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TRANSIENT CREEP IN SALT CAVERNS

Pierre Bérest, Solid Mechanics Laboratory, CNRS UMR 7649, Department of Mechanics, Ecole Poytechnique, 91128 Palaiseau Cedex France (33)169334128 berest@lms.polytechnique.fr

Mehdi Karimi-Jafari, Solid Mechanics Laboratory, CNRS UMR 7649, Department of Mechanics, Ecole Polytechnique, 91128 Palaiseau Cedex France (33)169333522 karimi@lms.polytechnique.fr

Benoit Brouard, LMS and Brouard Consulting, Ecole Polytechnique, 91128 Palaiseau Cedex France (33)169334128brouard@lms.polytechnique.fr

ABSTRACT
Interpretation of tightness tests in underground salt caverns is the main concern of this paper. Together with a liquid leak, several phenomena may explain the pressure drop observed after a cavern has been rapidly pressurized. They must be identified and quantified to allow a correct interpretation of the test results. The equations governing cavern brine warming, additional dissolution and rock mass transient creep are discussed. An in situ test is described and interpreted. It is proved that the results of numerical computations fit the results of the test, providing a sound basis for the interpretation of tightness tests.

INTRODUCTION
This paper deals with the transient behaviour of deep underground salt caverns. By "deep", we mean salt caverns whose depths range between 500m and 2000m. These caverns have been leached out from salt formations: a (typically) 1-km deep well is cased and cemented to the rock formation; its shoe is anchored to the top of the salt formation. A smaller central tube allows soft water injection at the bottom of the cavern; after leaching out of soluble rock-salt, brine is removed through the annulus between cemented casing and central injection tube. After one year or so, a 10,000 m^3 to 1,000,000 m^3 cavern has been created. In many cases the cavern is later used for hydrocarbon storage (crude oil, LPG or natural gas).

Our interest in salt transient creep is motivated by the need to correctly interpret tightness tests performed on storage caverns. Almost all solution-mined caverns are tested on a regular basis to prove the absence of significant leaks. Various tightness tests are currently used [1]. We focus on the simplest one: cavern pressure is built up to the testing figure, and pressure evolution as a function of time is recorded. A significant pressure drop is a clear sign of poor tightness. The key question thus becomes to ensure that pressure drop ("the apparent leak") is explained properly.

NOMENCLATURE
Key Words: Salt Cavern-Transient Creep-Tightness Test.

IDENTIFICATION OF FACTORS CONTRIBUTING TO AN APPARENT LEAK
Several phenomena contribute to brine pressure evolution in a closed cavern. A first group of phenomena pre-exist the test: they include ground and air temperature variations or atmospheric pressure variations and Earth tides (their effects are relatively small; some of them are more or less periodic and their effects can be neutralized by analyzing 24-hour long increments of the test.) More significant are brine thermal expansion (caverns are created by circulating cold soft water in a deep salt formation where geothermal temperature is warm.) and steady-state salt creep. A second group consists of test-triggered phenomena. They include transient brine permeation through the salt formation (pure rock salt permeability is exceedingly small; however salt-beds often contain a fair amount of insoluble rocks whose permeability is larger), additional dissolution (the amount of salt that can be dissolved in a given mass of water is a function of brine pressure; pressure build up in a closed cavern leads to additional dissolution; in the process the volume of cavern brine + dissolved salt decreases and pressure drops), brine cooling (a rapid pressure change leads to an instantaneous adiabatic

warming of cavern brine) and transient salt creep. A comprehensive account of these phenomena is provided in [2]; in the following we focus on the three main effects: brine thermal expansion, additional dissolution and transient creep.

ADDITIONAL DISSOLUTION

Consider a cavern filled with saturated brine. Cavern volume, brine volume, saturated brine concentration and density are $V_c^0, V_b^0, P_i^0, c_{sat}^0, \rho_{sat}^0$, respectively (Brine concentration, or c, is the ratio between the salt mass and the water + salt mass in a given volume of brine). At the beginning of the process, $V_c^0 = V_b^0$. Then a volume of brine, or v^{inj}, is injected in the cavern. After some time, the brine is saturated again and brine is said to have reached its "final state". Cavern pressure then is $P_i^0 + p_i^f$ and the other quantities are $V_c^f, V_b^f, c_{sat}^f, \rho_{sat}^f$. Brine concentration and density at saturation are function of pressure:

$$c_{sat}^f - c_{sat}^0 = c_{sat}^0 \psi p_i^f$$
$$\rho_{sat}^f - \rho_{sat}^0 = \rho_{sat}^0 a_s p_i^f \tag{1}$$

