SHUT-IN PRESSURE TESTS
Case Studies

P. Bérest, B. Brouard[⋆], J.G. Durup[⋆⋆]

LMS and G.3S
Ecole polytechnique
91128 Palaiseau

[⋆]Brouard Consulting
37, rue du petit-musc
75004 Paris

[⋆⋆]Gaz de France
361, Avenue du Président Wilson
93210 Saint Denis La Plaine

September 13, 2000

Introduction

Many ‘shut-in pressure tests’ have been performed in salt caverns (among others Bérest et al. 1979, Van Sambeek 1990). At the beginning of such tests, both the cavern and the well are filled with brine (the well can in some cases be filled with soft water or fuel-oil, the well-head valves are closed, and the evolution of pressure versus time is recorded for several months or years. Pressure builds up in all cases, with rates ranging from a few MPa (a few hundreds psi) per year to several dozens MPa (several thousand psi) per year. When the pressure build-up rate is large, or when the test is long, cavern venting is performed periodically to prevent pressure from building to levels that would cause rock fracturing or damage to the well. These tests are important for potential cavern abandonment; they provide direct information on the long-term behavior of closed caverns. The aim of this paper is to discuss several topics related to these tests.

Pressure in a closed cavern builds as a result of the combination of five phenomena (Ratigan, 2000):

1. salt creep;
2. thermal expansion of the brine;
3. transport of the brine into the formation
4. well leaks; and
5. additional dissolution

These phenomena contribute to cavern volume change or cavern-brine volume change. For a closed cavern, the conversion of volume changes into pressure changes is governed mainly by cavern compressibility. A brief discussion of the influence of these factors is provided here.

- **Salt Creep**

  A large variety of laboratory creep tests have been performed and described by many authors, and experts agree on the following important features.

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

  For a salt cavern, these properties have important consequences:

- All caverns slowly shrink, except perhaps when the brine pressure (P_i) is exactly equal to the overburden (lithostatic) pressure (P_∞) — a situation rarely encountered.
- The cavern creep rate is much larger when the difference (P_∞ -P_i) is large. Typical values of the convergence rate in an open brine-filled cavern are $\dot{V}/V = 3.10^{-4}$ per year at a depth of 1000 meters (3280 feet) and $\dot{V}/V = 3.10^{-2}$ per year at a depth of 2000 meters (6562 ft), but these figures are subject to large variations from one site to another (see Brouard and Bérest 1998 for a related discussion.) For a 100,000-m^3 (628,981 bbls) cavern, the corresponding volume loss rates are 30 m^3 (189 bbls) per year and 3000 m^3 (18870 bbls) per year, respectively.
- The cavern creep rate depends on cavern shape. For instance, the creep rate is faster in a cylindrical-shaped cavern than it is in a spherical-shaped cavern, but quickness does not depend on cavern size (i.e., the relative volumetric creep rate, $\dot{V}/V$, is the same in a large or small cavern at the same site provided their shapes and depths are similar).
- After some period of time (several months or years), a steady-state volume loss rate is reached in a cavern whose fluid pressure has been kept constant. However, caverns also experience a transient volume loss, which is significantly faster than steady-state volume loss (a) both during and after the leaching phase, and (b) every time the cavern's fluid pressure changes.

  The transient convergence rate in a salt cavern is a combination of "true" (or rheological) transient behavior (as can be observed in the laboratory during multi-step creep tests) and "geometrical" transient behavior (which is associated with the slow redistribution of stresses in the rock mass.)

- **Thermal expansion of the brine**

The temperature of rock salt increases with depth; caverns are leached using soft water pumped from shallow aquifers whose temperatures are significantly colder than the rock temperature at cavern depth. The difference between the cavern brine temperature and the temperature of the surrounding rock will slowly resorb with time; resorption is governed by heat conduction through the rock to the cavern and by heat convection in the cavern.

- This phenomenon is transient and vanishes after a time equal to several times t_c (after the end of cavern leaching); t_c, the characteristic time, is equal to $V^{2/3}/(4k)$, where V is the cavern volume (in m^3) and k is thermal diffusivity of salt ($k \approx 100$ m^2/year) — i.e., 75% of the initial temperature difference is resorbed after a time approximately equal to t_c.
- The thermal expansion rate is not influenced by cavern brine pressure (in sharp contrast to cavern creep).

  - The thermal expansion rate depends on cavern shape, the thermal properties or rock, the thermal expansion coefficient of the brine **and cavern size**, also in sharp contrast to cavern creep in this respect.
  - The typical thermal expansion of brine for an 8000-m^3 (50,320 bbls) volume is 70 m^3 (440 bbls) per year, but it rapidly decreases with time (Hugout 1988). For a larger cavern, this figure increases with the cavern radius [600 m^3 (3774 bbls) per year for a volume of 500,000-m^3 (3,145,000 bbls)].

- **Brine Transport Into the Formation**

  Two decades ago, salt was considered to be virtually impermeable, and fluid leakage into the formation was considered to be non-existent. Recent advances have disproved these assumptions.

  - Salt permeability, even if exceedingly small when compared to many other rocks, is not zero.
  - Intrinsic permeability of clean salt rock is in the range $K = 10^{-22}$ m^2 to $K = 10^{-21}$ m^2, and brine flow from a pressurized cavern into a salt formation is, in most cases, much smaller than 1 m^3 (6.3 bbls) per year. However, when the cavern pressure is close to or slightly higher than the overburden pressure (which is approximately P_∞ (MPa) $= 0.022\ H$ (meters, where H is the cavern depth), (i) rock can fracture, leading to a dramatic increase in permeability, (ii) or more likely, when the pressure build-up rate is small, a more diffuse but significant increase in permeability can take place, leading to an increase in brine flow.
  - The permeability of salt formations containing a significant amount of impurities (clay or anhydrite-interbedded layers) is in the range $K = 10^{-20}$ m^2 to $K = 10^{-19}$ m^2, and brine flow from a pressurized cavern can be of the order of 1 m^3/year (6.3 bbls/year). This figure is not totally negligible, especially when the effects of brine thermal expansion can be disregarded and cavern creep is slow. (See Bérest et al. (1999) for a discussion on this.)

- **Well Leaks**

  During a shut-in pressure test, well-head valves are closed at ground level. Both the salt cavern and the cased and cemented well can experience brine leaks. A rough estimate of possible leakage rates from the well to the surrounding rock can be obtained through the "mechanical integrity test" (M.I.T.), which is performed prior to commissioning a well (and sometimes even when a cavern is under operation). The most popular M.I.T. is the Nitrogen Leak Test (N.L.T.). Crotogino (1996) suggests 50 kg/day as a reference minimum detectable leakage rate and 150 kg/day as a maximum admissible leak rate during an N.L.T. (150 kg corresponds to a 0.8-m^3 nitrogen geometrical volume at 17 MPa and 300 K). Leakage rates using nitrogen are generally considered to be 10 times larger than those using equivalent liquids. In other words, a brine leak of 15 m^3 per year in a standard cavern well can be considered as a reasonably pessimistic figure. Of course, the actual value can be much smaller in any given well.

- **Salt Dissolution**

  The amount of salt that can be dissolved in a given quantity of water is a function of temperature and pressure. When temperature or pressure increase, salt dissolution takes place, resulting in a net increase in the cavern volume, which decreases the cavern's fluid pressure. This effect can be computed (Brouard 1998), and it can be taken into account by slightly modifying the thermal expansion coefficient (α) and the compressibility factor (β) [see below].

