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A CAVERN ABANDONMENT PROGRAM IN A CSME CAVERN AT GELLENONCOURT (LORRAINE, FRANCE)

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SUMMARY

A cavern abandonment program was established for the SG13-SG14 cavern of the Gellenoncourt brine field operated by CSME at Gellenoncourt in Lorraine, France. Cavern compressibility and the evolution of cavern brine temperature were measured. A 6-month brine-outflow test was performed, followed by an 6-month shut-in test. In this shallow cavern (250 m, or 800 ft, deep), which had been kept idle for 30 years, cavern-brine thermal expansion can be disregarded. Pressure evolution during the shut-in test is influenced by atmospheric pressure changes, ground temperature changes and Earth tides. From the average pressure-evolution rate, it can be inferred that the cavern closure rate is smaller than 10^{-5}/yr.

1. INTRODUCTION

The Solution Mining Research Institute (SMRI) has set the cavern abandonment issue at the centre of its research program for more than ten years (Ratigan, 2003). It has supported a series of tests performed in shallow caverns (i.e., those with depths less than 3000 ft, or 1000 m) in France, at Etrez (Bérest et al., 2001) and Carresse (Brouard et al., 2006), and Germany, at Stassfurt (Bannach and Klafki, 2009). An abandonment test supported by the SMRI currently is being performed in deep caverns at the Mont Belvieu site in Texas. Several papers have contributed to the discussion of this issue over the years (Wallner and Paar, 1997; Cosenza and Ghoreychi, 1993; Rokhar et al., 2003; Hévin et al., 2007; Lux et al., 2007), and several companies have performed abandonment tests that provide additional insights on pressure evolution mechanisms in a closed cavern (Rokhar et al., 2000; Brückner et al., 2007; Brückner and Wekenborg, 2006; Van Heekeren et al., 2009). In this paper, we describe the second part of a testing program performed in the Gellenoncourt brine-field cavern operated by Compagnie des Salins du Midi et Salines de l'Est (CSME). This cavern is shallower than the Etrez, Carresse and Stassfurt caverns; its depth is 700 ft, or 250 m. The cavern closure rate in such a cavern is slow, which raises a couple of specific measurement problems.

2. THE GELLENONCOURT CAVERNS

CSME has operated a brine field at Gellenoncourt in Eastern France since the beginning of the 20th Century; this brine field has been described by Buffet (1998). Figure 1 presents a map of the brine field. It is located at the eastern (and shallowest) edge of the Keuper bedded-salt formation of Lorraine-Champagne, in which the salt thickness is 150 m. Five horizontal "salt pencils" have been described by geologists. The salt content of this field is highest in the first (shallowest) and third pencils. The overburden layers include argillite, dolomite, sandstone and limestone.

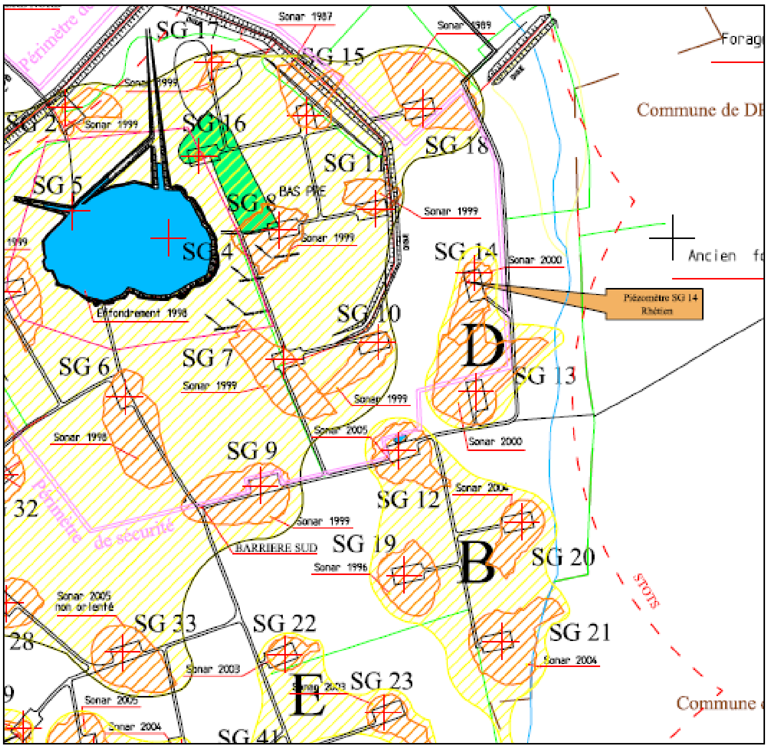

Figure 1 – Location of the SG13-SG14 cavern.

[The SG4-SG5 collapse was described by Buffet (1998).]

During the first half of the 20th Century, single wells were brined out. After 1965, the hydro-fracturing technique was used. For this brine field, cased and cemented wells are drilled to a depth of 280-300 m — i.e., at the base of the third pencil. The horizontal distance between two neighboring wells typically is 100 to 150 m. Through hydro-fracturing, a link is created between the two caverns at the base of the third pencil. Water then is injected in one well, and brine is withdrawn from the other well. The caverns grow, and their roofs actually reach the first pencil. Brining stops when the cavern roof is 10 m below the salt roof. This 10-m-thick salt slab is left to protect the overlying strata, which are prone to weathering when in contact with brine (Buffet, 1998).

In 2007, CSME decided to perform several field tests to prepare an abandonment file. (Field abandonment is not considered at this time.) The SG13-SG14 cavern was selected for performing in-situ tests, as this cavern is representative of the field and has been kept idle for a long period of time.

The SG13 and SG14 wells were drilled in May 1975, and operated as brine-production caverns from July 1976 to June 1977 (SG13), and from October 1978 to July 1980 (SG14). After some time, the two caverns coalesced, and SG13-SG14 now is composed of two parts connected by a large link; hydraulically, they can be considered as a single cavern. From latest sonar measurements (2000), it is inferred that the volumes of SG13 and SG14 are 107,000 m^3 and 34,000 m^3, respectively. However, sonar measurements are likely to underestimate the overall cavern volume, as they cannot "see" the insoluble-filled link between the two caverns. The vertical cross-section of the caverns is provided in Figure 2; a 3D view is provided in Figure 3Figure 3.

