SOLUTION MINING RESEARCH INSTITUTE

105 Apple Valley Circle
Clarks Summit, PA 18411, USA

Telephone: +1 570-585-8092
Fax: +1 570-585-8091
www.solutionmining.org

Technical Conference Paper

Cavern abandonment: three *in situ* tests

Pierre Bérest, LMS, Ecole Polytechnique, France

Benoît Brouard, Brouard Consulting, France

Emmanuel Hertz & Cédric Lheur, CSME, France

Grégoire Hévin, Storengy, France

Patrick de Laguérie, Géostock, France

Jean-Marc Hardy, Total-Retia, France

SMRI Fall 2013 Technical Conference
30 September – 1 October 2013
Avignon, France

Solution Mining Research Institute Fall 2013 Technical Conference

Avignon, France, 30 September – 1 October 2013

CAVERN ABANDONMENT: THREE IN SITU TESTS

P. Bérest[1], B. Brouard[2], E. Hertz[3], Lheur[3], G. Hévin[4], P. de Laguérie[5], J.M. Hardy[6]

[1] LMS, Ecole Polytechnique, France
[2] Brouard Consulting, France
[3] CSME, France
[4] Storengy, France
[5] Géostock, France
[6] Total-Retia, France

Abstract

Three tests, with the main objective of analyzing the long-term behavior of abandoned caverns, currently are performed: at Etrez, a gas storage facility operated by Storengy, since 1997; at Carresse, a decommissioned LPG storage facility operated by Total, since 2005; and at Gellenoncourt, a brine field operated by CSME, since 2009.

The Etrez and Carresse tests (trial-and-error tests) were supported by the SMRI. After these tests were completed, pressure gauges were left *at the wellhead*, providing additional available data.

The results of the Gellenoncourt test were not published yet. During this test, pressure and temperature gauges were set *in the cavern*.

These caverns are relatively shallow (950 m, 310 m and 250 m, respectively). They had been kept idle for a long time before the tests were run, and the rock masses had reached thermal equilibrium — except for the Carresse cavern, which had been "de-propaned" three years before the test began. In such conditions (1) cavern creep closure and brine permeation through the cavern walls are the main phenomena governing pressure evolution, (2) the pressure consistently remains smaller than geostatic, and (3) the risk of fracture onset due to high cavern brine pressure can be ruled out.

Key words: salt caverns, cavern abandonment, in situ tests

INTRODUCTION

An abundant literature was devoted to salt cavern abandonment. In addition to references cited in this report, see the works cited in the Bibliography section of this paper. The SMRI set this problem at the heart of its Research Program (Ratigan, 2003) and supported several in-situ tests and research projects in this field [see Bérest et al. (2001), Rokahr et al. (2002), Crotogino and Kepplinger (2006), Brouard et al. (2006 and 2010), Banach and Klafki (2009); an SMRI-sponsored test also is currently performed at Mt Belvieu, Texas]. A technical class dedicated to long-term abandonment was organized during the SMRI Leipzig Meeting, SMRI (2010).

It is now commonly accepted that pressure evolution in a closed and abandoned cavern is governed by four main factors: (1) cavern creep closure, (2) brine thermal expansion, (3) brine permeation through the cavern walls and (4) brine leaks. When brine thermal expansion and brine leaks can be neglected, cavern pressure slowly reaches an equilibrium pressure which is larger than the halmostatic pressure at cavern depth (i.e., the pressure in a brine-filled cavern opened at ground level) but smaller than the geostatic pressure at cavern depth.

The three in-situ tests presented in this paper clearly support the SMRI approach.

1. The EZ53, SPR2 and SG13-14 Caverns

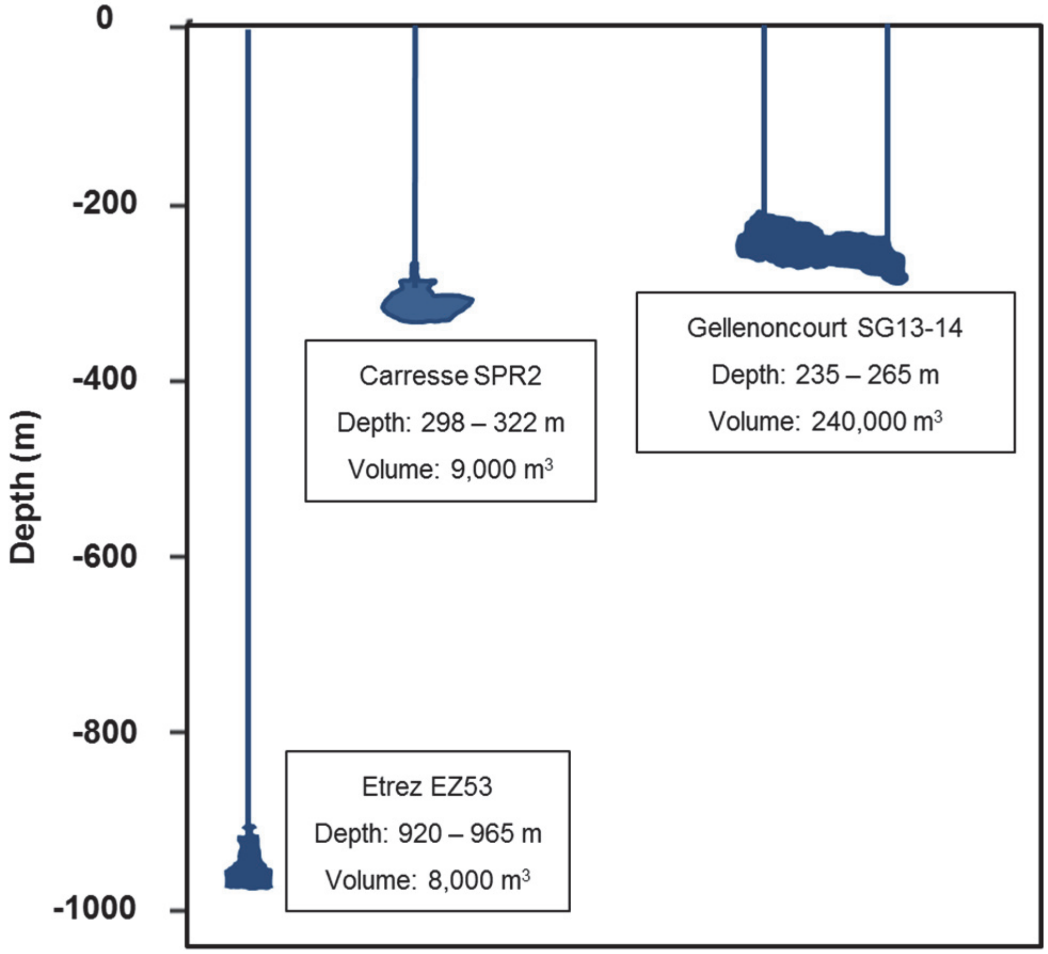

Figure 1. Shape and depth of the EZ53, SPR2 and SG13-14 caverns.