  The volume increase or loss caused by these various phenomena can be summarized as follows, using a 100,000-m^3 cavern as an example.

  - (a) cavern creep (open cavern): from 30 m^3 per year to 3000 m^3 per year, depending on cavern depth and salt properties;
  - (b) thermal expansion: from 50 m^3 per year to several thousand m^3 per year, depending on cavern size and age (i.e., the length of time the cavern has been idle before testing is performed);
  - (c) brine transport into the formation (closed cavern): much smaller than 1 m^3 per year to a few m^3 per year, depending on cavern pressure and salt permeability;
  - (d) well leaks: typically, from 0 to 15 m^3 per year; and
  - (e) salt dissolution: included as a corrective term in the thermal-expansion and brine-compressibility coefficients, which are larger by a few percent when salt dissolution is taken into account.

  The two first terms are the most predominant, except when the cavern is very old (when thermal expansion vanishes) or the brine pressure is high (when cavern creep is exceedingly low).

  When the cavern is closed, volume changes are partially constrained and brine pressure increases. The cavern compressibility factor, β, provides a relation between the unconstrained cavern volume changes, ΔV, and the resulting brine pressure increase, ΔP

$$\Delta V = \beta V \ \Delta P$$

  where the compressibility factor, or β, is in MPa^{-1} or psi^{-1}. Its value depends on cavern shape and the nature of stored fluid — but not on cavern size (Bérest et al. 1999). A typical value for a brine-filled cavity is $\beta = 4$ to $5\ 10^{-4}$ MPa^{-1}, but larger values can be observed in some cavities (due to gas pockets etc.) This parameter is extremely important and should be measured accurately prior to any shut-in pressure test.

From this relation, it is easy to infer that the pressure build-up rate in a closed cavern is simply related to the cavern closure rate due to creep ($\dot{V}_{creep}$), the cavern-brine thermal expansion ($\dot{V}_{th} = \alpha V \dot{T}_i$, where α is the brine-thermal expansion coefficient, T_i is cavern-brine temperature), the fluid transfer into the formation ($\dot{V}_{perm}$) and brine leakage through the well ($\dot{V}_{leak}$):

$$\beta V \dot{P}_i = \dot{V}_{creep} + \alpha V \dot{T}_i - \dot{V}_{perm} - \dot{V}_{leak}$$

Here, coefficients α and β are supposed to have been (slightly) modified to take into account additional salt dissolution.

Uncertainties and Inaccuracies

Despite its apparent simplicity, a pressure build-up test is difficult to perform and interpret. Pressure evolution is measured through a pressure gauge; a test can last several months or years, and offset or drift may affect pressure recordings during long testing periods. Pressure evolution is measured at the well head; the difference between cavern pressure and well-head pressure is equal to the brine column weight. This weight can change, for example, when ventings are performed during the test. In some cases during venting, saturated brine from the cavern displaces the lighter brine initially set in the well and modifies the column weight. The same is also true when the well is partially filled with soft water or fuel oil.

When the test is performed after a long period of idleness, the observed curve is smoother. When the test is performed a few days or weeks after the cavern leaching, several transient phenomena play important roles (transient cavern creep, brine saturation, temperature changes in the rock mass surrounding the well, etc.). These phenomena are difficult to assess precisely.

Test interpretation is not easy. Well leaks are difficult to estimate, but a simple procedure has been proposed (Bérest et al. 1999). A quantitative interpretation of the test needs information on such quantities as cavern volume (V), cavern compressibility factor (β), thermal diffusivity of the rock (k), brine thermal-expansion coefficient (α), history of the cavern brine temperature ($T_i = T_i(t)$), rock mechanics properties (i.e., $A, n, Q/R$ where the Norton-Hoff constitutive equation applies, see Brouard and Bérest 1998), and transient creep. These quantities can be inferred or extrapolated from laboratory tests, reference books and field tests, but, the uncertainty for each is 10% or more in most cases, and only rough estimates can be made. As such, they still can be quite useful. A perfectly quantified description is out of reach for many cases, but, when predicting the long-term behavior of caverns, the main objective is to avoid gross misinterpretation of data.

Test Interpretation

A method to interpret the recorded data of pressure evolution is proposed here.

1. In most cases, the two predominant phenomena governing pressure build-up are cavern creep and thermal expansion. The cavern creep rate is often difficult to assess precisely. On one hand, no laboratory-test results are available for many cases; on the other hand, transient creep effects, which are effective after venting or several months after leaching has been completed, are difficult to assess.

2. Temperature evolution is somewhat easier to assess.

    - Heat transfer through the rock mass is described by the Fourier equation, which involves only one parameter (thermal diffusivity, or $k = 100\ \mathrm{m}^2/\mathrm{year}$). This parameter is not subject to large differences from one site to another. The same can be said of the thermal conductivity of salt and the heat capacity of the brine.
    - Solving the heat transfer equation requires information on thermal boundary conditions as well as initial conditions. In principle, initial conditions must take into account the leaching rate and duration, injected water temperature, etc. Computations are easier when it is assumed that, at the end of leaching,
        - (1) the rock temperature is uniform throughout the rock mass is and equal to its natural geothermal value, and
        - (2) the brine temperature is uniform in the cavity.

      Thus, two quantities are needed: the natural rock temperature (which is easy to measure or to assess), and the initial cavern-brine temperature, which can be measured immediately after leaching has been completed. It is better to measure brine temperature at cavern depth. The temperature of the withdrawn brine, which is often easily available, can be different by several degrees from the cavern temperature.

      These two quantities, together with thermal rock and brine properties, which are not subject to large changes from one site to another, allow simple calculation of temperature evolution. In the following, the **LOSAC**©[1] program has been used to compute temperature evolution in a cylindrical or spherical cavern.

---

[1] This software is a property of Gaz de France. It has been developped by Brouard Consulting with assistance from Laboratoire de Mécanique des Solides (LMS), Ecole polytechnique, France. It has been specifically developed to serve as an aid in the field of predictive studies relative to the long term abandonment of underground salt caverns.

3. Thermal expansion effects can be computed easily; if $\dot{T}$ is the cavern brine average temperature increase rate, then contribution of thermal expansion to the pressure build-up rate is

   $$\dot{P} = \alpha \, \dot{T} / \beta$$

   where the parameters are assumed to be $\alpha = 4.4 \; 10^{-4}$ ^{o}C^{-1} and $\beta = 4 \; 10^{-4}$ MPa^{-1} (spherical cavern) or $\beta = 5 \; 10^{-4}$ MPa^{-1} (cylindrical cavern). (A 1^{o}C temperature increase in a closed cavern leads to a pressure build-up of 1.1 MPa or 0.88 MPa.)

4. The actual recorded pressure evolution is then compared to the computed pressure evolution caused by thermal expansion. The difference is mainly due to the effects of cavern creep. The cavern creep rate is compared to what is known about the cavern depth, rock temperature, brine pressure, results of the laboratory creep tests, etc., and the consistency of the results is discussed.

