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**Meeting Paper**



**A Salt-Cavern Abandonment Test**

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# A SALT-CAVERN ABANDONMENT TEST

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## Abstract

An 18-month test has been performed on a deep brine-filled cavern. The objective was to measure the equilibrium pressure reached when the cavern is closed. Such an equilibrium is reached when salt mass creep, which leads to cavern shrinkage, balances brine permeation through the cavern wall. This objective was met by imposing different pressure levels and observing whether the pressure increased (or decreased) with respect to time. Data misinterpretation (i.e., a well leak instead of a cavern-proper leak) was precluded by a special monitoring system. The observed equilibrium pressure was significantly smaller than lithostatic pressure, alleviating any fracture risk for a sealed and abandoned cavern in this salt formation.

## 1 INTRODUCTION

In the past several years, there has been concern about the thermomechanical behavior of deep underground salt caverns after they have been sealed and abandoned. By "deep", we mean caverns whose depths range between 500 m and 2000 m. These depths distinguish these caverns from older and shallower, frequently interconnected caverns, which are mainly used for brine production and whose abandonment raises serious problems.

Interest in the very long-term behavior of deep caverns has increased due to increasing concern for environmental protection, on one hand, and to several new projects in which caverns are used for disposal of non-hazardous, industrial or even low-level nuclear wastes, on the other. Many researchers have contributed to the discussion, including Langer *et al.* (1984), Wallner (1986), Cauberg *et al.* (1986), Bérest (1990), Cosenza and Ghoreychi (1996), Ehgartner and Linn (1994), You *et al.* (1994), Fokker (1995), Rolfs *et al.* (1996), Tomasko *et al.* (1997), Bérest and Brouard (1996, 1997a, 1997b), Wallner and Paar (1997), and Pfeifle *et al.* (1998). The *Solution Mining Research Institute*

which represents companies, consultants and research centers involved in the solution mining industry has set this problem at the center of its Research Program and has supported the test described in this paper.

Most experts agree on the following general scenario. If a closed and abandoned cavern is filled with fluid (brine, in most cases), its pressure will more or less rapidly build to reach a pressure significantly higher than that which results from the weight of a brine column filling the well from the surface to the cavern. (Hereafter, this pressure, which, in most cases, is the initial pressure when the cavern is closed, will be called the *halmostatic pressure*; it is equal to  $P_h$  (MPa) = 0.012  $H$  (meters) [or  $P_h$  (psi) = 0.52  $H$  (feet)], where  $H$  is the average cavern depth ( $H = 950$  m for the Ez53 cavern to be discussed later). Results of several so-called “shut-in pressure tests” clearly support this view (Bérest *et al.*, 1979; You *et al.*, 1994; Fokker, 1995; Bérest *et al.*, 1998).

The pressure build-up is due to two main phenomena:

- (i) salt creep [paragraph 1.1]; and
- (ii) brine thermal expansion [paragraph 1.2].

## 1.1 Salt Creep

The mechanical behavior of salt exhibits a fascinating complexity, and several aspects of it are still open to discussion. (See, for instance, the proceedings of the four “Conferences on the Mechanical Behavior of Salt” (Hardy *et al.*, 1984, 1988, 1996; Aubertin and Hardy, 1997). However, experts do agree on several features of importance to the problem under discussion.

- (a) Salt behaves as a fluid in the sense that it flows even under very small deviatoric stresses.
- (b) Creep rate is a highly non-linear function of applied deviatoric stress and test temperature.

Furthermore, experts generally distinguish between

- (i) steady-state (or secondary) creep, which is reached after some time (several weeks) when a constant mechanical loading is applied to a rock sample (Steady state is characterized by a constant creep rate, which is a function of the (constant) temperature and stress applied during a test.); and
- (ii) transient (or primary) creep, which is triggered when the stress applied to a sample is suddenly changed. (Transient creep is characterized by high initial rates (following a load increase) that slowly reduce to reach steady-state creep or by slow, sometimes reverse, initial rates (following a load decrease) that slowly increase to reach steady-state creep (see Van Sambeek, 1992)).

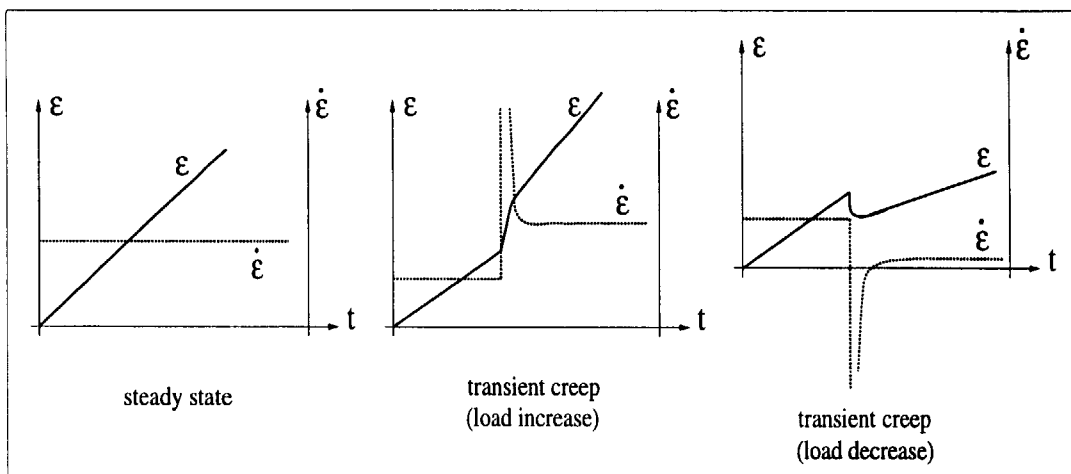


Figure 1: Steady-state creep, transient creep.

A similar distinction between steady-state and transient behavior can be made in a salt cavern, when, instead of sample strain rate ( $\dot{\epsilon}$ ), we consider the volumetric strain rate of the cavern ( $\dot{V}/V$ ) and, instead of the stress applied on the sample, we consider the difference ( $P_\infty - P_i$ ) between the natural geostatic pressure ( $P_\infty$ ) at cavern depth and the internal brine pressure in the cavern ( $P_i$ ). However, the analogy must be slightly corrected. On one hand, transient mechanical effects in a brine-filled cavern actually combine with the additional dissolution (or crystallization) that is triggered by any pressure increase (or decrease), leading to more pronounced transient effects; on the other hand, mechanical transient effects in a cavern can last much longer than in a rock sample, as stress changes due to brine pressure change must propagate throughout the rock mass before steady-state behavior is reached. (In other words, cavern transient behavior results from salt transient rheological behavior and from a factor of geometrical origin.)

Returning to the uniaxial behavior of a rock sample, the steady-state creep behavior is described by the following expression, sometimes called the Norton-Hoff (or power) law:

$$\dot{\epsilon} = A \exp(-Q/RT) \sigma^n$$

where  $A$ ,  $n$  and  $-Q/R$  are three parameters. ( $n$  belongs ranges from 3–6, and  $Q/R$  ranges from 4000 K–10,000 K.) A compilation of data published in the literature can be found in Brouard and Bérest (1998).

