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A 12-year cavern abandonment test

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Abstract. In 1997-1998, an abandonment test was performed in a 950-m deep, 8000-m^3 salt cavern operated by GDF SUEZ at Etrez, France. In this relatively small brine-filled cavern, which had been kept idle for 15 years before the test, thermal equilibrium was reached. A special system was designed to monitor leaks, which proved to be exceedingly small. In these conditions, brine permeation and cavern creep closure are the only factors to play significant roles in pressure evolution. This test strongly suggested that obtaining an equilibrium pressure such that the effects of these two factors were exactly equal would be reached in the long term. Four years later, pressure monitoring in the closed cavern resumed. Pressure evolution during the 2002-2009 period confirmed that cavern brine pressure will remain constant and significantly smaller than geostatic pressure in the long term, precluding any risk of fracturing and brine seepage to the overburden layers.

1 Introduction

In the past several years, there has been concern about the long-term behaviour of abandoned salt caverns. Such caverns are leached out from salt formations, with depths ranging from 300 m to 3000 m and volumes typically ranging from 10,000 m^3 to 1,000,000 m^3. Thousands of such caverns were created, and are used for brine production and/or hydrocarbon storage. Some day, they will be abandoned: the cavern will be filled with brine, a special plug will be set at casing seat, and cement will be poured in the well. A large “bubble” of saturated brine will be isolated. The long-term evolution of this brine is a serious concern. After cavern plugging, cavern brine pressure will build up, as has been proven by numerous “shut-in pressure tests” performed worldwide. The final value of cavern brine pressure is of utmost importance from the perspective of environmental protection. In some circumstances, brine pressure may reach a figure larger than the geostatic pressure, leading to hydro-fracturing: brine will flow upward through fractures to shallow water-bearing strata, leading to water pollution. In fact, pressure evolution in a closed cavern results from five main factors.

1.1 Cavern compressibility

Cavern compressibility is the ratio between any rapid change in cavern brine volume and cavern brine pressure. It results from the (adiabatic) elastic compressibility of brine and cavern itself, and is proportional to cavern volume, or $\dot{V} = \beta V \dot{P}$, where $\beta = 4\times10^{-4}$ /MPa is typical [1].

1.2 Cavern creep closure

Salt mass creep leads to cavern shrinkage. The driving force for cavern closure is the gap between geostatic pressure, P_∞, and cavern pressure, or P. In the long term, salt behaves as a (highly) nonlinear viscous fluid [The Norton-Hoff law often is assumed, $\dot{\varepsilon} = A(T)\sigma^n$.], and the rate of cavern closure is slower when cavern pressure is higher, vanishing to zero when $P = P_\infty$.

1.3 Brine permeation through the cavern walls

This process is still open to controversy. Brine permeation vanishes to zero when cavern pressure, P, equals natural pore pressure, P_0. It is generally assumed that brine permeation can be described by Darcy's law and that salt permeability is exceedingly small (typically, $K = 10^{-22} - 10^{-19}\,\text{m}^2$). However, even these low figures can lead to a significant brine pressure release.

1.4 Brine thermal expansion

The temperature history of cavern fluids during cavern operation generally is complex; in most cases, when a cavern is abandoned, brine temperature is smaller than geothermal temperature at cavern depth. Heat transfer from the rock mass to the cavern leads to brine warming. However, brine thermal expansion is hampered in a closed cavern, and brine pressure builds up. The thermal expansion coefficient of brine is $\alpha \approx 4.4\times10^{-4}/°\text{C}$, and a 1°C increase in brine temperature generates a pressure build-up of $\alpha/\beta \approx 1\ \text{MPa}$. After some time, however, thermal equilibrium is reached, and expansion no longer takes place. The characteristic time for conductive heat transfer is $t_c = V^{2/3}/4k$, where k = 100 m^2/yr is salt thermal diffusivity. For instance, in a cavern with V = 8000 m^3, the characteristic time is $t_c \approx 1$ yr, and it can be considered that thermal equilibrium is reached in a cavern after it has been kept idle (no liquid injection/withdrawal) during a period, say, of 5-6 years.

1.5 Brine leaks

Leaks through the casing or the casing shoe are known to have occurred in some underground storage environments [2]. The existence of such leaks — which are likely to vanish after the well of an abandoned cavern is plugged — would lead to severe misinterpretation of a cavern abandonment test (Salt permeability would be overestimated.) if casing leakage and brine permeation were not distinguished.