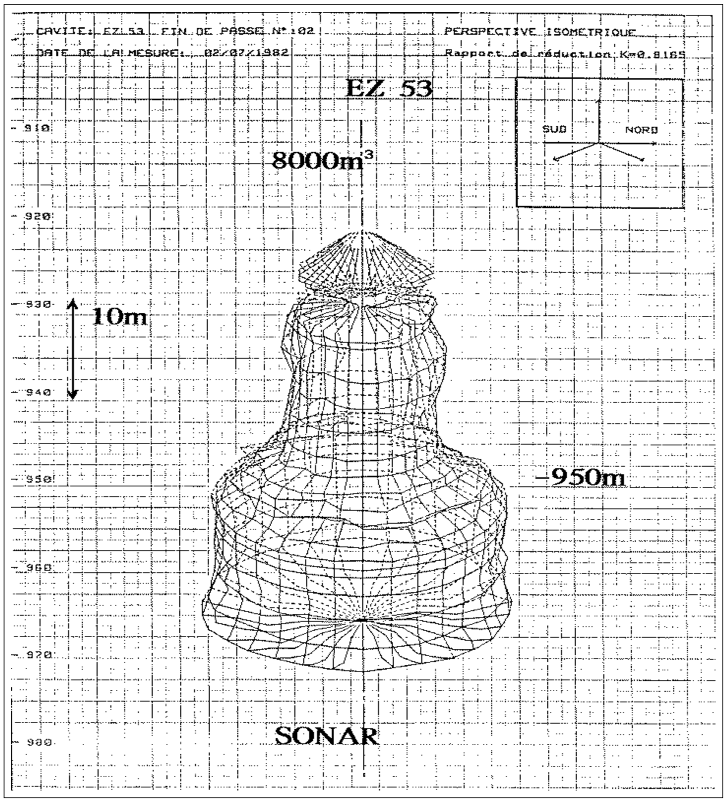


Figure 1: **Etrez Ez53 cavern (The indicated volume is the (cavern + sump) volume; the cavern brine volume is assumed to be 7500 m^3.)**

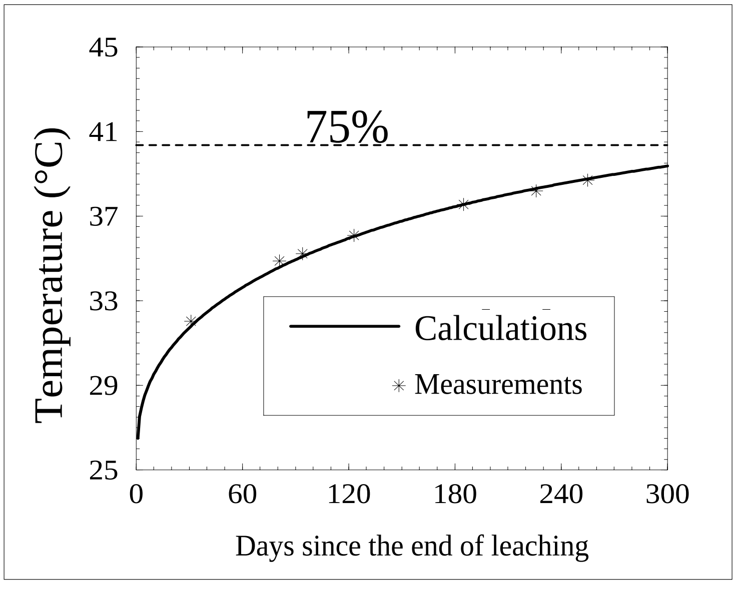


Figure 2: **Temperature evolution in the Ez53 cavern before the shut-in pressure test began.**

