t)}{\partial n}da \tag{2}$$

$$p(\infty,t)=p_0 \tag{3}$$

where p is the pore pressure; k_{hyd} is the hydraulic diffusivity of salt (in m^2/s) or $k_{hyd}=K/\mu\phi\beta'$, K (in m^2) is the intrinsic permeability of salt, μ is the brine dynamic viscosity, ϕ is the salt porosity, β' is the pore+brine compressibility, and $P=P(t)$ is the cavern brine pressure. The natural pore pressure is p_0. Eq. (1) describes the pore pressure evolution in the rock mass. Eq. (2) provides two boundary conditions at the cavern wall (brine pressure is continuous and brine flow from the cavern, or $Q>0$, results in a decrease in cavern pressure). From Eq. (1) a first characteristic time can be inferred, or $t_c^{hyd}=a^2/\pi k_{hyd}$; Eq. (2) provides a second characteristic time, or $t_c^{hyd'}=\beta t_c^{hyd}/\beta'\phi$. Typical values are $K=2\times10^{-19}\,\text{m}^2$, $\mu=1.2\times10^{-3}$ Pa s, $\phi=1\%$, $\beta=\beta'=4\times10^{-10}\,\text{Pa}^{-1}$ (β' is especially difficult to assess). When $a^2=150\,\text{m}^2$ (or $V=8000$ m^3), $t_c^{hyd}\approx12\,\text{days}$ and $t_c^{hyd'}\approx4\,\text{years}$. In other words, the steady-state distribution of pore pressure for a fixed cavern brine pressure is reached after a couple of years; however cavern pressure changes due to brine permeation are slower.

In the case of an idealized spherical cavern, steady-state pore pressure distribution and relative brine outflow are given by

$$p=p_0+(P-p_0)\frac{a}{r}\quad\text{and}\quad\frac{Q}{V}=\frac{3K(P-p_0)}{\mu a^2} \tag{4}$$

3.1.3. Cavern creep closure

Norton-Hoff constitutive behaviour is assumed. During an uniaxial test, when the axial applied load is σ, the axial steady-state strain rate is $\dot{\varepsilon}=-A(T)|\sigma|^n$ and $tr\dot{\varepsilon}=0$. When such a law is generalized to the 3-D problem of a cavern, the following equations hold:

$$\dot{\varepsilon}_{ij}(x_k,t) = \frac{1+\nu}{E}\dot{\sigma}_{ij}(x_k,t) - \frac{\nu}{E}\dot{\sigma}_{kk}(x_l,t)\delta_{ij} + \frac{3}{2}AJ_2^{(n-1)/2}s_{ij}(x_l,t) \quad (5)$$

$$\sigma_{ij,j}(x_l,t) = 0 \quad (6)$$

$$\sigma_{ij}(x_l,t)n_j = -P(t)n_i \quad (7)$$

$$\sigma_{ij}(\infty,t)n_j = -P_\infty n_i \quad (8)$$

where ε_{ij} is the strain tensor, σ_{ij} is the stress tensor, σ_{kk} is the first invariant of the stress tensor, s_{ij} is the deviatoric stress tensor, J_2 is the second invariant of the deviatoric stress tensor, E and ν are Young's modulus and Poisson's ratio, and A and n are two constants. Eq. (5) describes the constitutive law, Eq. (6) is the equilibrium condition, and Eqs. (7) and (8) are the boundary conditions at cavern wall and at a large distance from the cavern, respectively.

In the following, we consider the case of a spherical cavern, radius a, leached out from a deep salt formation. Radial displacement rate is $\dot{u} = \dot{u}(r,t)$. Cavern pressure is decreased at time $t=0$ from the geostatic value P_∞ to a constant value P_c. Due to spherical symmetry, Eqs. (5)–(8) can be rewritten as

$$\dot{\varepsilon}_{rr} = \frac{\partial \dot{u}}{\partial r} = \frac{1}{E}(\dot{\sigma}_{rr} - 2\nu\dot{\sigma}_{\theta\theta}) + A(\sigma_{rr} - \sigma_{\theta\theta})^n \quad (9)$$

$$\dot{\varepsilon}_{\theta\theta} = \dot{\varepsilon}_{\varphi\varphi} = \frac{\dot{u}}{r} = \frac{1}{E}[(1-\nu)\dot{\sigma}_{\theta\theta} - \nu\dot{\sigma}_{rr}] - \frac{A}{2}(\sigma_{rr} - \sigma_{\theta\theta})^n \quad (10)$$

$$r\frac{\partial}{\partial r}\sigma_{rr}(r,t) + 2[\sigma_{rr}(r,t) - \sigma_{\theta\theta}(r,t)] = 0 \quad (11)$$

$$\sigma_{rr}(a,t) = -P_\infty + (P_\infty - P_c)H(t) \quad \text{and} \quad \sigma_{rr}(\infty,t) = -P_\infty \quad (12)$$

