

**INFLUENCE OF THE LEACHING PHASE ON THE
MECHANICAL BEHAVIOR OF SALT CAVERNS**

B. Brouard, P. Bérest, J. Couteau

Laboratoire de Mécanique des Solides
(Centre commun X-Mines-Ponts, U.R.A 317 du C.N.R.S.)
Ecole Polytechnique, 91128 Palaiseau Cedex

ABSTRACT

Big caverns can be leached out from salt formations. During the leaching process, cold water is injected in the cavern through tubing; warmer brine is withdrawn through an annular space. Thermal balance is relatively intricate, because salt dissolution is an endothermic process, whereas brine and water exchange heat through the steel tubing inside the well. As a whole, the rock mass is cooler around the cavern after leaching than before, resulting in a small reduction of cavern creep.

INTRODUCTION

The fundamentals of salt leaching in the context of solution mining have been laid down by Durie and Jessen (1964^a, 1964^b), Kazemi and Jessen (1964), and Sears and Jessen (1966), who proved that the rate of salt removal from a cavern wall is related to the brine concentration in the cavern's main body. Pottier and Esteve (1973) used these results to develop a simple model that provides shape variation, brine quality and flow rate versus time. Similar models have been presented by Saberian (1974) and, more recently, by Guarascio (1996). Here, we use a simplified version of the Pottier-and-Esteve (1973) model adapted for a cylindrical cavern.

Fluid temperature evolution in petroleum wells has not been given much attention. (A recent interesting exception is the paper by Maury and Guenot, 1995.) In the case of cavern leaching, Kunstman and Urbańczyk (1995) have discussed the main phenomena that affect salt and brine temperatures in a cavern and in pipes during dissolution. In the following, we adopt a simplified formulation (for a spherical cavern whose volume is equal to the volume of the real cavern) similar to Pottier's, as it is described in *Manuel pour le transport et la distribution du gaz* (1985). It allows for calculations of brine and rock salt temperature evolutions during solution mining of a cavern. A simple estimation of temperature effects on cavern creep rate is also presented.

MASS BALANCE

Let c be the brine concentration (i.e., the mass of salt contained in a unit volume divided by the mass of brine contained in a unit volume) and ρ_b be the brine density. The brine density is a function of concentration (and temperature). For a saturated brine, $\rho_b \approx 1200 \text{ kg/m}^3$; for soft water, $\rho_w \approx 1000 \text{ kg/m}^3$. A simple approximation is sufficiently accurate for all practical purposes:

$$\begin{cases} \rho_b(c) = \rho_w + \lambda c \\ \lambda \approx 738.5 \text{ kg/m}^3 \end{cases}$$

The volume of a cylindrical cavern is $V = \pi R^2 h$; the cavern height h is supposed to be constant, for cavern top and cavern bottom are protected from leaching by a fluid blanket and a layer of stratified insolubles, respectively. If c is the average brine concentration in the cavern, $\rho_b V c$ and $\rho_b V (1 - c)$, respectively, stand for the dissolved salt mass and the water mass contained in the cavern (Figure 1).

Two mass-balance equations can then be written. First, the water-balance equation stipulates that the amount of water in the cavern at time t — namely, $\rho_b V(1-c)$ — is modified by a $(\rho_w q_w)$ -water-injection flow inside the cavern and by a $(\rho_b q_b)$ -brine-withdrawal flow from the cavern:

$$\frac{d}{dt} \{ \rho_b V(1-c) \} = \rho_w q_w - (1-c) \rho_b q_b$$

Second, the salt-balance equation stipulates that the amount of salt in the cavern is modified by the $(\rho_b q_b)$ -brine withdrawal and by leaching of the salt wall, which brings a $(\rho_{salt} \dot{V})$ -mass of salt in the cavern:

$$\frac{d}{dt} \{ \rho_b V c \} = \rho_{salt} \dot{V} - c \rho_b q_b$$

Some straightforward algebra leads to the formula

$$\rho_b V \dot{c} = (1-c) \rho_{salt} \dot{V} - c \rho_w q_w \quad (1)$$

We now need a physical law that governs the leaching rate — i.e., the derivative \dot{V} . Because the brine in the cavern main body is assumed to be homogeneous (Of course, brine is not homogeneous in a thin boundary layer at the cavern wall.), we can follow the Duries-and-Jessen assumption (1964^a, 1964^b) that states that the leaching rate is a given function of the brine concentration:

$$\begin{aligned} \dot{R} &= \varphi(c) \\ \left\{ \begin{array}{l} \varphi(c) = A_o [\gamma(c_{sat}) - \gamma(c)]^{\frac{5}{4}} \{ 1.70 + 0.26 [\gamma(c_{sat}) - \gamma(c)] \} \\ A_o = 9.77 \cdot 10^{-2} D^{\frac{3}{4}} (\mu_b h)^{-\frac{1}{4}} / \rho_{salt} \\ \gamma(c) = \frac{\rho_b(c) c}{M_{NaCl}} \quad (\text{mol/liter}) \\ c_{sat}(T_b, P_c) = c_o [1 + a_1 (T_b - T_o) + a_2 (T_b - T_o)^2 + a_3 (P_c - P_{atm})] \end{array} \right. \quad (2) \end{aligned}$$

where γ is the molar concentration of the brine, T_b is the temperature of the brine, P_c is the absolute brine pressure in the cavern, and P_{atm} is the atmospheric pressure.

$$\left\{ \begin{array}{lll} D \approx 1.3 \cdot 10^{-9} \text{ m}^2/\text{s} \quad (\text{diffusivity}) & \mu_b \approx 1.2 \cdot 10^{-3} \text{ Pa}\cdot\text{s} \quad (\text{viscosity}) & T_o = 25 \text{ }^\circ\text{C} \\ \rho_{salt} \approx 2165 \text{ kg/m}^3 & M_{NaCl} = 58.5 \text{ g/mol} & c_o \approx 0.2655 \\ a_1 \approx 4.07 \cdot 10^{-4} \text{ }^\circ\text{C}^{-1} & a_2 \approx 7.42 \cdot 10^{-6} \text{ }^\circ\text{C}^{-2} & a_3 \approx 2.62 \cdot 10^{-6} \text{ MPa}^{-1} \end{array} \right.$$

The brine concentration evolution is governed by the equation:

$$\rho_b V \dot{c} = (1-c) \rho_{salt} S \varphi(c) - c \rho_w q_w \quad (3)$$

where $S = dV/dR = 2\pi R h$ is the cavern wall area. For example, if the water injection rate, q_w , is kept constant and if the cavern brine is saturated at the beginning of leaching, the wall leaching rate, $\dot{R} = \varphi(c)$, is small and $\dot{c} < 0$. Then, with leaching continuing, the leached area, S , and the salt removal rate, $\dot{R} = \varphi(c)$, increase, and \dot{c} vanishes to zero when the salt production rate, $(\rho_{salt} S \varphi(c))$, and the water injection rate, $(\rho_w q_w)$, are proportional to the amount of salt and water in the brine (c and $(1-c)$, respectively). Then \dot{c} becomes positive, and brine density will slowly increase to saturated brine density.

EXAMPLE

An example is provided in Figure 2. The cavern is 100-m high; at $t = 0$, the well is 20 cm in diameter and is filled with saturated brine. For two months, a $20\text{-m}^3/\text{h}$ flow of soft water is injected in the cavern, resulting in a rapid brine concentration decrease followed by a slower increase. After two months, water injection is stopped for 15 days; then injection is resumed. During this last phase, several different water injection rates are considered.

HEAT BALANCE

In order to apply the heat-balance equation, we assimilate now the cavern to a spherical body whose radius a is such that $V = \pi R^2 h = 4\pi a^3/3$. This approximation allows for a better account of the 3-D character of the problem and for easier calculations. The approximation is poor when leaching begins and the cavern is slender; and much better when cavern height and cavern radius are of the same order of magnitude. Let $a(0)$ be the sphere radius at time $t = 0$, $a(t)$ the sphere radius at time t , and $\rho > a(t)$ the radius of a sphere which encloses the cavern as it develops from $t = 0$ to time t . Then, due to four factors, the amount of heat contained in the spherical box, radius ρ , increases during the interval of time between 0 and t :

1. fresh water injection through the tubing. If T_w is the water temperature, the corresponding heat input is

$$Q_w = \int_0^t C_w \rho_w q_w T_w dt$$

2. brine withdrawal through the annular space. If T_b is the brine temperature in the cavern, the corresponding heat output is

$$Q_b = - \int_0^t C_b \rho_b q_b T_b dt$$

3. heat production due to the *endothermal* process of salt (halite plus sulphates) leaching. If L_{salt} is the dissolution heat ($L_{salt} < 0$), the total heat output is

$$Q_d = \int_0^t L_{salt} \rho_{salt} dV$$

4. heat conduction through the cylindrical box wall, or

$$Q_c = \int_0^t \tilde{S} K \frac{\partial \theta}{\partial r}(\rho) dt$$

where K is rock salt thermal conductivity, $\tilde{S} = 4\pi a^2$ is the spherical cavern wall area, $\theta = \theta(r, t)$ is the temperature in the salt mass, and $\frac{\partial \theta}{\partial r}$ is the temperature gradient.