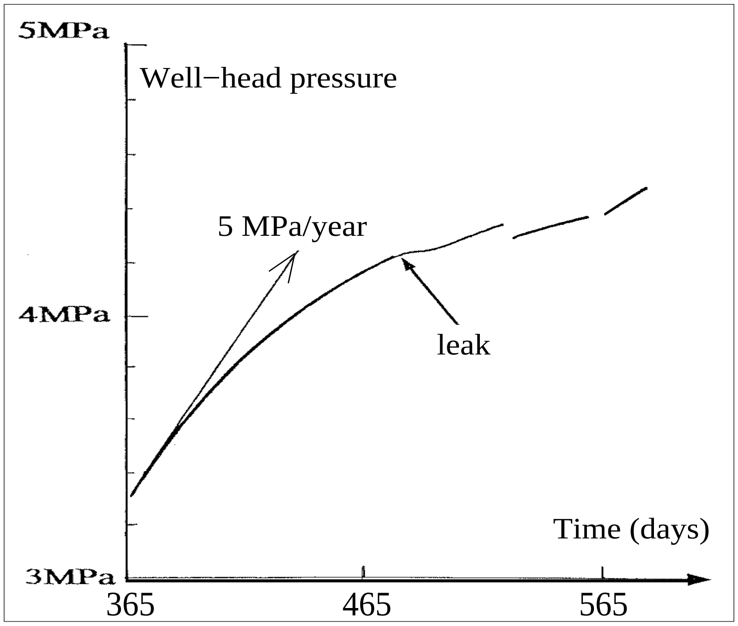


Figure 3: **Well-head pressure build-up (as measured) at the Ez53 cavern.**

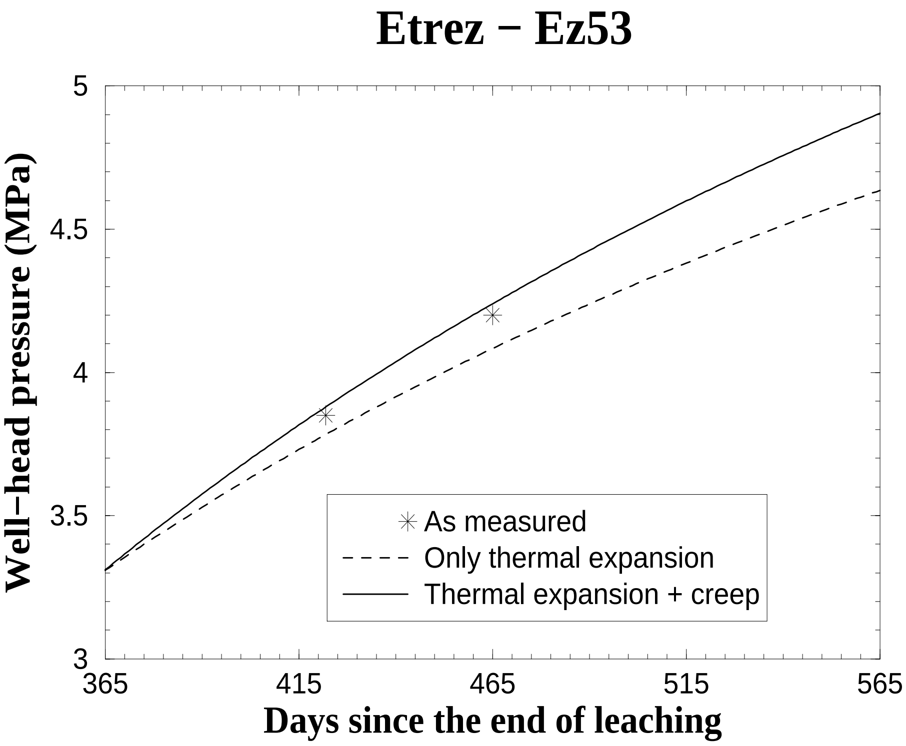


Figure 4: **Computed pressure evolution (Ez53).**

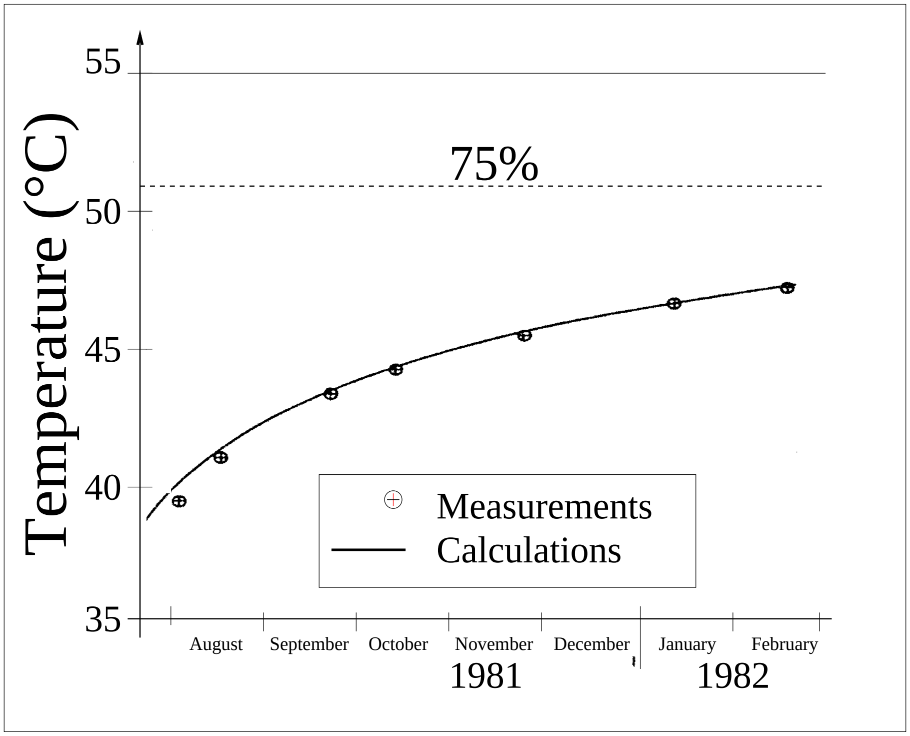


Figure 5: **Temperature evolution in the 1450-m deep Ez14 cavern (after Hugout, 1988).**

Example 1: Ez53 (Etrez upper salt)

From 1982 through 1998, several different in-situ tests have been performed on the Ez53 cavern, whose mechanical and thermal behaviors are well known. The Ez53 cavern is located at the Etrez site operated by Gaz de France. Its volume is 7500 m^3, and its depth is 950 m (Figure 1). Leaching was completed by June 1982, after which the cavern brine temperature was measured periodically (Figure 2). Brine flow expelled from the cavern was measured for a 50-day period, beginning 250 days after leaching ended; the flow rate was 50 liters per day. The cavern head was shut on 361 days after leaching ended (Figure 3). Note that well-head pressure was measured in a annular space filled with fuel-oil, which explains why the initial pressure is 3.3 MPa instead of 0 MPa. Well leaks and brine permeation were probably extremely small in this cavern, as was observed during later tests by Bérest et al. (1996).

Thermal simulation performed using **LOSAC**© fits the temperature data remarkably well. Similar computation performed on the smaller ($V = 4700$ m^3) and deeper (1430 m) Ez14 cavern led to similar conclusions (Figure 5). To compute the resulting pressure build-up (Figure 2) in the Ez53 cavern, we assumed $\beta = 4\ 10^{-4}$ MPa^{-1} (spherical shape, this value is consistent with the measured cavern compressibility $\beta V = 3.2$ m^3/MPa, Bérest et al. 1999). The creep effect was computed assuming the Norton Hoff law, whose parameters are given in Brouard and Bérest (1998). The computed curve fits the observed pressure build-up well (Figure 4). In this relatively shallow cavern, thermal expansion accounts for 80%-90% of the total observed pressure build-up.

Figure 3 shows that the pressure build-up rate decreases with time. This can be attributed to the decrease in cavern creep rate and, to a smaller extent, to the decrease in temperature rise. The test was stopped by well-head leaks after 100 days.

Example 2: Etrez lower salt (the influence of size)

It has been said that, in sharp contrast to cavern creep, the thermal expansion rate is influenced by cavern size. This statement is clearly illustrated by tests performed on caverns Ez A, Ez B and Ez C (see Figure 6). These three caverns had been leached out in the lower layer of the Etrez formation; their depths and volumes are significantly deeper and larger than in Ez53 (see Table below), cavern volumes are computed from brine production data. :

Ez 53	950 m	7500 m^3
Ez A	1450 m	346,000 m^3
Ez B	1465 m	147,000 m^3
Ez C	1590 m	48,600 m^3

Leaching was stopped in these three caverns by early June 1995, and the caverns were shut-in a few days later. Figure 7 focuses on the measured pressure evolution during the period June 21-July 20. The initial pressure build-up rates were as given below. The smaller the cavern, the faster the pressure build-up rate.

Ez A	4.0 ±0.1 MPa per year
Ez B	5.9 ±0.2 MPa per year
Ez C	10.0 ±0.2 MPa per year

Because the cavern depths are roughly similar, the differences in rates can be explained by the thermal expansion effect. (The pressure build-up rate due to thermal expansion varies as $V^{-2/3}$.) Note that these three caverns cannot be compared directly to the shallower Ez53 cavern, which was shut-in one year (instead of a few days) after leaching ended.

The results of the thermal computations are displayed in Figure 8. The rock temperature was assumed to be 55^{o}C (slightly warmer for Ez C, which is a little deeper.) Initial cavern temperatures were not known, but brine temperatures in May 95 (as measured at the well head) were

Ez A	31.1^{o}C
Ez B	29.3^{o}C
Ez C	27.7^{o}C

Actual cavern temperatures are likely to be a little warmer.

Computation results can be deceptive: the computed pressure build-up (when only thermal expansion is taken into account) is significantly larger than the observed pressure build-up by a factor of 2. This proves that thermal expansion is likely to be the major factor in pressure build-up for these three caverns, even though they are deeper than Ez53. However, since cavern creep is expected to be faster in these caverns than in Ez53, the total (creep + thermal expansion) expected effects are much larger than observed. Two explanations are proposed: (1) the compressibility factor (β) is much larger in these three caverns (due, for example, to some amount of gas trapped in the cavern, but no actual value was available), or (2) transient effects triggered when leaching stops (additional dissolution) play major roles in these large caverns. At present, we are not able to confirm either hypothesis (leaks seem unlikely in these wells whose mechanical integrity was measured before leaching began).