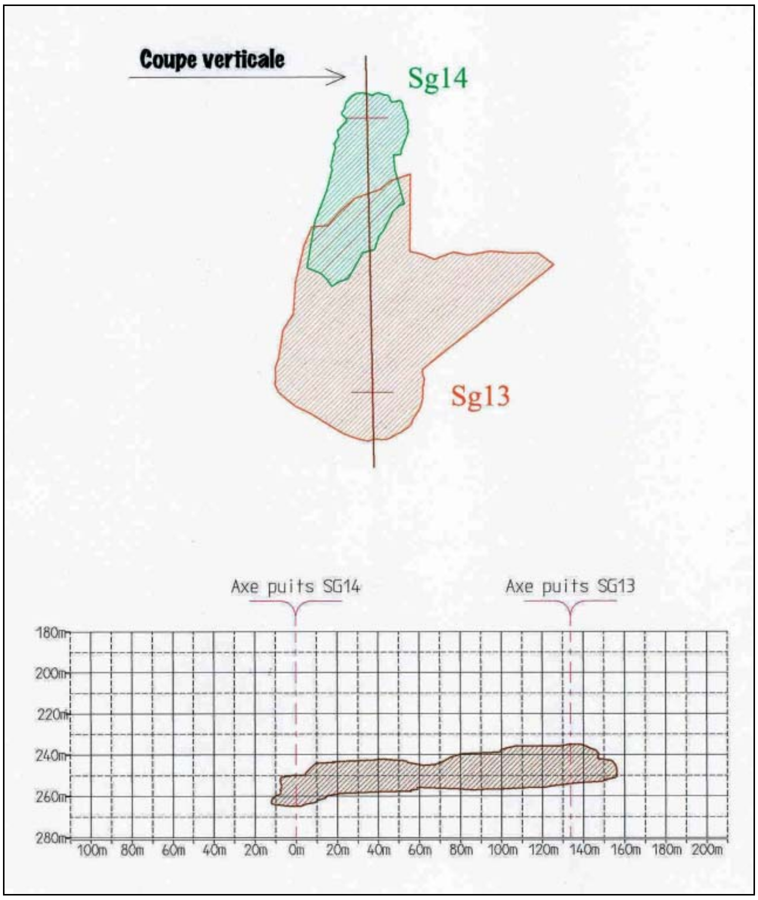

Figure 2 – Horizontal cross-section.

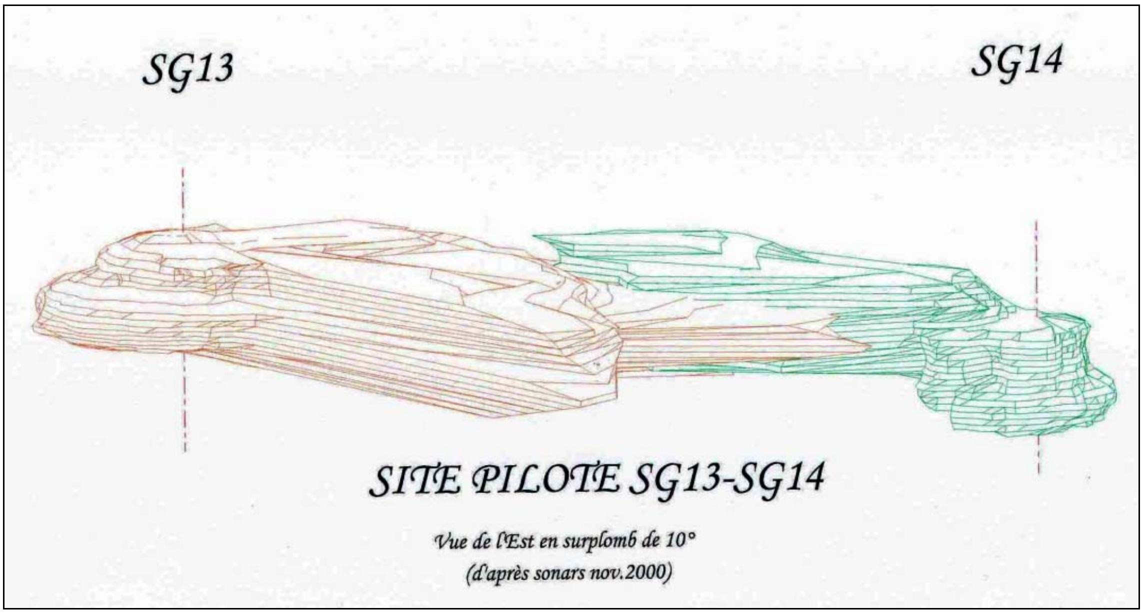

Figure 3 – 3D view of the SG13-SG14 cavern.

3. TESTING PROGRAM

A comprehensive abandonment testing program was designed in 2008. It was based partly on recommendations proposed by Bérest et al. (2004), and included the following tests and measurements:

- cavern compressibility measurement;
- cavern temperature measurement;
- brine-outflow and shut-in pressure tests;
- permeability measurement in a recently drilled borehole;
- Mechanical Integrity Test; and
- Abandonment test.

The three first tests are described in this paper (The two first tests and the brine flow test were described in Brouard et al, 2009). The permeability measurement was performed in 2009; the abandonment test will be completed by the end of 2011.

3.1 Cavern compressibility measurement

Cavern compressibility, or βV, in m^3/MPa or bbls/psi, is the ratio between the injected (or withdrawn) volume and the cavern pressure change during a rapid injection (or withdrawal). A correct assessment of this parameter is important when interpreting Mechanical Integrity Tests or Cavern Abandonment Tests (Bérest et al., 1999). On July 3, 2009, the compressibility of the SG13-SG14 cavern was measured by depressurizing SG13 by 0.1 MPa. Brine was expelled from the cavern to a 500-liter container. An accurate flowmeter had been set at the SG13 wellhead. The column composition and weight of SG13 changed during the test, because saturated brine rises in the well as a result of venting; for this reason, pressure evolution was measured at the SG14 wellhead.

