

Behavior of sealed solution-mined caverns

Comportement des cavernes dans le sel après fermeture

Das Verhalten von verschlossener soltechnisch hergestellten Kavernen

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ABSTRACT : When solution-mined caverns are sealed, rock-salt creep and brine heating generate a brine pressure build-up which in many cases leads to fracture. Brine seepage through the rock-mass mitigates pressure build-up and can prevent fracturing.

RESUME : Lorsque les cavernes réalisées dans le sel sont fermées, la pression dans la caverne augmente sous l'effet de l'échauffement de la saumure, du fluage du sel, peut conduire à la fracturation du massif. L'existence d'une perméabilité du sel permet une diminution de cet effet.

ZUSAMMENFASSUNG : Wenn soltechnisch hergestellte Kavernen verschlossen werden, führen das Kriechen des Steinsalzes und die Erwärmung der Sole zu einem Druckaufbau, der in vielen Fällen zu einer Ribbildung führt. Das Eindringen der Sole in das Gebirge vermindert den Druckaufbau und kann die Ribbildung vermeiden.

1 INTRODUCTION

Solution-mined caverns are designed to be sealed and abandoned one day (Ehgartner and Linn, 1994 or Bérest and Brouard, 1995). In some cases, wastes will be disposed in the cavern before sealing (in the case of Texas, see Argonne National Laboratory report, 1996). Due to increasing concern of environmental and safety issues, the long-term behavior of brine (or brine plus wastes) bubble initially enclosed in a cavern has been analyzed by several authors (Wallner, 1984, Ehgartner and Linn, 1994) who emphasize the fracture risk due to progressive pressure build-up in the cavern caused by brine heating and cavern creep.

In this paper, we examine rock-salt permeability : even if small, it results in some pressure release and leads to a final equilibrium pressure that is substantially lower, in many cases, than the lithostatic pressure.

Then, the fracture risk is restricted to the transient period during which the initial temperature disequilibrium has not yet been resorbed.

2 PRESSURE BUILD-UP IN A CLOSED CAVERN : TWO EXAMPLES

First, it is interesting to examine two in-situ tests during which the pressure build-up in closed caverns has been recorded at the well-head :

- The Ez 53 cavern, operated by Gaz de France, is located at a depth of 950 meters (3120 ft) ; its volume is 8,000 m³ (50 000 bbls). This cavern was closed one year after the leaching ended. The well pressure is recorded in the fuel-filled annular space (see Figure 1). A few days before closing, the cavern expelled 50 liters (0.31 bbls) per day through the well head. A complete description of the test can be found in Hugout, 1988.

- The Pa 1, 2, 4, 6 caverns of the Vauvert site are operated by Elf. Salt rock lays between 1800 meters (5900 ft) and 2500 meters (8200 ft) ; at that depth the rock temperature is higher than 100°C (212°F). The Pa 1, 2, 6 caverns are linked together ; their volumes are 84 000 m³ (528,000 bbls) , 64 000 m³ (402,000 bbls) and 16 000 m³ (100,000 bbls) respectively at the time of the test.

The very stiff slope of the curves (pressure build-up) versus (time) for these three caverns is typical of deep caverns (Figure 2). When the cavern pressure reaches the geostatic value, hydrofrac and reopening of the links between caverns prevent any further increase.