The salt-mass balance equation and the brine-mass balance equation can be written:

$$V_b^f \rho_{sat}^f c_{sat}^f = V_b^0 \rho_{sat}^0 c_{sat}^0 + \rho_{salt} v_{salt}$$
$$V_b^f \rho_{sat}^f = V_b^0 \rho_{sat}^0 + \rho_{sat} v_{salt} \tag{2}$$

where $\rho_{sat} v_{sat}$ is the mass of dissolved salt. These equations lead to:

$$v_{salt} = V_b^0 \frac{\rho_{sat}^0}{\rho_{salt}} \frac{c_{sat}^0}{1 - c_{sat}^0} \psi p_i^f = \lambda V_b^0 p_i^f \tag{3}$$

$$c_{sat}^0 = 0.2655, \rho_{sat}^0 = 1,200 kg/m^3, \rho_{salt} = 2160 kg/m$$

and $\psi = 2.6 \cdot 10^{-4}/MPa$ lead to $\lambda = 0.52 \cdot 10^{-4}/MPa$. Brine volume increase is:

$$V_b^f - V_b^0 = V_b^0(\frac{\rho_{salt}}{\rho_{sat}^0}\lambda - a_s)p_i^f \tag{4}$$

Now the change in cavern volume results from, on the one hand, the creation of new void, or v_{salt}, and, on the other hand, the cavern elastic volume increase or $\beta_c V_c^0$, where cavern compressibility factor, or β_c, is a function of cavern shape, rock salt Young modulus and Poisson ratio [3]:

$$V_c^f - V_c^0 = v_{salt} + \beta_c V_c^0 p_i^f = (\lambda + \beta_c)V_c^0 p_i^f \tag{5}$$

Taking into account $V_c^0 = V_b^0$, Eq.(4) and Eq.(5) lead to:

$$V_c^f = V_b^f + (\beta_c + a_s - \varpi)V_c^0 p_i^f \tag{6}$$

where $\varpi = \lambda \rho_{salt}/\rho_{sat}^0 - \lambda \approx 0.8\lambda$. Eq.5 and Eq.6 will be used later.

BRINE THERMAL EXPANSION

The temperature of rock increases with depth, a typical value being 45°C at a depth of 1000 m, but caverns are leached out using soft water pumped from shallow aquifers whose temperature is smaller. Brine temperature at the end of leaching

is close to the soft water temperature [2]. When the cavern remains idle, after leaching is completed, the initial temperature difference slowly resorbs with time, due to heat conduction in the rock mass and heat convection in the cavern. Appropriate heat-transfer equations can be written as follows:

$$\frac{\partial T}{\partial t} = k\Delta T$$
$$\int_\Omega \rho_b C_b \dot{T}_i d\Omega = \int_{\partial\Omega} K \partial T/\partial n da \tag{7}$$
$$T_i(t) = T_{wall}$$

The temperature in the rock mass is T; brine temperature is T_i. The first equation holds inside the rock-salt mass (k is the thermal diffusivity of salt, $k \approx 3 \cdot 10^{-6} m^{-2}$) ; the second equation is the boundary condition at cavern wall (K is the thermal conductivity of rock-salt, $K = 6$ W/m/°C is typical, and $\rho_b C_b = 4.8 \ 10^{-6}$ J/m³/°C is the volumetric heat capacity of brine). The third equation stipulates that rock temperature at cavern wall is equal to the average brine temperature in the cavern, a reasonable assumption as thermal convection stirs brine cavern effectively. The exact temperature evolution can easily be predicted through numerical computations. Back-of-the envelope estimations can be reached simply: dimensional analysis proves that heat transfer is governed by one characteristic time, $t_c = V_c^{2/3}/4k$, or $t_c(years) \approx V_c^{2/3}(m^2)/400$. In the case of a roughly spherical cavern, t_c is the time after which approximately 75% of the initial temperature difference has been resorbed. When $V_c = 8,000$ m³, $t_c \approx 1 year$. In a opened cavern, a temperature increase leads to thermal expansion and brine outflow at ground level, $Q = \alpha V_c \dot{T}_i$, where α is the brine thermal expansion coefficient, $\alpha \approx 4.4 \cdot 10^{-4}/°C$. In other words, when the initial temperature difference between rock mass temperature and brine temperature is $T_R - T_{i0}$, the average brine outflow during a $t_c -$ long period is $Q_{average}(in \ m^3/h) =$ $0.75\alpha V_c(T_R - T_{i0})/t_c = 1.32 V_c^{1/3}(in \ m)(T_R - T_{i0})(in °C)$.

