Creep closure rate of a shallow salt cavern

P. Bérest[1] , J.F. Béraud[1], B. Brouard (BC)[2], E. Hertz[3], V. de Greef[1], C. Lheur[3]

[1]Ecole Polytechnique Palaiseau France, [2]Brouard Consulting, Paris

[3] Compagnie des Salins du Midi et des Salines de l'Est, Varangéville, France

ABSTRACT: Cavern creep closure rate was recorded in the SG13-SG14 salt cavern of the Gellenoncourt brine field operated by CSME at Gellenoncourt in Lorraine, France. Cavern compressibility and the evolution of cavern brine temperature first were measured. 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. To assess cavern closure rate, a 10-month brine-outflow test was performed, followed by a 6-month shut-in test. During the tests, brine outflow or pressure evolution is influenced by atmospheric pressure changes, ground temperature changes and Earth tides. From the average pressure-evolution rate, it can be inferred that the steady-state cavern closure rate is slower than 10^{-5}/yr or 3×10^{-13}/s.

SUBJECT: site investigation and field observations

KEYWORDS: field measurements, rock caverns

INTRODUCTION

Thousands of caverns have been leached out worldwide from salt formations. Their depth ranges from 100 to 3000 m. In the long term, salt behaves as a viscous fluid and caverns gradually shrink. Deep caverns have experienced closure rates by several percent per year,. Creep closure rates in shallow caverns are much slower and must be assessed through *shut-in pressure tests*, which consist of closing the cavern and measuring the pressure evolution at the wellhead as a function of time or through *brine outflow tests*, which consist of opening the cavern and measuring the flow of fluid (brine or hydrocarbon) expelled from the wellhead (Bérest et al., 2000).

In this paper, we describe two such tests performed in the 250m-deep SG13-14 cavern of the Gellenoncourt brine-field operated by Compagnie des Salins du Midi et Salines de l'Est (CSME) in Lorraine, France. The objective of these tests was to assess long-term cavern closure rate. Cavern closure rate in such a shallow cavern is exceedingly slow, which raises specific measurement problems.

2. THE SG13-14 CAVERN

2.1. Cavern volume

The SG13 and SG14 7''-wells were operated as brine-production caverns from July 1976 to July 1980. After some time, the two caverns coalesced, and, in 1980, SG13-SG14 was composed of two parts connected by a large link. A 3D view is provided in Figure 1. Cavern volume, or V = 240,000 m^3, was inferred from the cumulated amounts of injected water and withdrawn brine during mining operation.

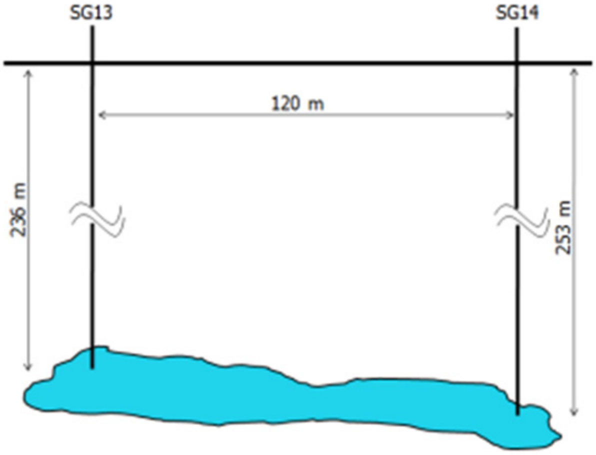

Figure 1 – SG13-SG14 cavern.