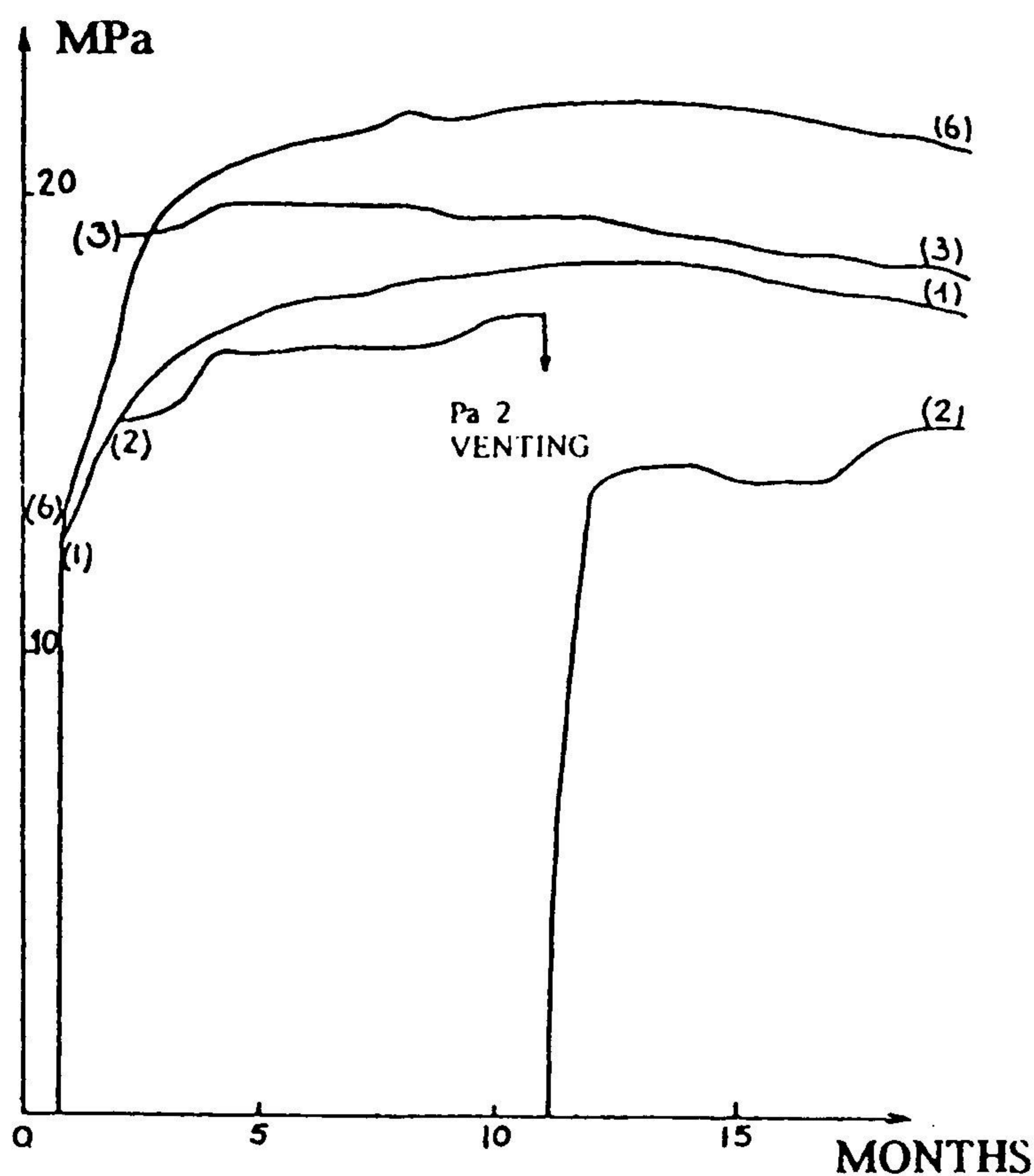
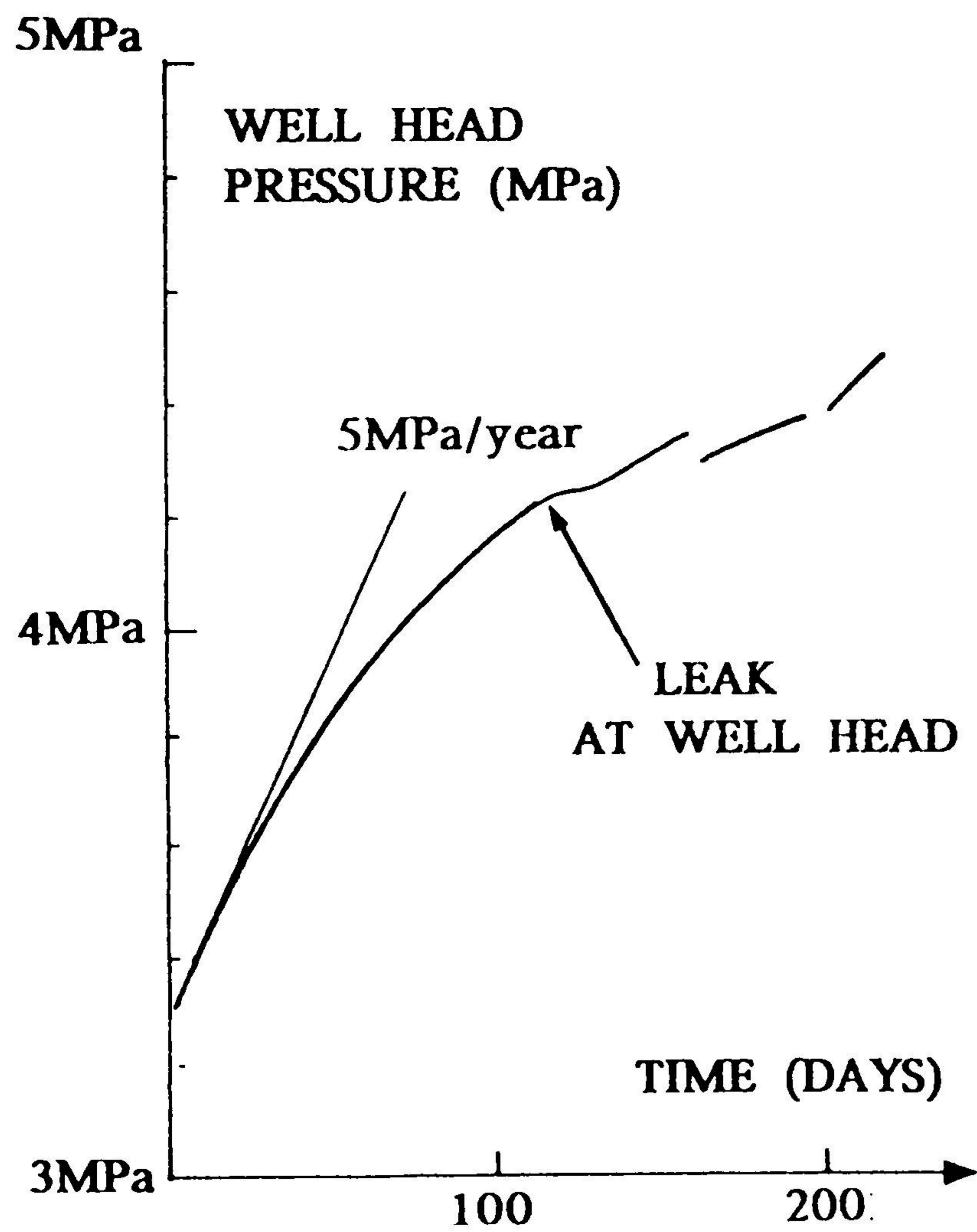


