FIELD TESTING ISSUES RELATIVE TO THE

LONG-TERM ABANDONMENT OF SALT CAVERNS

Pierre Bérest (LMS, Ecole Polytechnique Paris Tech, Palaiseau, France)

Benoît Brouard (Brouard Consulting, Paris, France)

1. INTRODUCTION

The abandonment of salt caverns raises two main issues:

- the long-term mechanical stability of the abandoned caverns; and
- the possible pollution of water-bearing strata by brine seeping from the cavern, especially when potable water resources are present.

The SMRI "Abandonment & Sealing" Research Program addresses the second issue.

It has been found that, especially when shallow caverns are concerned, potable water can be protected if, in the long-term, cavern brine pressure remains significantly lower than geostatic pressure. In this paper, "abandonment tests" are described that allow assessment of the long-term brine pressure in a sealed and abandoned cavern.

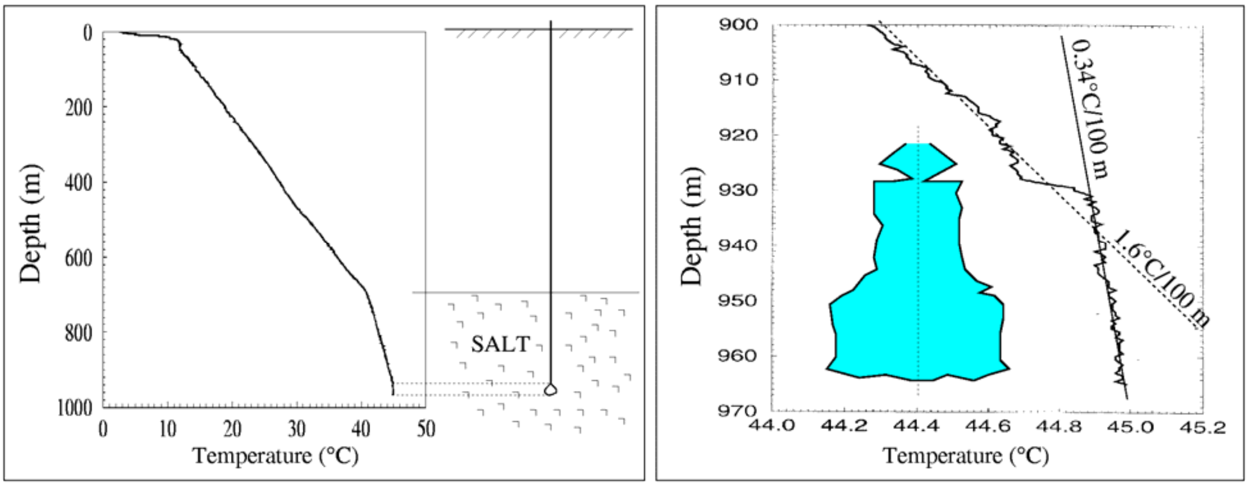
2. CAVERN THERMAL STATUS

When a cavern is to be sealed and abandoned, the first — and probably the most important — thing to be done is to assess the thermal status of the cavern. The temperature history of cavern fluids during cavern operation generally is complex; in most cases (not always, especially in shallow caverns), when a cavern is abandoned, the brine temperature is cooler than the geothermal temperature at average cavern depth. More precisely, the following procedures must have been performed prior to abandonment:

- Measure the rock geothermal-temperature profile (e.g., run a temperature log in a drill hole before leaching starts).
- Measure the cavern-brine temperature.
- Set a permanent temperature gauge in the cavern and measure the brine temperature evolution over a sufficiently long period of time (depending on cavern size and gauge accuracy; in large caverns, temperature evolution is slow).

The gap between the geothermal temperature of the rock and the brine temperature *(ΔT)* of the cavern governs any cavern abandonment strategy.

Figure 1 illustrates the EZ53 cavern, operated by GDF Suez at Etrez, Ain, France. The depth of this cavern is 950 m, and the cavern volume is V = 8000 m^3. Leaching was completed by June 1982, at which time the cavern brine temperature was 26.5 °C. The cavern brine temperature was measured again in February 1996. In this small cavern, brine warming is a fast process: the thermal characteristic time, or $t_c = V^{2/3} / 4k \approx 1$ year, is short, see Section 5). Fourteen years after leaching was completed, thermal equilibrium was achieved (cavern temperature at 45 °C). Note in Fig. 1a that, from top to bottom, the temperature is low at shallow depth, because the test was performed in February. In Fig. 1b, the thermal gradient is larger (3 °C/100m) in the upper part of the overburden, which is composed mainly of marly rocks than it is (1.6 °C/100m) in the bedded salt formation (below 700 m), as the thermal conductivity of salt is larger than the thermal conductivity of marl. The thermal gradient is smaller still (0.34 °C/100m) in the cavern itself, as cavern brine is stirred by natural convection.



(a) **(b)**

Figure 1. EZ53 cavern, operated by GDF Suez at Etrez, Ain, France: (a) temperature log; (b) cavern temperature.

Figure 2 illustrates a 1-year long temperature measurement in a large cavern. Cavern volume is approximately 250,000 m^3. Leaching was completed by 1980. At that time, the brine temperature was slightly warmer in this shallow cavern than the rock temperature. Thirty years later, thermal equilibrium was reached.

Because the temperature-vs-time curve is flat, temperature gauge default might be suspected. To check the temperature-gauge resolution, the cavern pressure was increased at the end of the test. It is known that in a brine-filled cavern, a pressure increase ΔP = 0.3 MPa generates a temperature increase of ΔT = 0.01 °C (Van Sambeek et al., 2005). In fact, the gauge measure changed from 17.70 to 17.72 °C when the pressure was increased by 0.6 MPa, proving than it worked properly and that its resolution was 0.02 °C.

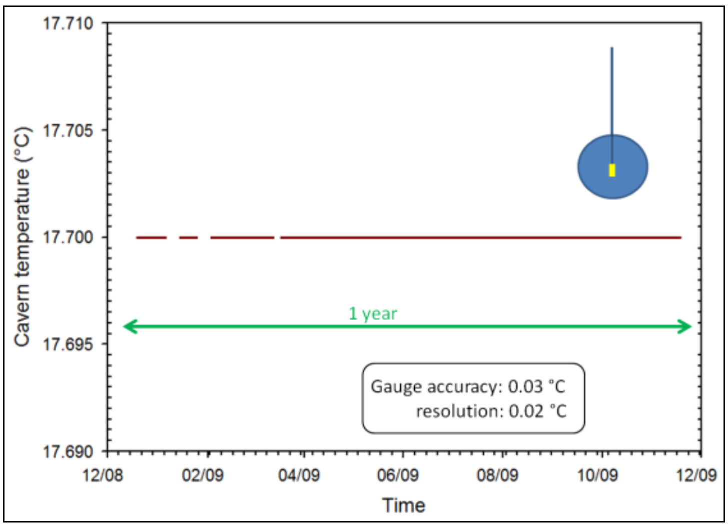


Figure 2 – 1-year long temperature measurement in a large cavern.

Figure 3 presents displays temperature evolution in the SPR2 cavern, operated by Total at Carresse, France, from June 12, 2002 to October 8, 2002. A temperature gauge was set in this 287-m-deep cavern with cavern volume of 8000 m^3. Thermal equilibrium was not reached at this time; brine warming rate was 0.58 °C/yr.

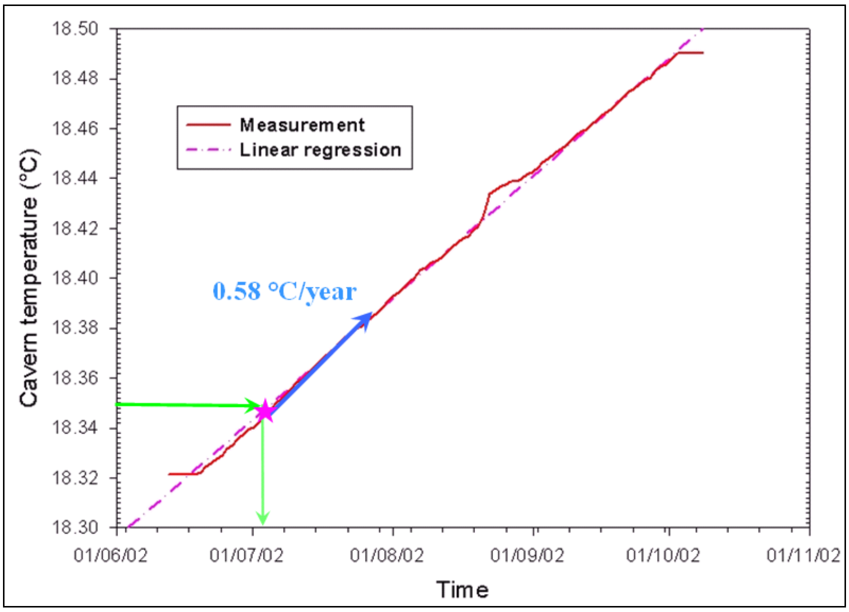


Figure 3. Temperature evolution in SPR2 cavern from June 12, 2002 to October 8, 2002.