1.1 EZ53

The EZ53 cavern was leached out in 1982 from a Stampian bedded-salt formation at Etrez, France where Storengy operates a gas storage. This salt formation contains a fair amount of insoluble materials that sediment at cavern bottom. After a cavern with volume $V = 7500 - 8000\ \mathrm{m}^3$ was created, economic conditions changed, and the cavern was kept idle; no hydrocarbon was stored. Well completion includes a 842-m deep, 9-⅝" last-cemented casing and a 929-m deep, 7" string.

1.2 SPR2

The SPR2 cavern is located in the southwest of France at Carresse, where Total operated a propane storage facility. SPR2 was leached out in the early 1960's in a diapiric structure of the Pyrenean foothills and used for storing liquid propane. It was decommissioned and propane was withdrawn in 2002. The salt formation contains relatively thin salt layers of Triassic age. The amount of insoluble materials, mainly clay and anhydrite, is relatively large (20% to 30%). SPR2 volume is $V \approx 9000\ \text{m}^3$. Well completion includes a 286.6-m deep 9-⅝" last-cemented casing and a 319.7-m deep 4" string. Cavern roof and bottom depths are 304.4 m and 321 m, respectively.

1.3 SG13-14

The Gellenoncourt brine field, operated by CSME since 1965, is located at the eastern (and shallowest) edge of the Keuper bedded-salt formation of Lorraine-Champagne (Buffet, 1998). The SG13 and SG14 7"-wells were drilled to a depth of 280-300 m in May 1975, and operated as brine-production wells 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, or SG13-14. From the latest sonar measurements (run in 2000), it was inferred that the volumes of SG13 and SG14 are 107,000 m^3 and 34,000 m^3, respectively. However, sonar measurements underestimate the overall cavern volume, as they cannot “see” the insoluble-filled link between the two caverns. Cavern volume at the end of the mining operations also can be inferred from “mass balance” — i.e., from the cumulated amounts of injected water and withdrawn brine during mining operations. “Mass balance” suggests that the actual cavern volume might be as large as $V \approx 240{,}000\ \text{m}^3$. The average cavern depth is 250 m.

1.4 Some Characteristic Features of the Three Caverns

Cavern compressibility was measured thoroughly in these three caverns. Cavern compressibility, 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). It is proportional to cavern volume, or V. The compressibility coefficient, β, which is related to the elastic (adiabatic) properties of the rock mass and of fluids contained in the cavern (see Bérest et *al.*, 1999), typically ranges in the $\beta = 4 - 5 \times 10^{-4}$ MPa range. This parameter is paramount when interpreting in situ tests in salt caverns. The as-measured compressibility of EZ53, SPR2 and SG13-14 is $\beta V = 3.97\ \text{m}^3/\text{MPa}$, $\beta V = 5.64\ \text{m}^3/\text{MPa}$, and $\beta V = 129.5\ \text{m}^3/\text{MPa}$, respectively — roughly proportional to cavern volume, as expected.

These three caverns can be characterized as shallow (950 m, 310 m and 250 m, respectively) and relatively old (Leaching at EZ53 and SG13-14 was completed in 1982 and 1980, respectively, and at the SPR2 cavern 50 years ago, with propane being removed from the cavern in 2002). EZ53 and SPR2 are small (their volumes are $V = 8000\ \text{m}^3$ and $V = 9000\ \text{m}^3$, respectively) while the volume of SG13-14 is larger ($V = 240{,}000\ \text{m}^3$).

These features have important consequences from the point of view of a shut-in test.

- Caverns are shallow, and creep closure is slow. Brine outflow tests were performed on the EZ53 and SG13-14 caverns, and proved that, when cavern pressure is halmostatic (i.e., the cavern pressure when both the cavern and the well are filled with saturated brine), steady-state cavern closure rate is $\dot{V}/V = -3 \times 10^{-4}/\text{yr}$ and $\dot{V}/V = -0.9 \times 10^{-5}/\text{yr}$, respectively.

- EZ53 and SPR2 are small. Any thermal disequilibrium between rock temperature and brine temperature is resorbed faster in a smaller cavern. SG13-14’s volume is large, but its characteristic smallest dimension (its height) is comparable to the diameters of EZ53 and SPR2. In addition, EZ53 and SG13-14 were kept idle for a long period after leaching was completed, giving thermal disequilibrium enough time to vanish.

2. Etrez EZ53 (a 17-year long test)

2.1 Test design

A trial-and-error test, supported by the SMRI, was performed from March 1997 to October 1998 (Bérest et al., 2001). Temperature logs were performed in February and March 1996, and clearly proved that, in this small cavern which had been kept idle since 1982, thermal equilibrium was reached. At that time, it was feared that some leakage might take place through the casing shoe, especially when cavern pressure is high, so a simple system was designed to assess well leaks. An 864.5-m high fuel-oil column was lowered in the annular space; the rest of the cavern was filled with saturated brine (except for a fuel-oil column, a few meters high, at the top of the central string). Any fuel-oil leak generates a rise of the brine/fuel-oil interface in the annular space. Because fuel-oil ($\rho_o = 850$ kg/m^3), is less dense than brine, ($\rho_b = 1200$ kg/m^3), any interface rise generates a change in the difference between annular space pressure and string pressure, as measured at the wellhead. This leak detection system has proved to be extremely effective.