Heat-balance equation

These four heat-production (or withdrawal) processes bring a temperature change in this spherical box, which can be written

$$H = \left[C_b \rho_b V T_b + \int_a^\rho \rho_{salt} C_{salt} \tilde{S}(r) \theta(r, \tau) dr \right]_0^t$$

The heat balance equation, $Q_w + Q_b + Q_c + Q_d = H$, can be derivated with respect to time, and ρ can be taken equal to $a(t)$:

$$\rho_w q_w C_w T_w - \rho_b q_b C_b T_b + L \rho_{salt} \dot{V} + \tilde{S} K \frac{\partial \theta}{\partial r}(a) = \frac{d}{dt} (\rho_b V C_b T_b) - \dot{V} \rho_{salt} C_{salt} T_b$$

It is convenient to take into account the mass-balance equations to derive the following relation:

$$\rho_b V \frac{d}{dt} (C_b T_b) = \rho_w q_w (C_w T_w - C_b T_b) + \tilde{S} K \frac{\partial \theta}{\partial r}(a) + \rho_{salt} \dot{V} (L + T_b C_{salt} - C_b T_b)$$

Taking into account the following approximation,

$$\begin{cases} C_b = (1 - c) C_w + c C_{salt} \\ C_w \approx 4186 \text{ J/kg/}^\circ\text{C} & C_{salt} \approx 875 \text{ J/kg/}^\circ\text{C} \end{cases}$$

then

$$\rho_b C_b V \dot{T}_b = \rho_{salt} L \dot{V} + \tilde{S} K \frac{\partial \theta}{\partial r}(a) - \rho_w C_w q_w (T_b - T_w) \quad (4)$$

The three terms (contributions of dissolution, conduction and forced convection, respectively, to cavern temperature change) that appear on the right-hand side of (4) will be discussed below. Notice that when there is no water injection ($q_w = 0$), brine becomes saturated and the cavern volume reaches a constant value, $\dot{V} = 0$. The temperature evolution satisfies a simpler relation:

$$\rho_b C_b V \dot{T}_b = \tilde{S} K \frac{\partial \theta}{\partial r}(a) = \Phi$$

(see, for example, Berest et al, 1979).

Salt dissolution

If the salt is pure (i.e., if it contains NaCl only), then its dissolution into water is *endothermal*. The dissolution heat for NaCl is a function of the concentration, c , and the temperature, T_b , of the brine. In the calculation $L_{NaCl} = -10$ kJ/kg has been selected, but some authors (Manuel pour le transport et la distribution du gaz, 1985) propose a larger value.

If the salt is not pure and, particularly if it contains a small amount of calcium sulphate (CaSO₄), the dissolution become less endothermal, because the dissolution of anhydrite is very exothermal — its dissolution heat typically $\approx +162$ kJ/kg.

The maximum ratio X_{CaSO_4} (i.e., the mass of $CaSO_4$ contained in a unit mass of brine) is given by the polynomial approximation:

$$X_{CaSO_4} = a_0 + a_1 c + a_2 c^2 + a_3 c^3 \quad (5)$$

with

$$\begin{cases} a_0 = 2.5 \cdot 10^{-3} & a_1 = 9.96 \cdot 10^{-2} \\ a_2 = -0.642 & a_3 = 1.125 \end{cases}$$

Then, the heat equation becomes:

$$\begin{aligned} \rho_b C_b V \dot{T}_b &= -\rho_w C_w q_w (T_b - T_w) + \tilde{S} K \frac{\partial \theta}{\partial r}(a) + \rho_{salt} L_{NaCl} \dot{V} \\ &+ \left\{ q_b \rho_b X_{CaSO_4} + \frac{d}{dt} [\rho_b V X_{CaSO_4}] \right\} L_{CaSO_4} \end{aligned} \quad (6)$$

Thus, the heat that is necessary to dissolve one kilogram of impure salt is

$$L = L_{NaCl} + \frac{L_{CaSO_4}}{\rho_{salt} \dot{V}} \left\{ \rho_b V \dot{X}_{CaSO_4} + \rho_w q_w X_{CaSO_4} \right\} + L_{CaSO_4} X_{CaSO_4}$$

Heat conduction

★ The solution for the problem of the **sphere** with surface $r = a$ at constant temperature θ_o before $t = 0$, and constant temperature $\theta_o + T_o$ after $t = 0$, is given in Carslaw and Jaeger (1959):

$$\theta(r, t) = \theta_o + T_o \frac{a}{r} \operatorname{erfc} \frac{r - a}{\sqrt{4kt}}$$