3. CAVERN COMPRESSIBILITY MEASUREMENT

When a certain amount of liquid, v_{inj}, is injected into a closed cavern, the wellhead pressure increases by δP^{wh}, which, at first approximation, is also the cavern pressure increase. The relation between these two quantities (v_{inj} and δP^{wh}) generally is linear during a rapid test. An example is given on Figure 4. A similar test can be performed by withdrawing a certain amount of liquid from a pressurized cavern. This test is simple, its cost is small, and its interpretation is straightforward.

The slope of the curve (injected brine volume versus brine pressure), or $\beta V = v_{inj} \big/ \delta P^{wh}$, is called the cavern compressibility (in m^3/MPa or bbls/psi). When this curve is not a straight line, the existence of severe leaks is likely. Note that tubing pressure is measured as liquid is injected into the annulus (or *vice versa*), as changes in the composition of the annulus column can lead to misinterpretation.

The cavern compressibility factor (β) is obtained by dividing the cavern compressibility, or βV, by the cavern brine volume, or V. This parameter is of utmost importance. A typical value of the compressibility factor is $\beta = 4-5\times10^{-4}$ / MPa (or $\beta \approx 3\times10^{-6}$ / psi).

Larger values of the compressibility factor (β) can be found when the cavern shape is flat or when the cavern contains some gas trapped at cavern roof. This can be an asset, as the effects of brine warming are less severe in a more “compressible” cavern.

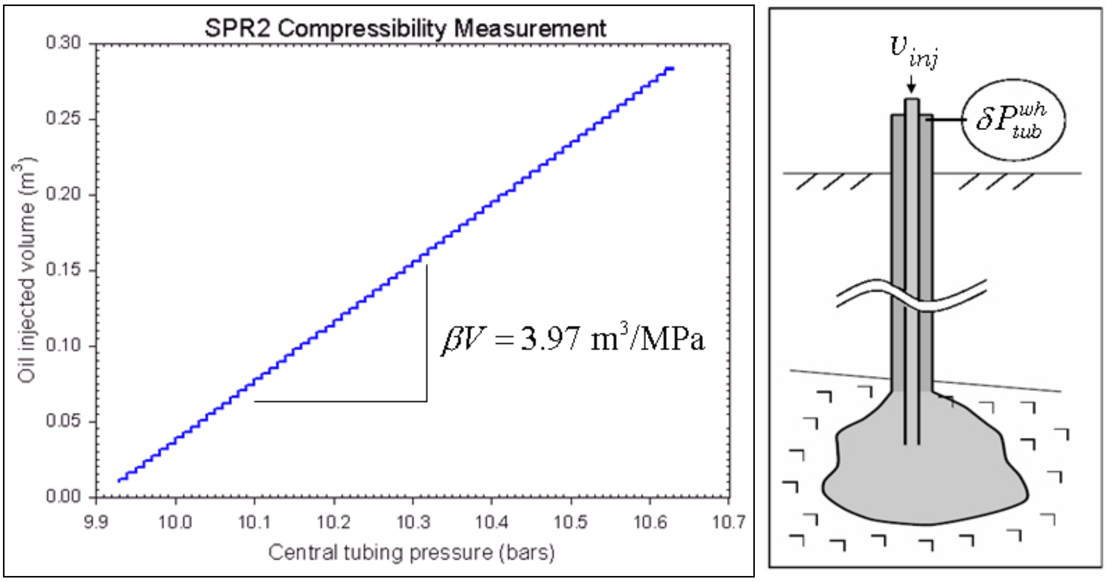


Figure 4. Compressibility Test at the SPR2 cavern. (Cavern compressibility is the slope of the injected-volume vs. wellhead-pressure-increase curve.)

4. COMPARE ROCK AND CAVERN BRINE TEMPERATURE

Two cases must be considered:

- when thermal equilibrium has been reached, or reached approximately (the gap between rock geothermal temperature and brine temperature at average cavern depth is small); and

- when the gap between rock geothermal temperature and brine temperature is large.

What is a "small" or a "large" gap between rock geothermal temperature and brine temperature? A more precise definition will be given later (Section 6.2), but a rough estimation can be made as follows.

- **Geostatic pressure at cavern depth** can be obtained readily through the formula: $P_\infty(\text{MPa}) = 0.022\,H(\text{meters})$. For example, when the cavern depth is H = 500 m, the geostatic pressure can be expected to be $P_\infty = 11$ MPa. A more precise assessment of the geostatic pressure can be reached when a density log is available or when micro-fracturing tests were performed (although interpretation often is tricky).

- **Halmostatic pressure at cavern depth** is the cavern brine pressure when wellhead pressure is zero (i.e., when the wellhead is opened). When the well is filled with saturated brine, the halmostatic pressure is $P_h(\text{MPa}) = 0.012\,H(\text{meters})$.

Halmostatic and geostatic pressures must be computed at the casing-seat depth.

The gap between geostatic pressure and halmostatic pressure is $P_\infty - P_h(\text{MPa}) = 0.01\,H(\text{meters})$. For instance, it is $P_\infty - P_h = 10$ MPa when H = 1000 m.

The gap between rock geothermal temperature and brine temperature is ΔT (in °C). The brine thermal-expansion coefficient is $\alpha = 4.4\times10^{-4}\,/\,°C$. The potential brine pressure increase due to brine thermal expansion is $\Delta P_{th} = \alpha\ \Delta T/\beta$. It has been said that a typical increase value is $\beta = 4 - 5\times10^{-4}$ / MPa. In such a case, ΔP_{th} (in MPa) $\approx \Delta T$(in °C); when $\Delta T = 5°C$, $\Delta P_{th} \approx 5$ MPa; and when $\Delta T = 5°F$, $\Delta P_{th} \approx 400$ psi.

The gap between rock geothermal temperature and brine temperature can be said to be small when ΔP_{th} is small compared to $P_\infty - P_h$. For example, consider a cavern whose depth is H = 1000 m, or $P_\infty - P_h = 10$ MPa. When the gap between the rock geothermal temperature and brine temperature is smaller than 1°C, $\Delta P_{th} \approx 1$ MPa $\ll P_\infty$ - P_h, and the gap is said to be "small" . A more precise definition should be: "The gap between the rock geothermal temperature and cavern brine temperature is such that the potential brine-pressure increase due to brine thermal expansion is smaller than the gap between geostatic pressure and equilibrium pressure." This more precise definition needs several parameters in order to be assessed; this will be discussed in Section 6.2.

5. WHAT CAN BE DONE WHEN THE GAP BETWEEN ROCK GEOTHERMAL TEMPERATURE AND CAVERN BRINE TEMPERATURE IS LARGE?

Consider the following case in which the gap between the rock geothermal temperature and the brine temperature is $\Delta T = 10$ °C, the brine pressure increase due to brine thermal expansion is $\Delta P_{th} = \alpha\,\Delta T/\beta = 10$ MPa, and the cavern depth is H = 1000 m. At such depth, the gap between geostatic pressure and halmostatic pressure is $P_\infty - P_h = 10$ MPa. Suppose that the cavern is sealed. In this case, the cavern brine pressure is likely to increase by more than 10 MPa, because of the additional effect of cavern creep closure — except, perhaps, if the rock mass were very permeable. There is a risk that hydro-fracturing will take place. What can be done? Two solutions can be considered:

1. Inject a small amount of gas (nitrogen) into the cavern before sealing. Injecting nitrogen into the cavern leads to a dramatic increase in cavern compressibility and a dramatic drop of the potential brine-pressure increase due to brine thermal expansion. This innovative method was discussed by Brouard et al. (2007), but it has not yet been used in an actual abandonment project.

2. Wait a sufficiently long period of time to allow the temperature gap to decrease.

How long should the waiting period be? Numerical computations can be performed (see Section 8.1). However, a simple rule-of-thumb can be used.