Figure 1&2 - Pressure build-up in closed caverns at Etrez (Ez 53) and Vauvert (Pa1, Pa2, Pa4, Pa6).

3 COMPRESSIBILITY AND THERMAL EXPANSION

The pressure build-up in a closed cavern is generated by several phenomena :

- elastic compressibility of the brine-filled cavern,
- brine heating and thermal expansion,
- salt-rock creep,
- brine percolation toward the rock-mass,
- brine saturation evolution.

This combination can be summed up by the relation

$$\bar{\beta} \cdot \dot{P}_i = \bar{\alpha} \cdot \dot{T}_i + \dot{\epsilon}_{cr} + \dot{\epsilon}_{perc} + \dot{\epsilon}_{sat}$$

1. A change in brine pressure (\dot{P}_i) or brine temperature (\dot{T}_i) generates an additional dissolution or crystallisation which modifies the concentration of the saturated brine. We consider only very slow processes ; then we can consider that an equilibrium is reached at any time. For instance, if the pressure or the temperature increases, some salt is dissolved and the brine + salt volume decreases, $\dot{\epsilon}_{sat} = \bar{\beta} \cdot \dot{P}_i - \bar{\alpha} \cdot \dot{T}_i$. This effect is taken into account by an appropriate modification of the α and β coefficients, $\alpha = \bar{\alpha} - \bar{\alpha}$, $\beta = \bar{\beta} - \bar{\beta}$.