This uniaxial expression can be generalized in a 3D formulation:

$$\underline{\dot{\epsilon}} = A \exp(-Q/RT) \frac{1}{n+1} \frac{\partial (\sqrt{3}J_2)^{n+1}}{\partial \underline{\sigma}}$$

where  $J_2 = \frac{1}{2} s_{ij} s_{ji}$ ,  $s_{ij} = \sigma_{ij} - \frac{1}{3}(\sigma_{ii})\delta_{ij}$ .

Using this formulation, a closed-form solution can be obtained for the idealized case of a perfectly spherical (or cylindrical) cavern that, over a long period of time, is subjected to an internal pressure ( $P_i$ ) smaller than the natural geostatic pressure ( $P_\infty$ ) at cavern depth.

For a spherical cavern, the steady-state relation between volume rate change, temperature and pressure is as follows:

$$\frac{\dot{V}}{V} = -\frac{3}{2} \left[ \frac{3}{2n} (P_\infty - P_i) \right]^n A \exp\left(-\frac{Q}{RT}\right) \quad (1)$$

A similar formula for a cylindrical cavern has been given by Van Sambeek (1992):

$$\frac{\dot{V}}{V} = -\sqrt{3} \left[ \frac{\sqrt{3}}{n} (P_\infty - P_i) \right]^n A \exp\left(-\frac{Q}{RT}\right) \quad (2)$$

An immediate consequence of the first above mentioned feature (a), which is captured by formula (1) and (2), is that, as long as the cavern fluid pressure is smaller than the lithostatic pressure (which it is when the cavern is abandoned and sealed in halmostatic conditions,  $P_i = P_h$ ), the cavern shrinks, leading to cavern pressure build-up in a closed cavern.

A typical value of the initial shrinkage rate for a 1000-m deep cavern is  $\dot{V}/V = -3.10^{-4} \text{ year}^{-1}$  (although there are large variations according to site-specific rock properties; see Brouard and Bérest, 1998). Such a shrinkage rate in a closed cavern will lead to a pressure build-up rate of  $\dot{P}_i = -\dot{V}/(\beta V)$ , where  $\beta$  is the cavern compressibility factor. In a standard cavern,  $\beta \approx 4.10^{-4} \text{ MPa}^{-1}$  or  $3.10^{-6} \text{ psi}^{-1}$  and  $\dot{P}_i \approx 0.75 \text{ MPa/year}$  (see Bérest *et al.*, 1997a). However, significantly larger values of the cavern compressibility factor (and, consequently, smaller values of the initial pressure build-up rate  $\dot{P}_i$ ) can be found either because cavern shape is irregular (flat, or “penny-shaped”, for instance), or because the cavern contains gas pockets (see Bérest *et al.*, 1997b). It must be noted that

pressure build-up progressively leads to smaller creep rates, because the difference between lithostatic pressure at cavern depth and cavern fluid pressure reduces with time. Equilibrium will not be reached for several centuries, as pointed out by Wallner and Paar (1997). Cavern pressure build-up, then, is a function of time as well as of cavern depth. According to formula (1) or (2), the effects of cavern depth are two-fold:

- (i) it increases the initial difference between lithostatic pressure [ $P_\infty$  (MPa) = 0.022  $H$  (meters)] and the initial halmostatic pressure [ $P_i = P_h$  (MPa) = 0.012  $H$  (meters)]; and
- (ii) it increases the average rock temperature, which influences rock-salt creep and results in a much faster creep rate (and subsequent pressure build-up rate) in a deeper cavern.

Both lead to a much faster initial pressure build-up rate in a deep closed cavern. A general discussion can be found in Bérest and Brouard (1998).

## 1.2 Brine Thermal Expansion

The temperature of rock salt increases with depth, a typical value being  $T_R = 45^\circ\text{C}$  at a depth of  $H = 1000$  m, but caverns are leached using soft water pumped from shallow aquifers whose temperatures can be  $15^\circ\text{C}$ . The transit time of water in the cavern is generally a few days, which means that brine temperature in the cavern during (and at the end) of leaching is close to the soft water temperature (say,  $T_o = 20^\circ\text{C}$  at a 1000- m depth). The initial temperature difference ( $T_R - T_o = 45 - 20 = 25^\circ\text{C}$  in the example) will slowly resorb with time, due to heat conduction through the rock to the cavern and heat convection in the cavern.

Appropriate heat-transfer equations can be written as follows:

$$\frac{\partial T}{\partial t} = k \Delta T$$

$$\int_{\Omega} \rho_b C_b \dot{T}_i d\Omega = \int_{\partial\Omega} \tilde{K} \partial T / \partial n da$$

$$T_i(t) = T_{\text{wall}}$$

The first equation holds inside the rock-salt mass ( $k$  is the thermal diffusivity of salt, which has a typical value of  $k = 3 \cdot 10^{-6} \text{ m}^2/\text{s} \approx 10 \text{ m}^2/\text{year}$ ); the second equation is the boundary condition at cavern wall: heat flux crossing a cavern wall ( $\tilde{K}$  is the thermal conductivity of salt;  $\tilde{K} \approx 3 \text{ W/m}^\circ\text{C}$  is typical.) warms up cavern brine with an average temperature of  $T_i$ . ( $\rho_b C_b$  is the volumetric heat capacity of brine;  $\rho_b C_b \approx 1200 \cdot 4000 = 4.8 \cdot 10^6 \text{ J/m}^3/^\circ\text{C}$  is typical.) The third equation stipulates that rock temperature of the cavern wall is equal to the average brine temperature in the cavern. This assumption is reasonable due to the effect of cavern brine stirring is due to thermal convection. (Clear evidence of thermal convection effects can be found in Figure 2, which provides the temperature distribution in the 950-m deep Ez53 cavern; the temperature in the cavern appears quite homogeneous, due to thermal convection patterns).

The exact temperature evolution can easily be predicted through numerical calculation. Back-of-the-envelope estimations can be reached simply by analysis of heat transfer equations. Dimensional analysis proves that heat transfer is governed by one characteristic time,  $t_c = V^{2/3}/4k$  [or  $t_c$  (years) =  $V^{2/3}/400$ , where  $V$  is the cavern volume (in  $\text{m}^3$ )] (the second characteristic time,  $t'_c = kt_c \rho_b C_b / \tilde{K}$  is not significantly different from  $t_c$ ). In the case of a spherical cavern,  $t_c$  is the time after which 75% of the initial temperature difference between the brine and the rock mass has been resorbed; brine heating will be slightly slower in a cylindrical cavern. This characteristic time is large ( $t_c \approx 1$  year for a  $V = 8000 \text{ m}^3$  cavern;  $t_c \approx 16$  years for a  $V = 500,000 \text{ m}^3$  cavern), which means that thermal equilibrium will be reached after a long period of time.