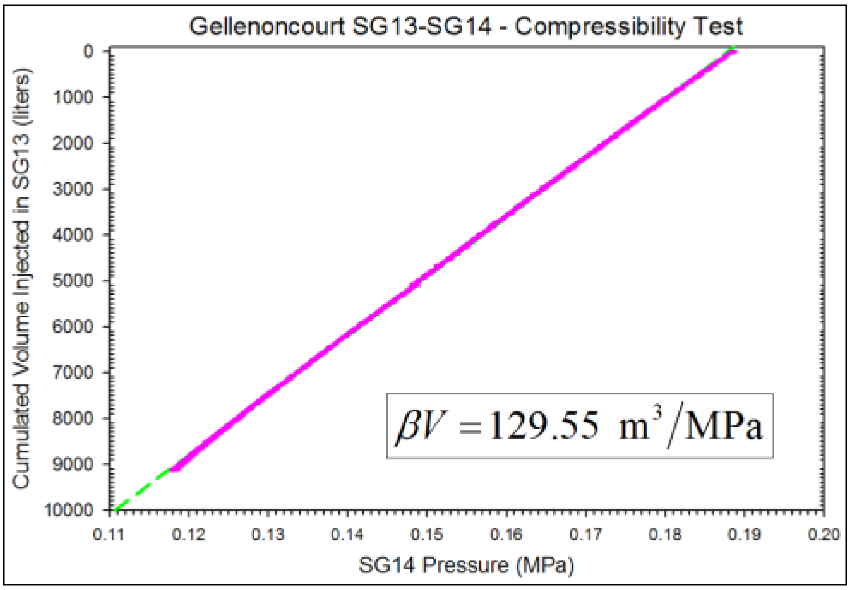

Figure 4 - Cavern compressibility measurement.

Erreur ! Source du renvoi introuvable. shows the expelled-brine-volume versus the SG14-pressure-drop-curve. The slope of this curve is the (as-measured) cavern compressibility, or $\beta V = 129.55$ m^3/MPa. When compared to cavern "sonar" volume (see Section 2), this figure is relatively high. (In most caverns, the ratio between cavern compressibility, βV, and cavern volume, V, is in the range $\beta \approx 4 - 5 \times 10^{-4}$ / MPa .) Cavern volume also can be assessed from "mass balance", which strongly suggests that the actual cavern volume might be as large as V = 240,000 m^3, from which a value of the cavern compressibility coefficient can be inferred to be $\beta = 5.4 \times 10^{-4}$/MPa ; this is slightly higher than usual but still credible. In fact, cavern compressibility often is a more significant parameter than cavern volume.

3.2 Cavern temperature

3.2.1 *Introduction*

Brine thermal expansion during an abandonment test is a real concern, as its effects often are larger than the effects of cavern creep closure. Brine thermal expansion (or contraction) results from the gap between the temperature of the cavern brine and the geothermal temperature of the rock. When cavern brine is colder than the rock mass, heat is transferred from the rock mass to the cavern, resulting in brine warming. Conversely, when the brine is warmer than the rock mass, heat is transferred from the brine to the rock mass, resulting in brine cooling. Brine warming (or cooling) generates brine expansion (or contraction), which contributes to brine outflow (when the cavern is opened) or to pressure build-up (when the cavern is shut-in).

The effect of brine thermal expansion often is dramatic in the context of an abandonment test. Brine thermal-expansion coefficient is $\alpha_b = 4.4 \times 10^{-4}$/°C .(The rock thermal-expansion coefficient only plays a minute role in this context; see Karimi-Jafari et al., 2007.). In a closed cavern a cavern brine temperature change by $\Delta T = 1$°C (1.8 °F) results in a brine pressure change of $\Delta P = \alpha \Delta T / \beta \approx 1$ MPa (140 psi) . In the following, it will be proven that the closure rate of the SG13-14 cavern is $\dot{\varepsilon} = 1 - 2 \times 10^{-5}$/yr. A brine temperature increase rate of $\dot{T} = 0.02$ °C/yr (0.038°F) would generate a relative brine volume increase of $\alpha \dot{T} \approx 10^{-5}$/yr — i.e., of the same order of magnitude as that of the cavern creep closure rate. In other words, correct interpretation of an abandonment test requires that brine temperature changes are nil or that these changes can be assessed precisely.

3.2.2 *Brine warming rate*

The brine warming process is slow —even slower in a larger cavern. In a cavern with volume V = 240,000-m^3 cavern, it is expected that, after approximately 10 years, the initial temperature gap is divided by a factor of 4 (Karimi-Jafari et al., 2007). For the SG13-SG14 cavern, soft water injected during the leaching process was slightly warmer (20 °C, or 68 °F) than the geothermal temperature of the rock, which typically is 18 °C (64.5 °F) at cavern depth (250 m, or 800 ft). The initial gap was small. Moreover, the cavern had been kept idle for nearly 30 years by the time the brine-outflow test began. It was believed that temperature increase rate was exceedingly small at that time. However, by December 2008, a temperature gauge was lowered into the SG13 well to assess changes in brine cavern temperature. The temperature evolution is represented in **Erreur ! Source du renvoi introuvable.**.

3.2.3 *Temperature measurement results*

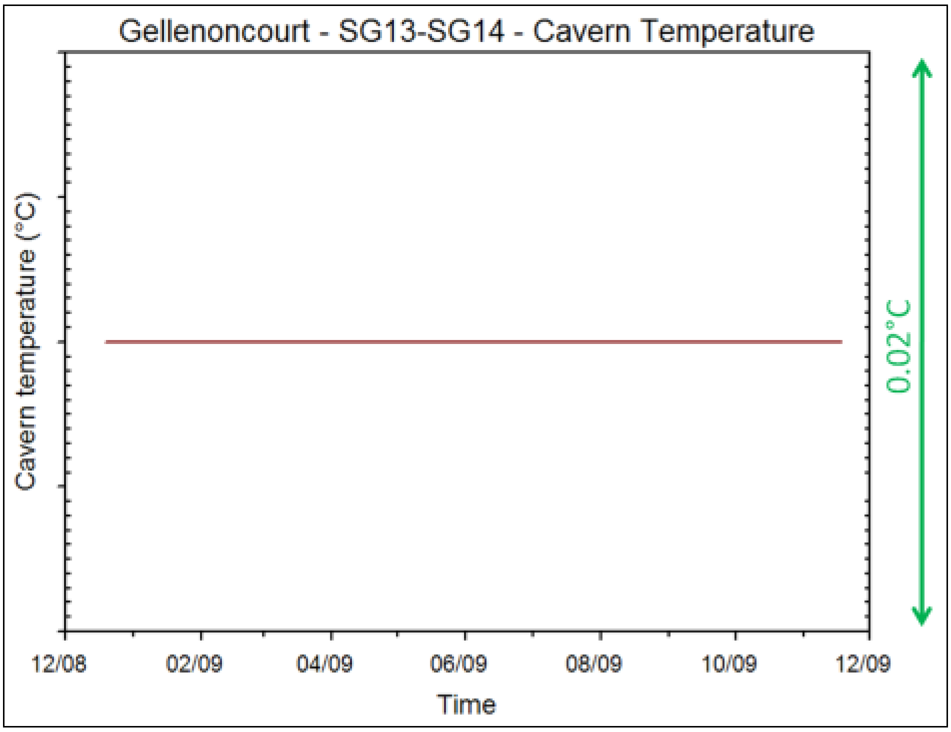

Figure 5 - Cavern temperature evolution from December 2008 to November 2009.