2. Both brine and rock-salt exhibit compressibility. When a brine flow Q is injected into a closed cavern, it results in a pressure build-up, \dot{P}_i , in the cavern : $\dot{P}_i = \beta V Q$. A typical value of the compressibility factor is $\beta = 4 \cdot 10^{-10} \text{ Pa}^{-1} = 2.8 \cdot 10^{-6} \text{ psi}^{-1}$ (Boucly, 1982 or Crotogino, 1995) but gas pockets, which can be found in some caverns, increase this feature by a large amount.

3. Brine thermal expansion coefficient, for saturated brine, is $\alpha = 4.4 \cdot 10^{-4} \text{ }^\circ\text{C}^{-1}$, Boucly (1982), or $\alpha = 4.5 \cdot 10^{-4} \text{ }^\circ\text{C}^{-1}$ according to Crotogino (1984). A rule of the thumb can be deduced from it : a 1°C (1.8°F) increase in a closed cavern leads to a 1.1 MPa (160 psi) build-up. Why does the brine temperature increase ?

Solution mining uses relatively cold water (12°C , or 54°F) pumped out from near-surface aquifers. The temperature of the salt mass is larger and increases with depth. A typical rock-mass temperature distribution is $T_R(z) = 12 + 0.03 z$ (meters), where z is the cavern depth ; it means that $T_R = 42^\circ\text{C}$ (108°F) at a depth of 1000 meters i.e. 3280 ft (in the salt itself, the temperature gradient can be smaller). During the leaching process, the thermal balance is intricate, the final temperature $T_i(o)$ is intermediate between 12°C and T_R ; then, if the brine remains in the cavern, its temperature gently increases : heat is transported by conduction through the rock-mass toward the cavern ; the gap between the rock-mass temperature and the brine temperature, which is $T_R - T_i(o)$ at the end of leaching, decreases and vanishes. The "characteristic time" of the brine heating process (e.g., the time after which 75% of the initial temperature gap has vanished) is given by :

$$t_c = V^{2/3}/(4k)$$

where V is the cavern volume (in m^3) and $k = 3 \cdot 10^{-6} \text{ m}^2\text{s}^{-1}$ is the rock-salt thermal diffusivity. For a $8,000 \text{ m}^3$ cavern (50,000 bbls), this time is $t_c = 1$ year ; for a $512,000 \text{ m}^3$ (3,220,000 bbls) cavity, $t_c = 16$ years. This last figure proves that, for

a large cavern, the heating process is relatively slow which raises difficult problems from the point of view of salt caverns abandonment. If, for the sake of simplicity, the exact thermal history during the leaching process is disregarded, we have

$$\alpha \cdot \dot{T}_i = \alpha \cdot \frac{\partial \varphi}{\partial u}(u) \cdot [T_R - T_i(0)] / t_c$$

where $u = t/t_c$ and $\varphi(u)$ is a function such as $\varphi(1) = 75\%$, which can easily be determined if the cavern shape is spherical (Bérest et al., 1979). The effects of brine heating are generally observed through thermal expansion. If the cavern is opened at the well head, some flow will be expelled, $Q = \alpha V \dot{T}_i$. It is easy to check that the flow varies as the 1/3 power of the cavern volume. If the cavern is closed and if the other effects can be neglected, $\dot{P}_i = \alpha \cdot \dot{T}_i / \beta$ varies as the 2/3 power of the cavern volume (for comparable values of the variable $u = t/t_c$).