Thus, the rock mass temperature (and then flux at cavern wall) can be computed as follows:

$$\theta(r, t) = \theta_o + \int_0^t \frac{\partial \theta}{\partial t}[a(\tau), \tau] \frac{a(\tau)}{r} \operatorname{erfc} \frac{r - a(\tau)}{\sqrt{4k(t - \tau)}} d\tau \quad (7)$$

where

$$\begin{aligned} \frac{\partial \theta}{\partial t} &= \dot{T}_b - \dot{a} \frac{\partial \theta}{\partial r} \\ \Phi = \tilde{S}(t) K \frac{\partial \theta}{\partial r}(a) &= \tilde{S}(t) K \left\{ \frac{\theta_o - \theta[a(t), t]}{a(t)} + \right. \\ &\left. \int_0^t \frac{\partial \theta}{\partial t}[a(\tau), \tau] \frac{a(\tau)}{a(t)} \frac{1}{\sqrt{k\pi(t - \tau)}} \exp \left[-\frac{(a(t) - a(\tau))^2}{4k(t - \tau)} \right] d\tau \right\} \end{aligned} \quad (8)$$

★ For the problem of the **cylinder** with surface $r = R$ at constant temperature T_o , the solution is

$$\begin{cases} \theta(r, t) = \theta_o + T_o \Upsilon \left(\frac{r}{R}, t \right) \\ \Upsilon \left(\frac{r}{R}, t \right) = 1 + \frac{2}{\pi} \int_0^{+\infty} e^{-ku^2 t} \frac{J_o(ur) Y_o(uR) - Y_o(ur) J_o(uR)}{J_o^2(uR) + Y_o^2(uR)} \frac{du}{u} \end{cases}$$

The flux at the surface is also given by

$$\left\{ \begin{array}{l} \Phi = -S(t)K \left[\frac{\partial \Upsilon(s, t)}{\partial s} \right]_{s=1} \\ \frac{\partial \Upsilon}{\partial r}(1, t) = \frac{-4}{\pi^2 R} \int_0^{+\infty} e^{-ku^2 t} \frac{du}{u [J_o^2(uR) + Y_o^2(uR)]} \end{array} \right.$$

It results that rock mass temperature (and then flux) can be computed as follows:

$$\theta(r, t) = \theta_o + \int_0^t \frac{\partial \theta}{\partial t}[a(\tau), \tau] \Upsilon \left(\frac{r}{R(t - \tau)}, t - \tau \right) d\tau \quad (9)$$

Thermal behavior of the well

In discussing the thermal behavior of the well, as a first approximation, thermal exchanges between the well and the rock mass are slow and negligible when compared to thermal exchanges between the downward flowing cold water and the rising warm brine. (This approximation may not hold true at the very beginning of a leaching phase.) As a second approximation, we assume that the injected cold water temperature, T_w^o , and the cavern brine temperature, $T_b = T_b(H)$, vary slowly when compared to the transit time of fluids in the well. In other words, it can be assumed that, at every instant, steady-state thermal equilibrium is reached in the well.

Let $T_w(z)$ be the water temperature — in particular, the temperature of the injected water is $T_w^o = T_w(0)$ and the temperature of the water entering the cavern at the bottom of the well at $T_w = T_w(H)$. Similarly, $T_b(z)$ is the brine temperature in the well; d is a diameter.

In the central tubing (through which soft water descends) and in the annular space (through which warm brine rises), the fluid temperatures are modified due to the following:

1. the heat conduction through the steel tubing and the boundary layers at the tubing wall in brine and soft water;
2. the heat production associated with head losses in the tubes.

With regard to item 1, an equivalent heat-transfer coefficient, \bar{K} , is used. This coefficient is a function of steel thermal conductivity, tubing thickness, fluid flow rates and thermal properties. With regard to item 2, the temperature increase is quite simply related to head losses:

$$\Delta = \pm \rho C v \frac{\partial T}{\partial z}$$

where ρC is the volumetric heat capacity of the fluid ($\text{J/m}^3/^\circ\text{C}$), $v = Q/\Sigma$ is the fluid speed (m/s), and $\Delta > 0$ is the head loss per unit of length in the tube (Pa/m). The “plus” sign holds for a downward movement (tubing) and the “minus” sign holds for an upward movement (annulus). The following approximations are adopted

(Pottier-and-Esteve, 1973).

$$\begin{cases} \Delta_w &= 0.61 \cdot 10^{-7} (\rho_w)^{0.85} \nu_w^{0.196} q_w^{1.80} d_{min}^{tubing}^{-4.65} \\ \Delta_b &= 0.285 \cdot 10^{-7} (\rho_b)^{0.85} \nu_b^{0.196} q_b^{1.85} [(d_{min}^{ann} - d_{max}^{tubing})^{-3.10} (d_{min}^{ann} + d_{max}^{tubing})^{-1.85}] \end{cases} \quad (10)$$