The test consists of a trial-and-error process (Figure 2) that includes several phases. At the beginning of each phase, a specific initial pressure value is imposed through brine injection or withdrawal. When the pressure consistently increases (or decreases) for a sufficiently long period of time, it can be inferred that cavern pressure is lower (or higher) than the equilibrium pressure. In such a case, a higher (or lower) initial pressure is tried at the beginning of the next phase. One significant advantage of this method is that, when transient effects can be neglected, it provides both lower and upper bounds for the equilibrium pressure.

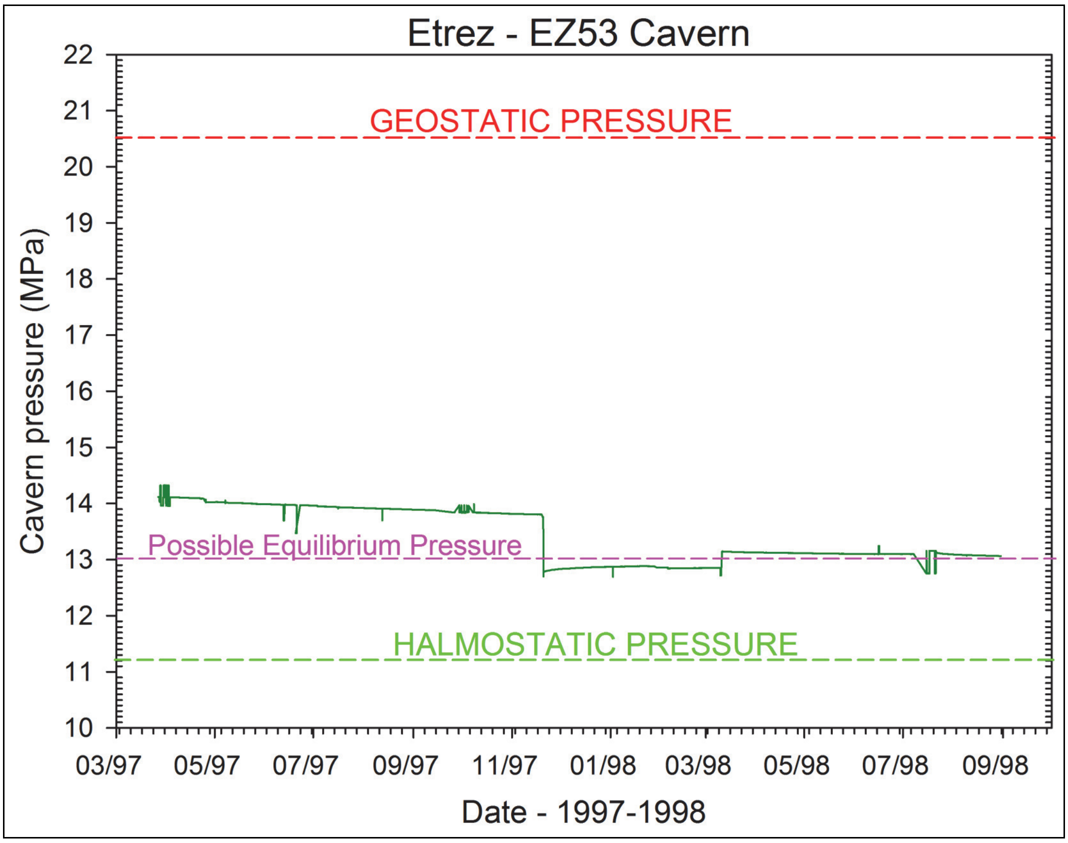

Figure 2. Cavern pressure evolution from March 1997 to October 1998 during the trial-and-error test.

2.2 Results of the 1997-1998 Trial-and-Error Test

In this *H* = 950-m deep cavern, geostatic pressure is $P_\infty = 20.5$ MPa and halmostatic pressure is $P_h = 11.2$ MPa. (When computing these pressures, $P_\infty = \rho_R gH$, $P_h = \rho_b gH$, $\rho_b = 1200\ \text{kg/m}^3$, $\rho_R = 2200\ \text{kg/m}^3$, $g = 9.8$ m/s are assumed).

The trial-and-error test began on March 27, 1997 (day 1) and lasted for 540 days. Four initial pressures were tested successively (Figure 2). The test ran smoothly except for a small leak through the string at the wellhead from day 293 to day 315. At the end of the test, the cavern pressure at a depth of *H* = 950 m was *P* = 13.1 MPa and slowly decreasing. It was inferred that the equilibrium pressure was: $P^{eq} = 13 \pm 0.1$ MPa, smaller than the geostatic pressure ($P_\infty = 20.5$ MPa) and larger than the halmostatic pressure ($P_h = 11.2$ MPa).

The cavern-creep closure rate upon reaching equilibrium pressure was estimated to be $\dot{V} = -1.4\ \text{m}^3/\text{yr}$ or $\dot{V}/V \approx -2 \times 10^{-4}$/yr. (The closure rate is $\dot{V}/V = -3 \times 10^{-4}$/yr when cavern pressure is halmostatic, as proved by a brine outflow test). It also was inferred that salt-formation permeability is $K \approx 2 \times 10^{-19}\ \text{m}^2$.

It must be mentioned that Durup (1994) performed a 1-year long permeability test on the 150-m high EZ58 borehole, located at a couple of hundreds of meters from EZ53; he proposed: $K = 6 \times 10^{-20}\ \text{m}^2$. Bérest et al. (2001) analyzed the results of six Mechanical Integrity Tests performed on four caverns of the Etrez site; the values of the permeability back-calculated from these tests ranged from $K = 4.6 \times 10^{-21}\ \text{m}^2$ to $K = 1.9 \times 10^{-20}\ \text{m}^2$. Permeability of Etrez salt samples had been measured by Leguen (1991), who found $K = 10^{-21}\ \text{m}^2$. These results are consistent with the generally accepted effects of scale on the permeability of crystalline rocks (Brace, 1980).