4 BRINE PERCOLATION

Rock-salt has long been considered as an impermeable rock and as a matter of fact, its permeability is extremely low (A common method is to define the impermeability of soils and rocks by the inequality $K < 10^{-17} \text{ m}^2$, where K is the intrinsic permeability. A pure and intact salt can satisfy $K = 10^{-22} \text{ m}^2$; for a salt formation at large scale, $K = 10^{-21} \text{ m}^2$ to $K = 10^{-19} \text{ m}^2$ is typical.) In the present paper, we adopt a more empirical perspective that is based on the results of in situ-tests. For instance, in the Etrez site, Durup (1994) has conducted a one-year test in the open hole of a well bore, at a depth of 1000 meters (3280 ft). He slowly increased the brine pressure at the well head, from atmospheric pressure to fracture pressure, each step being one month long. His main conclusions are as follows:

- The flow percolating through the rock-mass is proportional to the pressure at the well head. In other words, Darcy's law applies (at least, at the scale of the entire hole) and the pore pressure seems to be equal to the weight of a brine column running from the cavern to the well head at ground level, $P_0 = 0.012 z$ in MPA if z is the cavern depth (meters). (In the following, we assume this "halmostatic hypothesis" is satisfied). A notable exception is the WIPP site in the United States, where the brine pressure has been estimated to $0.014 z$, where z is the mine depth.

- The (global) intrinsic permeability is: $K = 6.10^{-20} \text{ m}^2$.

Percolation can be roughly estimated by assuming that the cavern behaves as a spherical cavern of radius R , such that $V = 4\pi R^3 / 3$, in a porous rock-mass in

which the water transfer satisfies Darcy's law. In the steady-state regime, pressure distribution in the rock-mass will be a harmonic function (i.e., $P \approx \frac{1}{r}$), and the relative loss of brine from the cavern will be (see Berest and Brouard, 1995):

$$\dot{\epsilon}_{perc} = -3K(P_i - P_0) / (\eta R^2)$$

P_i is the cavern brine pressure, R is the cavern radius, η is the brine viscosity (which is a decreasing function of temperature, $\eta \approx 1.2 \cdot 10^{-3} \text{ Pa.s}$ at 45°C and $0.6 \cdot 10^{-3} \text{ Pa.s}$ at 100°C i.e. $1.7 \cdot 10^{-7} \text{ psi.s}$ at 112°F and $8.7 \cdot 10^{-8} \text{ psi.s}$ at 212°F), and P_0 is the natural brine pore pressure.

5 CREEP

Many works have been devoted to the rheology of rock-salt, but the subject hardly seems to be exhausted. Nevertheless, many authors (see Hardy and Langer, 1984, 1988) agree on several main features of rock-salt constitutive behavior. First, salt behaves like a fluid in the sense that it flows even under small deviatoric stresses. Salt is a non-newtonian fluid and its strain rate is proportional to a rather high power of applied deviatoric stress (which means that the creep rate of a cavern is a highly non-linear function of its internal pressure). The strain rate is strongly influenced by temperature; it becomes larger by one or two orders of magnitude when the temperature increases by 100°C i.e. 180°F . The two effects will combine if one considers the behavior of caverns filled with brine and open to the atmosphere. At a depth of 1000 meters, the lithostatic pressure is $P_R(z) = 2.2 \cdot 10^{-2} \cdot z = 22 \text{ MPa}$ (3190 psi), the brine pressure is 12 MPa (1740 psi) and the rock temperature is $T_R(z) = 12 + 3 \cdot 10^{-2} z = 42^\circ\text{C}$ (108°F). The steady-state volume-change rate will typically be $2.5 \cdot 10^{-4}$ per year. (This figure has been measured by Berest and Blum (1992) in the Ez 53 cavern quoted above, eight years after the end of leaching.). At a depth of 2000 meters (6560 ft), this rate will probably increase by a factor of at least 100, due to both higher temperature and larger overburden pressure. We assume in the following that, in the steady-state regime, the cavern volume change rate can be described as follows (P_R and P_i in MPa):

$$\dot{\epsilon}_\alpha = A \cdot [(P_R - P_i) / 10]^m \cdot \exp[\delta(T - 45)]$$