The cavern temperature apparently was perfectly constant and close to T = 17 °C during the period December 2008 – November 2009. The temperature gauge resolution (the smallest detectable temperature change) is 1/1000 °C; however, the accuracy of the temperature gauge is 1/100 °C. For the 11-month temperature measurement period, it can be inferred that temperature rate is slower than $\dot{\theta} = 0.01°\text{ C/yr}$, and the brine-expansion/contraction rate certainly is slower than $\alpha V \dot{\theta} \approx 3\text{ litres/day}$ — possibly much slower. Thus, temperature effects can be neglected.

3.3 Brine outflow test

3.3.1 *Introduction*

When cavern abandonment is considered, the rate of cavern creep closure must be assessed precisely. In-situ tests are especially important in this context. Liquid out-flow tests consist of opening the cavern and measuring the flow of liquid expelled from the wellhead (see Figure 6). For example, the expelled volume can be collected in a container. In a small cavern, the daily flow rate is relatively small, and measurements of the container weight can be taken automatically. Outflow tests have been described in the literature; see, for example, Clerc-Renaud and Dubois (1980), Hugout (1988) and Brouard et al. (2004).

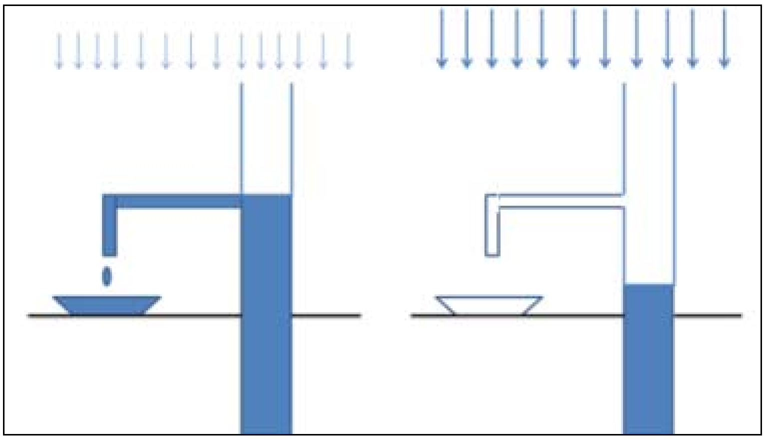

Figure 6 - Brine outflow from a shallow cavern: low atmospheric pressure and brine flow from the cavern (left);rapidly increasing atmospheric pressure with no observed brine flow (right).

One important asset of liquid-outflow tests is that, when properly assessed, the observed flow rate certainly is faster than the long-term brine flow rate from the cavern, providing an upper bound for long-term brine migration to the overlying strata. A second advantage is that during an outflow test, cavern pressure is almost constant, making assessment of steady-state cavern closure rate simpler. The liquid-outflow rate is governed by two main phenomena:

(1) cavern-creep closure rate; and

(2) cavern-brine thermal expansion.

In fact, in the case of the SG13-SG14 cavern, it was proved (see Section 3.2) that brine thermal expansion probably can be disregarded. The same can be said of possible leaks, as wellhead pressure is zero during a liquid outflow test.

Several more-or-less periodic phenomena also influence the brine-outflow rate:

- atmospheric pressure variations;
- ground-level temperature variations; and
- Earth tides.

However, when the testing period is sufficiently long (say, several weeks), the average effect of these periodic phenomena is nil, and the average brine-outflow rate mainly depends on the cavern-creep closure rate (both transient and steady-state).

In a deep cavern, the cavern closure rate and the brine thermal-expansion rate are fast, and the other phenomena are not able to make the brine outflow vanish. Only small fluctuations of the brine flow rate can be observed; precise interpretation of these fluctuations allows for assessment of the effects of Earth tides (Bérest et al., 1992). In a shallow cavern, the closure rate and the thermal expansion rate often are slow, and the other phenomena play a large role: brine outflow vanishes periodically — e.g., when the atmospheric pressure drastically increases (Figure 6).

3.3.2 *Average brine flow rate*

Before the compressibility test, the cavern had been shut-in for a long period of time (several years); when the compressibility test started, the wellhead (relative) pressure was 0.1 MPa (15 psi) or so. The outflow test began on July 23, 2008. This test was described in an earlier paper (Brouard et al., 2009a); only the main results will be discussed here. The cumulated volume of expelled brine as a function of time is shown in Figure 7. The average brine-outflow rate (i.e., the overall amount of brine expelled during the testing period divided by the testing period duration) is $\dot{V} \approx 12 \text{ liters/day}$.