2.3 Results of the 2002-2013 Pressure Records

No information on the period from October 1998 to April 2002 is available. On May 24, 2002, recording of the string pressure at the wellhead began again, and weekly recordings were performed (Figure 3). On June 13, 2002, a pressure gauge was set at the wellhead on the annular space. Computed downhole pressures inferred from string pressure and from annular pressure were almost equal (as expected!) and close to the equilibrium pressure observed at the end of the first test. (However, pressure gauges, with a resolution of 0.1 MPa, are much less accurate than the gauges used during the 1997-1998 test; in addition, the exact composition of the brine and fuel-oil columns is not perfectly known, and both factors lead to uncertainties).

On June 25, 2002, fuel-oil was withdrawn from the annular space and brine was injected in the string. Cavern pressure increased. Its value was inferred from annular space pressure and tubing pressure independently. The two values were consistent and led to a value of $P = 14.2 \pm 0.1$ MPa. The cavern pressure decreased in both summer and fall of the year.

On December 13, 2002, a small amount of fuel-oil was injected both in the string and in the annular space to prevent brine freezing. Wellhead pressures increased by 0.1 MPa. By mid-December, the annular pressure suddenly increased by 1.1 MPa. This increase cannot be explained, and gauge misreading is suspected, as, by the end of December, the pressure dropped to the value observed before this “pressure crisis”. Before and after the “crisis”, the pressure evolution is smooth.

From March 2003 to 2007, pressure evolutions were smooth; both pressures slowly decreased, as they did during the 1997-1998 test when pressure conditions were similar, and the gap between these two pressures remained roughly constant (strongly suggesting that no oil leak occured). At the end of 2007, string pressure readings became difficult, as the gauge clearly was not working properly. A new string gauge was set on June 4, 2008. A small pressure increase, smaller than gauge accuracy, was observed during the 2012-2013 period. It can be concluded that the cavern pressure at a 950-m depth is $P = 13 \pm 0.1$ MPa, a value that is consistent both with the value predicted at the end of the 1997-1998 test and with that observed in 2002, after the well was kept idle for four years.

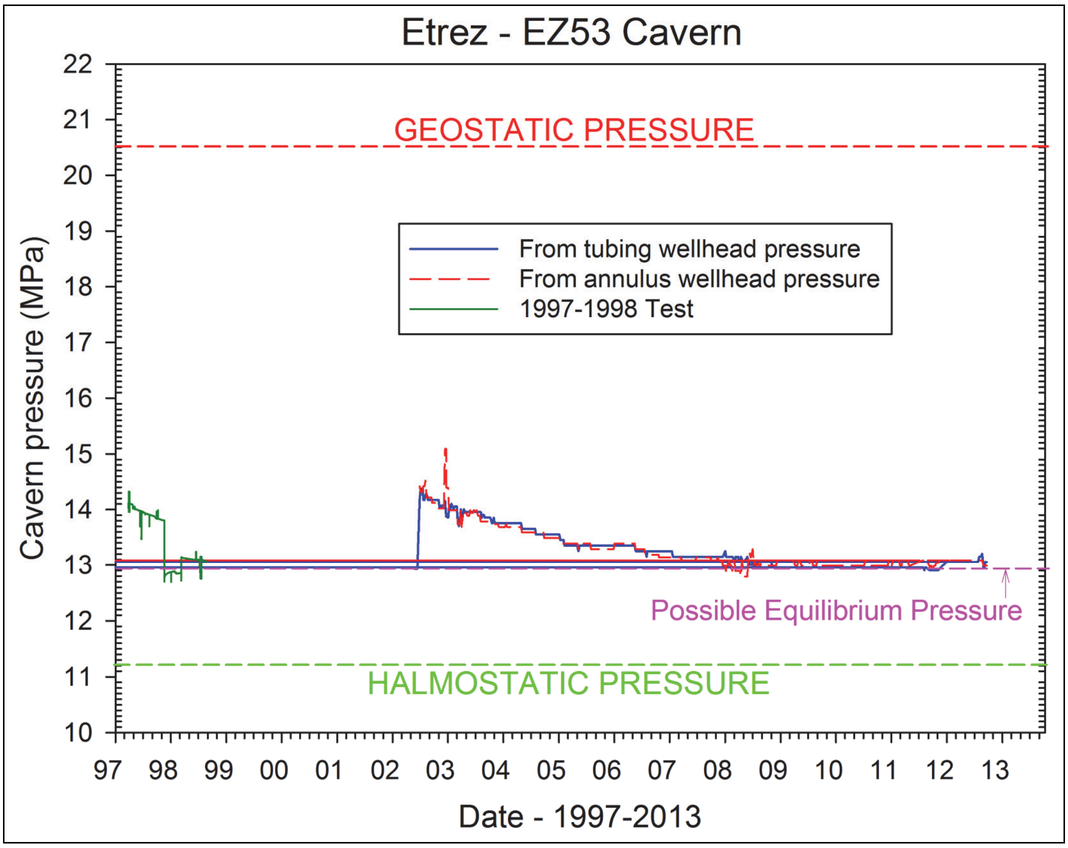

Figure 3. Cavern pressure evolution during the 1997-2013 period.

3. Carresse SPR2 (a 11-year long test)

3.1 Test design

In this 310-m deep cavern, the geostatic pressure is $P_\infty = 6.68$ MPa and the halmostatic pressure is $P_h = 3.64$ MPa. A trial-and-error test, supported by the SMRI, began on June 2004 on SPR2 (Brouard et al., 2006). SPR2, a propane storage cavern, had been re-filled with brine in July 2002. The temperature increase rate of the brine was measured from October 2002 to January 2003; it was $\dot{T} = 0.66$°C/yr. The gap between rock temperature and brine temperature was estimated to be 1.8°C. It was suspected that some liquefied propane had remained trapped in the cavern. Géostock designed an innovative method consisting of lowering brine pressure below propane-vaporization pressure (de Laguérie et al., 2004) to allow propane vaporization in the traps. Detrapped propane was vented and flared. In June 2003, a total of 22 metric tons of propane were released in 4 days. It is likely that propane vaporization slightly lowered cavern brine temperature.

In April 2005 (one year after the beginning of the test) a leak detection system (see Section 2.1) was set in the well.