1.6 Brine pressure evolution

In the following, our focus is on caverns in which brine thermal expansion and leaks can be disregarded, and brine pressure evolution is governed by a differential equation:

$$\beta V\dot{P} = Q_{creep}\left[P_\infty - P\right] - Q_{perm}\left[P - P_0\right] \tag{1}$$

where Q_{creep} is the cavern volumetric closure rate, which is an increasing function of the gap between geostatic pressure and cavern pressure, and Q_{perm}, is the brine outflow rate, which is an increasing function of the gap between cavern pressure and natural pore pressure. These two functions can be computed when, for instance, Norton-Hoff law and Darcy's law are assumed.

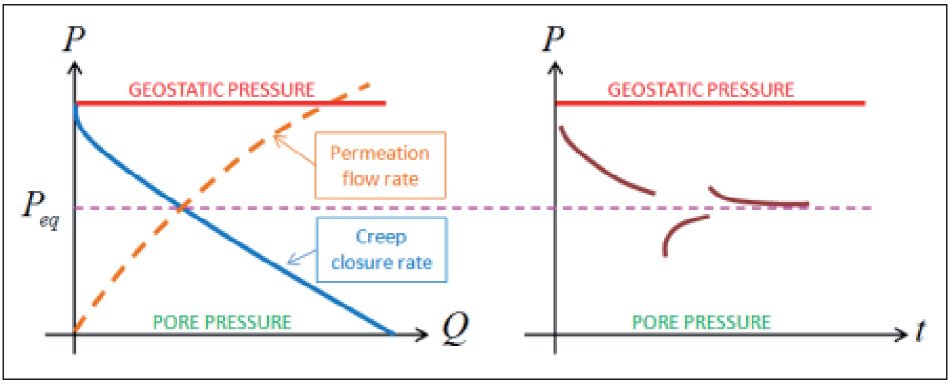

Fig. 1. Equilibrium pressure

It is found that equilibrium is reached ($P = P_{eq}$) when $Q_{creep} = Q_{perm}$ — i.e., when cavern closure rate exactly equals brine permeation rate (Figure 1, left). The objective of an abandonment test is to assess equilibrium pressure and to verify that it is significantly smaller than geostatic pressure. An abandonment test (Figure 1, right) is performed following a trial-and-error method: when cavern pressure is higher (resp., lower) than equilibrium pressure, cavern pressure as a function of time consistently decreases (resp., increases). One significant advantage of this method is that, when transient effects are neglected, it provides both lower and upper bounds for the equilibrium pressure.

2 The 1997-1998 abandonment test

An abandonment test was performed in the EZ53 salt cavern of the gas storage site operated by GDF SUEZ at Etrez in southeastern France. This cavern had been leached out in July 1982. It is 950-m deep, and its volume is V = 8000 m^3. Access to the cavern is through a 842-m-long 9-⅝" casing cemented to the rock formation; a 929-m-long 7" string is set in the well [3].

2.1 Brine thermal expansion and Brine leaks

When the test began in 1997, the cavern had been idle for 15 years, and it was assumed that, after such a long period, thermal equilibrium in this relatively small cavern had been reached (see Section 1.4). A temperature gauge lowered in the cavern in February 1986 proved that the cavern brine temperature equalled the geothermal temperature of the rock formation (45°C at a 950-m depth). Thus, brine thermal expansion could be disregarded. Possible leaks also were a concern. On March 20, before the test began, a light, liquid hydrocarbon column was lowered in the 7"×9-⅝" annular space to develop a brine-hydrocarbon interface at a depth of h = 864.5-m. Brine density was $\rho_b = 1200\ \text{kg/m}^3$, and hydrocarbon density was $\rho_o = 850\ \text{kg/m}^3$. Any hydrocarbon leak, Q_{act}, through the cemented casing or through the casing shoe, resulted in an interface rise by $\dot{h} = Q_{act}/\Sigma$, where Σ is the cross-sectional area of the annular space and, consequently, in a change by $\dot{P}_{ann}^{wh} - \dot{P}_{tub}^{wh} = (\rho_b - \rho_o)g\dot{h}$ in the difference between the string pressure P_{tub}^{wh} and the annular space pressure P_{ann}^{wh} as measured at the wellhead. This change can easily be measured.