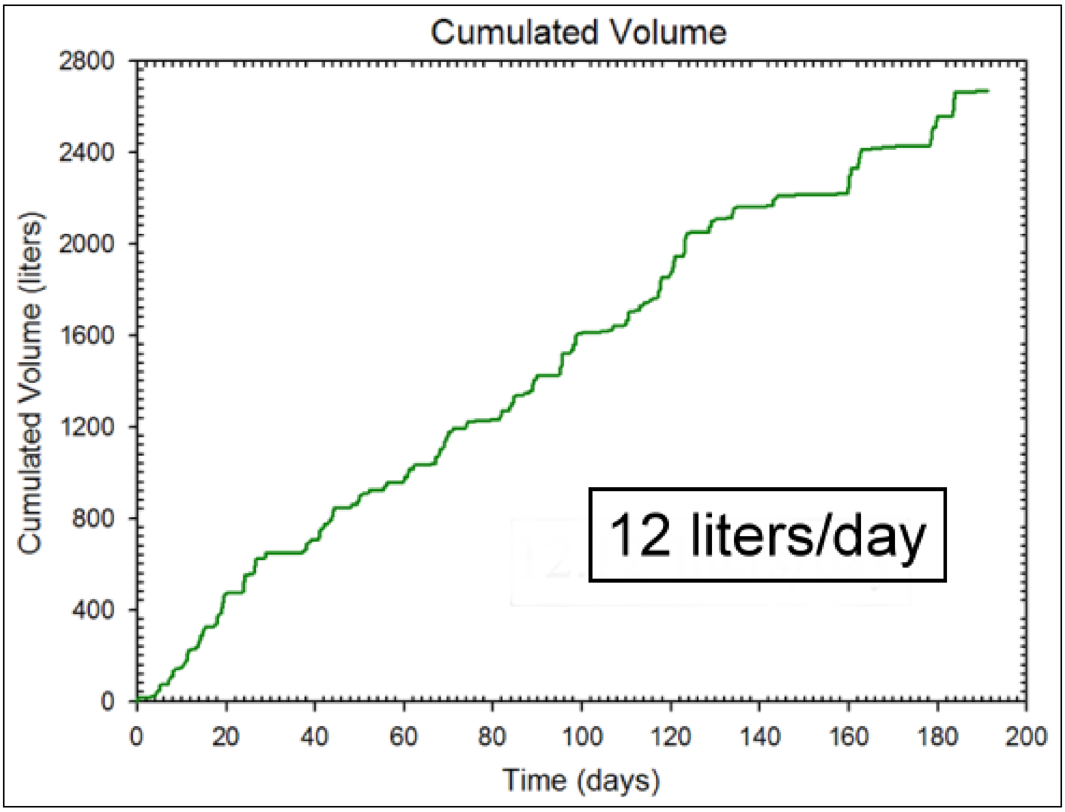

Figure 7 - Cumulated expelled volume as a function of time, or $v = v(t)$.

When this flow is compared to the cavern "mass balance" volume, $V = 240{,}000 \text{ m}^3$, the relative convergence rate is $\dot{V}/V = 5.8 \times 10^{-13} \text{ s}^{-1} = 1.8 \times 10^{-5} \text{ year}^{-1}$.

It was said that the average brine flow rate during the July 2008-April 2009 period is 12 liters per day. In fact, it can be observed (see Figure 8 and Figure 9) that the brine outflow rate slowly decreases during this period.

Figure 8 displays the average rate as a function of time (At anytime t after the test begins, the cumulated expelled volume from t = 0 to t is divided by t.); Figure 9 displays the average rate computed on a 1-month period as a function of time. Both curves prove that the brine flow rate, even if it experiences erratic fluctuations, slowly decreases during the test. It is believed that the initial flow rate is faster, as the cavern pressure was slightly higher than halmostatic before the test began. (by 0.1 MPa, or 15 psi.) Opening the wellhead at the beginning of the test triggers a transient creep closure that slowly dissipates (see Section 3.4.1).

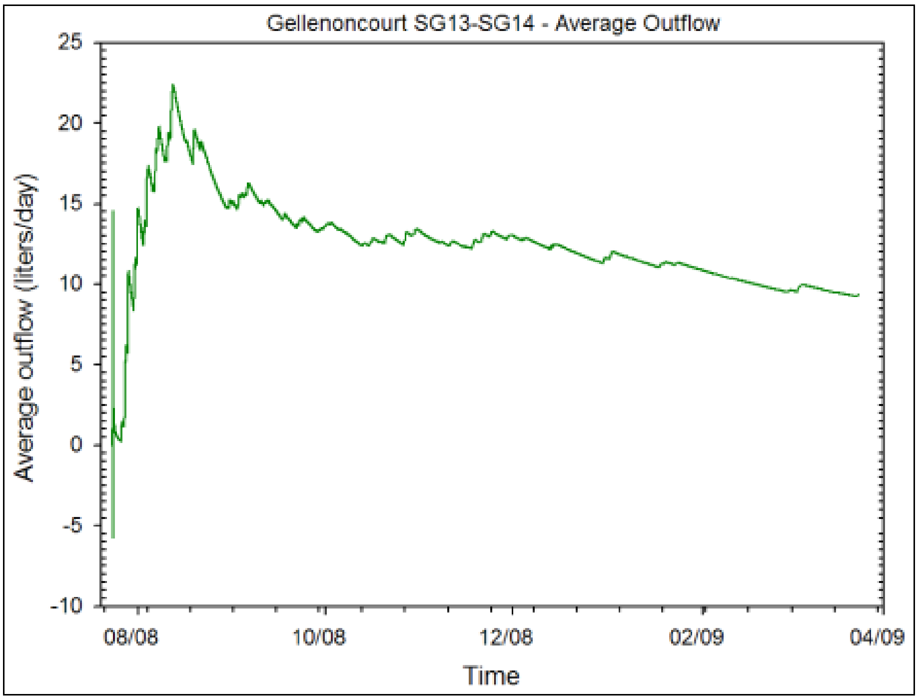

Figure 8 – Evolution of average brine outflow.

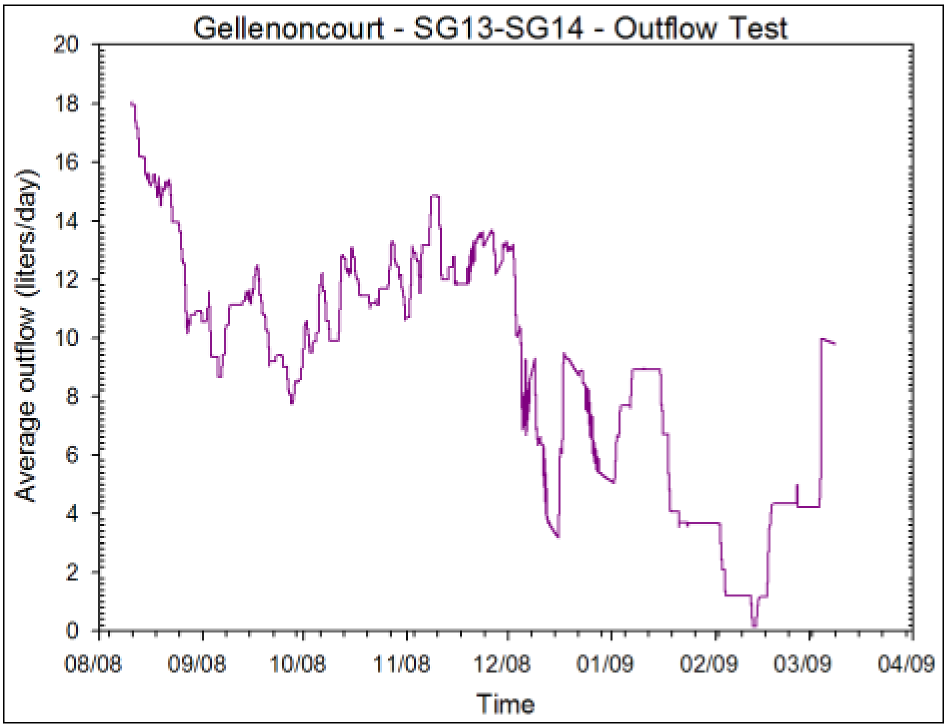

Figure 9 – Evolution of average brine outflow computed on a 1-month long period.