If we set $\delta_i = \frac{\Delta_i}{\rho_i C_i}$ and $m_i = \frac{\pi d \bar{K}}{q_i \rho_i C_i}$ in each fluid, then the thermal balances read:

$$\begin{cases} \frac{\partial T_w}{\partial z} - \delta_w &= m_w [T_b(z) - T_w(z)] \\ \frac{\partial T_b}{\partial z} + \delta_b &= m_b [T_b(z) - T_w(z)] \end{cases} \quad (11)$$

From these last relations, a straightforward calculation leads to

$$T_b - T_w = \frac{\delta_b + \delta_w}{m_b - m_w} [1 - \exp(\mu H)] + (T_b^o - T_w^o) \exp(\mu H)$$

and

$$T_b - T_w = \frac{\mu E}{m_b E - m_w} (T_b - T_w^o) - \frac{\mu E H (m_b \delta_w + m_w \delta_b) + m_w (1 - E) (\delta_b + \delta_w)}{\mu (m_b E - m_w)} \quad (12)$$

where $E = \exp(\mu H)$ and $\mu = m_b - m_w$.

If head losses can be disregarded,

$$T_w - T_w^o = (T_b - T_w^o) \frac{1 - E}{1 - \left(\frac{m_b}{m_w}\right) E} \quad (13)$$

The equivalent heat-transfer coefficient has been calculated for a 5" by 7^{1/8}" well completion. Steel conductivity is assumed equal to $\bar{K}_{steel} = 54 \text{ W/m/}^\circ\text{C}$ and the tubing width is 6.5 mm. For a 100 m³/h water flow, we get $\bar{K} = 3350 \text{ W/m}^2/\text{}^\circ\text{C}$. With $\rho_b C_b = 3.89 \cdot 10^6 \text{ J/m}^3$, $\rho_w C_w = 4.18 \cdot 10^6 \text{ J/m}^3$ we obtain approximately $m_w \approx 1.03 \cdot 10^{-2} \text{ m}^{-1}$, $m_b \approx 1.22 \cdot 10^{-2} \text{ m}^{-1}$. (The figures vary throughout the leaching period.) Finally, $\mu \approx 0.19 \cdot 10^{-2} \text{ m}^{-1}$ (but is significantly less at the beginning of leaching). This means that at a depth of 1000 meters, the temperature gap between brine and water is 8 times larger at the well bottom than at the well head; the difference increases when the cavern is enlarged. Noticed that if we call $\alpha = \pi d \bar{K}$, then $\alpha \approx 1350 \text{ W/m/}^\circ\text{C}$ instead of 205 to 500 W/m/°C, which have been suggested by Kunstman and Urbańczyk (1995).

EXAMPLES OF TEMPERATURE HISTORIES

Figure 3 provides a typical example. The injected water temperature (20 °C) can be considered as the original temperature; the cavern brine temperature and the brine temperature at the well-head are represented with respect to time.

Figure 4 shows the influence of cavern depth.

Figure 5 shows the respective effects of (1) heat conduction, (2) salt dissolution, and (3) heat exchanges through the steel tube.

MECHANICAL BEHAVIOR OF CAVERNS

From a mechanical perspective, the stresses and strain distributions in the rock mass are governed by three main phenomena: (1) instantaneous elastic behavior of rock salt, (2) thermal expansion of rock salt, and (3) rock salt creep, which is a non-linear function of both the applied deviatoric stress and the temperature. The mechanical loading encompasses lower pressure in the cavern and lower temperature at the cavern wall. The temperature effect is two-fold: cooling of the rock mass at the cavern-wall mitigates the large compressive tangential stresses generated by the low pressure in the cavern, and it slows down salt creep. In the following only the last phenomenon is considered; salt creep is assumed to be a non-linear function of the deviatoric stress (here T is expressed in Kelvin degrees):

$$\dot{\epsilon}_{ij} = \frac{\partial}{\partial \sigma_{ij}} \left[A_o \exp\left(-\frac{Q}{R_o T}\right) \right] \left(\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \right)^n \quad (14)$$

If we assume spherical symmetry, $\sigma_\theta = \sigma_\varphi$, the flow rate takes the special form $v = -\frac{C(t)}{r^2}$ due to material incompressibility, and we have the relation

$$\begin{cases} C(t) = \frac{1}{2} \left[\frac{\sigma_i - \sigma_\infty}{I(t)} \right]^{n-1} \\ I(t) = \int_{a(t)}^{\infty} \left\{ \frac{\exp \frac{Q}{R_o T(u)}}{n A_o u^3 (\sqrt{2})^n} \right\}^{\frac{1}{n-1}} \frac{2du}{u} \end{cases} \quad (15)$$