2.2. Cavern compressibility

Cavern compressibility, or βV, is the ratio between the injected volume and the cavern pressure change during a rapid injection, or $q = \beta V \dot{P}$. . It is proportional to cavern volume, or V, and it is related to the elastic (adiabatic) properties of the rock mass and of the fluids contained in the cavern, Bérest et al., 1999. SG13-SG14 compressibility, as measured on July 3, 2008, is $\beta V = 129.55\ \text{m}^3/\text{MPa}$, from which a $\beta = 5.4\times10^{-4}/\text{MPa}$ cavern compressibility coefficient was inferred

2.3. Cavern temperature

At SG13-14 depth, creep closure rate can be expected to be $\dot{\varepsilon}_{cr} \approx -10^{-5}/\text{yr}$. Brine thermal-expansion coefficient is $\alpha_b = 4.4\times10^{-4}/°\text{C}$. A brine temperature decrease rate of $\dot{T}_c = -0.02\ °\text{C/yr}$ would generate a relative brine volume decrease rate of $\alpha_b \dot{T}_c \approx -10^{-5}/\text{yr}$ — i.e., of the same order of magnitude as that of the cavern creep closure rate: temperature evolution must be carefully assessed. By December 2008, a temperature gauge was lowered into the SG13 well. The cavern temperature remained perfectly constant during the period December 2008 – June 2010. Gauge accuracy was tested as follows: in June 2010, cavern pressure was rapidly increased. In such a context, brine evolutions are almost perfectly adiabatic and a $\Delta T(°C) = \alpha_b T \Delta P / \rho_b C_b \approx 0.03 \Delta P(MPa)$ temperature increase can be expected. In fact, gauge temperature increased by 0.02°C when pressure increase was approximately $\Delta P_c \approx 0.6\ \text{MPa}$, proving that the gauge was sensitive, that its resolution was 0.02°C and that temperature evolution was exceedingly slow.

3. THE BRINE OUTFLOW TEST

3.1. Average brine flow-rate

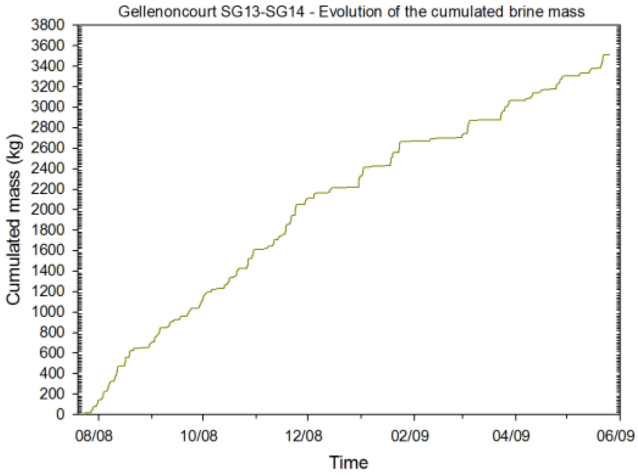

Figure 2 - Cumulated expelled mass as a function of time.

A hole was drilled through the upper part of the casing to allow evacuation of the out-flowing brine to a plastic container whose weight was measured every minute.

In 2000 the cavern had been shut-in after a sonar survey. Eight years later, before the test began, wellhead pressure had built up to approximately 0.08 MPa. On July-3, 2008, , the cavern was opened and wellhead pressure dropped to zero. The outflow test began on July 23, 2008 and was completed by May 25, 2009. In principle, the *average* brine outflow rate, or q, is governed by cavern-creep closure and cavern-brine thermal expansion: $q = -\dot{\varepsilon}_{cr} V + \alpha_b \dot{T}_c V$.

In the case of the SG13-SG14 cavern, it was proven that brine thermal expansion rate is exceedingly slow. Various effects generate flow-rate fluctuations; they are more or less periodic and their *average* effect during a 10-month long test is negligible. In other words, the observed average flow-rate is representative of cavern creep closure during the test. The cumulated mass of expelled brine as a function of time is shown in Figure 2. The average brine-outflow rate during this 306-day long test is 9.5 liters/day. When this flow is compared to the cavern volume, or $V = 240{,}000\ \text{m}^3$, the relative creep closure rate is $\dot{\varepsilon}_{cr} = -q/V = -4.6\times10^{-13}\ \text{s}^{-1} = -1.45\times10^{-5}\ \text{yr}^{-1}$. However brine outflow clearly decreases during the test period; a part of the initial flow was triggered by the July-3 cavern pressure drop and is transient in nature.