3.3.3 *Brine Flow-Rate Fluctuations*

The *average* brine flow-rate was computed in Section 3.3.2. However, from Figure 10, it can be seen that brine flow rate (as measured from October 14, 2008 to October 17, 2008) is far from being constant. In fact, large fluctuations can be observed: periodically, the brine flow rate is several hundreds of liters per day — i.e., larger than the average flow rate by one or two orders of magnitude. However, for most of the time, the flow rate is nil: no flow is expelled from the cavern, and the air/brine interface drops down into the well. As mentioned above, these fluctuations can be related to the effects of atmospheric pressure variations (They are transmitted to cavern brine both through the rock mass and through the opened well.), ground-level temperature variations (They make the upper part of the brine column in the well successively lighter or heavier, resulting in a smaller or larger cavern pressure.), and Earth tides (They generate cavern expansion or contraction every 12 hours 25 minutes and every 24 hours) [see Brouard et al., 2009]. How these effects can be observed during a shut-in pressure test is explained in the next section.

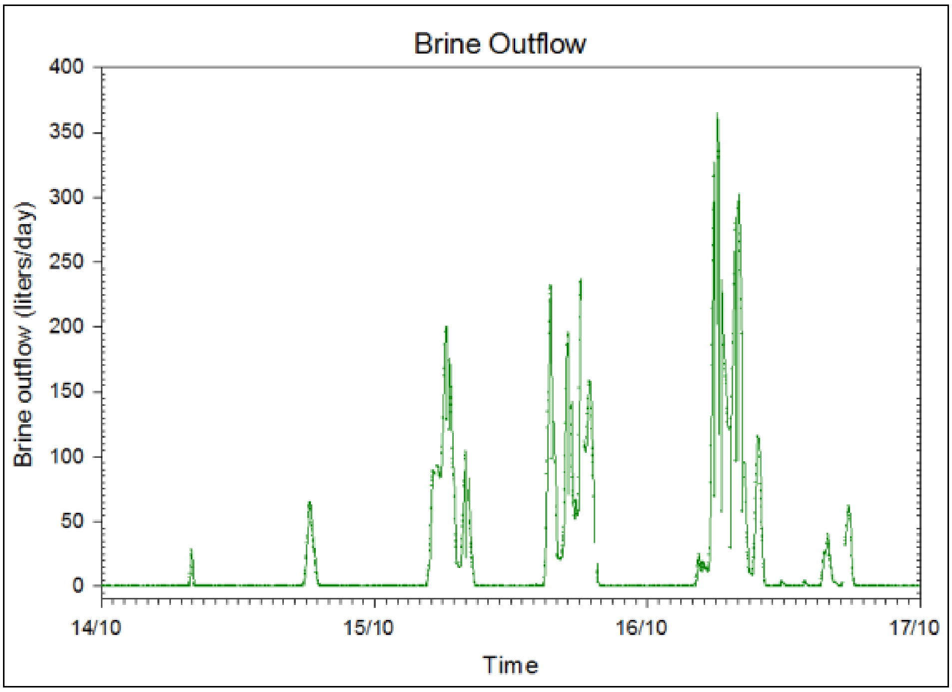

Figure 10 - Brine flow-rate as a function of time, flow rate computed every 10 minutes.

3.4 Shut-in pressure test

3.4.1 *Average pressure build-up rate*

The cavern was shut-in from May 25, 2009 to November 19, 2009. Wellhead pressure evolution is shown on Figure 11. Pressure build-up during this 6-month period is 80 kPa, making the average pressure build-up rate $\dot{P} = 47.1$ Pa/day (0.007 psi/day). Cavern compressibility is $\beta V = 129.55\ \text{m}^3/\text{MPa}$ (see Section 3.1). The inferred cavern closure rate is $\dot{V} = \beta V \dot{P} = 6.1$ liters/day (1.6 gal/day). This figure is two times smaller than the average figure observed during the brine outflow test, which is $\dot{V} \approx 12$ liters/day (see Section 3.3.2), raising a somewhat puzzling question.

In fact, it was mentioned that the wellhead (relative) pressure was 0.1 MPa (15 psi) before the compressibility test was performed. When this test began, the cavern pressure suddenly dropped by 0.1 MPa, triggering transient cavern closure. Generally speaking, transient cavern closure is extremely fast — faster when the pressure drop is larger. In the SG13-SG14 cavern, the brine pressure at cavern depth is $P =$ 3 MPa, and the gap between geostatic pressure and cavern pressure is $P_\infty - P_c \approx 2.5$ MPa . A wellhead pressure drop of $\Delta P_c = -0.1$ MPa generates an increase of this gap by $\Delta P_c / (P_\infty - P_c) = 4\%$ — a small figure, but large enough to trigger a significant transient cavern creep, as was verified by numerical computations. (A simplified shape of the cavern was adopted for these computations.) Conversely, cavern pressure slightly increases during the shut-in pressure test, resulting in a slight decrease in cavern closure rate over time. In other words, the brine outflow test provides an upper bound ($\dot{V} \approx 12$ liters/day) of cavern closure rate when the cavern pressure is halmostatic (i.e., when the well is filled with saturated brine and wellhead pressure is zero).

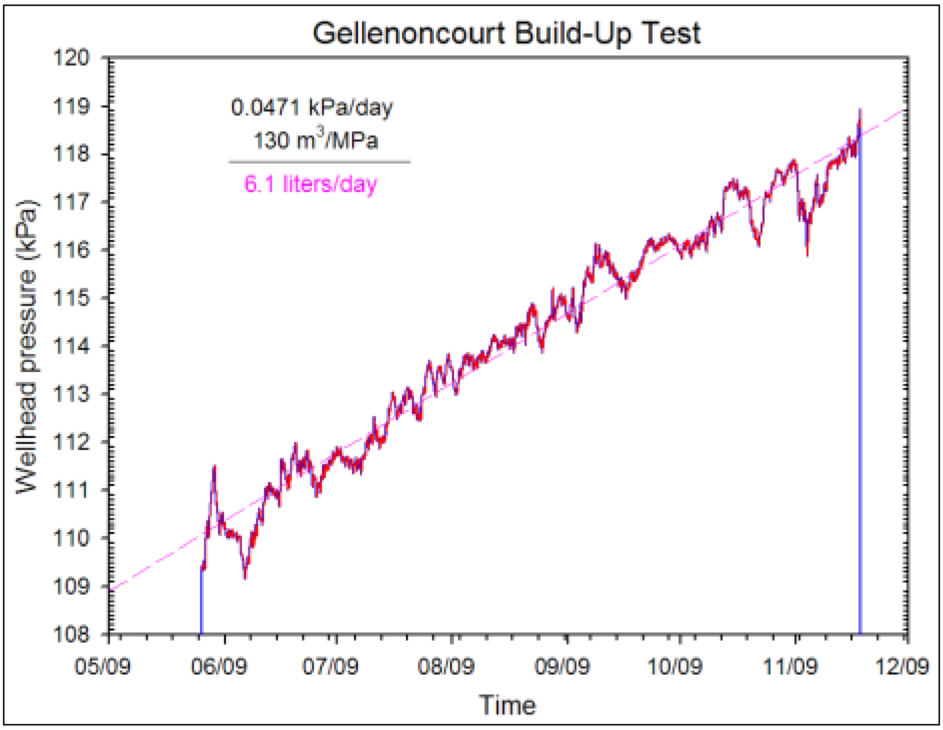

Figure 11 – Wellhead pressure evolution during shut-in test.