The average temperature change rate (from cavern sealing time to  $t = t_c$ ) is  $\dot{T}_i \approx 0.75 (T_R - T_o)/t_c$  — i.e., where  $T_R - T_o = 25^\circ\text{C}$ ,  $\dot{T}_i \approx 18^\circ\text{C}/\text{year}$  in an  $8000 \text{ m}^3$  cavern and  $\dot{T}_i \approx 1.2^\circ\text{C}/\text{year}$  in a  $500,000 \text{ m}^3$  cavern. In an opened cavern, a temperature increase leads to thermal expansion and brine outflow at ground level,  $Q = \alpha V \dot{T}_i$ , where  $\alpha$  is the brine thermal expansion coefficient,  $\alpha \approx 4.4 \cdot 10^{-4} \text{ }^\circ\text{C}^{-1}$ . In a closed cavern, temperature increase leads to pressure build-up (i.e.,  $\dot{P}_i = \alpha \dot{T}_i / \beta$ ). The ratio  $\alpha/\beta$  is close to  $1 \text{ MPa}/^\circ\text{C}$ , which means that a  $1 \text{ }^\circ\text{C}$  brine temperature increase leads to a 1-MPa pressure build-up. In other words, when an initial temperature difference of  $25 \text{ }^\circ\text{C}$  is resorbed, after a time equal to several times  $t_c$ , the related pressure build-up should be 25 MPa — far exceeding the initial difference between lithostatic and halmostatic pressure — and leading to salt fracture. How fast this difference is resorbed depends on cavern size; the initial rate is typically  $18 \text{ MPa}/\text{year}$  in an  $8000\text{-m}^3$  cavern and  $1.2 \text{ MPa}/\text{year}$  in a  $500,000\text{-m}^3$  cavern. Keep in mind that creep effect in a 1000-m deep cavern leads to a typical pressure build-up change rate of  $0.75 \text{ MPa}/\text{year}$ ; it is clear that, in most cases, pressure build-up due to thermal expansion predominantly governs the behavior of a closed cavern. Most data published in the literature are not helpful from the perspective of a thorough analysis of creep effects, because temperature increase is by far the primary cause of pressure build-up. Outstanding exceptions are found in the case of very deep caverns (2000 meters below ground level; see You *et al.*, 1994), creep-prone evaporitic layers (see Fokker, 1995) or brine fields whose extraction ratios are high (Guarascio *et al.*, 1998). This phenomenon must be avoided when closing a cavern, as it leads to cavern fracturing. However, and clearly different from cavern creep effects in this respect, brine expansion effects can be avoided — for instance, by waiting a sufficient amount of time before closing the cavern (i.e., until thermal equilibrium is reached).

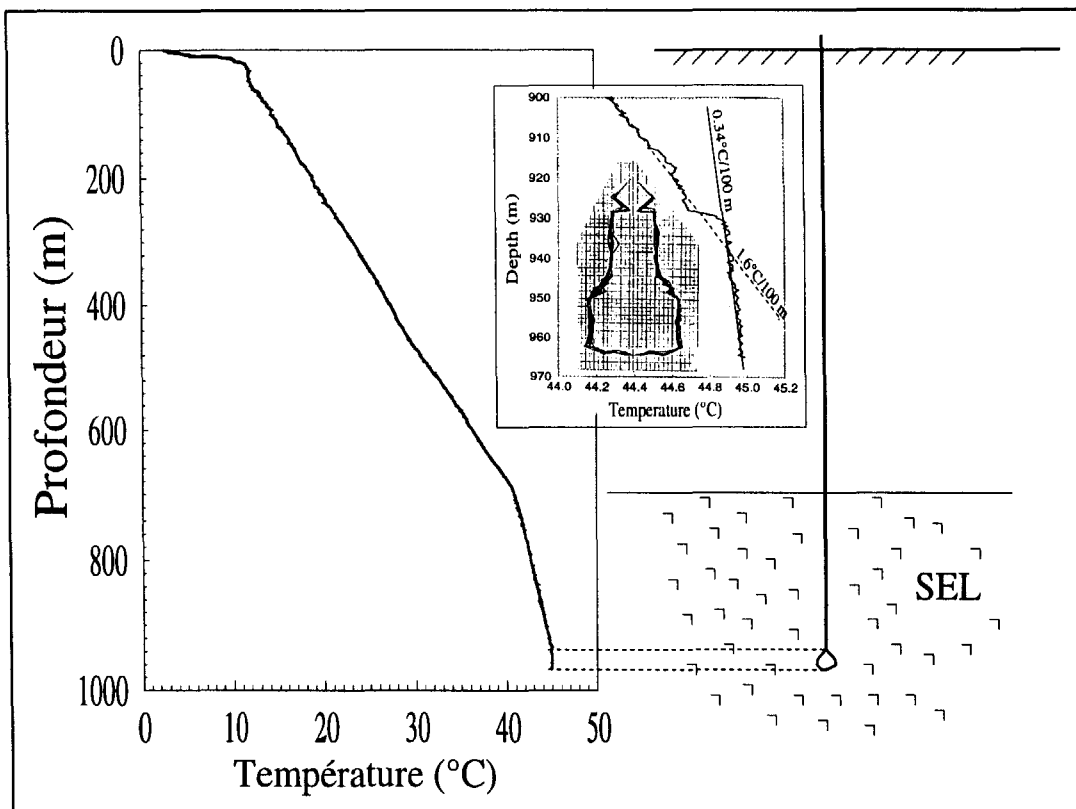


Figure 2: Geothermal profile in the Ez53 cavern and well (February 1996).

### 1.3 Fracture Risk

If brine thermal expansion (which leads to fracture) is disregarded, one can expect that cavern creep will end when brine pressure in the cavern exactly equals overburden (i.e., lithostatic) pressure; however, such an equilibrium does not exist, as has been clearly demonstrated by Cauberg *et al.* (1986), Wallner (1986), Ehgartner and Linn (1994), and Wallner and Paar (1997). As stated above, rock salt behaves as a liquid: two liquids whose densities are distinct, as is clearly the case when brine and rock salt are considered, cannot reach equilibrium unless they are separated by a flat, horizontal interface. In other words, brine pressure in the cavern cannot equal rock pressure at both the top and bottom of the cavern. In the final state, brine pressure at the cavern top will exceed the lithostatic pressure by an amount which depends on cavern height. The tensile strength of the rock will be exceeded at the top of the cavern, and fracture risk will become highly probable. Furthermore, fracture is likely to develop upward (except perhaps in a strongly interbedded salt layer), increasing the total (cavern + fracture) height and leading to further upward movement of the fracture and brine transport through the fracture.

### 1.4 Effect of Permeability

This pessimistic scenario can be alleviated by taking rock-salt permeability into account. For every standard engineering purpose, rock salt can be considered as an impermeable rock. The generally small permeability numbers resulting from laboratory tests are scattered, but they are suspect of being influenced by several biases (sampling, rock decompression, etc.). Few in-situ tests are available; experiments performed at the WIPP site (Howarth *et al.*, 1991) provide permeabilities as small as  $K = 10^{-21} \text{ m}^2$  for undisturbed salt. A one-year-long test performed in a well (Durup (1994), in research supported by the SMRI) gave  $K \approx 6.10^{-20} \text{ m}^2$ . How small these numbers are is clearly demonstrated when one remembers that hydrogeology textbooks generally define an impermeable rock as a one whose permeability is smaller than  $K = 10^{-17} \text{ m}^2$ , a figure that exceeds the measured values described above by two orders of magnitude. Thus, provided a relevant tightness test is performed, hydrocarbon storage in salt caverns can be considered to be extremely safe from the perspective of product confinement.