3.2. Flow-rate fluctuations

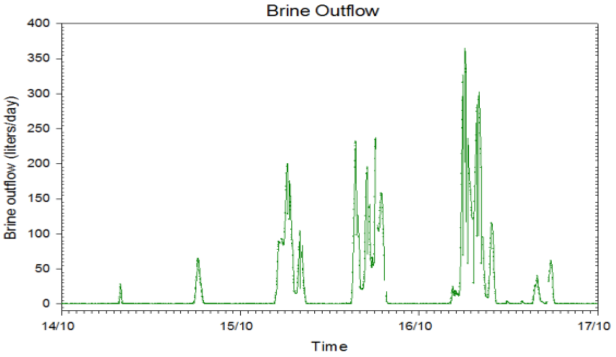

Figure 3 - Brine flow-rate from October 14 to 17, 2008.

Figure 3 displays flow-rate evolution during a 3-day long period (from October 14, 2008 to October 17, 2008). Large fluctuations can be observed: periodically, the brine flow rate is several hundreds of liters per day. Conversely, 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. Several phenomena contribute to this apparently erratic behavior, among which the most significant are atmospheric pressure variations.

3.2.1. Atmospheric pressure fluctuations

Let h be the height of the brine column in the well; $h = H$ when brine is evacuated through the venting hole. Cavern pressure, or P_c, and atmospheric pressure, or P_{atm}, are related by (1), where $\rho_b g$ is brine volumetric weight:

$$P_c = \int_0^h \rho_b g dz + P_{atm} \quad \text{or} \quad \dot{P}_c = \rho_b g \dot{h} + \dot{P}_{atm} \tag{1}$$

Brine is expelled from the cavern. When brine is expelled from the cavern, $h = H,\ \dot{h} = 0,\ \dot{P}_c = \dot{P}_{atm}$ and the flow of brine, or q, can be written:

$$q = -\dot{\varepsilon}_{cr} V + \beta_\infty V \dot{P}_{atm} - \beta V \dot{P}_{atm} \tag{2}$$

where $-\beta_\infty V\dot{P}_{atm}$ is the cavern contraction rate generated by stress changes in the rock mass due to atmospheric pressure fluctuations and $-\beta V\dot{P}_{atm}$ is the brine expelled flow rate resulting from cavern pressure changes Atmospheric pressure fluctuations are transmitted to the rock mass through the ground (and also through the brine column in the well). Except during a severe storm, pressure changes are almost uniform in a large horizontal domain whose dimensions are much larger than cavern depth (H = 250 m). Hence, at such a depth, it can be assumed that the additional stresses generated by these fluctuations can write: $\dot{\sigma}_{zz} = -\dot{P}_{at}$ and $\dot{\sigma}_{xx} = \dot{\sigma}_{yy} = -\bar{v}\dot{P}_{atm}/(1-\bar{v})$ where $\bar{v}$ is an equivalent Poisson's ratio for the rock mass between ground surface and cavern depth. These stresses generate a cavern-volume variation of $-\beta_\infty V\dot{P}_{atm}$ where β_∞ is a function of the elastic properties of the rock mass and of the shape of the cavern. Combining (1) and (2) leads to:

$$q = -\dot{\varepsilon}_{cr}V - (\beta - \beta_\infty)V\dot{P}_{atm} \quad ; \quad h = H \qquad (3)$$

The brine/air interface is below the venting hole. Conversely, when the brine/air interface is below the venting hole, $h < H$, (Figure 4, left picture) and:

$$S\dot{h} = -\dot{\varepsilon}_{cr}V + \beta_\infty V\dot{P}_{atm} - \beta V\dot{P}_{atm} \; ; \qquad h < H \qquad (4)$$

Combining (1) and (4) leads to:

$$(S + \beta V\rho_b g)\dot{h} = -\dot{\varepsilon}_{cr}V - (\beta - \beta_\infty)V\dot{P}_{atm} \; ; \qquad h < H \quad (5)$$

Where the cross sectional area of the well, or $S = 2.1\times10^{2}$ m^2, is much smaller than $\beta V\rho_b g \approx 1.56$ m^2; $\chi = (\beta - \beta_\infty)/(\beta + S/\rho_b g V) < 1$, can be compared to the "barometric efficiency", a notion defined in wells tapped in aquifer layers, Jacob 1940.