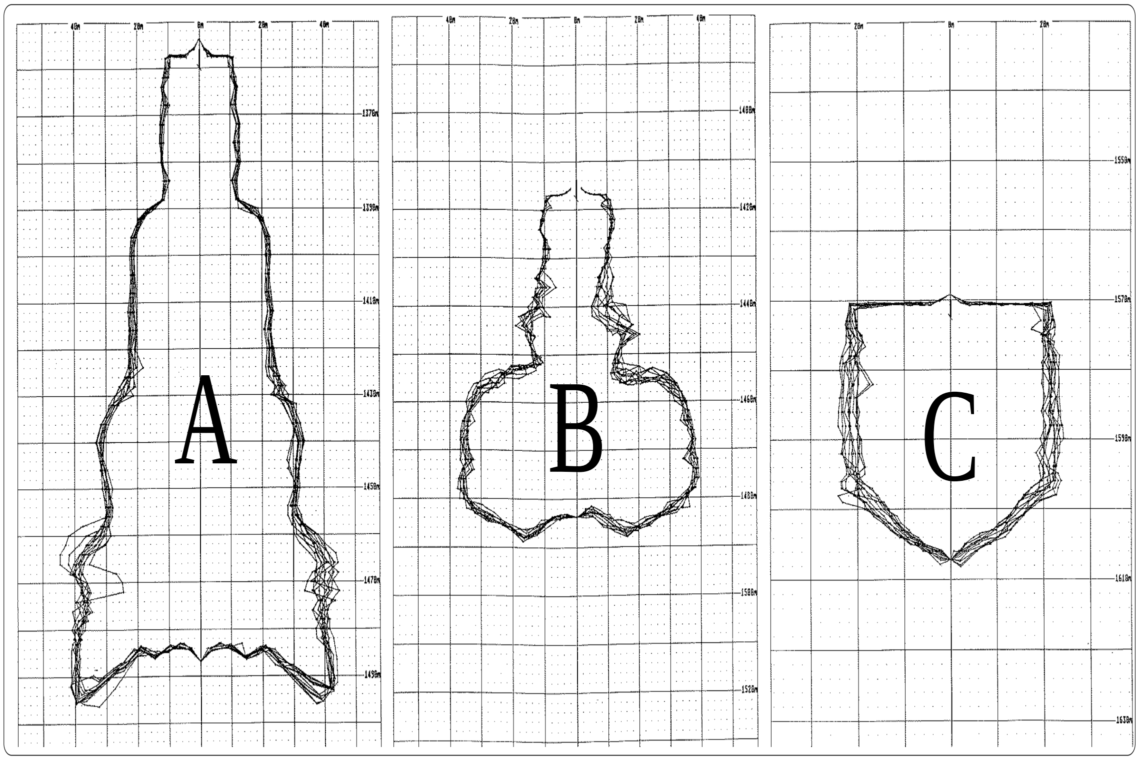
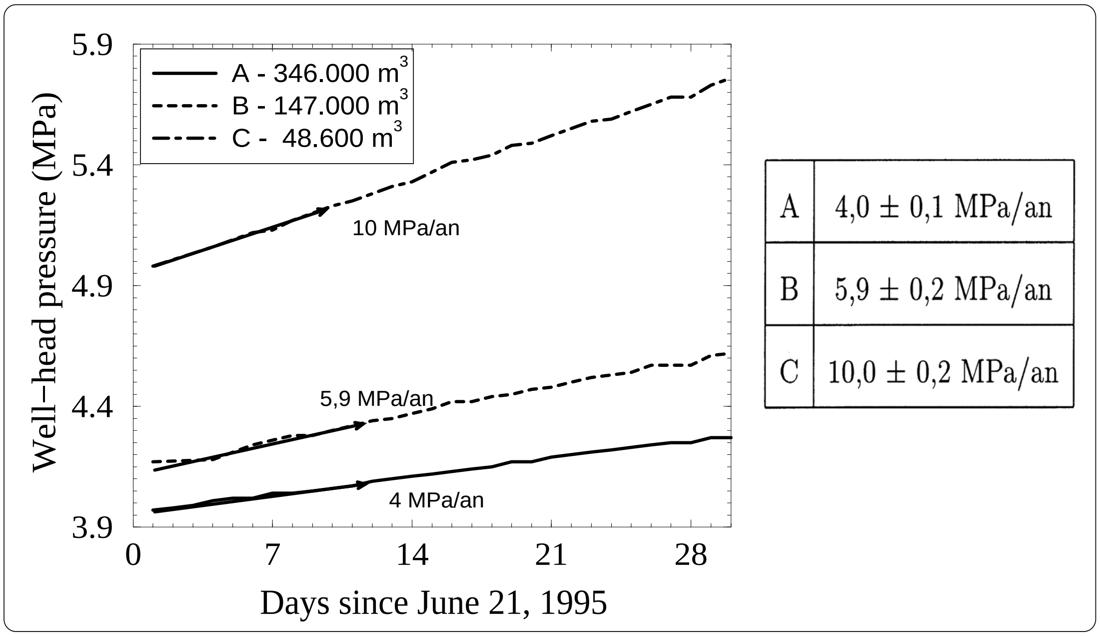


Figure 6: **Shapes of Caverns Ez A, Ez B and Ez C.**



A	4,0 ± 0,1 MPa/an
B	5,9 ± 0,2 MPa/an
C	10,0 ± 0,2 MPa/an

Figure 7: **Well-head pressure build- up at the beginning of the shut-in pressure test (the smaller the cavern, the faster the build-up rate.)**

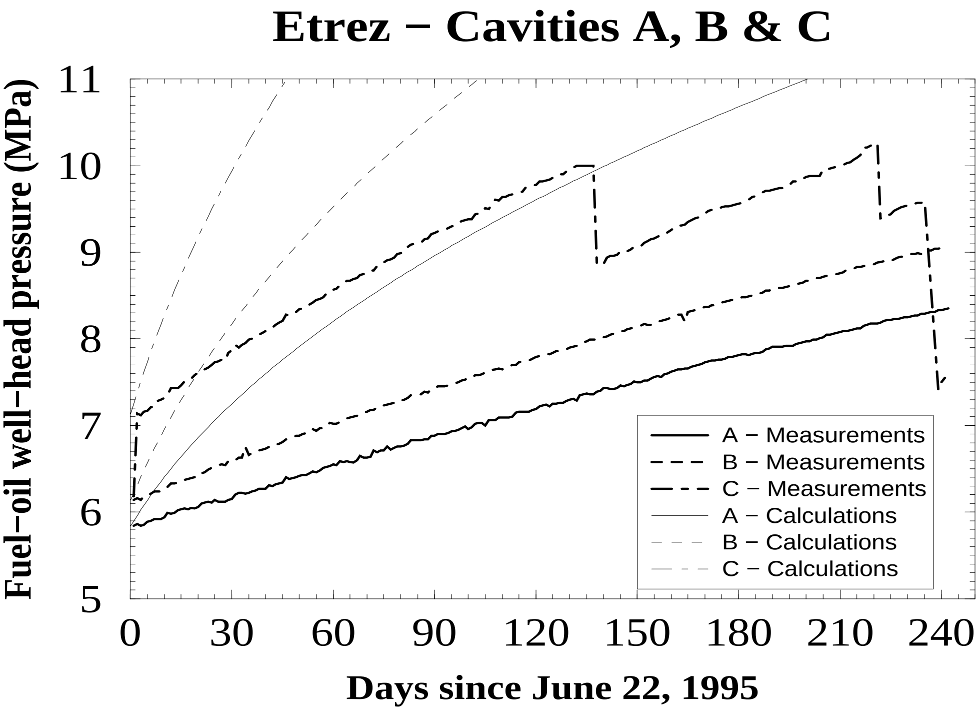

Etrez − Cavities A, B & C

Figure 8: **Measurements and calculations results (Calculations overestimate pressure build-up.)**