STEADY-STATE AND TRANSIENT CREEP
Introduction
At this step, a few comments on the mechanical behaviour of salt are helpful. No other rock has given rise to such a comprehensive set of lab experiments, motivated, to a large extent, by the specific needs of nuclear waste storage – see, for instance, the proceedings of the five Conferences on the Mechanical Behaviour of Salt ([4] to [8]). Outstanding contributions were made by Professor Cristescu [9].
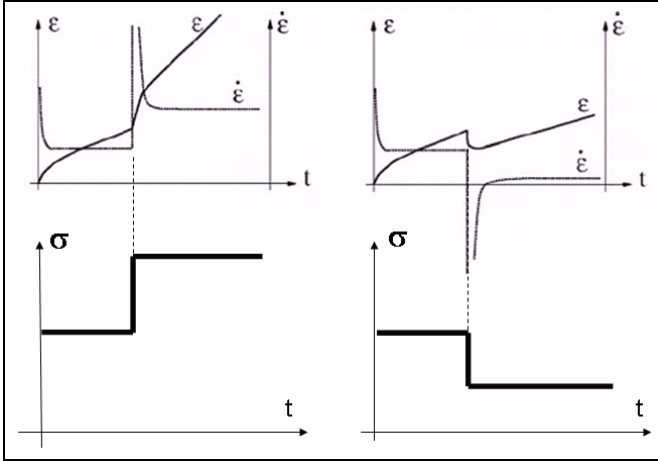
Figure 1. Strain and strain rate as a function of time during a creep test.

Most experts agree on the main features of steady-state rock-salt behaviour:

a) In the long term, rock-salt flows even under very small deviatoric stresses

b) Creep rate is a highly non-linear function of applied deviatoric stress and temperature

c) Steady-state creep is reached after several weeks or months when a constant load is applied to a sample; it is characterized by a constant creep rate.

d) Transient creep is triggered by any rapid change in the applied stress. Transient creep is characterized by high initial rates (following a load increase) or by "reverse" initial rates (following a load decrease; "reverse creep" refers to a transient sample height increase following a decrease in the applied stress during an uniaxial test performed on a cylindrical sample) that slowly decrease or increase to reach steady-state creep (Fig.1).

Steady-state creep

Main features of steady-state creep are captured by the following simple model (Norton-Hoff power law):

$$\dot{\varepsilon}_{ss}^{ij} = A \exp(-\frac{Q}{RT})\frac{1}{n+1}\frac{\partial}{\partial \sigma_{ij}}\left[(\sqrt{3J_2})^{n+1}\right] \quad (8)$$

Where J_2 is the second invariant of the deviatoric stress tensor; A, n, Q/R are model parameters. Values of these parameters were collected by Berest and Brouard [10]: for 12 different salts, the constant n is in the range n = 3-6, illustrating the highly non-linear effect of the applied stress on the strain rate. Note that when a cavern (instead of a cylindrical sample) is considered, "transient" behaviour can be observed following a cavity pressure change – although Norton-Hoff constitutive behaviour includes no transient rheological behaviour. The reason is that after a pressure change, stress redistribute slowly inside the rock mass. Such a transient behaviour is called "geometrical".

Munson transient model

The Norton-Hoff model does not account for rheological transient creep. Better accounting for in situ observations require that transient creep be incorporated in the constitutive model. Munson and Dawson [11] suggested the following model:

$$\dot{\varepsilon}_{vp}^{ij} = F\dot{\varepsilon}_{ss}^{ij} \quad \begin{array}{l} F = e^{\Delta(1-\varsigma/\varepsilon_t^*)^2} when \ \varsigma \leq \varepsilon_t^* \quad (9) \\ F = e^{-\delta(1-\varsigma/\varepsilon_t^*)^2} when \ \varsigma \geq \varepsilon_t^* \end{array}$$

$$\dot{\varsigma} = (F-1)\dot{\varepsilon}_{ss}, \quad \dot{\varepsilon}_{ss} = \sqrt{3J_2}$$

$$\varepsilon_t^* = K_0 e^{cT}\sigma^m \ and \ \Delta = \alpha_w + \beta_w Log_{10}\sigma/\mu \quad , \delta = \delta_0$$

Note that this model accounts for "transient" creep, but predicts no "reverse creep" following a stress decrease.