In other words, the relative loss of volume at time t will be

$$\frac{\Delta V}{V} = \frac{3}{a^3(t)} \int_0^t C(\tau) d\tau$$

The values of the parameters that appear in (14) can be easily deduced from the following field observations. At a depth of 1000 m, the lithostatic pressure is 22 MPa, the halmostatic pressure (i.e., the brine pressure in the cavern if the well is filled with brine to ground level and opened to the atmosphere) is 12 MPa, and the rock temperature is 45 °C. In such conditions, a typical steady-state volume-change rate is $2.5 \cdot 10^{-4}$ per year, as measured by Berest and Blum (1992). At a depth of 2000 meters, this rate will probably increase by a factor of at least 100 due to larger overburden pressure (e.g., if $n = 3$,

the creep rate will be multiplied by 8) and higher temperature (e.g., if $Q/R = 5300 K^{-1}$, the creep rate will be multiplied by 12). Figure 6 shows creep rate during leaching for a 1500 meter deep cavern, the injected water temperature is 20°C.

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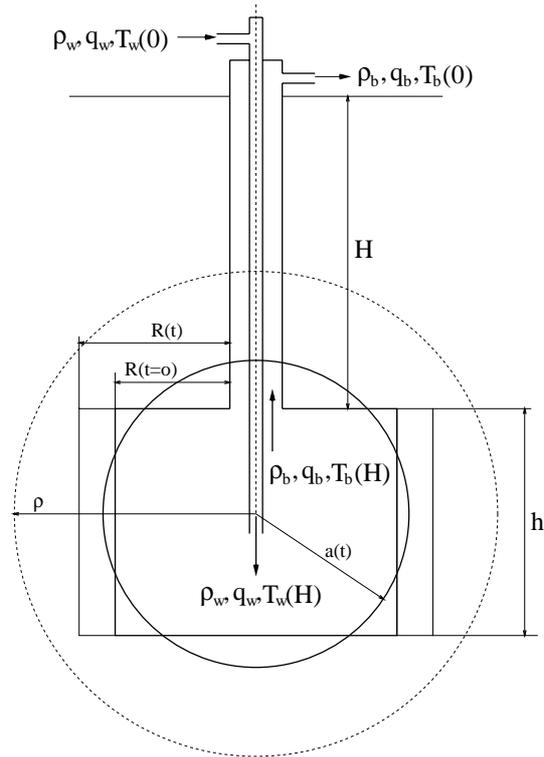