3.4.2 *Fluctuations in wellhead pressure evolution*

It can be observed that wellhead pressure experiences significant fluctuations, even if a general trend can be observed clearly (Figure 10). A striking correlation can be observed between wellhead pressure and atmospheric pressure (Figure 12). Atmospheric pressure fluctuations cannot be transmitted through the wellhead, which is closed (in sharp contrast with the brine outflow test), but they are transmitted through the rock mass: an increase in atmospheric pressure generates a cavern contraction and an increase in cavern pressure.

Figure 13 displays the wellhead pressure (upper-left picture) and atmospheric pressure (lower-left picture) changes as a function of time from May 25, 2009 to November 19, 2009. It also was suspected that ground-level temperatures (upper-right picture) had possible effects on the wellhead pressure, as they had during the brine outflow test: a wellhead temperature increase generates brine warming in the upper part of the well, the brine column in the well becomes slightly lighter, and the wellhead pressure increases. (However, note that this change mainly affects wellhead pressure; the change in cavern pressure is almost null.) However, because heat transfer from air to wellhead brine is slow (a couple of hours,) it was expected that a time lag would be observed between air-temperature changes and resulting wellhead-pressure changes. For this reason, we searched for an empirical correlation between wellhead pressure, atmospheric pressure evolutions and ground-level temperature changes of the following form:

$$P^{wh}(t) = (P_0 + at) + b\left[T^{wh}(t-\varphi) - \overline{T}^{wh}\right] + c\left[P_{atm}(t) - \overline{P}_{atm}\right] \qquad (1)$$

where $a = 47.1$ Pa/day is the average wellhead-pressure increase rate, $\overline{T}^{wh}$ and $\overline{P}^{wh}$ are the average ground temperature and atmospheric pressure, respectively, and φ is the time lag associated with heat transfer through the wellhead. When corrected from atmospheric pressure variations, wellhead pressure evolution as a function of time is much smoother (Figure 13, lower-right picture). The coefficient of correlation between cavern pressure variations and atmospheric pressure variations is $c \approx 0.542$, which means that approximately 54% of atmospheric pressure variations are transmitted to cavern brine through the ground.

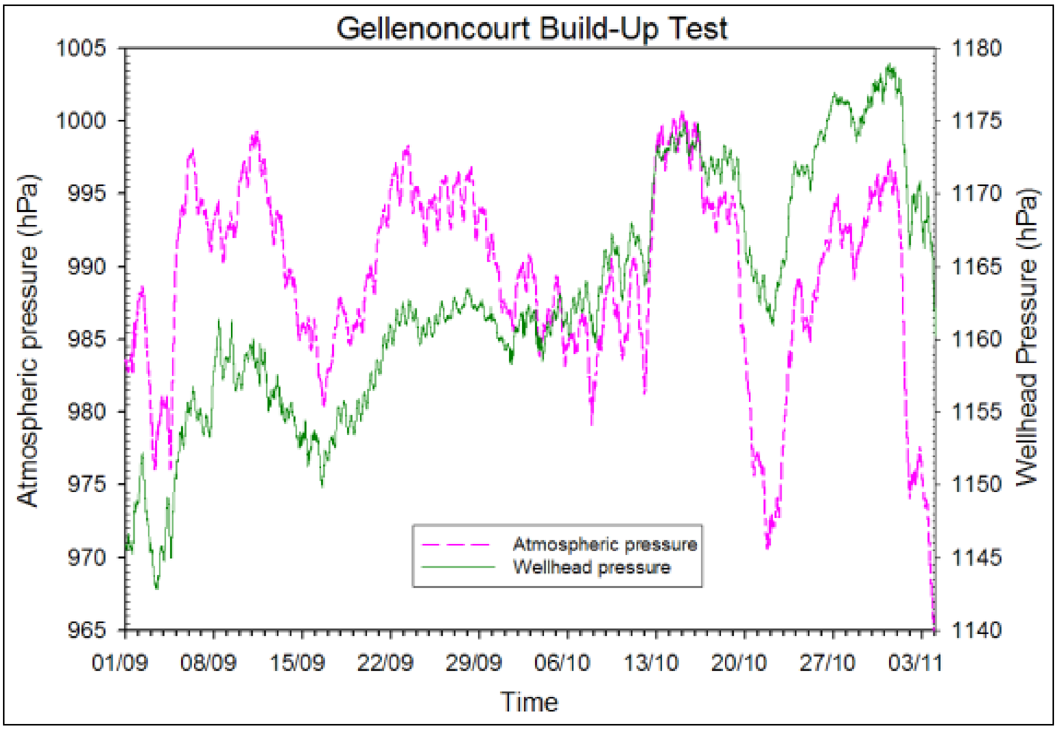

Figure 12 - Wellhead pressure and atmospheric pressure as measured during the September-November period.

Tiny fluctuations in the corrected pressure evolution can be observed (Figure 12, lower-right picture). A Fourier analysis was performed (**Erreur ! Source du renvoi introuvable.**), and two peaks clearly can be observed. Corresponding periods (12 h 25 minutes and 24 h) strongly suggest that these peaks are associated with the effects of Earth tides.

Analysis of wellhead pressure fluctuations provide some confidence in the assessment of pressure build-up rate, which is $\dot{P}_c = 47.1$ Pa/day (or 7×10^{-3} psi/day). The cavern compressibility coefficient is β = 5.4 x 10^{-4}/MPa, from which it can be inferred that cavern closure rate is $\dot{V}/V \approx 0.93 \times 10^{-5}$ /yr. (Cavern complete closure is reached after more than 100,000 years.)