Where $m = 3$, and $\delta = 4.5 \cdot 10^{-2} (\text{C}^\circ)^{-1}$. This means that cavern creep in an open cavern is equal to $A = 2.5 \cdot 10^{-4}$ per year at a depth of 1000 m where the temperature is 45°C and $2.5 \cdot 10^{-2}$ per year at a depth of 2000 m if the temperature at this depth is $T = 100^\circ\text{C}$. The pressure gap increase (respectively temperature increase) is responsible for a multiplication by 8 of the creep rate (respectively by

12). These estimations have benefited from comments by Gerard Vouille. In the following we note $B(z) = A \cdot \exp[\delta \cdot (T - 45)] \cdot 10^{-m}$ and $\dot{\epsilon}_{cr} = B(z) \cdot (P_R - P_i)^m$.

6 THE EFFECT OF CREEP AND BRINE PERCOLATION

If thermal expansion can be disregarded, the pressure build-up in the closed cavern is given by :

$$\beta \cdot \dot{P}_i(t) = -3K \cdot [P_i(t) - P_o(z)] / (\eta(z)R^2) + B(z) \cdot [P_R(z) - P_i(t)]^m$$

The brine pressure tends to an equilibrium value between the lithostatic pressure $P_R(z)$ and the initial brine pressure $P_i(0) = P_o$, which is obtained by setting $\dot{P}_i = 0$ in the above formula. The bigger and deeper the cavern, the smaller the permeability, the less effective the percolation, and the higher will be the equilibrium pressure.

For instance, at a 1000 meters depth, if $V = 225,000 \text{ m}^3$ (1,415,000 bbls) and if the permeability is $K = 6 \cdot 10^{-20} \text{ m}^2$, then, the final pressure is 17 MPa (i.e., half way between the lithostatic pressure P_R and the initial brine pressure P_o). At a greater depth, the conclusions are different because the creep is strongly influenced by depth : for instance, at a depth of 2000 meters (6560 ft), we have $P_o = 24 \text{ MPa}$ (3480 psi) and $P_R = 44 \text{ MPa}$ (6380 psi), the final pressure will equal 39 MPa (5660 psi). These results prove that, when brine percolation is taken into account, the final pressure in the cavern can remain far below the lithostatic pressure : then, the risk of fracture practically vanishes.

This statement is incorrect, however, as will be seen in the next paragraph, if thermal expansion due to brine heating cannot be disregarded.

7 EFFECTS OF CREEP, BRINE PERCOLATION AND THERMAL EXPANSION

If we take into account the effects of brine heating, what is absolutely necessary for times short compared to the characteristic time t_c , we get :

$$\beta \cdot \dot{P}_i(t) = B(z) \cdot [P_R(z) - P_i(t)]^m + \frac{1}{R^2} \{ \alpha \cdot [T_R(z) - T_i(0)] \cdot \varphi'(t/t_c) / C - 3K \cdot [P_i(t) - P_o(z)] / \eta(z) \}$$

where $C = (4\pi/3)^{2/3} / (4k)$ and $P_i(0) = P_o(z)$. In the beginning, the thermal expansion is predominant for a small and shallow cavern, the same role is devoted to the creep when the cavern is big and deep.

When brine pressure reaches a high level, brine percolation is no more negligible when compared to creep and vanishing thermal expansion. Then, the brine pressure will decrease and, after a long time, reach an equilibrium value, when creep equals percolation. From a practical point of view, it is essential to check whether the brine pressure can reach and exceed the lithostatic pressure during the transient period. Figure 3 shows different examples :

- In the first case the cavern is 1000 meters (3280 ft) deep and is small (8,000 m³ or 50,000 bbls), the thermal transient period is short, initial creep is very slow, thus, the equilibrium between creep and percolation is reached relatively quickly. The pressure build-up is practically proportional to the temperature increase, $\dot{P}_i = \alpha \cdot \dot{T}_i / \beta$, during the first step.

- In a deeper and bigger cavern (2000 meters and 512,000 m³ i.e. 6560 ft and 3,220,000 bbls), the initial gaps between brine temperature and pressure, and rock temperature and pressure, are larger ; thus, the brine heating effect is more intense. Nevertheless, the initial pressure build-up is governed by creep. When the cavern pressure nears the overburden pressure, creep vanishes and thermal expansion leads the pressure to exceed the overburden pressure. If there is no fracture of the rock-mass, the percolation slowly lowers the internal pressure to its final value.