However, when very long-term behavior is considered, the general picture changes — especially when considering the problem of pressure build-up in a closed cavern. Due to high cavern compressibility, even tiny losses of fluid can significantly lessen the effect of cavern creep and prevent cavern pressure from reaching high levels.

To be more specific, consider the case of a spherical cavern with radius  $R$ , excavated in a salt mass with permeability  $K$ , cavern brine pressure  $P_i$  and natural pore brine pressure  $P_o$ . If  $\mu$  is the brine dynamic viscosity ( $\mu \approx 1.2 \cdot 10^{-3} \text{ Pa}\cdot\text{s}$ ) then, assuming Darcy's law — a somewhat arguable hypothesis — steady-state brine seepage rate will be of the order of

$$Q_b/V = 3 K (P_i - P_o)/(\mu R^2) \quad (3)$$

This rate is quite small (For instance,  $P_i - P_o = 5 \text{ MPa}$ ,  $R = 12.5 \text{ m}$  ( $V = 8000 \text{ m}^3$ ), and  $K = 10^{-20} \text{ m}^2$  leads to  $Q_b/V \approx 0.25 \cdot 10^{-4} \text{ year}^{-1}$ , or  $0.2 \text{ m}^3$  per year), but it can balance creep rate, especially when cavern brine pressure is high. One example (for the Ez53 cavern) will be discussed later.

## 2 TEST PREPARATION

The objective of the test described in this paper was to verify that pressure build-up in a closed and abandoned cavern does not reach lithostatic values but, rather, due to the combined effects of salt creep and salt (micro) permeability, will vanish when a certain steady-state value of the cavern pressure (significantly smaller than the lithostatic figure) is reached.



## 2.1 Main Goals and Prerequisites

Because we are interested in the combined effects of creep and percolation, test conditions must be selected to minimize the effect of the third factor contributing to pressure changes (i.e., thermal expansion). Keep in mind that the expression of the characteristic time of thermal conduction is  $t_c = V^{2/3}/k$ ; thus, it is necessary to use a cavern that is small and/or has been leached out long before the test. The Ez53 cavern of the Gaz de France storage site in Etrez (Figure 2), in Southeastern France, meets these conditions: it was leached out in Spring 1982 (i.e., 15 years before the test), and its volume is small ( $V \approx 7500 \text{ m}^3$ ), which means that the characteristic time of thermal conduction in this cavern is approximately one year.

The thermal behavior of Ez53 during the first year after the end of leaching was monitored via cavern brine-temperature measurements (Hugout, 1988) that confirmed that approximately 65% of the initial temperature difference between the rock mass and the cavern brine had been resorbed after 250 days. Temperature profiles were performed in February and March 1996 and clearly prove that thermal equilibrium was reached at that time. From then on, cavern behavior is governed only by cavern creep and brine permeation.

The average cavern depth is 950 meters; at such depth, moderate creep rates are expected. Brine outflow (Brine permeation is then null.) from the opened cavern was measured for several weeks before the test; these measurements are described in Brouard (1998) and confirm that the cavern convergence rate is approximately  $3.10^{-4}$  per year. Because the cavern had been at rest for most of the time since the end of leaching, this figure is considered to be representative of steady-state cavern creep. It must be noted that the Etrez site cavern closest to Ez53 is Ez04, which is one kilometer away, precluding any significant influence of neighboring caverns.

The rock salt belonging to the so-called upper layer of the Etrez salt formation, in which the cavern has been leached, has been studied by Charpentier (1984) and Pouya (1991). The latter has fit laboratory data to the Norton-Hoff uniaxial constitutive (or power) law described above and suggests the following parametric values:

$$A = 0.64 \text{ MPa}^{-n} \text{ year}^{-1} \quad Q/R = 4100 \text{ K} \quad n = 3.1$$

which are in good agreement with the in-situ observations. In fact, a simple estimation can be reached by considering the case of a spherical cavern located at the Ez53 cavern depth (see formula 1); the above-cited values then lead to a steady-state cavern creep rate of  $3.10^{-4}$  per year. Such perfect agreement between observed and computed figures must be considered as partly fortuitous, but it does provide some confidence in the estimation.

Note that the steady-state law is not able, as stated above, to capture the effects of rapid changes in cavern pressure. The so-called Lemaitre strain-hardening constitutive law, based on in-situ pressure tests carried out by Gaz de France (Hugout, 1988), appears to provide satisfactory predictions.

Etrez salt permeability has been studied through laboratory experiments by Le Guen (1991) who found an intrinsic permeability as low as  $K = 10^{-21} \text{ m}^2$  for some samples. According to the generally accepted effects of scale on rock permeability (Brace, 1980), larger values are expected when in-situ measurements are considered. In fact, Durup (1994) has performed an in-situ permeability test (supported by the SMRI) on the Ez58 well, which belongs to the same salt formation as the Ez53 cavern and has similar depth. Durup found that pore pressure,  $P_o$ , was very close to halmostatic pressure ( $P_h \approx P_o$ ) and suggested a value of  $K = 6.10^{-20} \text{ m}^2$  for the average intrinsic permeability of the 150-m-high Ez58 well. (Note that 10% of the Etrez upper salt layer contains impurities, anhydrite beds (such as is visible at a 928- m depth on Ez53 cavern profile; see Figure 2) and thin inter-granular clay layers, which may contribute to higher large-scale permeability).

Assuming both steady-state cavern creep and steady-state brine percolation (as well as Darcy's law), the long-term equilibrium pressure can be computed by making the cavern creep rate and the relative brine leak rate equal (see Brouard and Bérest, 1998):

$$\frac{3K}{\eta R^2} (P_i - P_o) = A^* \exp(-Q/RT) (P_\infty - P_i)^n \quad (4)$$

$$A^* = \frac{3}{2} \left[ \frac{3}{2n} \right]^n A$$

$$\left\{ \begin{array}{lll} K = 6.10^{-20} \text{ m}^2 & R = 12.1 \text{ m} & P_o = 11.2 \text{ MPa} \\ \eta = 1.2 \cdot 10^{-3} \text{ Pa}\cdot\text{s} & Q/R = 4100 \text{ K} & T = 318 \text{ K} \\ A^* = 0.14 \text{ MPa}^{-n} \text{ year}^{-1} & P_\infty = 20.5 \text{ MPa} & n = 3.1 \end{array} \right.$$

when Ez58 (permeability) and Ez53 (creep) parameters are used. In the case of a spherical cavern, we get  $P \approx 14.2$  MPa. (The brine leakage through the cavern wall is then  $0.8 \text{ m}^3$  per year.) As we will see, the actual value appears to be smaller. Returning to the general formula (4), it is clear that, the larger ( $R$  large) or deeper ( $T$ ,  $P_o$ , and  $P_\infty$  large) the cavern, the higher the equilibrium pressure.

### 3 TEST STRATEGY

The test basically consists of a “duck-walk” process (Figure 3) to approach the expected steady-state pressure, which is roughly estimated (see the last paragraph). Different pressure levels are tested successively. When the well-head pressure rate consistently remains negative for a sufficiently long period of time, it is re-adjusted to a slightly smaller value, in hopes of triggering a change in sign for the well-head pressure rate. (Alternatively, when the well-head pressure rate consistently remains positive for a sufficiently long period of time, it is re-adjusted to a slightly higher value.) Re-adjustments are made via small withdrawals or injections of brine and/or fuel-oil in the cavern.