These equations prove that the cavern behaves as an extremely sensitive barometer. Equation (4) predicts that a change in atmospheric pressure by $\dot{P}_{atm}$ generates a change in brine flow rate by $q = -(\beta - \beta_\infty)V\dot{P}_{atm}$. It will be proven in that $\beta_\infty/\beta \approx 0.542$, or q (l/d) $\approx -6\,\dot{P}_{atm}$(hPa/d). On a short time-scale, erratic fluctuations of atmospheric pressure can be observed, typically a 30 Pa drop in a 30 s period due for instance to a sudden gust of wind. Such a drop generates an additional 1.8 liters brine flow in a short period of time – i.e., a dramatic increase in brine flow rate.

Atmospheric pressure fluctuations can be accurately measured and it was expected, before the test, that the brine outflow rate could easily be corrected from their effects. However data processing led to relatively poor results. Several factors explain this disappointing result. They include oscillations of the brine column, brine cooling in the well, ground temperature fluctuations and earth tides.

3.2.2 Dynamic oscillations of the brine column in the well

Rapid changes in pressure trigger oscillations of the brine column in the well. Consider the case when $h = H$ (brine is expelled from the well). Equations (2) and (4) must be rewritten as follows. The mass of brine contained in the well is $\rho_b SH$. When this mass moves up and down in the well, its acceleration is $\gamma = \dot{q}/S$. When derivated with respect to time, Newton's law of motion can be written:

$$\dot{P}_c = \left[\rho_b g\dot{h} + \dot{P}_{atm}\right] + \rho_b H\ddot{q}/S \qquad (6)$$

And the brine outflow from the cavern is:

$$q = \left[-\dot{\varepsilon}_{cr}V + \beta_\infty V\dot{P}_{atm}\right] - \beta V\dot{P}_c \qquad (7)$$

In the context of rapid oscillations, the terms between brackets can be disregarded. Eliminating cavern pressure leads to a second order differential equation, $(S/\beta V)q + \rho_b H\ddot{q} = 0$. This equation describes harmonic oscillations. As $\beta V\rho_b g \approx 1.56$ m^2 and $S = 2.1\times10^{2}$ m^2, the period of small oscillations is $\tau = 2\pi\sqrt{H\beta V\rho_b/S}$ or 4 minutes. These oscillations are slowly dampened, [8], and they blur the relation between atmospheric pressure variations and brine outflow to the container.

3.2.3. Cooling of the brine column rising inside the well

When the well is at rest, cavern brine temperature is warmer than brine temperature in the well, When brine moves upward, cool brine expelled at ground level is substituted by warm brine flowing from the cavern and the brine column in the well is made lighter, cavern pressure decreases, and brine flow is made faster. Heat exchange in the well between the rock formation and the warm brine in the well must also be taken into account. (1) must be re-written in the more precise form:

$$\dot{P}_c = \int_0^H \frac{\partial \rho_b}{\partial t} g\,dz + \dot{P}_{atm} = \rho_b g\alpha_b \int_0^H \frac{\partial T}{\partial t}\,dz + \dot{P}_{atm} \qquad (8)$$

It can be proved [x] that when warm brine starts rising in the well, brine outflow rate can be written as follows:

$$q\left(1 - \beta V\rho_b g\alpha_b\Gamma H/S\right) = -\dot{\varepsilon}_{cr}V - (\beta - \beta_\infty)V\dot{P}_{atm} \quad (9)$$

Where $\beta V = 130$ m^3/MPa, $\Gamma = 3\times10^{-2}$ °C/m, $H = 250$ m, $\beta V\rho_b g\alpha_b\Gamma H/S \approx$ 0.24: $S = 2.1\times10^{-2}$ m^2, (9) proves that brine rate is significantly accelerated when warm cavern brine enters the well.

3.2.4 Ground temperature fluctuations and earth tides

They are not specific to the brine outflow test; their effects are relatively small in the context of a brine outflow test and they will be discussed in Section 4.