Figure 1: Main notations

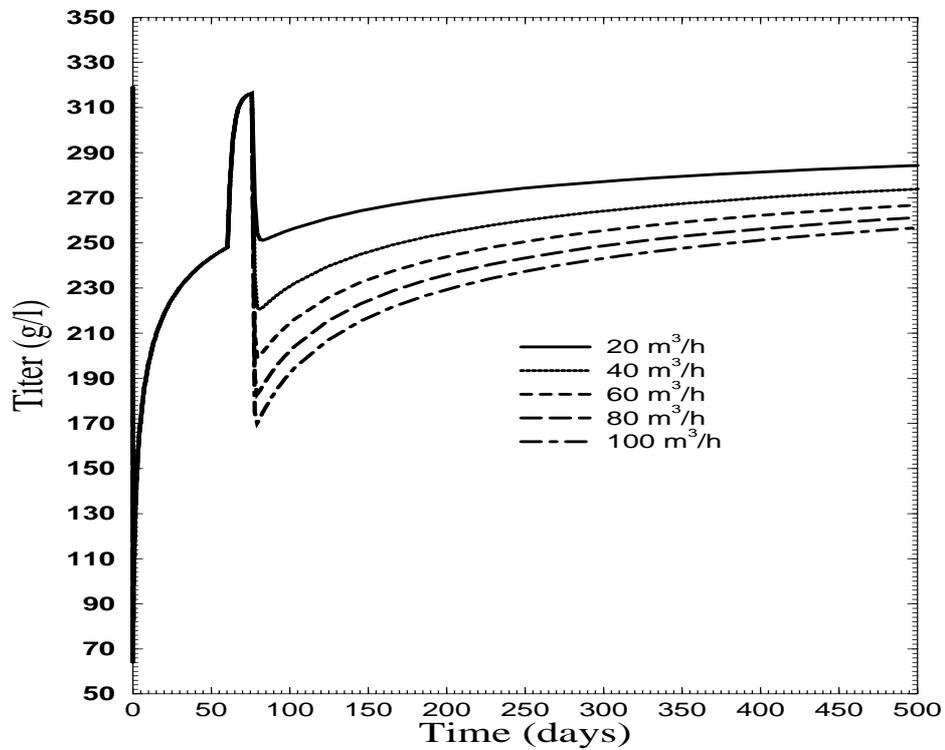


Figure 2: Brine concentration versus time for different injected water flows

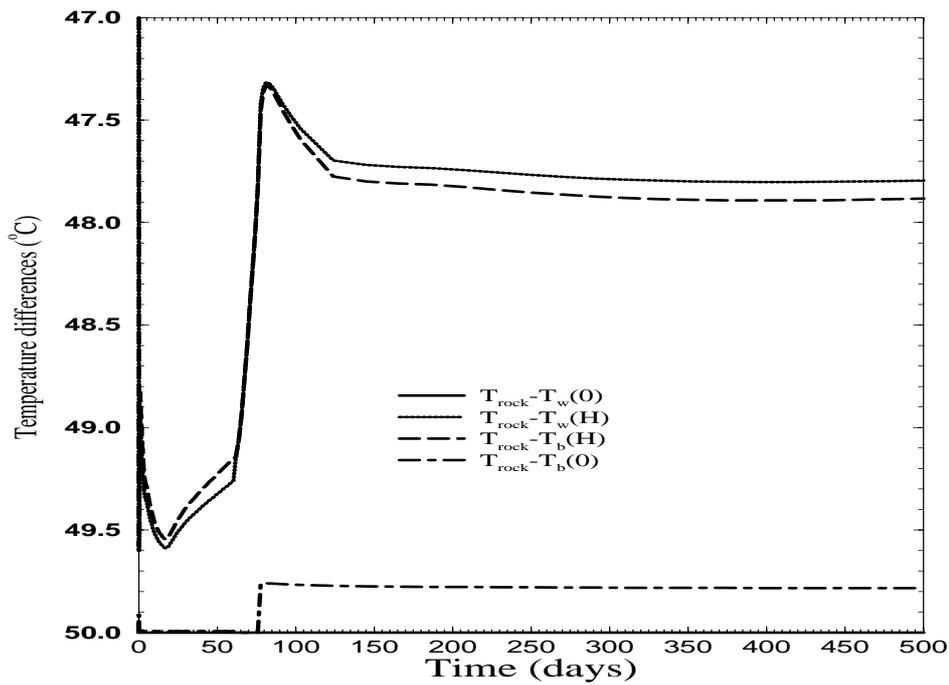


Figure 3: Temperature evolutions (The rock temperature is $T = 70$ °C, the injected water temperature is 20 °C, the cavern is 100 meters high, and the injected water flow is 20 m³/h during 2 months, is equal to 0 during 15 days and then is 100 m³/h)