Figure 2 presents both pressure variations, as measured from day 112 (after test began) to day 150. They are measured through pressure gauges whose resolution is 1 kPa. The rate of pressure difference change is almost null, precluding any significant leakage. (Small fluctuations can be observed; these are due to the effects of daily ground-level temperature and pressure fluctuations and to the effects of Earth tides). Later, on day 293, a rapid increase in pressure difference took place —

clear evidence of a hydrocarbon leak. The cumulated differential pressure increased to 21 kPa after 23 days: the interface rose by 6 m in this period, and 124 litres of hydrocarbon were lost. On day 315, the leak was fixed. (The leak was through the wellhead; it was detected on pressures evolution curves before being observed in the field.) Except for this period, there was no leak from the well, and only two phenomena played significant roles in pressure evolution: cavern creep closure and brine permeation.

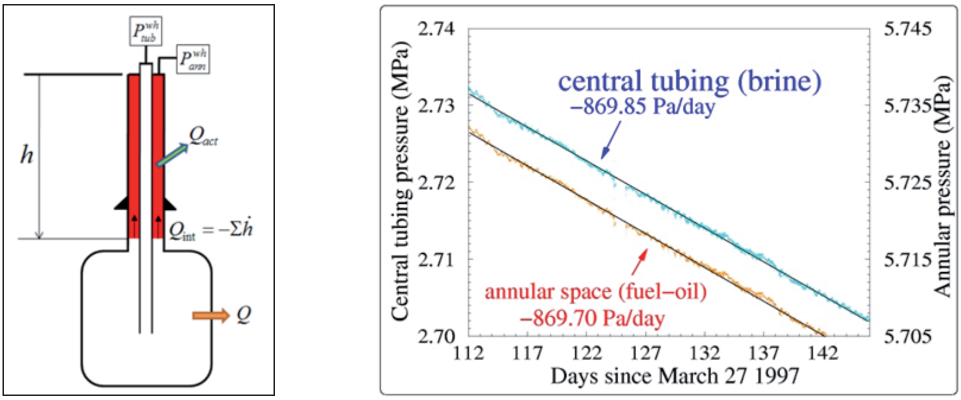

Fig. 2. Wellhead pressure evolution day 112 to day 142.

2.2 Test results

The test began on March 27, 1997 (day 1) and lasted for 540 days. The test (Figure 3) included four phases. At the beginning of each phase, a different pressure was applied in the cavern. The test ran smoothly except for the period from day 293 to day 315, described above. At the end of the test, the cavern pressure was P = 13.1 MPa and slowly decreasing. It was inferred that the equilibrium pressure at a depth of $H = 950\,\text{m}$ was $P^{eq}_{950} = 13 \pm 0.1$ MPa — i.e., smaller than the geostatic pressure $\left(P_\infty = 20.5 \text{ MPa}\right)$ and larger than the halmostatic pressure, $\left(P_h = 11.2 \text{ MPa}\right)$ at cavern depth. It also was inferred that salt-formation permeability was $K \approx 2\times10^{-20}$ m^2 and that cavern-creep closure rate was $\dot{V}/V \approx 2\times10^{-4}\,\text{yr}^{-1}$ [3].

3 WAS THE 1997-1998 TEST LONG ENOUGH?

In principle, the results of this test can be considered to be convincing. The physical phenomena that play a role are identified clearly, and the test results provide an upper and lower bound for the "equilibrium pressure". The Solution Mining Research Institute (SMRI), which represents companies, consultants and research centres involved in the solution mining industry, has set the cavern abandonment issue at the centre of its research program, and SMRI supported the 1997-1998 test [4]. It also supported similar later tests performed at Carresse (France) [5] and Staβfurt (Germany) [6]. Many papers [7, 8, 9] contributed to the discussion over the years, and many companies performed abandonment tests following the same methodology [10, 11, 12, 13]. These efforts provide some confidence in the selected approach. However, the Etrez test lasted 540 days, and one could question whether the evolution observed during that period of time can be extrapolated to much longer periods. A pragmatic approach was considered suitable: recording pressure evolution several years after the initial test was over should provide additional insight and help build confidence in the test results.