3.2 Results of the Trial-And-Error Tests

At the beginning of the test (June 2004), cavern pressure was increased by 1.15 MPa through brine injection (A'-B' on Figure 4). During the course of the test, several pressure steps were managed, through injection/withdrawal of green oil (C'-D', E'-F', G'-H'). As it was known that the cavern was not in thermal equilibrium with the rock mass, temperature evolution was computed based on earlier measurements, and the effect of brine warming was substracted from the actual (as-measured) pressure evolution (see green curve on Figure 4). This computation proved that inferring equilibrium pressure from test results is difficult when thermal equilibrium has not been reached yet. From September 15, 2005 to mid-November, 2005, pressure consistently decreased (a transient effect generated by transient "reverse" creep, transient permeation and additional dissolution, see Bérest et al., 2007). After December 2005, pressure increased again and no additional injection/withdrawal was performed.

It was predicted at that time that brine temperature increase would slowly decrease to reach a maximum and, that after several years, thermal expansion would become small enough to be unable to prevent cavern pressure drop.

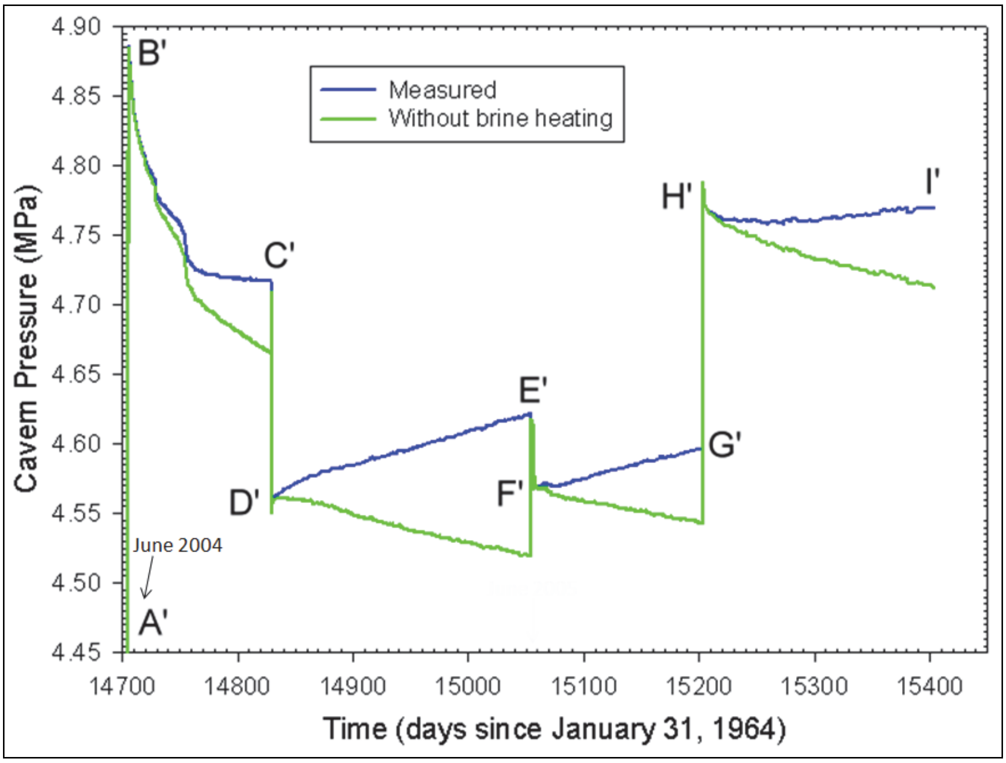

Figure 4. SPR2 pressure evolution from June 2004 to April 2006 during the trial-and-error test.

3.3 Further evolution of the cavern pressure from 2005 to 2013

Pressure evolution was recorded both in the annular space and in the central tubing from October 2005 (end of the trial-and-error test) to now (see Figure 5). Pipes were removed at ground level in May 2010, leading to an increase in annular space pressure by 0.17 MPa, but this operation was not fully documented. It was expected that pressure reaches a maximum after several years; in fact the pressure increase rate consistently decreases but, 8 years after the October 2005 injection, no maximum was reached.

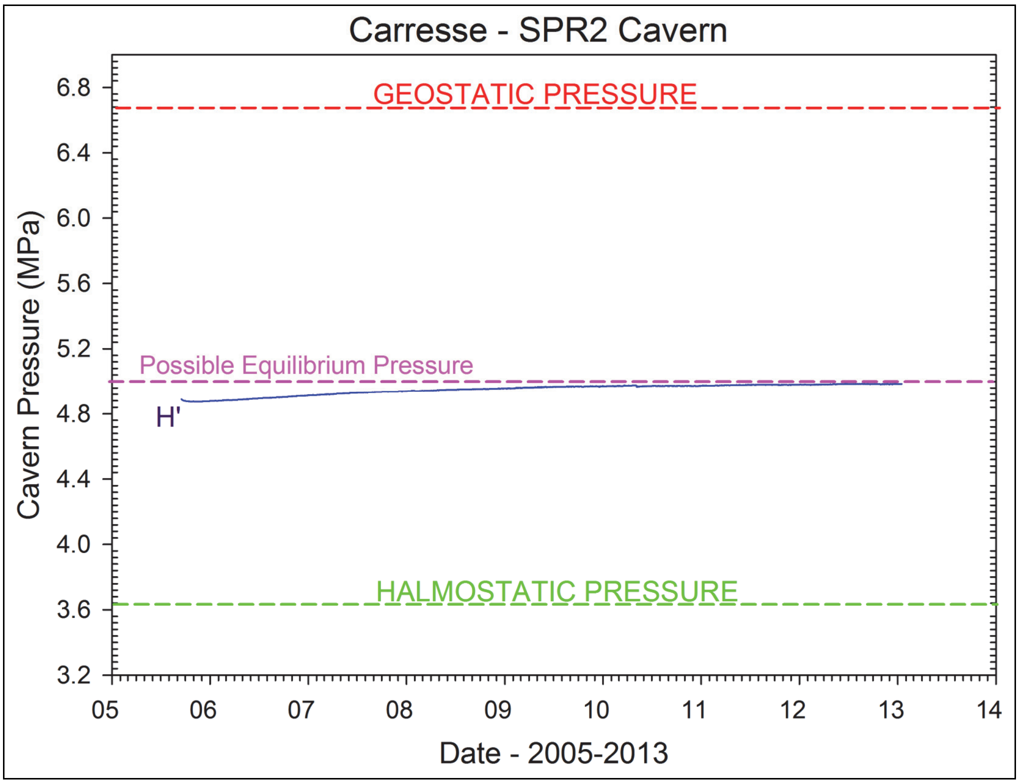

Figure 5 - Cavern pressure evolution during the 2005-2013 period.