The timing of each step between injection and withdrawal (or vice-versa) must be thoroughly examined. It is well known that any rapid pressure change (such as takes place when fluid injection or withdrawal is performed) triggers transient effects (e.g., transient creep, additional dissolution or crystallization), which, according to the general Le Chatelier (or Braun) principle, tend to reduce the pressure change slightly (see above). Thus, each step must be long enough for these transient effects to vanish and for a more-or-less steady-state to be reached. Former tests (Hugout, 1988) have proven that transient effects following any rapid pressure change were most significant during a period of approximately 12 days. During the test described below (see Figure 4), the duration of each step was long enough (longer than 3 months) to allow transient effects to vanish.

### 4 CASING LEAKAGE VERSUS CAVERN LEAKAGE

An important difference between a shut-in test and actual cavern abandonment lay in the fact that, during a shut-in test, the cavern is closed **at the well-head** — not at the bottom of the well. As a result, brine (or, more generally, liquid) leaks can occur both in the cavern and in the well itself through the casing (or casing-shoe) or through the well-head. Such leaks are known to have occurred in some underground storage environments; this is why casings are thoroughly checked prior to commissioning, and intermittently during the cavern life span, through tests generally referred as “Mechanical Integrity Tests” or MIT (Crotogino, 1994). The existence of such leaks would lead to severe misinterpretation of the test if casing leakage and brine percolation through the cavern wall were not distinguished.

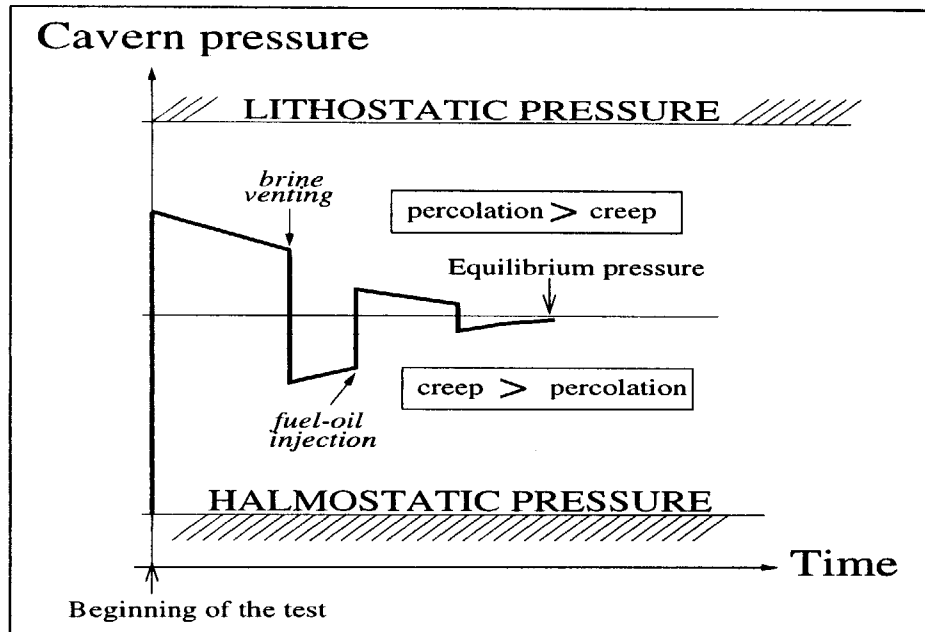


Figure 3: Test strategy: “duck walk”.

We have designed a system based on the density difference between brine and fuel-oil that allows differentiation of cavern brine seepage (the topic of interest) and well leakage. The system is similar to that suggested by Diamond *et al.* (1993) for testing brine production wells.

Well completion includes a 9<sup>5/8</sup>” cemented casing and a 7” string. Before the test on March 20, 1997 (day -7), a fuel-oil column was lowered to a depth of 864.5 meters in the 7” × 9<sup>5/8</sup>” annular space, where the horizontal cross-section is approximately  $\Sigma = 5.7$  liters per meter.

On November 20 (day 238), the system was completed by lowering a smaller fuel-oil column into the 7” central tubing, to a approximate depth of 9.5 meters. (It would have been better to set this second column before the test.) The horizontal cross-section of the tubing is constant and approximately equal to  $S = 21.1$  liters per meter. The monitoring system was then completed; however, following the leaks in days 293 to 315, additional fuel oil was injected (on March 10, 1998; day 348) into the 7” central tubing, which lowered the fuel-oil/brine interface to an approximate depth of 43 meters.

This system allows easy comparison of the various types of leaks (see Figure 5). Let  $\dot{V}$  be the cavern volume loss rate due to creep,  $\dot{V} < 0$ ;  $Q_b$  is the brine outflow from the cavern to the rock mass through the cavern walls;  $Q_a$  is the fuel-oil leakage rate through the casing (or casing shoe);  $Q_t$  is the fuel-oil leakage rate through the well head. A brine leak ( $Q_b$ ) from the cavern generates the same pressure drop rate ( $\dot{P}_i$ ) in the cavern as well as in both the annular space ( $\dot{P}_a$ ) and the central tubing ( $\dot{P}_t$ ) at the well head:  $\dot{P}_i = \dot{P}_a = \dot{P}_t = -Q_b/(\beta V)$ , where  $\beta V$  is the cavern compressibility, as defined above. Brouard (1998) has measured compressibility of the Ez53 cavern as approximately  $\beta V \approx 3 \text{ m}^3/\text{MPa}$ . (In other words, brine seepage of 3-liters per day will lead to a pressure drop rate of 1 kPa per day.)

An example of this is given in Figure 6. During days 112 to 146, the average pressure drop rate is -869.70 Pa/day in the annular space and -869.85 Pa/day in the central tubing; the two curves (pressure versus time) are then almost perfectly parallel, proving that seepage takes place in the cavern itself (in sharp contrast to what happens in the case of a fuel-oil leak). During this period, brine seepage from the cavern (or, more precisely, the difference  $(Q_b - |\dot{V}|)$  between brine seepage and cavern creep) is  $3 * 0.87 = 2.6$  liters per day. Note that very small oscillations (period  $\approx 12$  hours,

amplitude  $\approx 0.5$  kPa) can sometimes be observed on the two curves; these are related to terrestrial tidal waves and ground-level temperature changes.