Example 3: Ha6 and Ha7 (Hauterives), 1975

The Ha6 and Ha7 caverns are located in the Hauterives brine production field now operated by Chloralp. The distance between the two wells is 250 meters, and the caverns have been linked through fracturation. Soft water is injected in one well, and brine is withdrawn from the other well. When this test was performed, the volume in Ha6 was 450,000 m^3; the cavern was 100 meters high, its bottom depth was 1650 m and its top depth was 1550 m. The rock temperature at these depths is 58^o-62^oC. The volume in Ha7 is much smaller (25,000 m^3). The temperature of the injected soft water was 12^oC, and the average brine temperature (as measured at the well head) was 26^oC — i.e., smaller than the rock temperature by 34^oC. Observed and computed pressure build-up (taking only thermal expansion into account) are displayed in Figure 9. A spherical shape was assumed for computation. A well-head leak was observed and repaired 60 days after the end of leaching. Well-head pressures were measured on both the Ha6 and Ha7 well heads. Ha7 was filled with under-saturated brine, which explains the initial offset. The agreement between the observed and computed curves is good, but, again, the predicted thermal expansion effects are larger than the observed pressure build-up, which prevents evaluation of the creep effects, although they are suspected to be significant. (In this geological formation, rock salt is known to be more creep-prone than Etrez rock salt.) Again, the temperature effects are probably overestimated, especially during the 0-90 days period. However, pressure build-up rates fit measured data in the 120-270 days period.

Example 4: Ha6 and Ha7 (Hauterives), 1977-1984

The same two wells were shut-in again from 1977 to 1984. Between 1975 and 1977, these two caverns were used for brine production, resulting in an increase in total volume and a drastic change in cavern shape. (During this period, anhydrite layers broke and fell to the cavern bottom, leading to the apparent upheaval of the cavern floor.)

Well-head pressure histories are displayed in Figure 10. Several ventings took place, resulting in a rather complex pressure history (Here, again, well-head pressures are measured in both the Ha6 and Ha7 well heads.) Thermal computations are difficult to perform in this situation, and we have attempted a more qualitative description by measuring the pressure build-up rate each time the cavern pressure reached 5 MPa (or 6 MPa) after venting. The corresponding points are displayed in Figure 11. The following two features are clear.

- (1.) The pressure build-up rate decreases with time (by a factor of 2-3 during the 7-year period). Since the cavern pressure is the same for each considered set of points, this decrease must be related to the decreasing rate of thermal expansion. For such large caverns, the characteristic time, t_c, is approximately 15 years, which is consistent with the observed sharp decrease in the pressure build-up rate during this 7-year period.
- (2.) The pressure build-up rate is significantly smaller when the well-head pressure is

6 MPa. This effect cannot be attributed to thermal effects, which are not pressure-dependent (in contrast to cavern creep), proving that cavern creep contributes significantly to the pressure build-up rate.

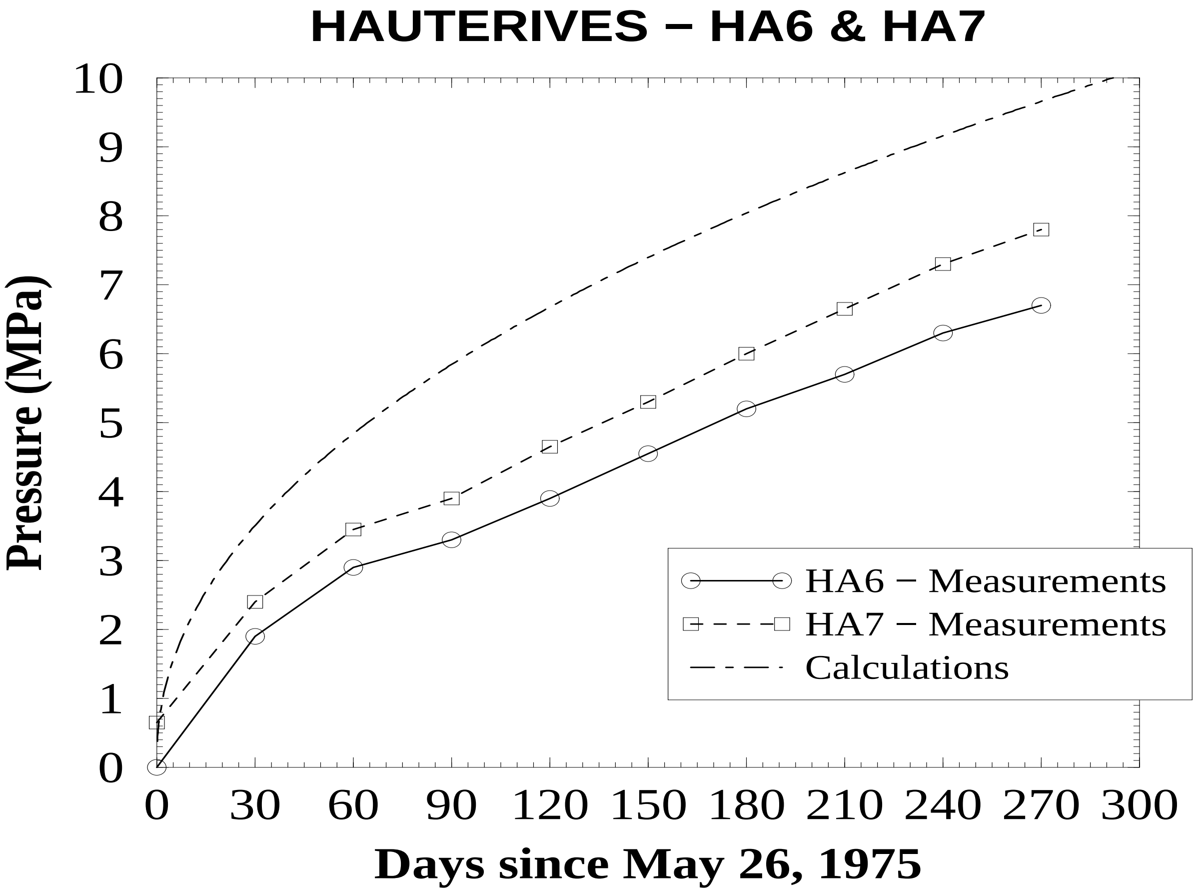


Figure 9: **Observed and computed well-head pressure build-up in Caverns Ha6 and Ha7 (A leak appeared on day 60 and was repaired; computation slightly overestimates pressure evolution.)**

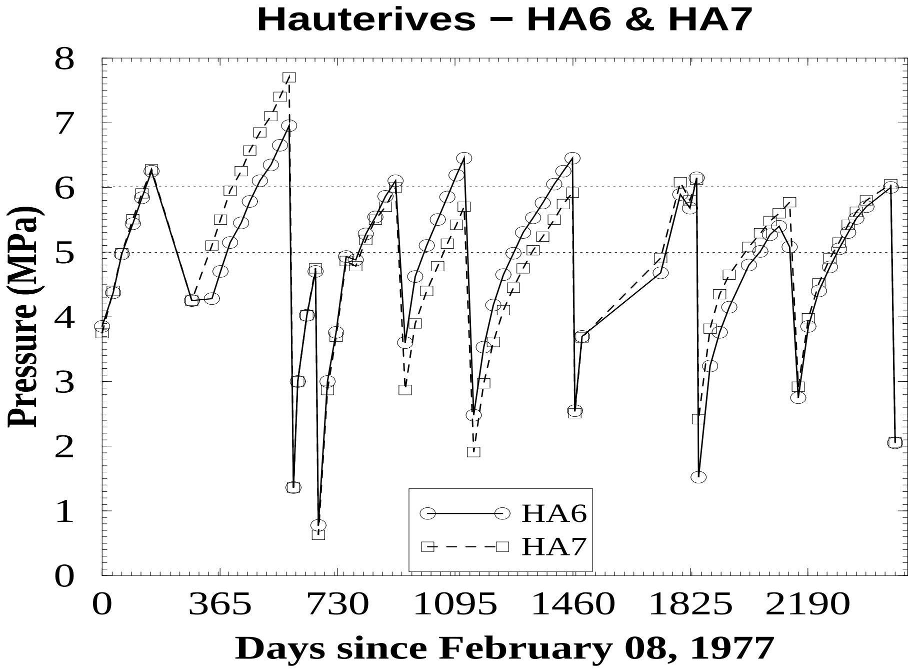


Figure 10: **Well-head pressure evolution, 1977-1984 (Pressure rates for pressures of 5 MPa and 6 MPa are displayed in Figure 11.)**