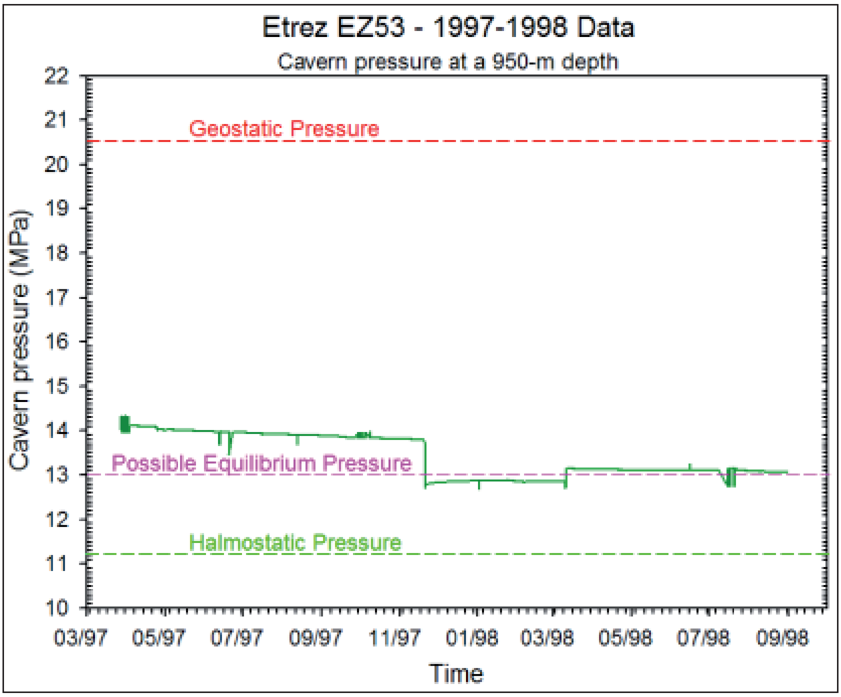

Fig. 3. The 1997-1998 Abandonment test.

4 The 2002-2009 test

4.1 November 1998 to May 2002

The EZ53 well completion was discussed briefly in Section 2. The well has a 7” central string that is 929-m (H_{tub}) long, and a 842-m long 9-⅝" cemented casing shoe. The internal volume of the string is 19.5 m^3. At the end of the 1997-1998 test, the cavern and the central string are filled with saturated brine except for a 3.5-m liquid hydrocarbon column at the top of the string. The annular space is filled with liquid hydrocarbon to a depth h = 858.5 m. From depth 0 to 32 m, the cross-sectional area of the annular space is 52.4 litres/m; from 30 m to 842 m, it is 14.7 litres/m; and, from 842 m to 890 m (location of the cavern chimney), it is Σ = 5.7 litres/m. The liquid hydrocarbon volume injected in the annular space in 1997 was approximately 14.5 m^3.

No information is available for the period November 1998 to April 2002. On May 24, 2002, recording of the string pressure at the wellhead began again, and weekly recordings were performed. The pressure gauge, with a resolution of 0.1 MPa, is much less accurate than that used during the 1997-1998 test, although 0.05-MPa pressure changes can be detected. Wellhead string pressure from May 24 to June 6 was $P_{tub}^{wh} = 1.75$ MPa, a figure observed consistently during one month. Because the string is filled with saturated brine, cavern pressure can be deemed to be

$$P_{950} = P_{tub}^{wh} + \rho_b gH = 1.75 + 11.2 = 12.95 \text{ MPa} \tag{2}$$

This is a figure that ranges between the upper and lower bounds of the predicted equilibrium pressure.

On June 13, 2002, a pressure gauge was set at the wellhead on the annular space (partly filled with oil). At that point, the wellhead annular pressure was $P_{ann}^{wh} = 4.4$ MPa, from which the value of

$$P_{950}^{'} = P_{ann}^{wh} + \rho_o gh + \rho_b g(H-h) = 12.6 \text{ MPa} \tag{3}$$

can be inferred. This figure is smaller than that inferred from the wellhead string pressure. (Obviously, they should be equal.) Thus, the following two hypotheses must be considered.

1. A liquid hydrocarbon leak occurred during the 1998-2002 period. Such a leak would result in a heavier annular space column, because the brine/hydrocarbon interface rises and hydrocarbon is replaced by saturated brine. This hypothesis is not fully convincing, as the leak was almost zero during the 1997-1998 period.

2. There were uncertainties in pressure measurements and liquid densities. Accuracy of pressure gauges is poor: liquid densities are not constant, but depend on liquid pressure and temperature (which, from the wellhead to the cavern bottom, vary from a couple of MPa to 11 MPa, and from 10 °C to 45 °C, respectively). These result in variations of liquid density by 1% for brine (and more for liquid hydrocarbon).