A modified version of the Munson model

Munson et al. [12] suggested a modified model taking into account the onset of "reverse creep" following a stress drop (i.e., a rapid pressure build up in a closed cavern). We propose a slightly modified version of this law that allows for simple computations:

$$F = 1 - (1-\varsigma/\varepsilon_t^*)^p/(1-k)^p \ when \ \varsigma \geq \varepsilon_t^* \quad (10)$$

And reverse creep appears when $\varsigma > k$.

A TEST ON THE EZ 53 CAVERN

We consider now an in situ test, first described by Hugout [13], which allows to illustrate the various factors described above. The EZ53 cavern was leached out during the Spring of 1982 from the Etrez salt formation in France where Gaz de France operates natural gas storage caverns. It is a small cavern (7,500 +/500 m³) and its average depth is H = 950-m. At this depth, rock temperature is 45°C. At the end of leaching phase, average cavern brine temperature was 26.5°C. Cavern was kept idle after the leaching phase was completed. Cavern brine slowly warms up; temperature was recorded from time to time. As explained above, brine warming results in brine outflow from the open well-head. The cavern brine temperature was 35.22°C on September 8, 1982 (day 94 after leaching ended) and 36.09°C on day 123. The average temperature increase rate during this period was 0.032°C/day, a figure consistent with back-of-the-envelope calculations (see above) and a Q = 100

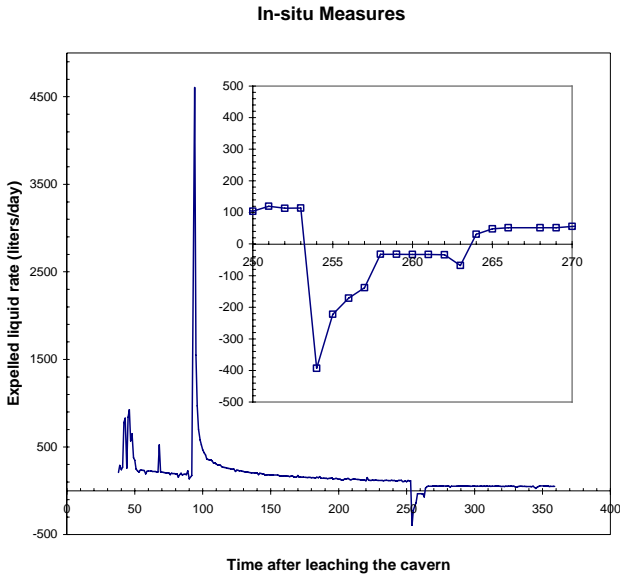litres/day brine outflow rate could be expected.

In-situ Measures

Figure 2. Liquid outflow rate (as observed)

In fact the actual rate was a little faster (Fig.2); it is suspected that the difference was due to creep-induced cavern shrinkage. The annular space was filled with a light hydrocarbon (whose density was $\rho_h = 850$ kg/m^3). Hydrocarbon pressure at the well-head was approximately $p = g\ H\ (\rho_b - \rho_h) = 3.4$ MPa (no pressure did exist at the brine-filled central tube well-head, which was opened to atmosphere, allowing brine to outflow from the cavern). On day 93, a valve was opened at the well-head to partially remove the hydrocarbon; the hydrocarbon pressure at the well head suddenly dropped to atmospheric pressure; the air/brine interface in the central string dropped by $h = p\ /\ g(\rho_b - \rho_h) = 290$ m to balance the pressure drop in the annular space.

The hydrocarbon outflow rate was measured from day 93 to day 254 (Fig. 2). During a dozen of days, the hydrocarbon flow-rate is very fast, a clear sign of large transient effects in the cavern (the main effects are transient creep and additional crystallization). The flow more or less stabilizes after this initial period. It was larger than what the brine flow was before the pressure drop, a clear proof of the effect of cavern pressure on cavern creep rate (at a 950-m depth, the geostatic pressure is $P\infty = 21$ MPa. Cavern pressure was $P_i = 11.4$ MPa before the pressure drop (brine density is $\rho_b = 1200$ kg/m^3) and $P_i = 11.4 - 3.4 = 8$ MPa after the pressure drop; in the idealized case of a spherical cavern, Norton-Hoff law, see Eq.(9), predicts that steady-state cavern volume loss is:

$$\dot{V}_c / V_c = -\frac{3}{2}(\frac{3}{2n})^n \exp(-\frac{Q}{RT})(P_\infty - P_i)^n$$

a simple relation which captures the non-linear influence of the cavity brine pressure, or P_i). The initial cavern pressure, or $P_i = 11.4$ MPa, was restored on day 253. This phase of the test is of special interest as it simulates the effect of a rapid cavern pressure increase. The annular space was closed at the well-head and the central tubing was filled with brine (Fig. 2). After this injection was completed, the brine level dropped in the central tubing (an effect of additional dissolution and transient

cavern creep). Every 24 hours, brine was added to fill the central tubing. The daily amount of brine to be added gradually decreased, as transient effects slowly vanish. Eventually, 10 days after the first filling took place (day 263), brine was again expelled from the well-head and a constant brine-flow rate was observed, equivalent to 52 litres per day. The difference between the 100-litres per day outflow observed before the pressure drop (day 93) and the 52 litres per day observed a couple of weeks after cavern pressure was restored (day 270) is because brine thermal expansion is less and less active.

We focus now on transient phenomena, which are especially effective during the day 253 to 263 period. During this period brine was injected in the cavern (during days 253 to 261) or expelled from the cavern (during days 262 and 263). The total amount of brine injected (+) or withdrawn (-) during this period was carefully measured: -393-222-171-138-32-32-33-33-34-68+31+48 = -1077 litres (Note how rapidly injected brine flow-rate decreases at the beginning of this transient phase).

Thermal expansion and additional dissolution.
During the same 12-day period, the brine expelled flow due to brine warming should have been 52 litres/day (as it will be a few days later), or 624 litres during the 12-day period. As a whole, the cavern volume increase is $1077 + 624 = 1700$ litres. A part of this volume increase is due to additional dissolution. At the beginning of this phase, brine was poured into the central tubing, resulting in an increase in cavern pressure by $p = 3.4$ MPa. The injection was rapid; no additional dissolution had time to take place during the injection. The initial amount of injected brine was $v_0^{inj} = \beta_c V_c^0 p + hS_t$, where S_t is the cross sectional area of the central string. In the following days, brine was injected in the cavern to keep cavern pressure constant or $p = p_i^f$. The volume of brine to be injected to balance the effect of additional dissolution is $v^{inj} - v_0^{inj} = (a_s - \varpi)V_c^0 p$, or 444 litres when $V_c^0 = 7500 m^3$ and $p = 3.4\ MPa$. In other words, transient creep is responsible for a cavern volume increase by $1700 - 444 = 1350$ litres (or a fraction of $1.8\ 10^{-4}$ of the overall volume). This volume increase is spread over a 10-day long period of time. After this period, cavern volume decreases again.

Transient creep
In order to analyze the effects of transient creep, numerical computations were performed. Cavern creation is simulated by a 3-month long linear decrease in cavern pressure from the geostatic figure to $p_i = 11.4$ MPa. Brine temperature at the end of the leaching phase is $T_i = 26.5$ °C. Pressure history is as during the actual test. Brine warming and additional dissolution or crystallization (following a pressure change) are taken into account. Brine volume change rate due to additional dissolution is assumed to vary as follows: $Q = v\ \exp(t/t_0)/t_0$ where $t_0 = 2.5$ days. Transient behaviour is successively taken into account

through the three above mentioned constitutive laws.
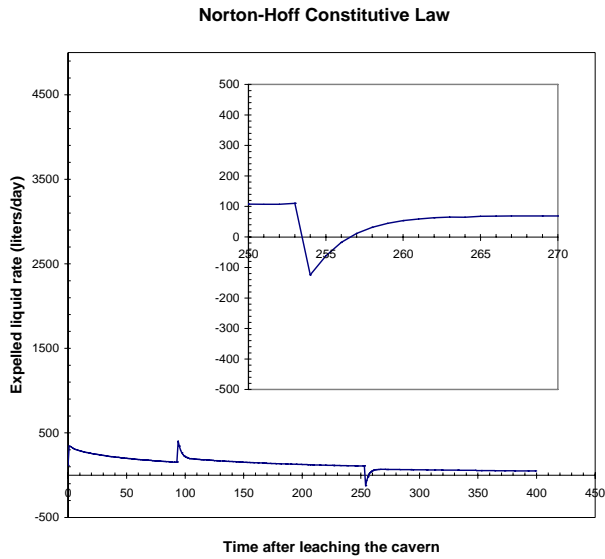
Norton-Hoff Constitutive Law

Figure 3. Expelled liquid rate when Norton-Hoff constitutive law is considered.