A fuel-oil leak ( $Q_t$ ) from the central tubing through the well head will produce a similar pressure drop both in the cavern and in the annular space — i.e.,  $\dot{P}_i = \dot{P}_a = -Q_t/(\beta V)$ . However, brine density ( $\rho_b = 1200$  kg/m<sup>3</sup>) is significantly larger than fuel-oil density ( $\rho_f = 850$  kg/m<sup>3</sup>); a fuel-oil leak yields to both an upward vertical displacement of the brine/fuel-oil interface and an additional pressure drop in the central tubing,  $\dot{P}_t = \dot{P}_a - (\rho_b - \rho_f)gQ_t/S$ , where  $S = 21.1$  liters per meter is the 7" central tubing cross-section. A fuel-oil leak from the annular space acts in the reverse: the pressure drop rate in the tubing is simply  $\dot{P}_t = \dot{P}_i = -Q_a/(\beta V)$  and is  $\dot{P}_a = \dot{P}_t - (\rho_b - \rho_f)gQ_a/\Sigma$  in the annular space, whose cross-section is  $\Sigma = 5.7$  liters per meter. As a whole, when taking into account the cavern-volume loss rate, we get the following formulae:

$$\left. \begin{array}{l} \dot{P}_a \\ \dot{P}_t \end{array} \right\} = -\frac{Q_b + Q_a + Q_t - |\dot{V}|}{\beta V} - (\rho_b - \rho_f)g \cdot \begin{cases} Q_a/\Sigma \\ Q_t/S \end{cases} \quad (5)$$

Figure 7 provides an example of the pressure difference between the annular space and the central tubing, as measured through the 10- hPa resolution pressure gauges and plotted versus time. Between days 240 to 293 the difference is fairly constant — as a matter of fact, there is a slight negative slope, approximately 60 Pa/day. On day 293, a rapid and severe increase of the pressure difference takes place — clear evidence of a fuel-oil leak through the central tubing well head. The cumulated differential pressure increase is  $\delta P_a \approx 21$  kPa, which proves that the fuel-oil leak during this phase is  $V_a = S\delta P_a/g(\rho_b - \rho_f) = 21/0.17 \approx 124$  liters; the interface has risen by 6 meters in the central tubing. On day 315, the leak was repaired. (Note that the leak had been detected through curve observation before being observed in the field.); the pressure difference remained constant afterward.

In conclusion, field data allow for a clear distinction between brine seepage (from the cavern) and fuel-oil leakage (from the well), precluding any misinterpretation.

## 5 TEST RESULTS

### 5.1 Main Results

Redundant pressure measurements were necessary to provide reliable results. Cavern pressure was measured at a depth of 925 meters, and pressures at the well head were measured both in the annular space ( $P_a$ ) and in the central tubing ( $P_t$ ). Two pressure-measurement systems were used, of which the higher resolution ( $\pm 10$  hPa) system proved to be more reliable. Figure 4 has been drawn using the data provided by this system.

The test consists of three main stages; the cavern pressure was (roughly) constant during all stages. After the test ended (day 446), a part of the measurement system was still working, and we took advantage of that to measure the pressure evolution (4th stage); see Figure 4.

- One month before the test (i.e., before March 27, 1997), a tubing pressure of approximately 3.1 MPa (resulting in a cavern pressure of  $3.1+11.2=14.3$  MPa) was applied in order to avoid a too steep pressure change at the beginning of the test (Such a steep pressure is known to trigger transient creep.)
- From day 1 (March 27, 1997) to day 238 (November 19, 1997), the well-head pressure decreased by a roughly constant rate of -0.9 kPa per day (or an apparent leak of 2.7 liters per day), with the initial well-head pressure being 2.92 MPa (14.13 MPa at a depth of 950 m). During this stage, permeation effects clearly prevail over creep effects which, according to both the  $n = 3.1$  exponent proposed by Pouya (1991) for the steady-state creep law, and the

brine flow measurements of Brouard (1998), should be 2.5 liters per day — which means that the total brine leak during this stage is  $2.7+2.5=5.2$  liters per day.

- On day 239, cavern pressure was lowered by 1 MPa, and some fuel oil was injected in the central tubing (to complete the monitoring system described above). Up to day 250, the average pressure build-up rate was 6.1 kPa per day (The influence of transient creep was probably very significant during this 12-day period.) and then slowly decreased. Its average value was +0.6 kPa per day between days 275 to 290: creep prevailed over permeation. A fuel-oil leak appeared around January 25, 1998: as described above, it was first detected when analyzing pressure measurements and then observed in situ and repaired. Between days 320 to 345, the average pressure build-up rate was 0.32 kPa per day.
- On day 349, a small amount of fuel oil was injected in the central tubing, leading to a 0.3 MPa increase of cavern pressure. From then until day 446, cavern pressure decreased by -0.44 kPa per day on average.
- From day 446 to day 540, several fluid injection or withdrawals occurred. During a twenty-day period, the cavern pressure, which was then smaller than 12.5 MPa, built up; later, over a longer period, the cavern pressure, which was 13.1 MPa, slowly decreased.

From these results, it can be inferred that the equilibrium cavern pressure decreases when higher than  $13. \pm 0.1$  MPa (Permeation prevails over creep.) and increases when smaller than this value. (Creep prevails over permeation.) The “equilibrium pressure” is much smaller than the lithostatic pressure, which is 20.5 MPa, and slightly smaller than expected before the test ( $13. \pm 0.1$  MPa instead of 14 MPa). This discrepancy may be due to an initial underestimation of the permeability of a full-sized cavern.

## 5.2 Long-term evolution of a sealed cavern

The test results show that cavern sealing in the Etrez site, will not lead to fracture of the salt mass — provided that thermal expansion can be disregarded — and brine pressure will not exceed a figure smaller than a geostatic value. This should be true even when the cavern has experienced large losses of volume; formula (4) proves that the equilibrium pressure is a decreasing function of cavern size because the surface/volume ratio is larger in a small cavern, making brine permeation more effective. After a long period of time, a large volume of rock salt around the cavern will be impregnated by brine expelled from the cavern. A full description of this process is still under investigation.

Finally, it must be noted that the Etrez salt formation, which contains a significant amount of impurities, appears to be relatively permeable. Several authors argue that other salt formations are far more impermeable. (For instance, Klafki *et al.* (1998) recommend  $K < 10^{-20}$  m<sup>2</sup> as a general rule). However, such theories are often based on small-scale permeability tests, whose relevance for the problem of large cavern tightness is arguable; large scale permeability of salt formations remains an opened question.

## 5.3 Practical recommendations for cavern abandonment

1. The thermal expansion of brine leads to a large pressure build-up that can lead to fracture, which must be avoided. Before sealing a cavern, the brine temperature must be measured and compared to the natural rock temperature at cavern depth. A 1 °C difference can lead to a 1- MPa pressure build-up after sealing. If thermal equilibrium is not reached by the time the cavern is to be sealed, two remedial actions can be considered:

(i) wait for thermal equilibrium to be reached, which sometimes takes a long time; or

(ii) inject a small amount of inert gas into the cavern to increase its compressibility.

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2. When thermal expansion can be disregarded, an equilibrium pressure will be reached when cavern creep and brine seepage are exactly equal.

Cavern creep can be estimated through laboratory experiments and numerical computations, or through brine outflow tests (The daily brine flow from the cavern is measured for a few days; correct interpretation is much easier when thermal equilibrium has already been reached). Brine seepage is preferably estimated through in-situ permeability tests performed in a well before leaching. Simple calculations then allow estimation of the equilibrium pressure.

3. Before sealing the cavern, additional brine can be injected in the cavern to reach a pressure slightly higher than the anticipated equilibrium pressure (checking that pressure rate remains negative after one month). During such a test, the absence of a leak from the well must be checked thoroughly to prevent misinterpretation. An accurate method based on the injection of fuel oil in the well has been suggested in this paper.