3.2.5 Conclusion

This analysis proves that, even if the average brine flow-rate clearly is representative of cavern behavior, flow-rate daily behavior is blurred by large fluctuations from external origin. Interpretation of the shut-in pressure test will prove to be simpler.

4 THE SHUT-IN PRESSURE TEST

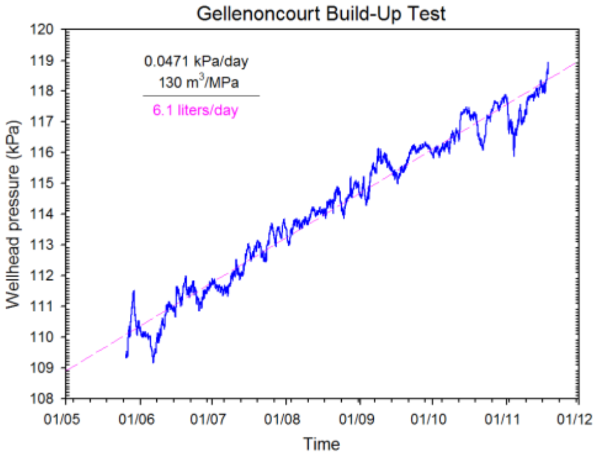

Figure 5 – Pressure evolution during the shut-in test.

4.1 Average pressure build-up rate

The cavern was shut-in from May 25, 2009 to November 19, 2009. During a shut-in test, (1) and (2) which describe averaged evolutions must be re-written:

$$q = 0 = -\dot{\varepsilon}_{cr} V - \beta V \dot{P}_c \qquad \dot{P}_c = \dot{P}_{wh} \qquad (14)$$

Where P_{wh} is the wellhead pressure. Wellhead pressure evolution is shown on Figure 5. Wellhead pressure increase during this 10-month period is 80 kPa, making the average pressure build-up rate due to cavern creep closure $\dot{P}_{wh} = -\dot{\varepsilon}_{cr}/\beta \approx 47.1$ Pa/day. from which it can be inferred that cavern closure rate is $\dot{\varepsilon}_{cr} = \dot{V}/V \approx -0.93\times10^{-5}$ /yr and $\dot{\varepsilon}_{cr} V = -\beta V \dot{P} \approx -6.1$ liters/day $= -2.2$ m³/yr. (Cavern complete closure is reached after more than 100,000 years.)

4.2 Wellhead pressure fluctuations

Even if a general trend can be observed clearly, wellhead pressure experiences significant fluctuations. For example, Figure 6 displays wellhead pressure and atmospheric pressure as measured from September 1, 2009 to November 3, 2009. The wellhead is closed; however atmospheric pressure fluctuations are transmitted to the cavern through the rock mass, as explained above. The coefficient of correlation between cavern pressure variations and atmospheric pressure variations is $\beta_\infty/\beta \approx 0.542$, which means that approximately 54% of atmospheric pressure variations are transmitted to cavern brine through the rock mass. Daily fluctuations in wellhead pressure also are generated by daily changes in ground level temperature; they will not be discussed here (they are relatively small). A

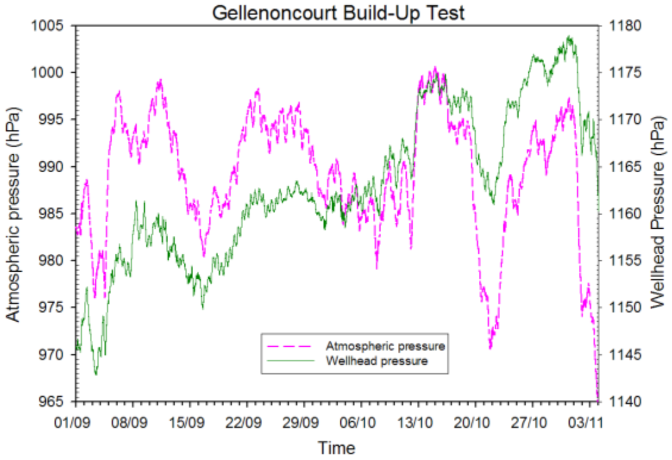

Figure 6 - Wellhead pressure and atmospheric pressure during the September-November period.