First, consider the steady-state problem ($t \to \infty, \dot{\sigma}_{rr} = \dot{\sigma}_{\theta\theta} = 0$). It is easy to check that $\dot{\varepsilon}_{rr} + 2\dot{\varepsilon}_{\theta\theta} = 0$,hence $\dot{u}/r = a^2\dot{a}/r^3$ and the rate of steady-state cavern volume loss rate is

$$\left.\frac{\dot{V}}{V}\right|_{t=\infty} = 3\left.\frac{\dot{a}}{a}\right|_{t=\infty} = -\frac{3A}{2}\left[\frac{3}{2n}(P_\infty - P_c)\right]^n \quad (13)$$

Consider now the transient problem. When $\nu=0.5$ is assumed, no volume change takes place, $\dot{u}/r = a^2\dot{a}/r^3$ holds again and the following development can be computed:

$$\left.\dot{V}/V\right|_{t=0+} = -\frac{3}{2n}A^*\left[\frac{3}{2}(P_\infty - P_c)\right]^n \left(= n^{n-1}\left.\dot{V}/V\right|_{t=\infty}\right) \quad (14)$$

$$\left.\frac{d}{dt}(\dot{V}/V)\right|_{t=0+} = -\frac{3}{2}EA^{*2}\frac{(n-1)^2}{n(2n-1)}\left[\frac{3}{2}(P_\infty - P_c)\right]^{2n-1}$$
$$= -\frac{4E}{9(P_\infty - P_c)}\frac{n(n-1)^2}{(2n-1)}\left[\left.(\dot{V}/V)\right|_{t=0+}\right]^2 \quad (15)$$

When the exponent of the power law, or n, is high, the initial (transient) creep closure rate (14) is much faster than the steady-state creep closure rate (13). This transient behaviour must be related to the slow stress re-distribution in the rock mass.

Eqs. (14) and (15) allow us to define a characteristic time:

$$t_c^{mech} = -\left.\dot{V}/V\right|_{t=0+} \Big/ \left.\frac{d}{dt}(\dot{V}/V)\right|_{t=0+}$$
$$= -\frac{9(P_\infty - P_c)}{4E}\frac{2n-1}{n^n(n-1)^2} \Big/ \left[\left.\dot{V}/V\right|_{t=\infty}\right] \quad (16)$$

In the case of the EZ53 cavern, $\dot{V}/V|_{t=\infty} \approx -3 \times 10^{-4}$/yr, $n \approx 3$, $P_\infty - P_c = 10$, $E = 20{,}000$ MPa and $t_c^{mec} \approx 2$ months. This time is relatively short, which means that the initial drop in convergence rate is very fast. In situ tests confirm this statement. However, as proved by numerical computations, the steady-state rate is reached (say, with an accuracy of 1%) after a long period (one century is typical). What formula (16) shows is that a large gap between transient and steady-state convergence rates cannot exist during a long period of time.

3.2. Conclusions

Two important conclusions can be drawn. Firstly, when combining Eqs. (4) and (13), it can be inferred that, when steady-state is reached, cavern pressure reaches an equilibrium value, P_{eq}, such that cavern creep closure rate exactly equals brine outflow from the cavern [1] and:

$$\frac{3}{2}A(T)\left(\frac{3}{2n}\right)^n(P_\infty - P_{eq})^n = \frac{3K(P_{eq} - p_0)}{\mu a^2} \quad (17)$$

and four constants are involved, n, $(1/2)\mu a^2 A(T)(3/2n)^n/K$ (these constants are site specific, but laboratory tests and in situ tests allow for an empirical assessment), p_0 (poorly known, but close to P_h) and P_∞ (relatively well known). This formula holds for an idealized spherical cavern; numerical computations allow for computing the equilibrium pressure for any given shape of a cavern.

Analysis of the thermal, hydrogeological and mechanical transient behaviour of a cavern also strongly suggests that at the end of the initial test, 26 years after the EZ53 cavern was created, its mechanical and hydrogeological behaviour cannot be very different from steady-state behaviour. However, a pragmatic approach also 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

4.1. November 1998 to June 2002

The EZ53 well completion was briefly discussed in Section 2 (Fig. 1). It includes a 7″ central string that is η=929-m long and has a cross-sectional area of 21.1 l/m making its volume 19.5 m^3. At the end of the 1997–1998 test, the well is filled with saturated brine except for a 3.5-m fuel-oil column at the top of the string. From 0 to 32 m, the cross sectional area of the annular space is 52.4 l/m; from 30 to 842 m (the location of the 9-5/8″ cemented casing shoe), it is 14.7 l/m; and, from 842 to 890 m (location of the cavern chimney), it is 5.7 l/m. The annular space is filled with fuel-oil down to a depth of h=864.5-m. The fuel-oil volume injected in the annular space in 1997 was approximately 14.5 m^3.