This first model (Fig.3) takes into account brine thermal expansion, additional dissolution and steady-state creep(Norton-Hoff law). The mechanical model parameters were $E = 25,000$ MPa, $\nu = $ O.25, $A = 0.64$ /MPa$^{3.1}$/year, $n = 3.1$, $Q/R = 4100$ K; these figures were obtained from laboratory tests performed on Etrez salt samples. The model is not able to describe the transient evolutions following pressure changes.
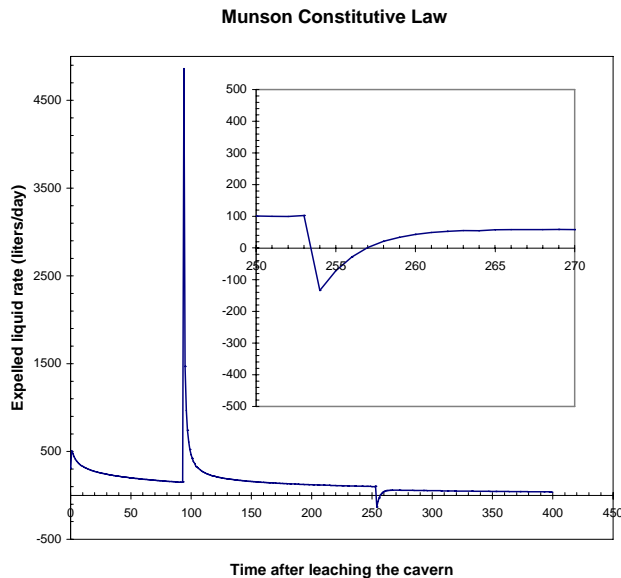
Munson Constitutive Law

Figure 4. Expelled liquid rate when Munson constitutive law is considered

The second model (Fig.4) includes Munson-Dawson transient creep model. The model parameters were: m = 3.5, $K_0 = 6.7$ 10^{-11} /MPa$^{3.5}$, C = 0.0315, $\alpha_w = 10$, $\beta_w = 0$, $\delta = 0.58$. These

figures were partly obtained from laboratory tests; figures published in the literature were also used. The effect of a pressure drop is correctly captured. The "reverse" volume increase (negative brine outflow) observed after the day 253 pressure build-up is due to additional dissolution alone.

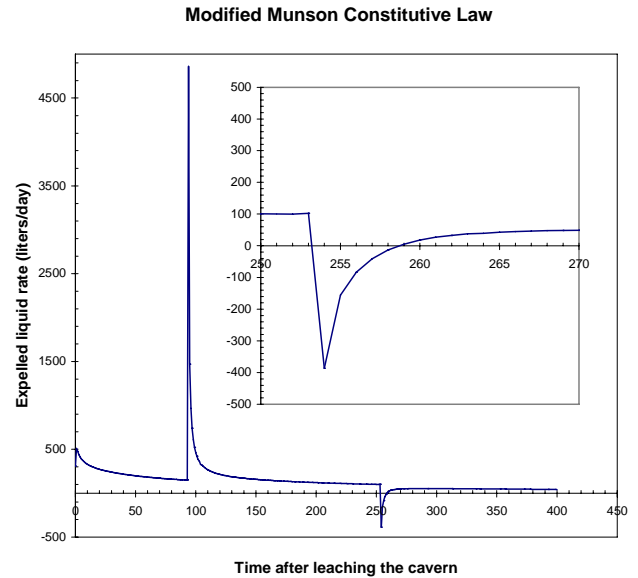**Modified Munson Constitutive Law**

Figure 5. Expelled liquid rate when Munson modified constitutive law is considered.

The third model (Fig.5) includes the modified Munson-Dawson model to reach a better description of transient "reverse" creep following a cavern pressure build-up. The model parameters are p = 5 and k = 4. These figures result partly from a (single) creep test performed on an Etrez salt sample; back-calculations also were used to reach a better agreement with in situ data.

CONCLUSION

The changes in the expelled brine flow-rate observed after a rapid pressure build-up in an underground salt cavern have been discussed. The effects of brine thermal expansion (an effect pre-existing the rapid pressure build-up), additional dissolution and transient "reverse" creep (two effects triggered by the rapid pressure build-up) were described and quantified. A good agreement between observed and calculated flow was reached, providing a sound basis for the interpretation of tightness tests.

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