Fourier analysis also was performed and two peaks clearly can be observed. Their periods are 12 h 25 minutes and 24 h, strongly suggesting that these peaks are associated with the effects of Earth tides. In fact, fluctuations generated by Earth tides are visible clearly on Figure 6, for instance between September 15 and September 25, a period during which their amplitude is $\Delta P^{wh} \approx 1$ hPa from which it can be inferred that cavern deformation is $\beta \Delta P^{wh} \approx 5\times10^{-8}$, a figure that is typical of the strains induced by Earth tides.

5. STEADY-STATE CAVERN CREEP VS TRANSIENT CAVERN CREEP

5.1 Closure rate decrease during the outflow test

It was observed during the brine outflow test that the *average* brine flow rate, computed from July 23, 2008 to May 25, 2009, was: $q/V = 4.6\times10^{-13}$ s^{-1}, or 1.45×10^{-5} yr^{-1}. During the shut-in test, from May 25, 2009 to November 19, 2009 the cavern creep closure rate, inferred from pressure increase rate, was slower, $-\dot{\varepsilon}_{cr} = -\dot{V}/V = \dot{P}/\beta \approx 2.9\times10^{-13}$ s^{-1} $= 0.93\times10^{-5}$ yr^{-1}.

It was mentioned that the cavern had been shut-in from 2000 to 2008; on July 2008, when the compressibility test started, the wellhead (relative) pressure dropped by slightly more than $\Delta P_c = -0.08$ MPa. In the SG13-SG14 cavern, the brine pressure at cavern depth is $P_c \approx 3$ MPa, and the gap between geostatic pressure and cavern pressure is $P_\infty - P_c \approx 2.5$ MPa. A wellhead pressure drop of

$\Delta P_c = -0.08$ MPa generates an increase of this gap by $\Delta P_c / (P_\infty - P_c) = 3.2$ % — a small figure, but large enough to trigger various transient phenomena. Salt crystallization and transient creep are especially important.. Immediately after the pressure drop by $\Delta P_c = -0.08$ MPa, cavern brine is over-saturated in the new pressure conditions and crystallization takes place. After some time, saturation is reached again. The volume of brine expelled as a consequence of crystallization can be computed, Karimi-Jafari et al., 2007]; it is $\Delta V^{\exp} \approx 1200$ liters. The kinetics of salt crystallization is difficult to compute; however a significant part of it certainly took place during the July 3 to July 23 period, i.e., before the brine flow test began. Transient creep also has significant effects. It includes both the rheological transient creep, as can be observed during a standard triaxial creep test performed at the laboratory and the geometrical transient creep, or the slow redistribution of stresses in the rock mass following any cavern pressure change, an effect which is not present in the case of a uniformly loaded sample. It can have a significant effect during a long period of time, several decades when the pressure change which triggered transient creep was large.

6 CONCLUSIONS

A 10-month long brine outflow test and a 6-month long shut-in test were performed in a 250-m deep salt cavern at Gellenoncourt in Lorraine, France. Cavern volume approximately was 240,000 m^3. This cavern had been kept idle for 30 years before the tests and brine temperature changes were exceedingly small during the tests.

During the brine outflow test, atmospheric pressure fluctuations generate large erratic changes in the expelled brine flow rate, as the cavern behaves as an extremely sensitive barometer. These perturbations are much smaller during the shut-in test and small effects such that fluctuations in wellhead pressure generated by Earth tides can clearly be observed.

A few days before the test began, the cavern was decompressed by 0.08 MPa. Even if small, this pressure drop triggered a transient creep closure whose effects were clearly observed during the outflow test.

The steady-state creep closure rate, as observed during the shut-in test, is slightly slower than 10^{-5}/year or 2 m^3/year. This value proves that even in the long term (several centuries) subsidence and possible brine leaks from the cavern should have negligible impact from the point of view of environmental protection.

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