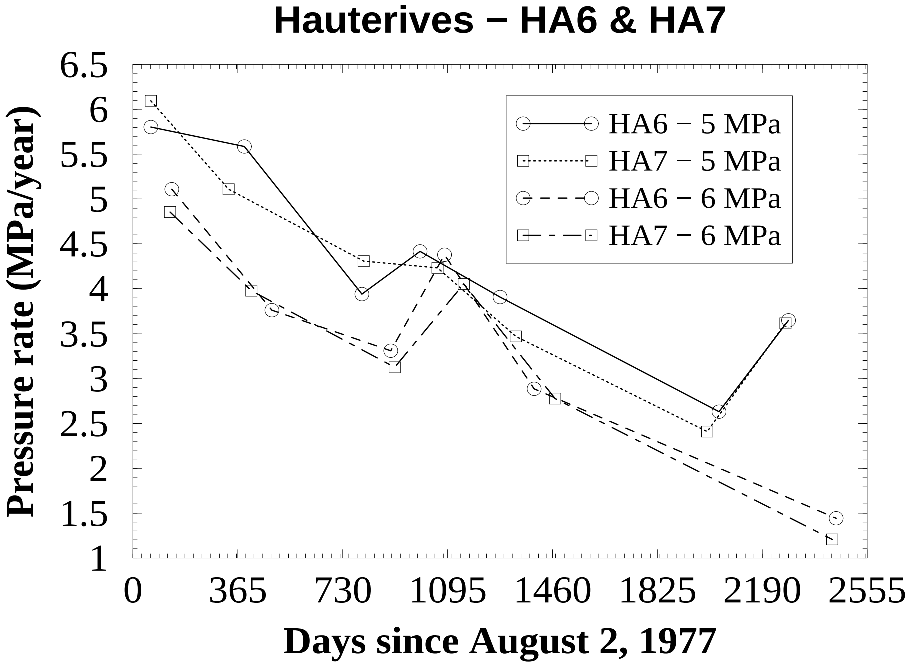


Figure 11: **Build-up pressure rates observed in Caverns Ha6 and Ha7 when the well-head pressure is 5 MPa and 6 MPa.**

Example 5: Vauvert

The Pa1, Pa2, Pa3 and Pa6 caverns are located in the Vauvert brine production field, operated by Elf. The salt formation depth is 1800-2500 m, the rock temperature at these depths is 100^{o}C and above, and the clay content is high. Pa3 has not been linked to other wells. Caverns Pa1, Pa2 and Pa6 are linked, but connections between those wells close when brine is not circulated, due to very high creep rates. For instance, brine was extracted from Pa1-Pa6 a few days before the test began: water was injected in Pa1, and brine was withdrawn from Pa6, clear proof of connection. However, as can be seen in Figure 12, measured pressures on Pa1-Pa6 become significantly different after a few day, at which time, the connection was closed.

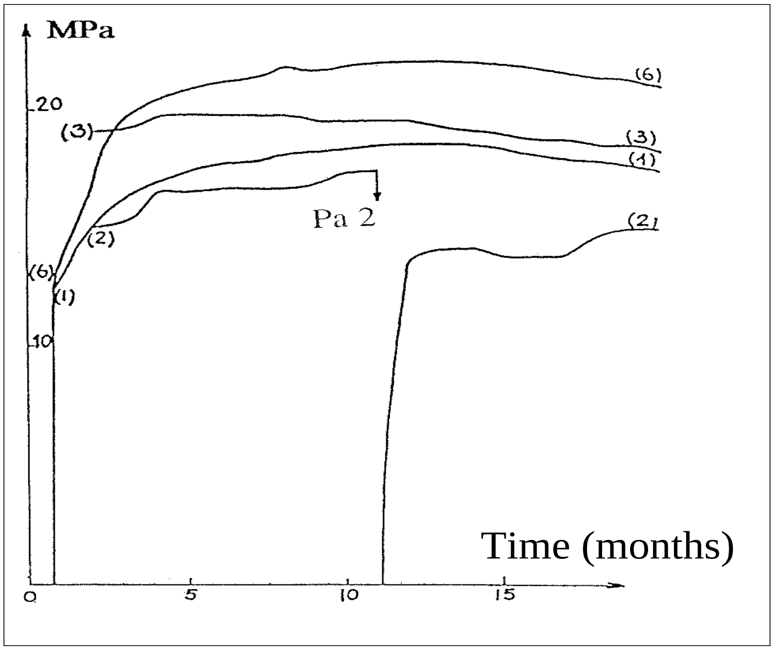
It is difficult to distribute the total amount of leached salt (360,000 tons) between the three caverns (Pa1-Pa2-Pa6). We assumed the following values:

Pa1	84,000 m^3
Pa2	68,000 m^3
Pa6	16,000 m^3

We computed the effects of thermal expansion and creep, although little information was available concerning temperatures and creep data. A rock temperature of 100^{o}C and an initial cavern brine temperature of 40^{o}C were assumed, and data from Avery Island provided by Van Sambeek (1993), who compiled De Vries (1988), were used to describe rock salt creep.

Figure 13 displays the computation results for the case of Cavern Pa6. Thermal expansion alone leads to fracturing after 4 months. However, creep is also very effective in this deep cavern. When creep is taken into account, the pressure build-up is much faster at the beginning of the test, leading to a 15-MPa pressure rise a few days after the start of the test. Creep then slows down, and pressure build-up is governed by thermal expansion. Fractures (more exactly, pre-existing connections) open after 3 months. These results fit the measured data reasonably well, as displayed in Figure 12.

Similar computations have been performed for the larger Pa1 cavern (Figure 14). As expected, pressure evolution is a little slower, because temperature rises more slowly in a larger cavern.