The difference between predicted and observed evolutions is relatively small (see Figure 6). In the framework of its Abandonment Research Program, the SMRI issued an RFP focused on obtaining a better explanation of this difference. The report by Brouard et al. (2010) considered several hypotheses and proved that the discrepancy can be explained by underestimating the geothermal temperature by 0.1°C, a small figure.

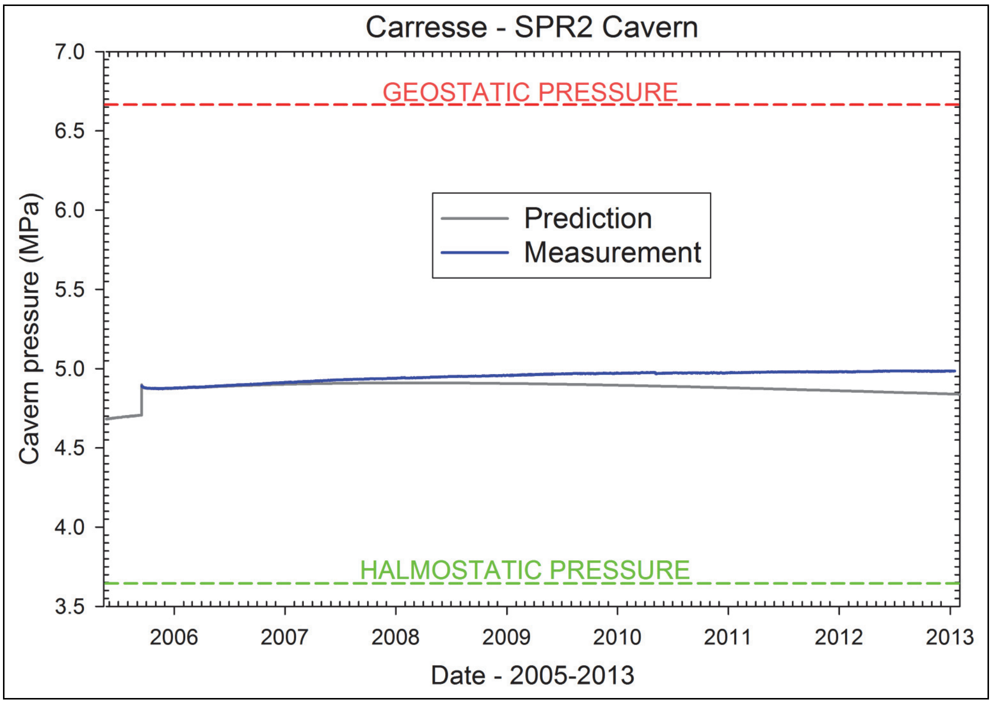

Figure 6. SPR2 — Comparison between predicted cavern-pressure evolution and measured pressure. (Computed cavern pressures were predicted using the 2004-2006 test results.)

4. Gellenoncourt SG13-14 (a 3-year long test)

4.1 Test design

In the framework of ACSSL (*Abandon de Cavités Salines Stables en Lorraine*), a CSME project, a trial-and-error test began in June 2010 and is currently on-going. During the leaching process of the SG13-14 cavern, soft water injected into the cavern was slightly warmer (20°C) than the geothermal temperature of the rock, which typically is 17-18°C at cavern depth (250 m). The initial gap between geothermal temperature and brine temperature certainly was small; moreover, the cavern, whose smallest dimension (its height) is relatively small, had been kept idle for nearly 30 years by the time the testing campaign began. Thus, it was reasonable to assume that, in 2010, the temperature gap was exceedingly small. However, the Carresse test example had proved that even a tiny temperature gap was able to generate a significant difference between prediction and measurements. A temperature gauge was lowered into the SG13 well at a 247-m depth, and a perfectly constant temperature was recorded from December 2008 to November 2009. In June 2010, cavern temperature was measured again using the same gauge: the recorded temperature was exactly the same as in December 2008. Gauge resolution was tested as follows (Brouard et al., 2013). It is known that when cavern brine pressure is rapidly increased by ΔP_c, its temperature adiabatically increases by $\Delta T_c / \Delta P_c = \alpha_b T_c / \rho_b C_b$, where $T_c = 290$ K is the absolute brine temperature, $\rho_b C_b = 3.8 \times 10^6$ J/m^3-°C is the volumetric heat capacity of brine and $\alpha_b = 4.4 \times 10^{-4}$/°C is the thermal expansion coefficient of the brine, leading to $\Delta T_c / \Delta P_c \approx 0.03$ °C/MPa. At the beginning of the trial-and error test, on June 2010, brine pressure was gradually increased. When pressure increase reached $\Delta P_c \approx 0.6$ MPa, gauge temperature abruptly “jumped” by $\Delta T_c = 0.02$°C, proving that the gauge was sensitive and that its resolution was 0.02°C.

It was not possible to install a “leak detection system” (see Sections 2.1.1 and 2.2.1), as there is no string in this two-well cavern. However brine leaks (and/or brine permeation) were deemed to be small as leak tests had been performed on SG13 and SG14 wells before the trial-and-error test. In addition it was known that, before the test, from 2000 to 2008, wellhead pressure had increased by 0.08 MPa, a figure which is not consistent with high leak rates in a cavern in which thermal expansion is exceedingly small and the cavern closure rate is slow.

During the SPR2 and EZ53 tests, it was observed that computation of cavern pressure changes were hampered by the injection/withdrawal of brine, oil or water during the course of the test, as these movements change the density distribution in the wells and the relation between wellhead pressures and cavern pressure. For this reason, in addition to the temperature gauge, a pressure gauge was set in the well at cavern depth.