Let V be the cavern volume and k be the thermal diffusivity of rock salt (typically, $k = 100\ \text{m}^2/\text{yr}$). The cavern thermal characteristic time, or $t_c = V^{2/3} / 4k$ [or $t_c(\text{years}) = V^{2/3}\ (\text{m}^2) / 400\ (\text{m}^2/\text{yr})$] is the time after which the initial temperature gap (or ΔT) is divided by a factor of 4. For example, consider a cavern with volume V = 512,000 m^3. The cubic root of V = 512,000 m^3 is $V^{1/3} = 80$ m, and $V^{2/3} = 80 \text{ x } 80 = 6400\ \text{m}^2$. It can be inferred that the thermal characteristic time of this cavern is $6400/400 = 16$ years. After 16 years, the initial temperature gap will be divided by a factor of 4 or so. This simple formula holds for an idealized spherical cavern; the thermal characteristic time is somewhat shorter in a slender or flat cavern. More precise figures can be computed numerically when cavern shape is known.

For a cylindrical cavern with height H and diameter D, the following formula can be used: $t_c\,(\text{years}) \approx 4.67 \times \left[V(\text{m}^3)/100{,}000\right]^{2/3} \times \exp\left\{-\left[Ln\left(A/0.91\right)/1.97\right]^2/2\right\}$, where Ln is the Neperian logarithm, and $A = H/D$ is the cavern aspect ratio (see Karimi-Jafari et al., 2007).

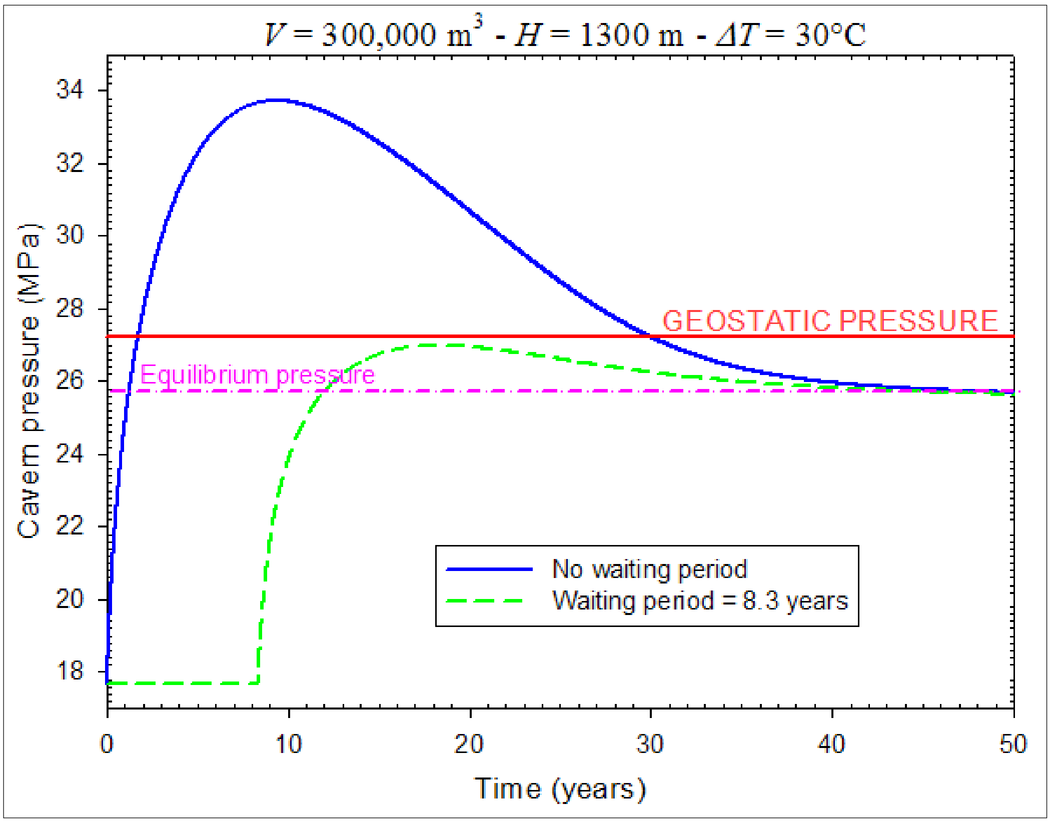


Figure 5. A hypothetical, average, 1300-m-deep cavern. Its volume is V = 300,000 m^3. The gap between the rock geothermal temperature and the brine temperature is ΔT = 30 °C. If no waiting period is observed, hydro-fracturing will take place. (The cavern pressure will be higher than the geostatic pressure.) The thermal characteristic time is $t_c \approx 7$ years. **A waiting period of 8.3 years (before sealing the cavern) allows for a significant decrease in brine temperature.**

Note that the waiting time is longer when cavern volume is larger. For this reason, the abandonment of large caverns raises a difficult problem when the initial temperature gap (between rock mass and cavern brine) is not small, as the brine-warming rate is slow. (Note, also, that when measuring temperature evolution in a very large cavern, gauges must be accurate, as the rate of temperature increase is exceedingly slow.)

6. WHAT CAN BE DONE WHEN THE GAP BETWEEN THE ROCK GEOTHERMAL TEMPERATURE AND THE CAVERN-BRINE TEMPERATURE IS SMALL?

When thermal equilibrium has been reached, or when the gap between the rock geothermal temperature and the brine temperature is small, various abandonment procedures (consisting of abandonment tests) can be used. Some abandonment tests are rough and simple; however, the conclusions drawn from these tests are based on less firm ground. Other tests are more comprehensive, and predictions inferred from these tests are more reliable.

When a cavern field must be abandoned, a good compromise consists of performing a comprehensive test on one cavern to get a better insight to the rock-mass physical properties. Simpler tests can be performed on the other caverns; such tests are described in the following.

6.1 THE SIMPLEST ABANDONMENT TEST

The simplest test consists of increasing cavern pressure to a high figure (say, a gradient of 1.8). For example, for a cavern whose casing seat is anchored at a depth of 1000 m, the initial cavern pressure will be 18 MPa, and wellhead pressure 6 MPa; however, in a tall cavern, maximum pressure may be limited by safety considerations. Cavern pressure as a function of time is recorded *over a sufficiently long period of time*. If wellhead pressure consistently decreases during this period, it can be expected that the initial pressure was larger than the equilibrium pressure (This notion is discussed in Section 6.2), and the cavern can be sealed and abandoned.

What is a “sufficiently long period of time?” From a theoretical perspective, this question is difficult to answer. Following any rapid pressure increase (for instance, at the beginning of the test, after brine is injected into the cavern to increase cavern pressure), many “transient” phenomena take place. (Transient phenomena, in contrast with steady-state phenomena, vanish after some time.) These phenomena include additional dissolution, transient “reverse” creep, transient permeation, “adiabatic” temperature increase, etc. A more complete description can be found in Van Sambeek et al. (2005). Transient effects are longer in a larger cavern or when the initial pressure change (at the beginning of the test) is larger. An example is provided in Figure 6. From this figure, it can be inferred that the abandonment test must be at least 1-year long. A more precise answer can be obtained when additional information on rock properties is available.

This test is simple and cost-effective. No string is needed. However, several flaws or weaknesses can be identified:

- No difference is made between brine permeation (through the cavern walls) and leaks (through the casing and through the casing shoe). In fact, when a pressure decrease is observed consistently during the test, this drop may be due to brine leaks. However, before the cavern is abandoned, a tight plug will be set in the well (Crotogino and Kepplinger, 2006). After the plug is set, leaks might be much slower than they were during the test, leading to pressure values larger than those observed during the test. Too optimistic a conclusion might be drawn from this test when leaks are not assessed properly.

- The exact value of the equilibrium pressure is difficult to determine, as the pressure-drop rate becomes slower and slower during the course of the test (The test only provides an upper bound for the equilibrium pressure.), and it is more difficult to know whether the existing temperature gap (as defined in Section 3) can be considered as “small”.