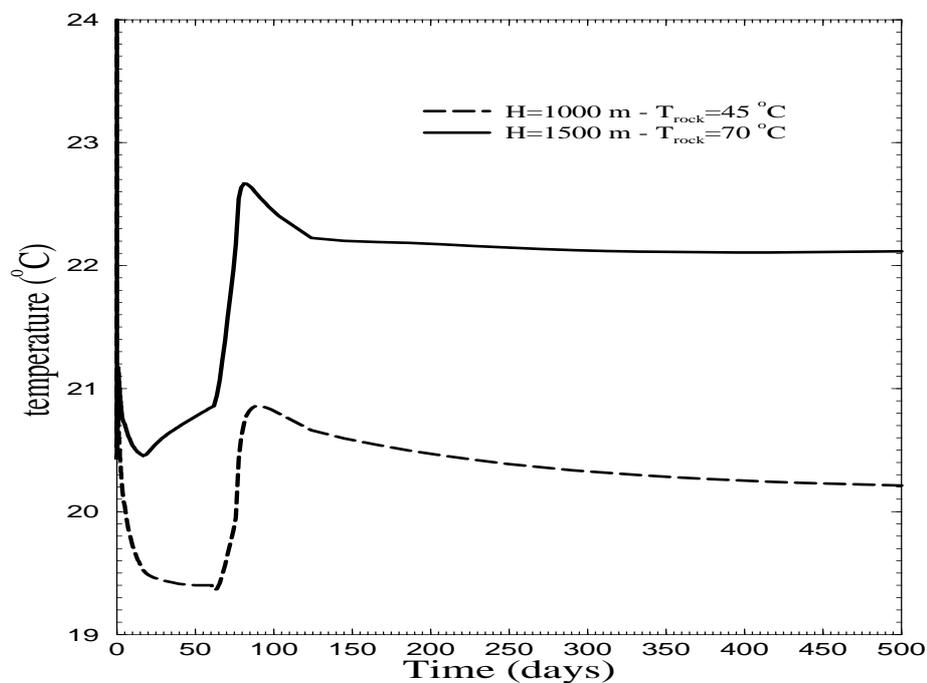


Figure 4: Evolution of the brine temperature in the cavern

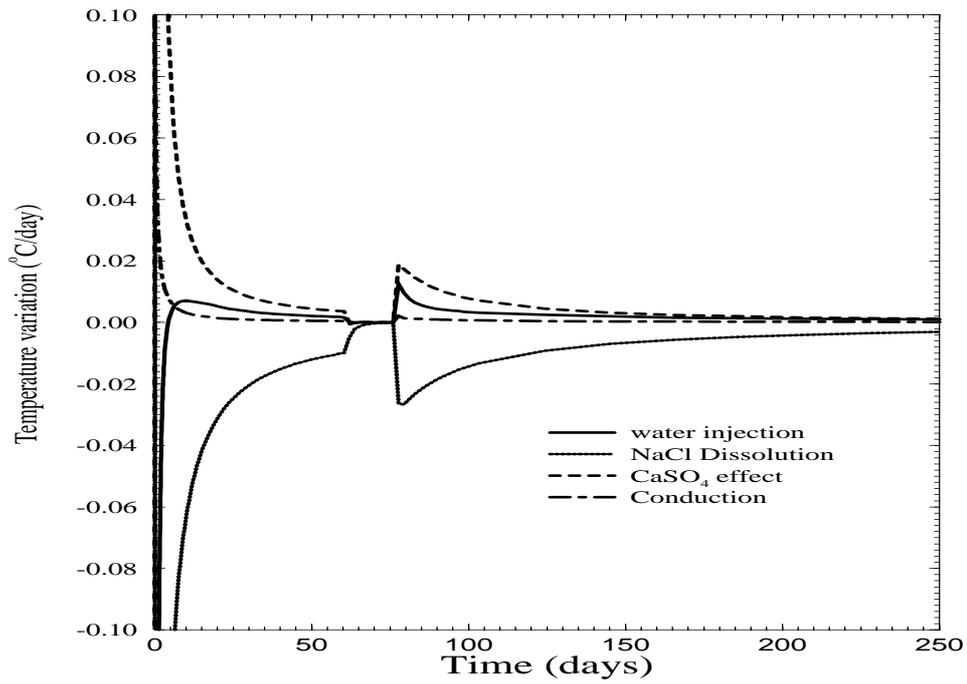


Figure 5: Contributions in brine temperature evolution

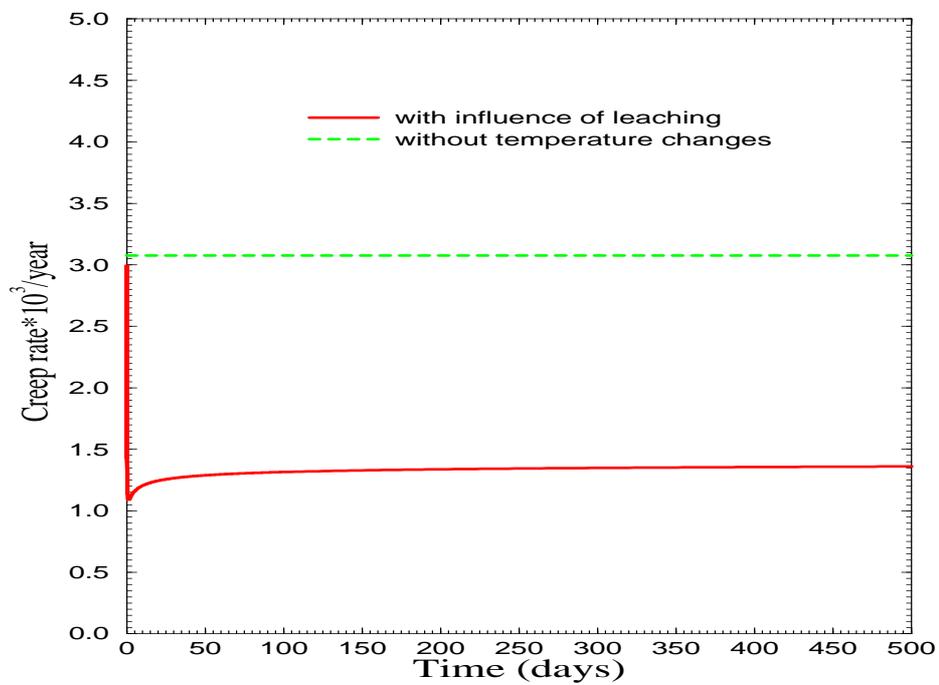


Figure 6: Evolution of creep rate during leaching, injected water flow is 100 m³/h.