4.2 From June 2002 to December 2002

On June 25, 2002, liquid hydrocarbon was withdrawn from the annular space, and brine was injected in the tubing to increase cavern pressure. The injected brine was slightly undersaturated, with a density of $\rho_b^{uns} = 1177 \text{ kg/m}^3$. The annular space was filled with the fully saturated brine from the cavern that displaced the fuel-oil column. The tubing pressure fluctuated from $P_{tub}^{wh} =$ 3.2 to 3.4 MPa, an increase of $\Delta P = 1.45$ to 1.65 MPa when compared to the May 2002 period (see Figure 4). Because the cavern compressibility is $\beta V = 3 \text{ m}^3/\text{MPa}$, it can be inferred that the injected brine volume was $\beta V \Delta P \approx 4.5 \text{ m}^3$ (to increase cavern pressure) plus 14.5 m^3 (to withdraw liquid hydrocarbon from the annular space), or 19 m^3. It also can be inferred that the string, whose volume is 19.5 m^3, is filled with unsaturated brine and that the cavern pressure is:

$$P_{950} = P_{tub}^{ann} + \rho_b^{uns} gH_{tub} + \rho_b g(H - H_{tub}) = 14.2 \text{ to } 14.4 \text{ MPa} \tag{4}$$

The annular space pressure during this period is $P_{ann}^{wh} = 3.1$ to 3.2 MPa, from which a cavern pressure ranging from

$$P_{950}^{'} = P_{ann}^{wh} + \rho_b gH = 14.3 \text{ to } 14.4 \text{ MPa} \tag{5}$$

can be inferred; the two figures are consistent (suggesting that the discrepancy observed in June 2002 resulted from poor estimation of liquid hydrocarbon density, the second hypothesis mentioned in Paragraph 4.1).

4.3 From December 2002 to July 2009

On December 13, 2002, a small amount (110 litres) of hydrocarbon was injected in both the

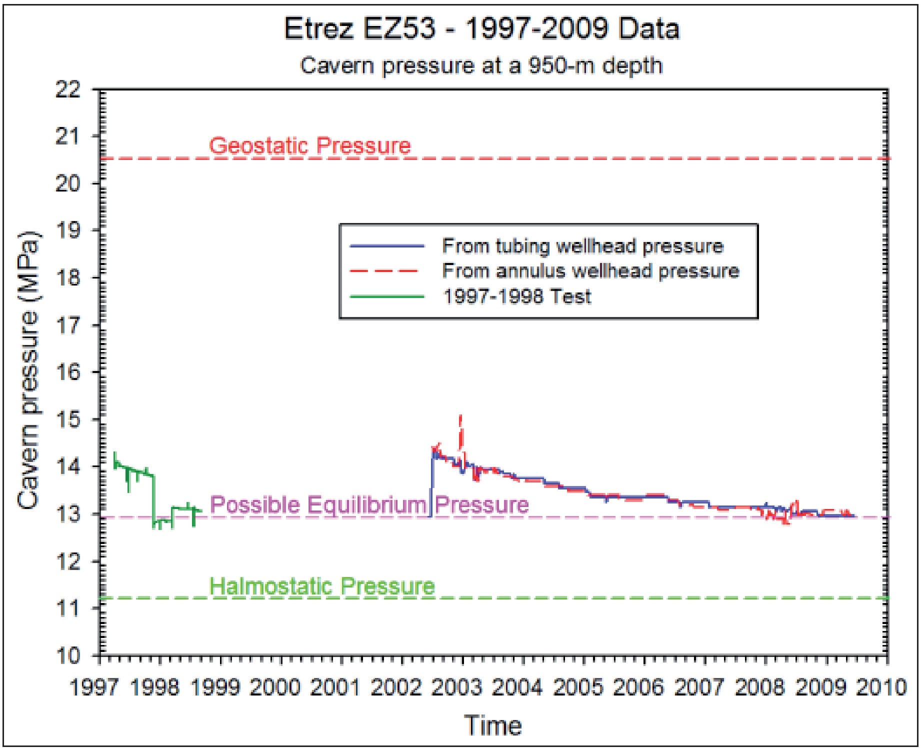

Fig. 4. Cavern pressure evolution in the 1997-2009 period.

string and the annular space to prevent brine freezing. Both wellhead pressures increased by 0.1 MPa, a figure consistent with what is known of cavern compressibility and hydrocarbon density. By mid-December, the annular pressure suddenly increased by 1.1 MPa (see Figure 4). This increase cannot be explained; gauge misreading is suspected, as, by the end of December, the pressure drops to the figure observed before this “pressure crisis”. A similar “pressure crisis” can be observed in March 2003, when both pressures unexpectedly dropped by 0.2 to 0.3 MPa. This pressure drop remains puzzling; both surface temperature and atmospheric pressure fluctuations generate small changes in wellhead pressure (These phenomena clearly were observed during the 1997-1998 test, when pressure gauge resolution was much better.), but these changes typically are 0.01 MPa in magnitude (see Figure 3) and cannot explain the much larger pressure drop observed in March 2003.