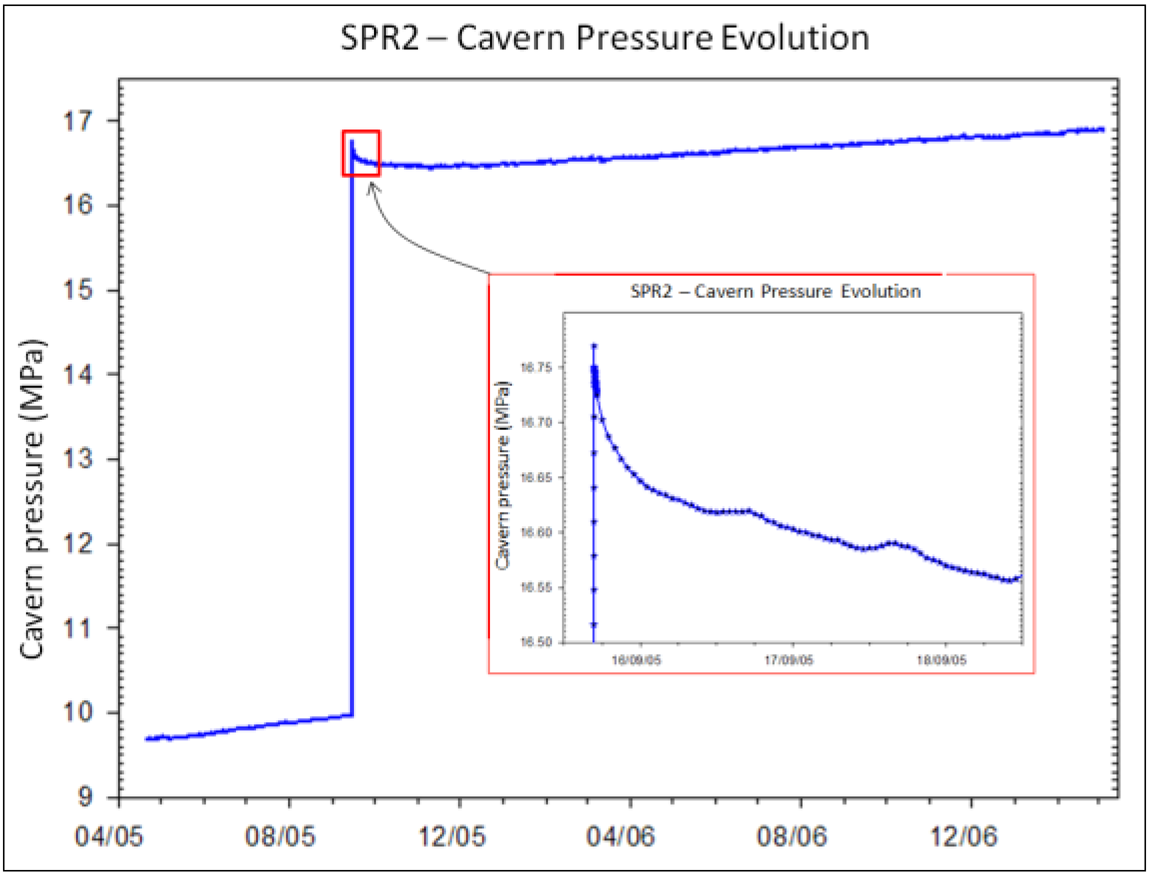


Figure 6. SPR2 cavern, operated by Total at Carresse, France. The cavern depth is *H* = 287 m and the cavern volume is *V* = 9000 m^3. On September 15, 2005, cavern pressure was increased from 4.63 MPa to 4.83 MPa. From September 15 to mid-November (a 2-month period), the wellhead pressure consistently decreased. (During this period, the effects of transient "reverse" creep and brine permeation prevail on the effects of cavern creep closure and brine warming). However, after December 2005, pressure increased again. Too short an abandonment test can lead to severe misinterpretation.

6.2 TWO IMPROVEMENTS OF THE SIMPLEST TEST

6.2.1 Leak detection system

Some leakage may take place through the casing or through the casing shoe, especially when cavern pressure is high during an abandonment test. A simple system first proposed by Diamond et al. (1993) allows well leaks to be assessed. Figure 7 shows leak detection principle. A liquid hydrocarbon column is lowered in the annular space to develop a brine-hydrocarbon interface *below the casing shoe*. The rest of the cavern is filled with saturated brine. Any hydrocarbon leak generates a rise of the brine/hydrocarbon interface in the annular space. Because liquid hydrocarbon ($\rho_o = 850$ kg/m^3 is typical) is less dense than brine ($\rho_b = 1200$ 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 $\delta h = 1$ m (3 ft), this drop is $\delta P = (\rho_b - \rho_o) g \delta h \approx 3.5$ kPa (35 millibars, or 0.5 psi), a value that can be measured easily when accurate pressure gauges are used.

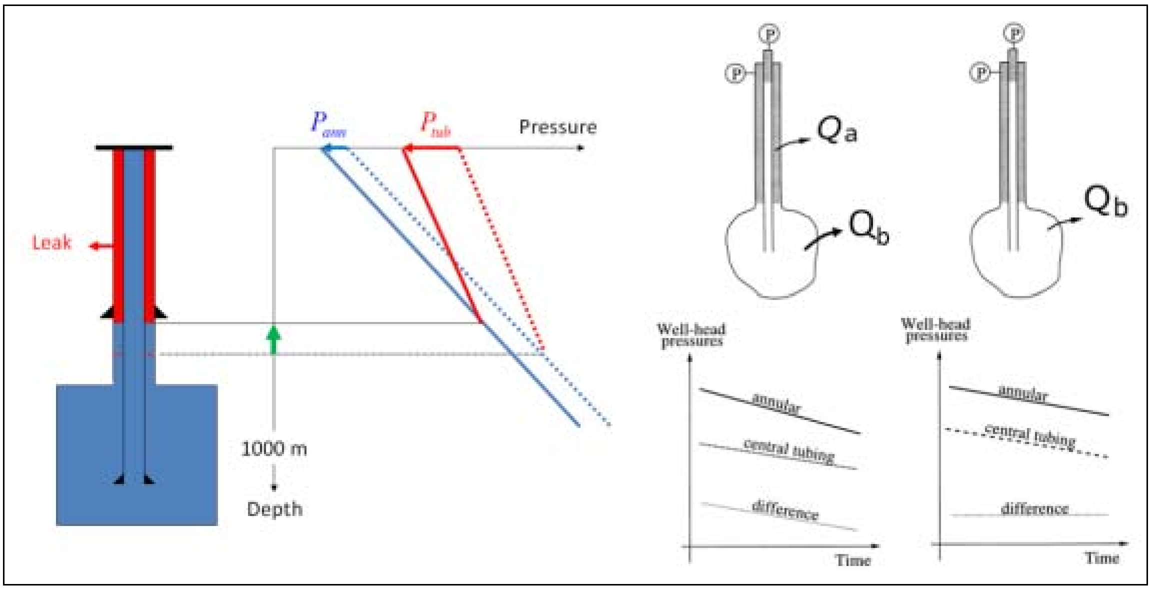


Figure 7. Leak detection system. The annular space is filled with a light liquid hydrocarbon. Q_a is the hydrocarbon leak rate and Q_b is the brine permeation rate. When the hydrocarbon leak rate is zero, the "annular pressure vs. time" and the "central tubing pressure vs. time" curves are exactly parallel, as no change in interface location takes place. When hydrocarbon seeps to the rock formation, the interface rises, and the two curves are not parallel. Note that the cavern neck must be consistent and sufficiently high to be able to perform such a test.

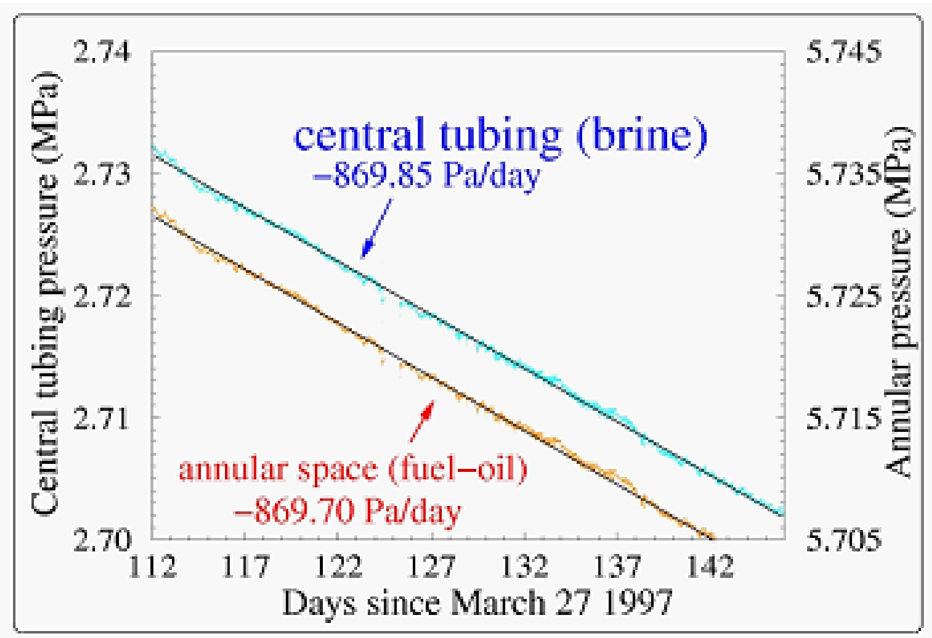


Figure 8. This test is described on Figure 10. The difference between the tubing pressure and the annular space pressure, as measured at the wellhead, remains almost perfectly constant — clear proof that there is no leak through the casing or casing shoe. Tiny fluctuations of both pressures can be observed; they can be attributed to atmospheric pressure variations and earth tides.