4.2 Test results

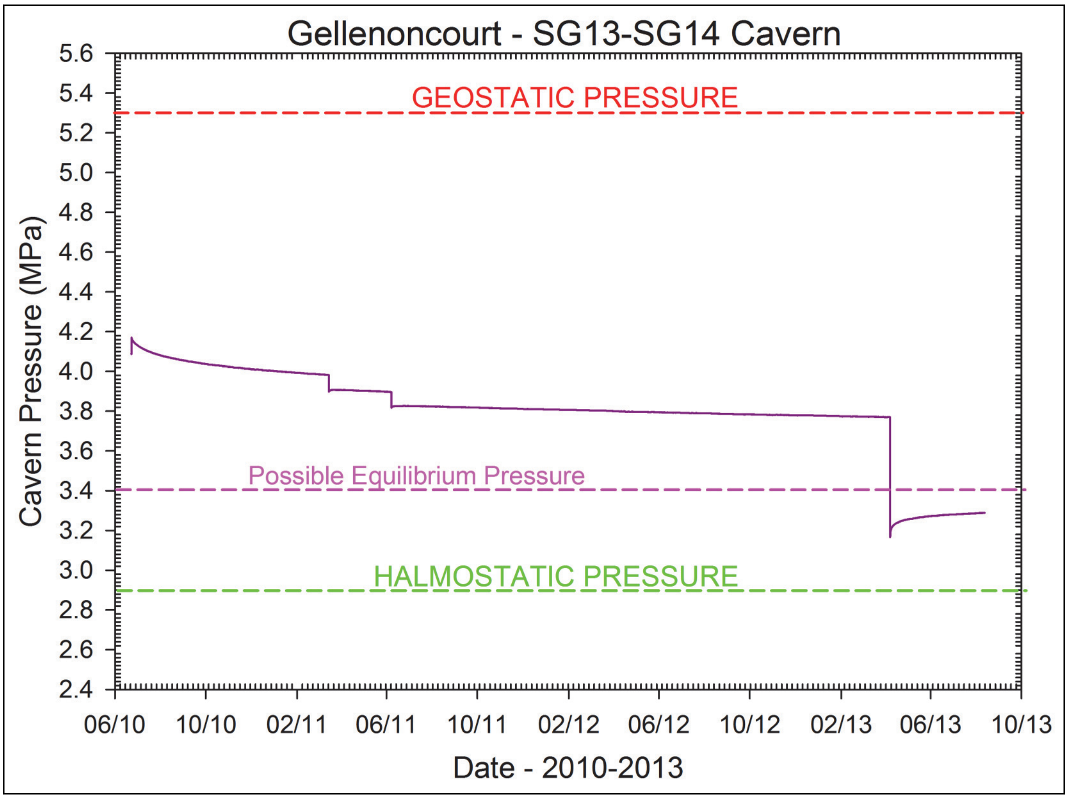

Figure 7 – SG13-14 pressure evolution from June 2010 to August 2013 during the trial-and-error test.

In the SG13-14 cavern (250-m deep), the halmostatic pressure is $P_h = 2.97$ MPa and the geostatic pressure is $P_\infty = 5.39$ MPa. Pressure evolution is very slow (Figure 7). Small amounts of brine were withdrawn periodically in order to reach equilibrium pressure more rapidly. Any pressure drop is followed by a transient period during which pressure increases before decreasing again. (This phenomenon was explained in Section 3.2) Because it was observed that the cavern pressure consistently decreased, it was decided, in spring 2013, to lower the cavern pressure from $P \approx 3.79$ MPa to $P \approx 3.16$ MPa. After this pressure drop, cavern pressure consistently increases, proving that equilibrium pressure is smaller than 3.75 MPa and larger than 3.2 MPa. A more precise estimate will be available in a couple of years.

5. Conclusions

Three shut-in tests currently are being performed at three different sites at Etrez, Carresse and Gellenoncourt. The tests began 17, 11 and 3 years ago, respectively. Their results are consistent with the conclusions of research projects and tests supported by the SMRI in the framework of its Abandonment Research Program: cavern brine pressure slowly converges to an equilibrium pressure which, at cavern mid-depth, is smaller than geostatic pressure. They are also consistent with the results of a test (supported by the SMRI) performed on Staβfurt caverns (Banach and Klafki, 2009).

The following lessons were learned as a result of these three tests:

- Conclusions are more difficult to draw when thermal equilibrium between geothermal and cavern brine temperature was not reached before the test began.
- The initial trial-and-error test allows definition of a lower and upper bound for the equilibrium pressure that will be reached over the long-term.
- Test interpretation is made easier when the composition of the liquid columns in the borehole experiences no or small changes or, still better, when pressure and temperature gauges are set in the cavern (rather than at the wellhead).
- During a trial-and-error test, pressure steps must be long enough to allow the transient phenomena that follow each pressure change to vanish.
- Interpretation is more certain when a leak detection system is installed in the well.
- Provided that in situ salt properties and cavern shape are known, long-term creep-closure rate, which equals brine outflow rate to the rock mass, can be back-calculated.

ACKNOWLEDGEMENTS

Special thanks to Kathy Sikora and Hippolyte Djizanne.

6. References

Banach A. and Klafki M. (2009). *Staβfurt Shallow Cavern Abandonment Field Tests.* SMRI Research Report RR 2009-01.

Bérest P., Bergues J. and Brouard B. (1999). *Static and dynamic compressibility of deep underground caverns*. Int. J. Rock Mech. Min. Sci., 36, 1031-1049.

Brouard B., Bérest P. and Durup J.G. (2001). *In-situ salt permeability testing*. In Proc. SMRI Fall Meeting, Albuquerque, USA, pp. 139-157, 2001.

Bérest P., Bergues J., Brouard B., Durup J.G. and Guerber B. (2001). *A salt-cavern abandonment test.* Int. J. Rock Mech. Min. Sci. 38(2), 343-355.

Bérest P., Brouard B., Karimi-Jafari M. and Van Sambeek L. (2007). *Transient behaviour of salt caverns. Interpretation of Mechanical Integrity Tests*. Int. J. Rock Mech. Min. Sci., 44, 767-786.

Brace W.F. (1980). *Permeability of crystalline and argillaceous rocks*. Int. J. Rock Mech., XVII, 241-251.