From March 2003 to 2007, pressure evolutions were smooth; both pressures slowly decreased (see Figure 4), as they did during the 1997-1998 test when pressure conditions were similar, and the gap between these two pressures remained roughly constant. At the end of 2007, string pressure readings became difficult, as the gauge clearly no longer worked properly. A new string gauge was set on June 4, 2008. From then until July 2009, the string pressure is $P_{tub}^{wh} = 2.0$ MPa, and the annular space pressure is $P_{ann}^{wh} = 1.8 - 1.9$ MPa. It can be concluded from these figures that the cavern pressure is $P_{950} = 13 \pm 0.1$ MPa, which is consistent both with the figure predicted at the end of the 1997-1998 test (see Section 2.2) and with that observed in 2002, after the well was kept idle for four years. It must be kept in mind, however, that a couple of short “pressure crises”, a couple of weeks long, were observed during the 2002-2009 observation period. They remain unexplained. Misreading and/or gauge faults are the most likely explanations.

5 CONCLUSION

A 12-year-long test was performed on the 950-m deep, 8000-m^3 EZ53 cavern of the Etrez cavern field. Pressures were monitored precisely during the 1997-1998 period; less accurate gauges were used during the 2002-2009 period. It is observed that, at the end of any period during which the cavern was kept idle (e.g., October 1998, May 2002, July 2009), cavern pressure remained constant at 13.0 ± 0.1 MPa . The notion of a steady-state “equilibrium pressure” in a closed cavern, resulting from the opposing effects of brine permeation and cavern creep closure, clearly has been confirmed.

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REFERENCES

[1] P. Bérest, J. Bergues, B. Brouard. *Int J Rock Mech Min Sci,*;36:1031-49b (1999)

[2] P. Bérest, B. Brouard. *Oil & Gas Science and Technology - Rev. IFP.* 58, n°3, 361-384 (2003)

[3] P. Bérest, J. Bergues, B.Brouard, J.G. Durup, B. Guerber. *Int J Rock Mech Min Sci, 38:343-55* (2001)

[4] J. Ratigan. *Proceedings SMRI Spring Meeting, Houston, Texas.*, p.141-64 (2003)

[5] B. Brouard, P. Bérest, M. Karimi-Jafari, R.B. Rokahr, K. Staudtmeister, Zander-Schiebenhöfer D, D. Foumaintraux, P. de Laguérie, T. You. *Report 2006-1 for the SMRI,* (unpublished, 2006)

[6] A. Bannach, M. Klafki. *Report 2009-1 for the SMRI (*unpublished, 2009)

[7] M. Wallner, W. Paar. *Proceedings SMRI Fall Meeting, El Paso, Texas,* p.177-88 (1997)

[8] R.B. Rokhar, R. Hauck, K. Staudtmeister, D. Zander-Schiebenhöfer. *Proceedings SMRI Fall Meeting, San Antonio, Texas,* p.89-103 (2000)

[9] Ph. Cosenza, M. Ghoreychi. *Int J Rock Mech Min Sci,* 36:527-533 (1993)

[10] D. Brückner, A. Lindert, M. Wiedeman. *Proceedings sixth Conference on Mechanical Behaviour of Salt. London: Taylor & Francis Group*, p.417-26 (2007)

[11] G. Hévin, C. Caligaris, G. Durup, O. Pichayrou, C. Rolin. *Proceedings sixth Conference on Mechanical Behaviour of Salt. London: Taylor & Francis Group*, p.427-34 (2007)

[12] D. Brückner, H. Wekenborg. *Proceedings SMRI Fall Meeting, Rapid City, South Dakota,* p.81-103 (2006)

[13] H. Van Heekeren, T. Bakker, T. Duquesnoy, V. de Ruiter, L. Mulder. *Proceedings, SMRI Spring Meeting, Krakow, Poland,* p.30-42 (2009)