This "leak detection system" proved to be extremely effective, but it cannot be used when the cavern neck is not high enough. (With regard to leaks, when there is no cavern neck, the interface rapidly rises above the casing seat, and leaks through the casing shoe no longer can be detected).

6.2.2 Trial-and-error abandonment test

In the trial-and-error abandonment test, instead of a single phase, several phases are managed (Fig. 9). At the beginning of each phase, a specific initial pressure value is imposed through liquid (brine or liquid hydrocarbon) 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 and brine warming can be neglected, it provides both lower and upper bounds for the equilibrium pressure.

The temperature gap was tentatively defined in Section 2. A more precise definition can be proposed now: the temperature gap can be considered as small if the brine pressure increase due to brine thermal expansion, or $\Delta P_{th} = \alpha \; \Delta T \,/\, \beta$, is smaller than the difference between the geostatic pressure and the equilibrium pressure at casing seat depth, $\Delta P_{th} < P_\infty - P_{eq}$. Note that when long-term safety is considered, the cavern brine pressure must be smaller than the geostatic pressure *at cavern-roof depth* — not at cavern mid-depth, as was explained by Wallner and Paar (1997).

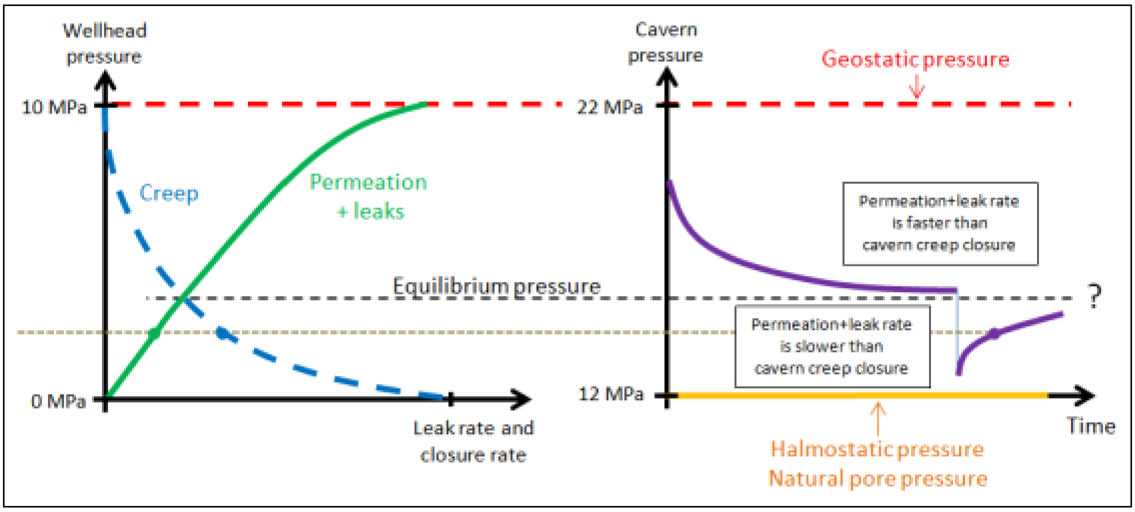


Figure 9. Cavern closure rate is a decreasing function of cavern pressure: it vanishes to zero when cavern pressure = geostatic pressure. Brine permeation + leak flow-rate is an increasing function of cavern pressure. When the two curves cross (left), the equilibrium pressure is reached. The trial-and-error method consists of successively testing several cavern pressure to obtain lower and upper bounds for the equilibrium pressure.

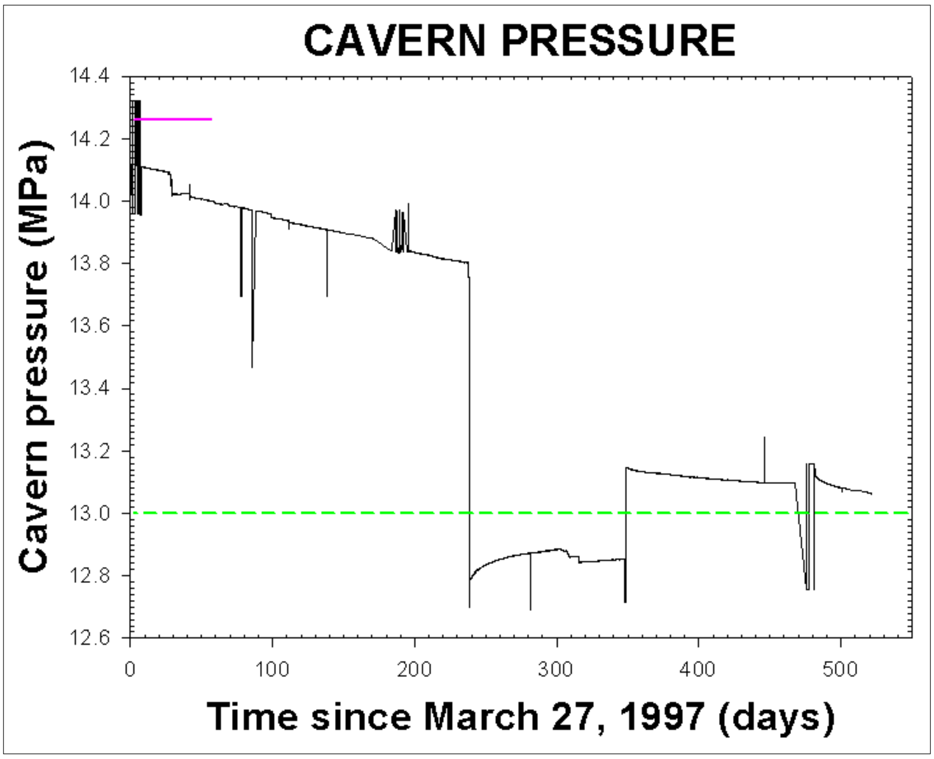


Figure 10. EZ53 cavern, operated by GDF Suez at Etrez, Ain, France (see Figure 1). This test was supported by the SMRI. The cavern's halmostatic pressure is P_h = 11.2 MPa, with geostatic pressure of $P_\infty = 20.5$ MPa. **Four phases were managed. When the test started, a cavern pressure of P = 14.1 MPa was tried. Pressure consistently decreased, and, after some time, a lower pressure was tested. "Jumps" in the pressure-vs-time curve are due to electronic instabilities. Note that a leak appeared on day 293 (pressure decreased over a couple of weeks, although cavern pressure was below equilibrium pressure); it was detected by the leak detection system and repaired on day 315. From this test, the equilibrium pressure can be inferred to be:** $P_{eq} = 13.0 \pm 0.1$ MPa.