## CONCLUSIONS

The 18-month-long test (a “shut-in pressure test”) performed on the Ez53 cavern proves that brine pressure reaches an equilibrium value of  $13. \pm 0.1$  MPa at a depth of 950 m, which is significantly smaller than the geostatic pressure (20.5 MPa) at the considered depth. This equilibrium is reached when cavern creep (which leads to cavern shrinkage) exactly equals brine percolation toward the rock mass (which reduces the brine volume contained in the cavern).

While Ez53 creep, which had been measured through in-situ tests, can be considered to have been reasonably well estimated, it is logical to conclude that cavern back-calculated permeability must be larger than the value estimated earlier (Durup, 1994) through well tests and can be  $K = 2.10^{-19}$  m<sup>2</sup>; the variations of cavern volume and brine volume are then of the order of 1.4 m<sup>3</sup> per year — or  $2.10^{-4}$  per year when compared to overall cavern volume. A significant misinterpretation (fuel-oil leak from the well, instead of brine leak from the cavern) can be precluded, due to the adopted monitoring system. This test confirms that salt permeability must be taken into account when analyzing cavern abandonment conditions.

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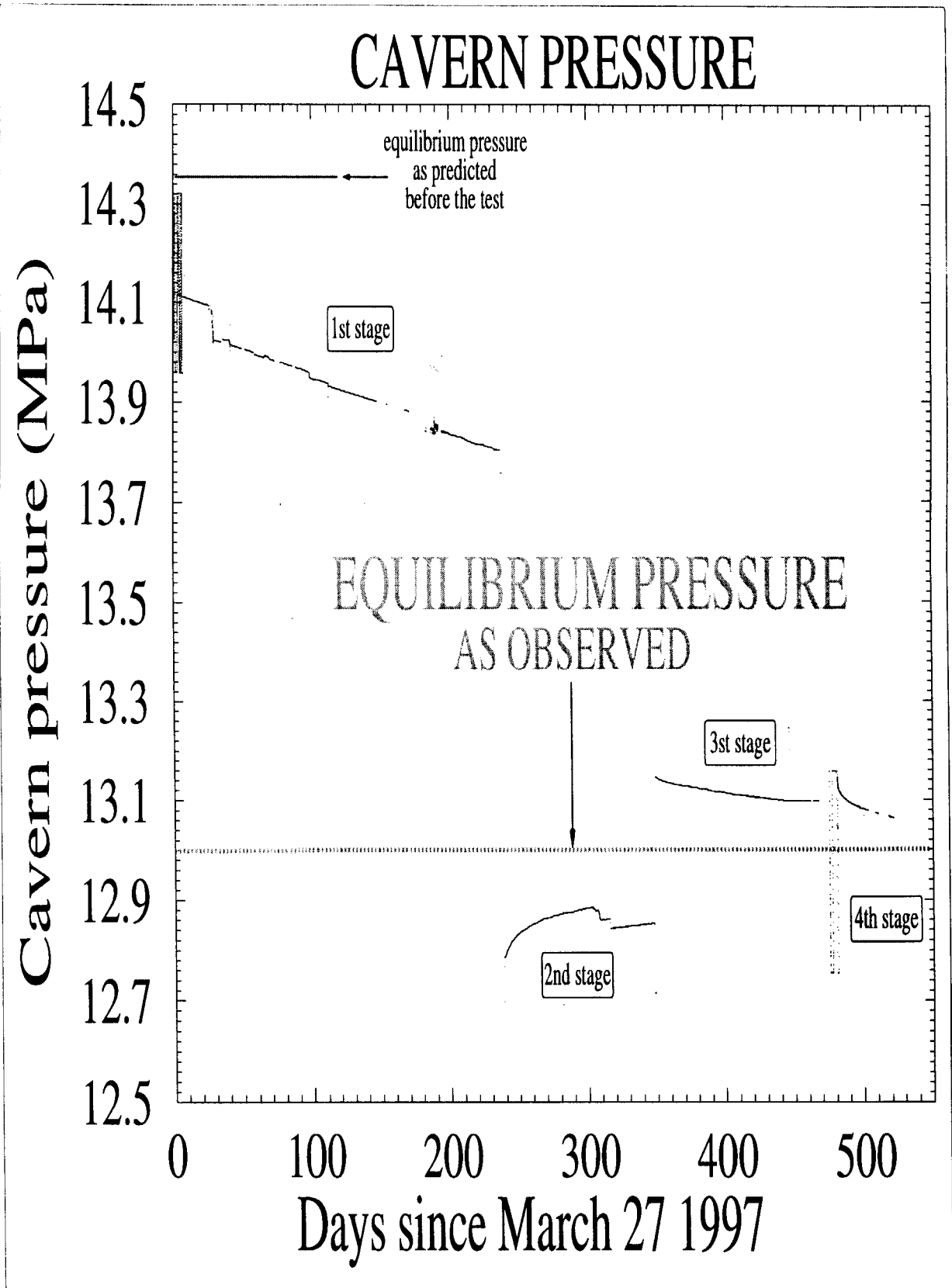


Figure 4: Cavern pressure evolution during the test.