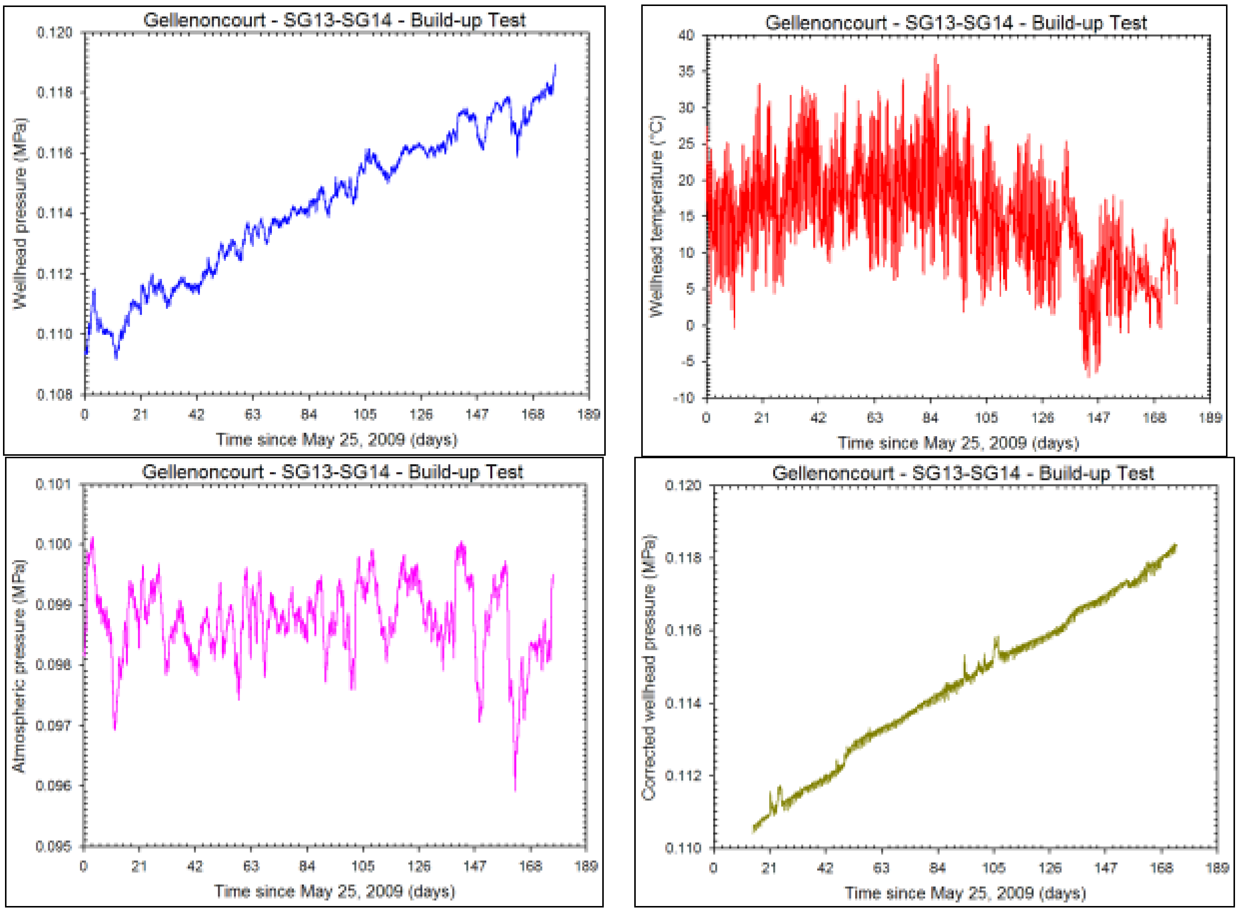

Figure 13 – Measured pressure (top left), atmospheric pressure (bottom left), atmospheric temperature (top right) and corrected pressure (bottom right).

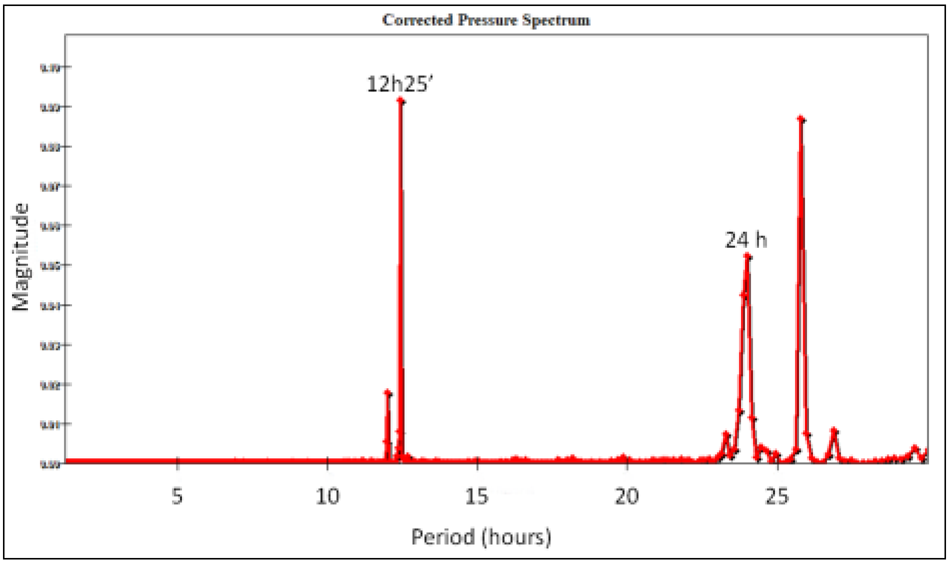

Figure 14 - Spectrum of corrected pressure minus trend.

4. CONCLUSIONS

Several conclusions can be drawn from this preliminary analysis. It can be assumed that, before abandonment, that cavern wells will be plugged (Crotogino and Kepplinger, 2006). Two cases must be considered:

1. The plug is ineffective (worst-case scenario): brine will flow from the cavern to the overlying strata. An upper bound of the leak flow rate is $\beta V \dot{P}_c$ = 130 m^3/MPa × 47 Pa/day × 365 days = 2.2 m^3/yr (or 13 bbls/yr), a small figure.
2. The plug is effective, even in the very long term: no brine will leak to the overlying strata, a tiny amount of brine will seep to the salt formation, and cavern brine pressure will reach an equilibrium value, intermediate between geostatic pressure and halmostatic pressure. At this stage of the study, salt permeability has not been assessed, and equilibrium pressure cannot be computed. However, it is clear that the cavern closure rate at equilibrium pressure will be exceedingly slow and that this equilibrium pressure will be reached after a very long period of time (several dozens of centuries).

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