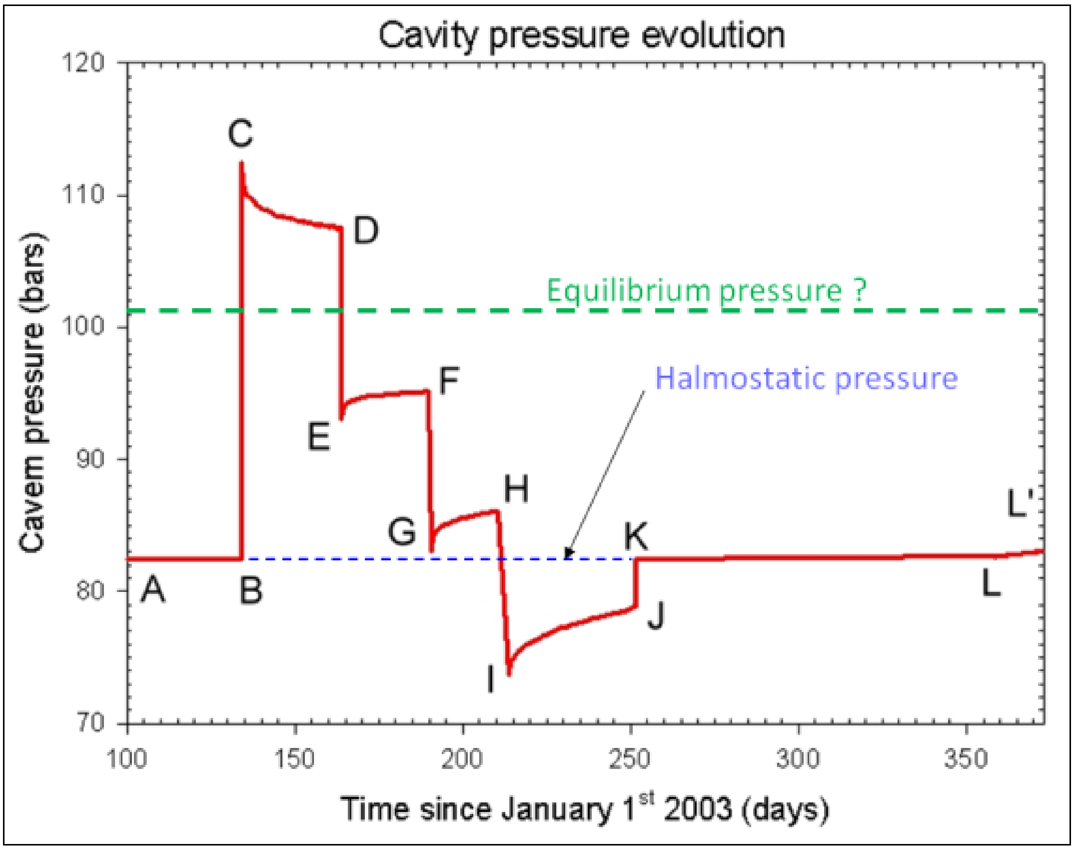


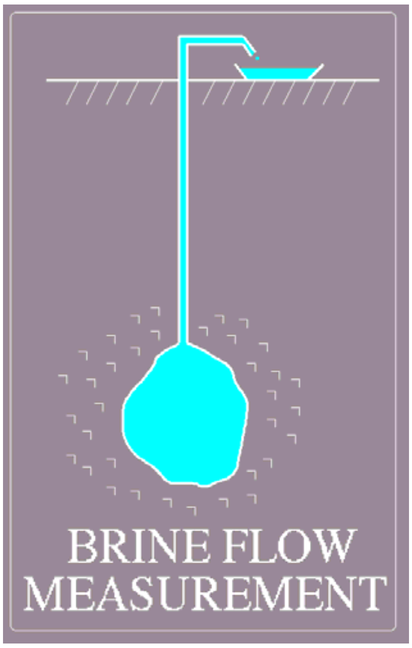
Figure 11. SPR3 cavern, operated by Total at Carresse, France. This cavern is 700-m deep and its volume is $V \approx 10-11{,}000\ \mathrm{m}^3$; it has a halmostatic pressure is P_h = 8.2 MPa. Various pressures were tested successively. The equilibrium pressure seems to be in the range P_{eq} = 9.5 to 10.5 MPa (9.5 to 10 bars). However, during this test, the duration of the various phases was too short, and a definite conclusion difficult to draw. Note that a brine outflow test (see Section 7.1), was performed during the IJ phase.

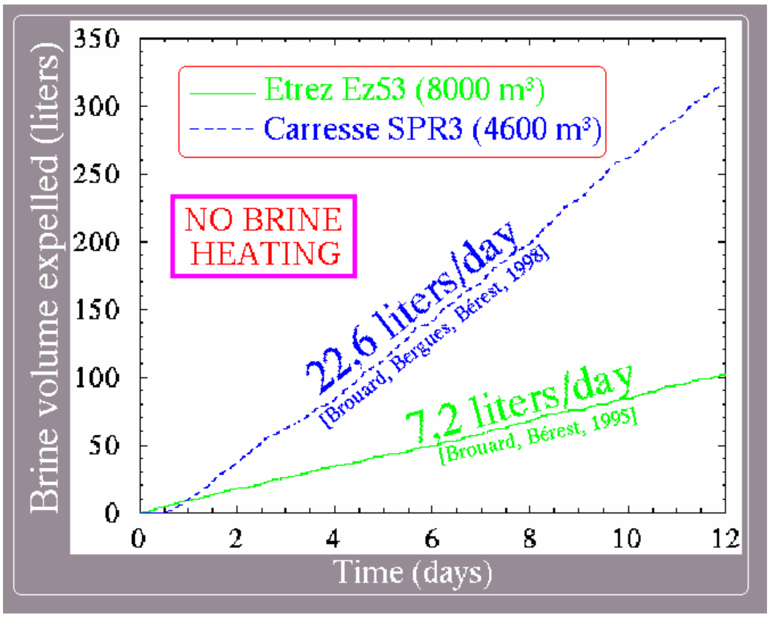
7. AN UPPER BOUND FOR LONG-TERM PERMEATION AND LEAK RATES

It is interesting to obtain directly an upper bound for the rate of maximum brine flow that can seep to the overburden layers after the cavern has been sealed and abandoned. A simple method can be used when cavern brine is cooler than the rock geothermal temperature at cavern depth and when the cavern has been kept idle during a long period of time with little or no pressure was applied at the wellhead. The test consists of opening the wellhead and measuring the brine outflow rate. In the long term, when thermal equilibrium is reached, the flow rate of brine expelled from the cavern to the rock mass exactly equals the cavern closure rate. The driving force for the creep-closure rate is the difference between geostatic pressure and cavern brine pressure. This driving force is largest when the cavern is opened and brine pressure is halmostatic. A brine outflow test provides an upper bound for the long-term rate of expelled brine. This method works well when the rate of increase in brine temperature is zero, or when it can be assessed accurately and its effects taken into account.

7.1 Brine outflow test

Brine outflow test are more difficult to perform than shut-in tests: brine flow must be collected in a container, and the volume of brine in the container must be measured as often as possible. Figure 12 present the results of two brine outflow tests. In a large and shallow cavern, the effects of atmospheric pressure variations are dramatic during a brine outflow test, and the brine outflow rate is somewhat erratic when short periods of time (a couple of days) are considered. In fact, the brine-outflow rate must be averaged over a long period of time to provide reliable results.





(a) **(b)**

Figure 12. Brine outflow tests on (a) the SPR3 cavern (depth: 700 m, volume: 11 000 m^3) operated by Total and (b) the EZ53 cavern (depth: 950 m, volume: 8 000 m^3) operated by GDF Suez. Thermal equilibrium was reached in these two caverns. From these tests, it can be inferred that an upper bound for brine seepage when the caverns are sealed and abandoned is 22.6 liters/day and 7.2 liters/day (8 m^3/yr and 3 m^3/yr), respectively. Much faster brine outflow must be expected in larger or deeper caverns.

7.2 Shut-in test

An example of a shut-in test is given on Figure 13. At the beginning of this 6-month-long test, the cavern was shut in. (The *absolute* wellhead pressure is represented in the figure). The rate of pressure increase was $\Delta P / \Delta t$ = 0.01471 kPa/day —a very low figure, as this cavern is shallow (H = 250 m) and the cavern-closure rate is exceedingly slow. Cavern compressibility is $\beta V = 130$ kPa/liter, and the upper bound for the long-term brine outflow rate is $Q^{upper} = 6$ liters/day or 2 m^3/yr. This example highlights the significance of thermal equilibrium. A brine-temperature increase rate of $\Delta T / \Delta t = 0.02$ °C/yr (definitely a slow temperature-increase rate!) would generate a pressure increase rate of $\Delta P / \Delta t = (\alpha / \beta)\, \Delta T / \Delta t = 20$ kPa/yr $= 0.055$ kPa/day — i.e., a pressure increase rate *faster* than the pressure increase rate observed during this test.

A simpler but slightly less direct method consists of shutting the well and measuring the pressure build-up rate over a couple of weeks. Let $\Delta P / \Delta t$ be the pressure build-up rate (for instance, in MPa/day). An upper bound for brine outflow rate (in m^3/day) when the cavern is sealed and abandoned is $Q^{upper} = \beta V \times \Delta P / \Delta t$, where βV (in m^3/MPa) is the cavern compressibility (as explained in Section 2).