Pa6	16 000 m^3
Pa2	68 000 m^3
Pa1	84 000 m^3

Figure 12: **Well-head pressure evolutions for Caverns Pa1, Pa2, Pa3 and Pa6.**

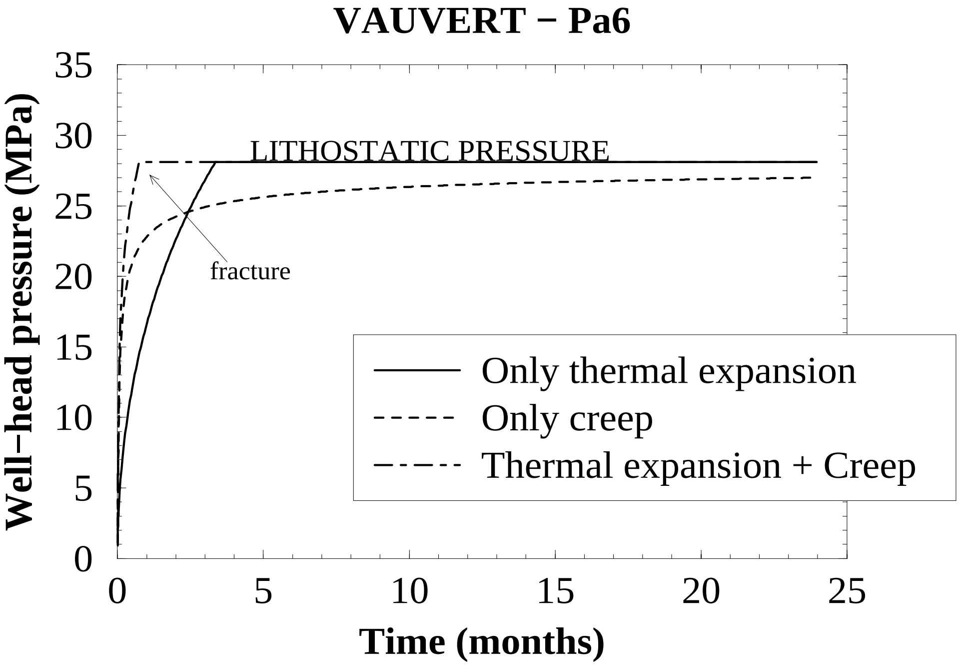


Figure 13: **Computed pressure evolution of Cavern Pa6. Creep is extremely effective a few days after leaching ends, leading ro rapid pressure build-up; then creep slows down and thermal expansion governs pressure further build-up.**

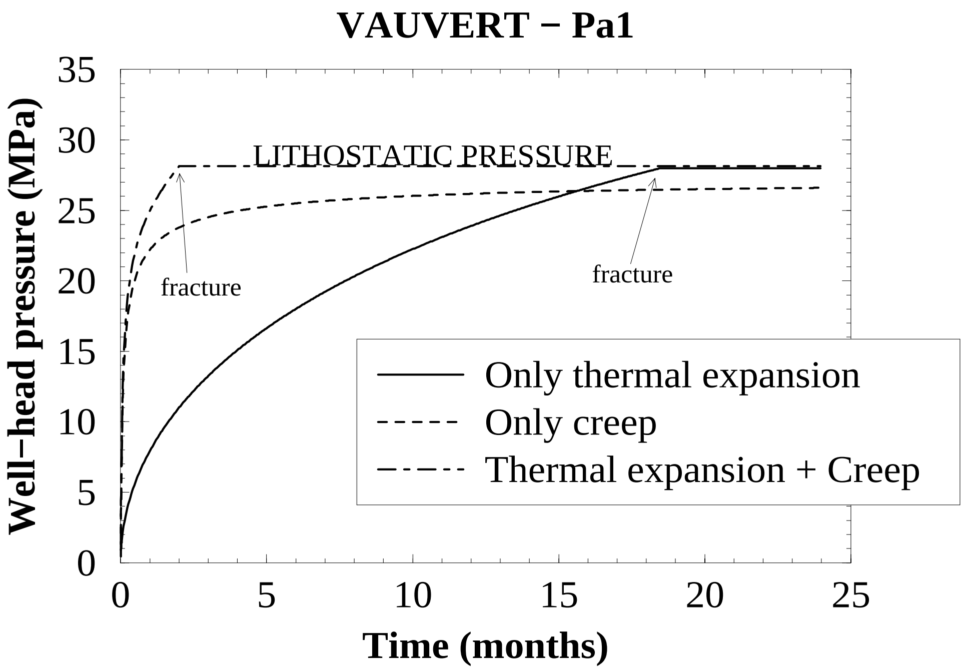


Figure 14: **Computed pressure evolution of Cavern Pa1 (In this larger cavern, thermal expansion is slower.**

Conclusions

Shut-in pressure tests are of major importance for practical cavern abandonment. They provide direct information on pressure build-up rates that are expected when a well is sealed and abandoned.

1. Tests must be performed carefully . Testing a cavern immediately after it has been leached out is not recommended. A test procedure allowing to ckeck the existence of leaks must be adopted.
2. Data published in the literature are difficult to interpret, and much information is missing. Of particular importance are:
   - (a) the natural temperature of the rock;
   - (b) the temperature of the cavern brine at the beginning of the test; and
   - (c) the cavern compressibility.
3. Except for very deep or very old caverns, cavern-brine thermal expansion is the main factor in initial cavern pressure build-up.

4. Computing (or measuring) cavern temperature evolution allows good interpretation of shut-in pressure tests.

Acknowledgements

The authors are indebted to Bernard Thomas, of the Chloralp Hauterives Facility, for his extremely useful comments.

References

Bérest P., Ledoux E., Legait B., de Marsily G., 1979. “Effets thermiques dans les cavitésen couche salifère”, Proc. 4th Int. Cong. Rock Mechanics, Balkema, p. 31-35 (in French.)

Ratigan J., 2000. “A status report on the SMRI cavern sealing and abandonment program”.

Van Sambeek L.L., 1990. “A simple method for modeling the pressure build up or flow of an abandoned solution well”, SMRI Spring Meeting, Austin, p. 583-590.

Brouard B., Bérest P., 1998. “A tentative classification of salts according to their creep properties”, SMRI Spring Meeting, New Orleans, p. 18-38.

Crotogino F., 1996. “SMRI Reference for External Well Mechanical Integrity Testing/Performance, Data Evaluation and Assessment”, SMRI Spring Meeting, Short Class, Houston.

Bérest P., Bergues J., Brouard B., Durup J.G., Guerber B., 1999. “A salt-cavern abandonment test”, SMRI Spring Meeting, Las Vegas, p. 229-247.

Brouard B., 1998. “On salt-cavern behavior”, Ph.D. Thesis, Ecole polytechnique (in French).

Hugout B., 1988. “Mechanical behavior of salt cavities - In situ tests - model for calculating the cavity volume evolution”, 2nd Conf. Mech. Beh. Salt, Trans Tech. Pub., Clausthal-Zellerfeld, p. 291-310.

Bérest P., Bergues J., Brouard B., Durup J.G., Guerber B., 1996. “A tentative evaluation of the M.I.T.”, Spring SMRI Meeting, Houston.

Bérest P., Bergues J., Brouard B., 1999. “Review of Static and Dynamic Compressibility Issues relating to Deep Underground Salt Caverns”, Int. J. Rock Mech. Min. Sc., 36, p. 1031-1049.

Bérest P., Brouard B., Durup J.G., 1998. “Abandonment of Salt Caverns”, Rev. Fr. Géotechnique, 82, p. 23-36 (in French).

De Vries K.L, 1988. “Viscoplastic laws for Avery Island Salt”, RE/SPEC INC. Report prepared for Stone and Webster Engeineering Corporation (quoted by Van Sambeek, 1993).

Van Sambeek L.L., 1993. “Evaluating cavern tests and subsurface subsidence using simple numerical models”, 7th Symp. on Salt, Elsevier, Amsterdam, Vol. I, p. 433-439.