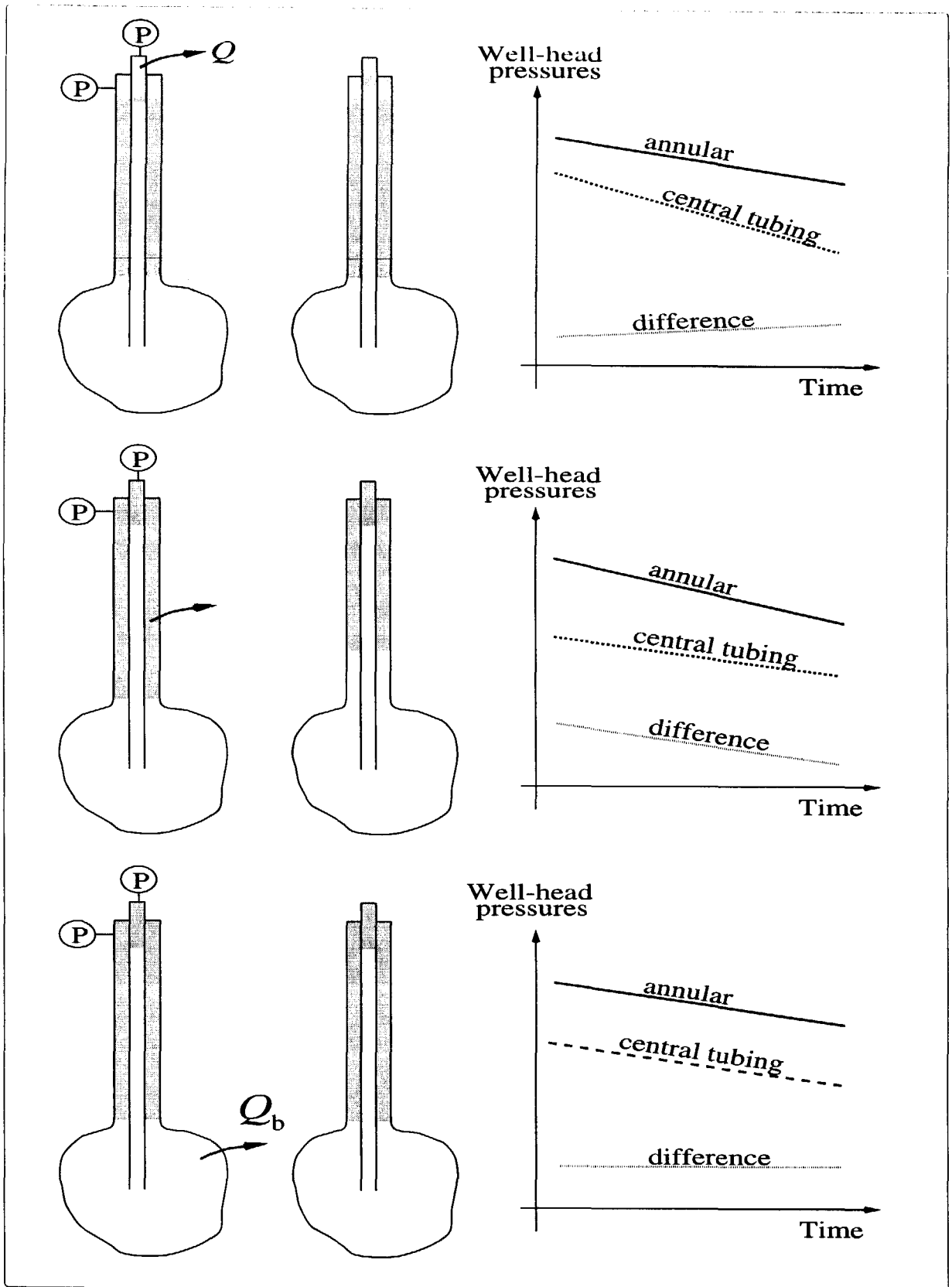


Figure 5: Three kinds of possible leaks.



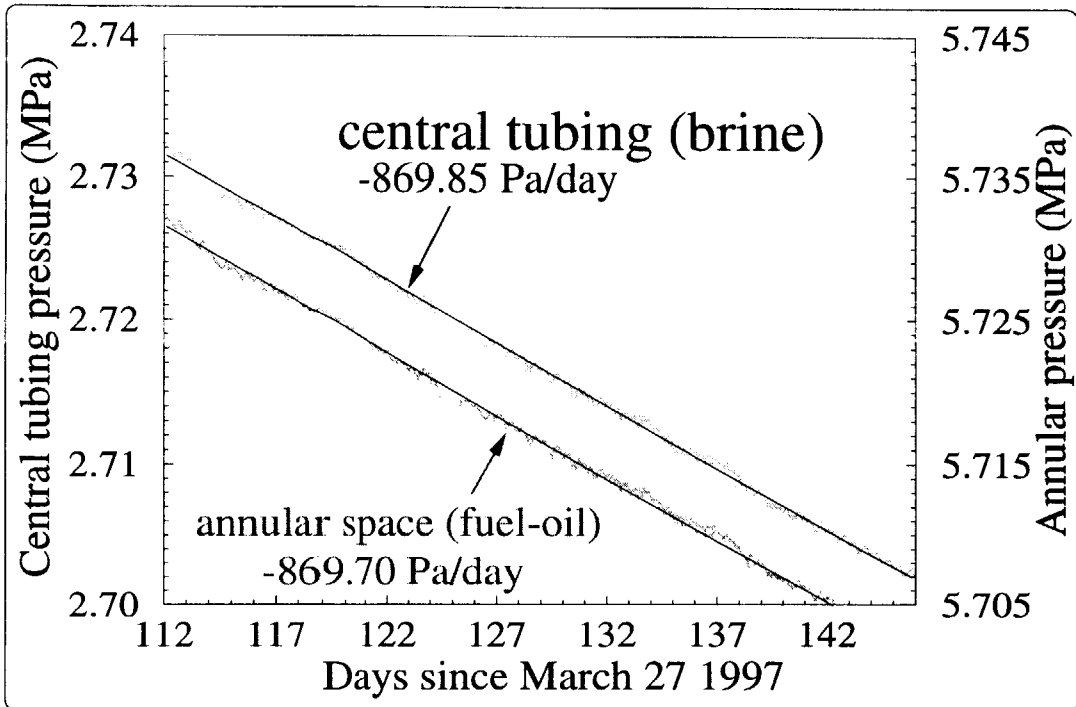


Figure 6: Annular and tubing pressure variations from days 112 to 150.

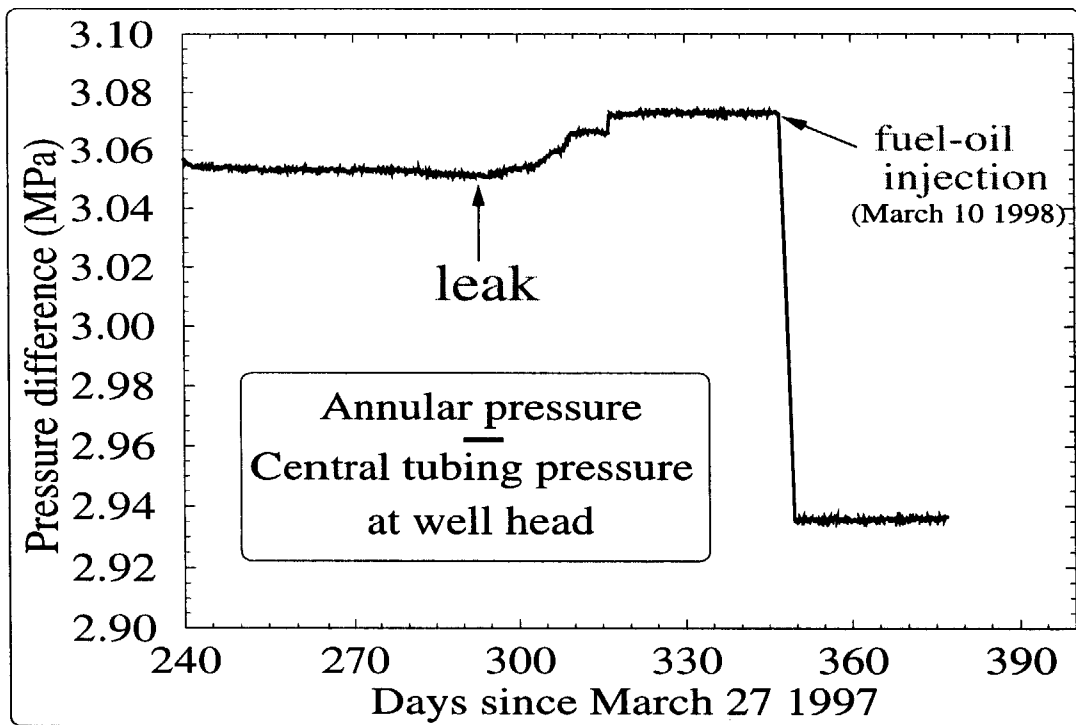


Figure 7: Pressure difference between annular and tubing from day 240 to day 375 (The increasing pressure difference indicates leakage from the tubing. A pressure increase of 0.01 MPa is equivalent to a 60- liter leak. The decreasing pressure difference indicates leakage from the annular space. A pressure decrease of 0.01 MPa is equivalent to a 16- liter leak.)

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