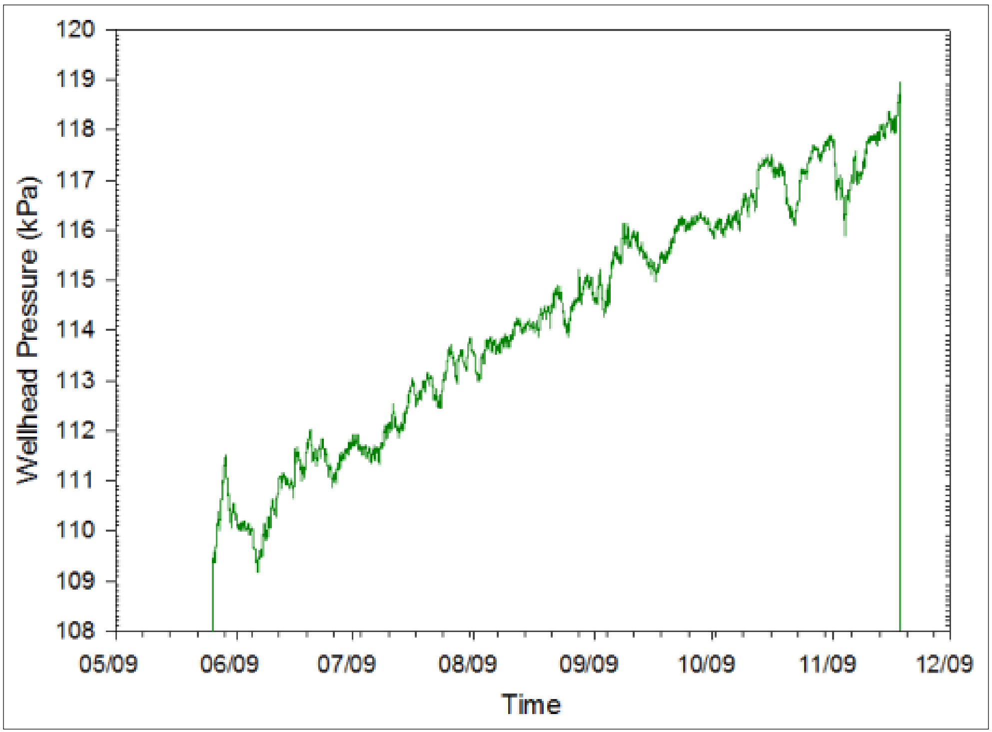


Figure 13. Example of a 6-month-long shut-in test.

8. A COMPREHENSIVE ABANDONMENT TEST

When the temperature gap is assessed correctly, when the duration of each phase is long enough, and when, in addition, a leak-detection system is set in the cavern, as explained in Sections 6 and 7, the "abandonment test" performed according to the trial-and-error method can be considered the best test to be performed. Strictly speaking, no further data or tests are required. However, the abandonment test is more convincing still when pressure evolution can be predicted *before the test* and/or when physical parameters can be back-calculated accurately after the test.

A complete discussion of this issue is beyond the scope of this paper. Examples will be provided during the afternoon session. The objective of this section is to highlight the main parameters required to be able to perform numerical computations.

8.1 Temperature evolution computation

Together with the cavern shape and the results of *in situ* temperature measurements (Section 1), three parameters are needed: (1) rock thermal conductivity, or K; (2) rock thermal diffusivity, or k; and (3) the brine thermal-expansion coefficient, or α [Note that rock thermal-expansion coefficient plays a minor role, as temperature changes in the cavern only generate tiny changes cavern volume, (Karimi-Jafari et al., 2007)]. These parameters are site-specific, although the following figures can provide, at least, a first approximation: $K = 6$ W/m/°C, $k = 3\times10^{-6}$ m^2/s (or 100 m^2 / yr); $\alpha = 4.4\times10^{-4}$ / °C. The equations that describe temperature evolution are provided in Van Sambeek et al. (2005) The difficult point is with the initial temperature conditions as, in most cases, a cavern experiences many temperature changes during operation (for instance, when fluids are injected/withdrawn from the cavern). However one considerable asset of thermal evolution lays in the fact that it is not strongly coupled with mechanical and hydraulic phenomena. (Thermal evolution can be computed independently.)

8.2 Computation of mechanical evolution

To determine the equilibrium pressure, we must know the steady-state cavern closure rate as a function of cavern pressure. As seen in Figure 14, the corresponding curve is non-linear. The closure rate is zero when cavern pressure is geostatic. Laboratory tests and numerical computations allow us to draw this steady-state curve. The Norton-Hoff law often is accepted: $\dot{\varepsilon} = A\ \exp-(Q/RT)\ \sigma^n$, where n, Q/R and A are three site-specific constants. However, it must be kept in mind that when a full prediction of the test is required (not only a prediction of the equilibrium pressure value), a description of the transient mechanical behavior of salt also is needed.

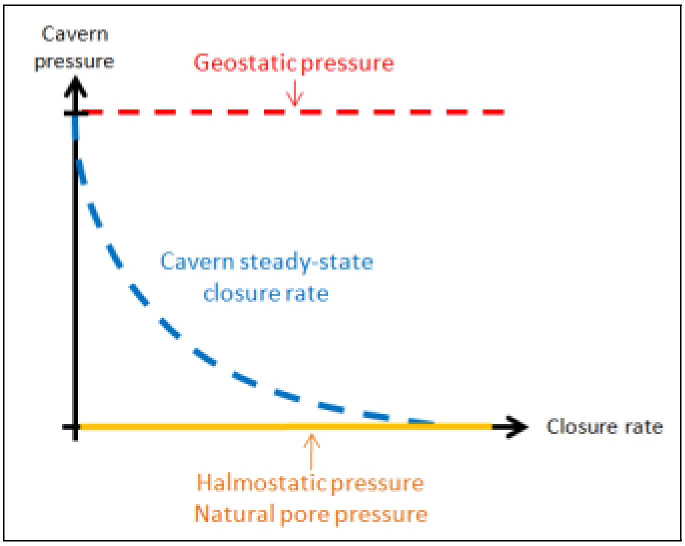


Figure 14. Steady-state cavern closure rate as a function of cavern pressure

Note that when the effects of brine thermal expansion can be neglected or can be computed precisely, a brine outflow test allows (determination of one point of the curve (the point at which the curve crosses the halmostatic pressure line).

8.3 Computation of permeation and leaks

Leaks through the casing and casing shoe are a well-specific phenomena. They can be determined only when a leak-detection system is used. A tentative prediction of brine *permeation* rate can be made when permeability tests are performed in the laboratory. Rock-salt permeability is in the range $K^{hyd} = 10^{-22} - 10^{-18}\ \text{m}^2$, but the hydraulic diffusivity of rock is more difficult to assess. However, laboratory tests performed on rock samples often underestimate the permeability of the rock mass. For this reason, it is better to perform *in situ* permeability tests in a drill hole before leaching starts. Examples of this are described in Durup (1990) and Brouard and Bérest (2001).

Most authors [see, for example, Fokker (1995)] agree that, at the cavern wall, salt experiences a dramatic increase in permeability when cavern pressure is close to geostatic (or, more precisely, when brine pressure is close to the least compressive main stress, which can be lower than the geostatic pressure when cavern pressure has remained low during a long period of time). For this reason, the brine flow rate vs. cavern pressure curve is linear only when small cavern pressures are considered.

However, several authors believe that rock salt is (almost) perfectly impermeable in its virgin state. According to these authors, salt permeability is secondary — i.e., generated by stress changes in the vicinity of the cavern walls.

In principle, the steady-state brine-outflow rate as a function of cavern pressure can be computed when salt permeability is known: it is zero when cavern pressure equals brine pore pressure. It often is assumed that brine pore pressure equals halmostatic pressure (No brine seepage occurs takes place when the wellhead is opened.), but this assumption is difficult to substantiate.

Here, again, it must be kept in mind that when an accurate prediction of the test (not only a prediction of the value of the equilibrium pressure) is required, a description of the hydraulic transient behavior also is needed.

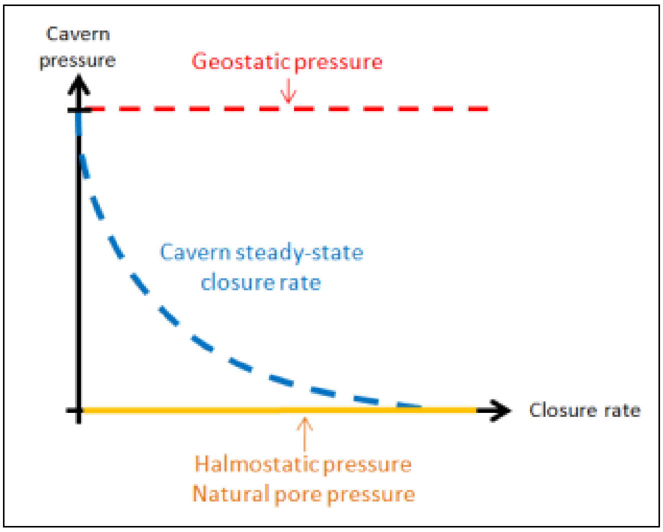


Figure 15. Steady-state brine seepage+permeation rate as a function of cavern pressure

8.4 Determination of the equilibrium pressure

When the two above-mentioned curves are drawn, the equilibrium pressure can be computed. When designing a trial-and-error test, it is better to select a test pressure not too different from the (predicted) equilibrium pressure (see Figure 16).