No information on 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 (Fig. 3). The pressure gauge, with a resolution of 0.1 MPa, is much less accurate than the gauges used during the 1997–1998 test, although 0.05 MPa pressure changes can be measured. Wellhead string pressure from May 24 to June 6 is P_{tub}=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 $P_{950} = P_{tub} + \rho_b g\ H = 1.75 + 11.2 = 12.95$ MPa, which exactly 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}=4.4 MPa, from which the value of $P'_{950} = P_{ann} + \rho_O gh + \rho_b g(H-h) = 12.6$ MPa can be inferred.

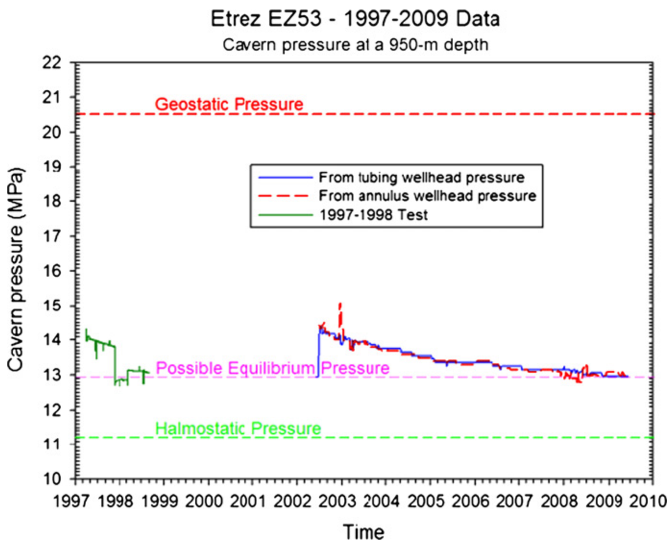

Fig. 3. Cavern pressure evolution in the 1997–2009 period.

This value is smaller than that inferred from the wellhead string pressure (they obviously should be equal). Two hypotheses can be considered. In the first one, a fuel-oil leak took place during the 1998–2002 period. Such a leak would result in a heavier annular space column, because the brine/fuel-oil interface rises and hydrocarbon is substituted by saturated brine. This hypothesis is not fully convincing, as the leak was almost zero during the 1997–1998 period. In the second hypothesis, there were uncertainties in pressure measurements and liquid densities. Accuracy of pressure gauge is poor; liquid densities are not constant, but depend on liquids pressure and temperature (which, from the wellhead to the cavern bottom, vary from a couple of MPa to 11 MPa, and from 10 to 45 °C, respectively). These result in variations of liquid density by 1% for brine (and more for fuel-oil).

4.2. *From June 2002 to December 2002*

On June 25, 2002, fuel-oil was withdrawn from the annular space and brine was injected in the tubing to increase cavern pressure. The injected brine was slightly under-saturated; its density was $\rho_b^{uns} = 1177\,\mathrm{kg}/m^3$. The annular space was filled with the fully saturated brine that displaced the fuel-oil column and comes from the cavern. The tubing pressure fluctuates from P_{tub}=3.2 to 3.4 MPa, an increase of ΔP=1.45 to 1.65 MPa when compared to the May 2002 period. Because the cavern compressibility is βV=3 m^3/MPa, it can be inferred that the injected brine volume was $\beta V \Delta P \approx 4.5$ m^3 (to increase cavern pressure) plus 14.5 m^3 (to withdraw fuel-oil 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 $P_{950} = P_{tub} + \rho_b^{uns} g\eta + \rho_b g(H-\eta) = 14.2\text{-}14.4\,\mathrm{MPa}$.

The annular space pressure during this period is: P_{ann}=3.1 to 3.2 MPa, from which a cavern pressure ranging from $P'_{950} = P_{ann} + \rho_b gH = 14.3\text{-}14.4\,\mathrm{MPa}$ can be inferred; the two values are consistent (suggesting that the discrepancy observed in June 2002 resulted from poor estimation of fuel-oil 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 l) of fuel-oil was injected in both the string and the annular space to prevent brine freezing. Both wellhead pressures increase by 0.1 MPa, a value consistent with what is known of cavern compressibility and fuel-oil density. By mid-December, the annular pressure suddenly increased by 1.1 MPa. This increase cannot be explained, and gauge misreading is suspected, as, by the end of December, the pressure drops down to the value observed before this "pressure crisis". A similar "pressure crisis" can be observed in March 2003, when both pressures unexpectedly drop down by 0.2–0.3 MPa. Before and after this "crisis", pressure evolution is smooth. These pressure drops remain 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 gauges resolution was much better) but these changes typically are 0.01 MPa in magnitude, 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, 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 become difficult, as the gauge clearly no longer works properly. A new string gauge was set on June 4, 2008. From then until July 2009, the string pressure is P_{tub}=2.0 MPa, and the annular space pressure is P_{ann}=1.8 − 1.9 MPa. It can be concluded from these figures that the cavern pressure is P_{950}=13 ± 0.1 MPa, which is 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 4 years.

5. Conclusion

A 12-year long shut-in test was performed on the 950-m deep, 8000 m^3 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 clearly been confirmed.

Acknowledgements

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