Brouard Consulting, Institute für Unterirdishches Bauen (IUB), Ecole Polytechnique, Total E&P France and Géostock (2006). *Salt Cavern abandonment Field Test in Carresse*. SMRI RFP 2003-2-B, Final Report.

Brouard B., Bérest P., Staudtmeister K., de Laguérie P. and Réchède A. (2010). *Update of the SMRI 2006 Carresse Research Report.* SMRI Research Project Report 2010-S.

Brouard B., Bérest P., de Greef V., Béraud J.F., Lheur C., Hertz E. (2013). *Creep closure rate of a shallow salt cavern at Gellenoncourt, France*. Int. J. Rock Mech. Min. Sc. (62), 2013, 42-50.

Buffet A. (1998). *The collapse of Compagnie des Salins SG4 and SG5 drillings.* Proc. SMR Fall Meeting, Roma, Italy, 79-105.

Crotogino F. and Kepplinger J. (2006). *Cavern Well Abandonment Techniques. Guidelines Manual.* SMRI Research Report 2006-3-SMRI, September.

de Laguérie P., Héas J.Y., Fourmaintraux D., You Th., Brouard B. and Bérest P. (2004). *Decommissioning and Abandonment Procedure of LPG Caverns at Carresse (France).* Proc. SMRI Fall Meeting, Berlin, 28-42.

Durup J.G. (1994). *Long term tests for tightness evaluations with brine and gas in salt*. Proc. SMRI Fall Meeting, Hannover.

Ghoreychi M. and Cosenza Ph. (1993). *Quelques aspects de la sûreté à long terme de stockages dans le sel* (in French). Proc. 4ème Colloque franco-polonais, ISBN 2-85555-048-3, 209-218.

Ratigan J. (2003). *The SMRI Cavern Sealing & Abandonment Research Program Summary.* Proc. SMRI Spring Meeting, Houston, Texas, 141-164.

Rokahr R.B., Hauck R., Staudtmeister K. and Zander-Schiebenhöfer D. (2002). *High Pressure Cavern Analysis.* SMRI Research Report 2002-2-SMRI, October.

SMRI (2010). *Fundamentals for the Long-term abandonment of Salt Caverns*. Technical Class Book, SMRI Fall Meeting, Leipzig.

Wallner M. (1988). *Frac-pressure risk for cavities in rock salt.* H. Reginald Hardy, Jr. & Michael Langer (Eds.), *Proc. 2nd Conf. Mech. Beh. of Salt,* 645-658. Clausthal-Zellerfeld: Trans Tech Pub.

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

You Th., Maisons Ch. and Valette M. (1994). *Experimental procedures for the closure of the brine production caverns of the "Saline de Vauvert" site*. Proc. SMRI Fall Meeting, Hannover.

BIBLIOGRAPHY, Salt Cavern Abandonment

Bérest P., Brouard B. and Durup G. (2000). *Shut-in pressure tests – Case studies.* Proc. SMRI Fall Meeting, San Antonio, Texas, 105-126.

Brouard B., Bérest P., Héas J.Y, Fourmaintraux D., de Laguérie P. and You T. (2004). *An in situ test in advance of abandoning of a salt cavern*. Proc. SMRI Fall Meeting, Berlin, Germany 45-64.

Bérest P. (2007). *Questions on the Prediction of the long-term behaviour of underground openings.* Proc ISRM Congress, Lisbon, Vol. 3, 1413-1425.

Bérest P. (2010). *Field testing issues relative to the long term abandonment of salt cavern*s. Technical Class Book Fundamentals for the long-term abandonment of salt caverns, SMRI Fall Meeting, Leipzig, Germany, 31-49.

Brouard B., Bérest P. and Karimi-Jafari M. (2007). *Deep salt cavern abandonment.* Proc. 6th Conf. Mech. Beh. Salt, 445-452. London: Taylor & Francis Group.

Brückner D., Lindert A. and Wiedeman M. (2007). *The Bernburg test cavern – in situ investigations and model studies on cavern abandonment.* Proc. 6th Conf. Mech. Beh. Salt, 417-426. London: Taylor & Francis Group.

Hévin G., Caligaris C., Durup G., Pichayrou O. and Rolin C. (2007). *Deep salt cavern abandonment. A pilot experiment. Proc*. 6th Conf. Mech. Beh. Salt, 427-434. Taylor & Francis Group, London.

Leguen C. (1991). *Mesure de la perméabilité de roches très peu perméables et étude de son évolution sous sollicitations thermomécaniques* (in French). PhD Thesis, Ecole Nationale des Ponts et chaussées, France.

Lux K.H. (2007). *Long-term behaviour of sealed brine-filled cavities in rock salt mass. A new approach for physical modelling and numerical computation.* Proc. 6th Conf. Mech. Beh. Salt, 425-444. Taylor & Francis Group, London.

Rokahr R.B., Hauck R., Staudtmeister K. and Zander-Schiebenhöfer D. (2000). *The Results of the Pressure Build-Up Test in the Brine Filled Cavern Etzel K102*. Proc. SMRI Fall Meeting, San Antonio, 89-103.

Tomasko D., Elcoq D. and Veil J. (1997). *Estimated Human Health Risks of disposing on Nonhazardous Oil Field Waste in Salt Caverns.* Proc. SMRI Fall Meeting, El Paso, 145-155.

Van Heekeren H., Bakker T., Duquesnoy T., de Ruiter V. and Mulder L. (2009). *Abandonment of an extremely deep Cavern at Frisia Salt.* Proc. SMRI Spring Meeting, Krakow, 30-42.

Veil J.A., Smith K.P., Tomasko D., Elcock D., Blunt D.L. and Williams G.P. (1998). *Disposal of NORM-Contaminated Oil Field Wastes in Salt Caverns.* Argonne National Laboratory (prepared for U.S. Department of Energy, Office of Fossil Energy, National Petroleum Technology Office, Contract W-31-109-Eng-38.

Wolters R., Lux K.H and Düsterloh U. (2012). *Evaluation of rock salt barriers with respect to tightness: influence of thermomechanical damage, fluid infiltration and sealing/healing*. P. Bérest, M. Ghoreychi, F. Hadj Hassen, M. Tijani (Eds.), Proc. Mech. Beh. Salt VII. London, 425-434. Taylor & Francis.