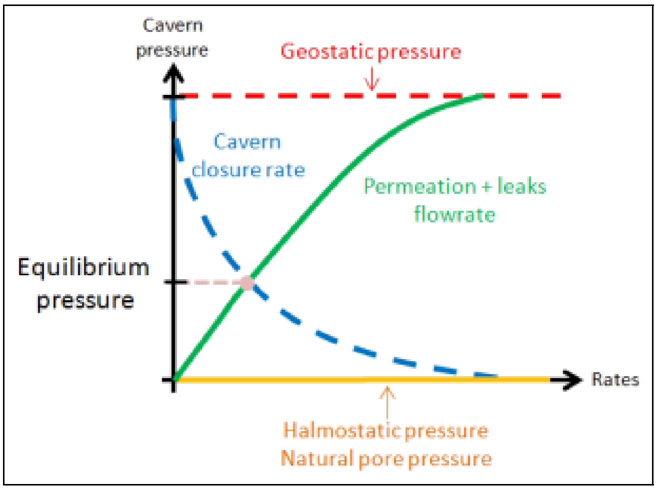


Figure 16. Definition of the equilibrium pressure.

8.5 Computation of pressure evolution during an abandonment test

When rock thermal properties, rock mechanical properties, rock hydraulical properties and cavern compressibility are known, pressure evolution during an abandonment test can be computed. Note that this problem is fully coupled. (Except for brine-temperature evolution, each of these three phenomena is influenced by the other two.) Transient phenomena (additional dissolution, transient creep, transient permeation, etc.) must be taken into account, and dedicated software is needed. Details can be found in the presentation by Benoît Brouard.

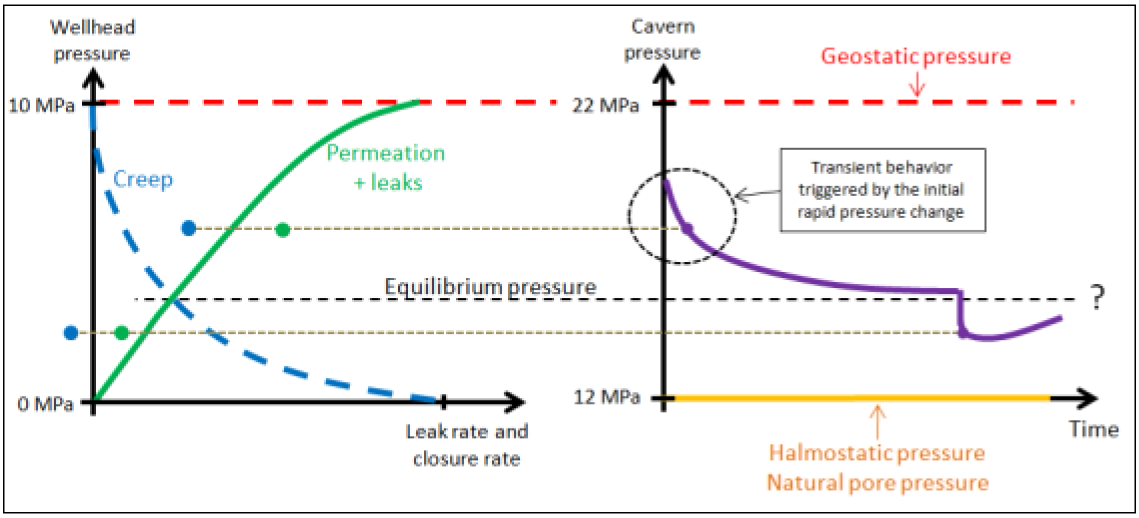


Figure 17. Trial-and-error test: The influence of transient phenomena is illustrated — after a rapid pressure change, pressure evolution is transient.

8.6 Back-analysis

In most cases, accurate, "blind" prediction of pressure evolution is difficult: if some parameters are relatively well known (cavern compressibility, rock steady-state mechanical behavior, etc.), the values of other parameters (for example, rock permeability and history of cavern temperature before the test) often are affected by a large uncertainty. However, an inverse problem can be solved by performing different computations; in each computation, reasonable values of the main parameters are used. Computation results are compared with selected parts of the as-measured cavern-pressure evolution curve, and a best-fit (which provides a best-estimate of the parameters) is sought. This process can be made automatic, and hundreds of computations can be performed, allowing fast convergence toward the optimal solution. (Examples are provided during the afternoon session). Figure 18 presents an example of the optimization procedure.

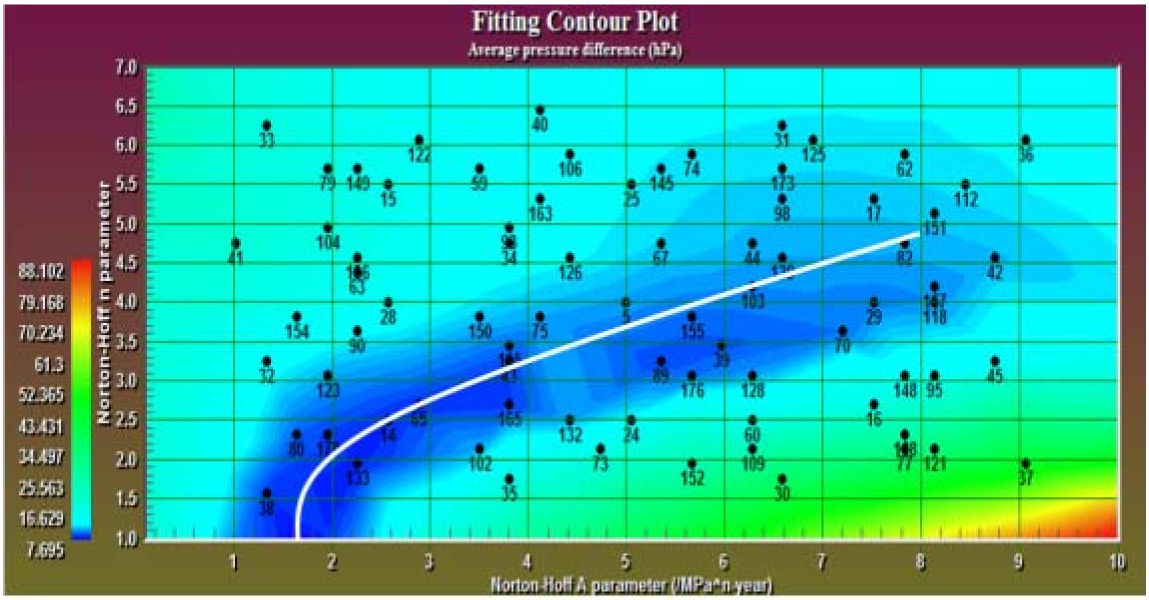


Figure 18 - Example of an optimization procedure. The abandonment test was performed on a Carresse cavern. Permeability is fixed ($K^{perm} = 4\times10^{-20}$ m^2), and the best $\left(A^*,n\right)$ pair of parameters of the Norton-Hoff law is searched for. No clear optimum is found, as the range of variation of cavern pressure is small, but suitable $\left(A^*,n\right)$ pairs can be identified.

REFERENCES

Brouard B., Karimi-Jafari M., Bérest P., Durup G. (2007). Pressure build-up in a sealed cavern: effect of a gas blanket. Proc. SMRI Spring Meeting, Basel, Switzerland, p.179-190.

Brouard B., Bérest P., Durup G. (2001). In-situ Salt Permeability Tests. Proc. SMRI Fall Meeting, Albuquerque, New Mexico, p.139-157.

Crotogino F., Kepplinger J. (2006) Cavern Well Abandonment Techniques Guidelines Manual. Report 2006-3 for the SMRI.

Diamond H.W., Bertram B.M., French P.S., Petrick G.D., Schumacher M.J.,Smith J.B. (1993). Detecting very small casing leaks using the water-brine interface method. Proc. Seventh Symp. Salt, Vol. I. Amsterdam: Elsevier Science Publishers B.V., p.363-368.

Durup G. (1990). Field Tests in Well EZ 58. SMRI Project Report n°90-00002-S.

Fokker P.A. (1995). The behavior of salt and salt caverns. PhD thesis, Delft University of Technology, The Netherlands.

Jafari-Karimi M., Bérest P., Brouard B. (2007). Thermal Effects in Salt Caverns. Proc. SMRI Spring Meeting, Basel, Switzerland, p.165-177.

Van Sambeek L.L., Bérest P., Brouard B. (2005). Improvements in Mechanical Integrity Tests for solution-mined caverns used for mineral production or liquid-product storage. SMRI Research Project Report 2005-1.

Wallner M. & Paar W.A. (1997). Risk of progressive pressure build up in a sealed cavity. Proc. SMRI Fall Meeting, El Paso, Texas, p.177-188.