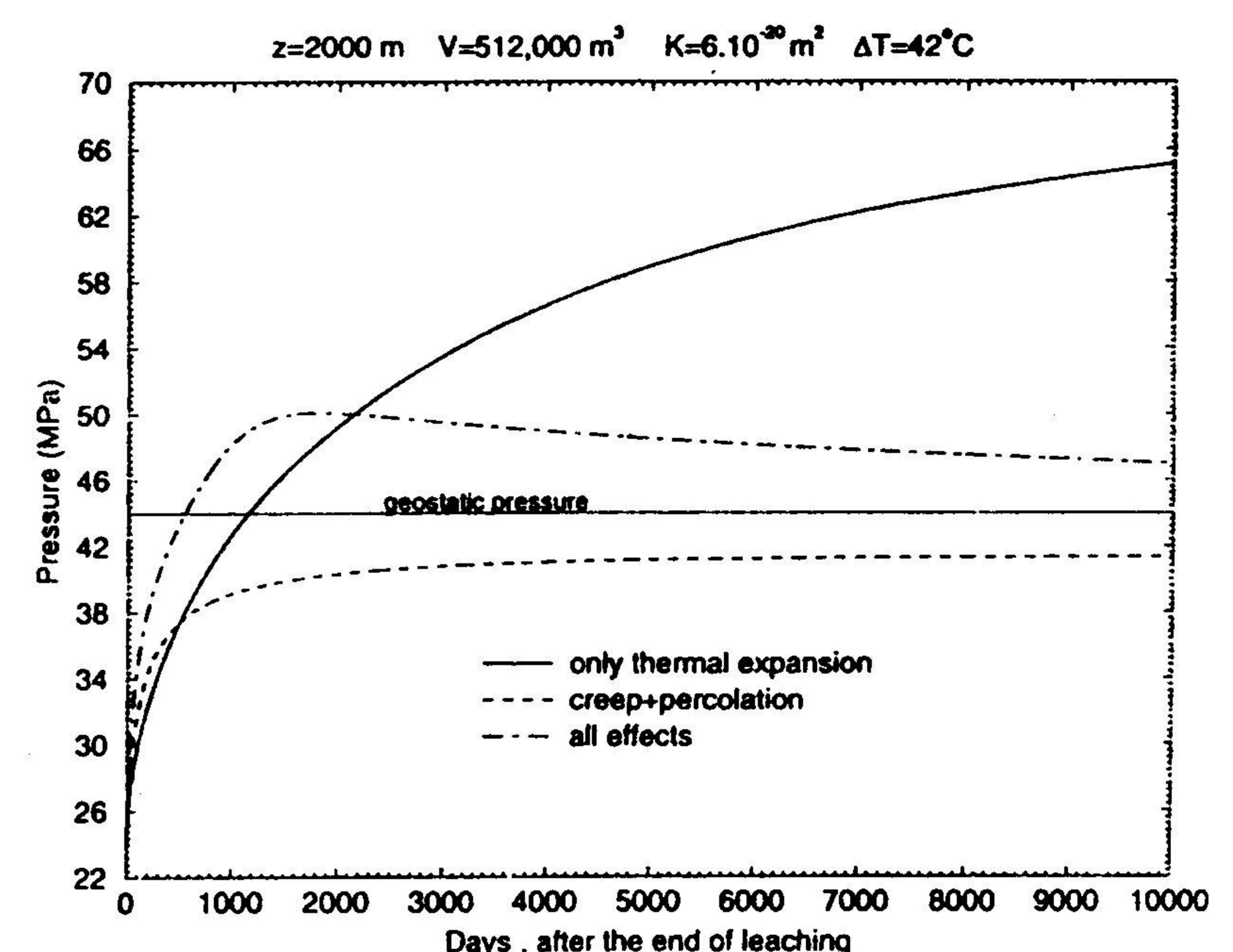
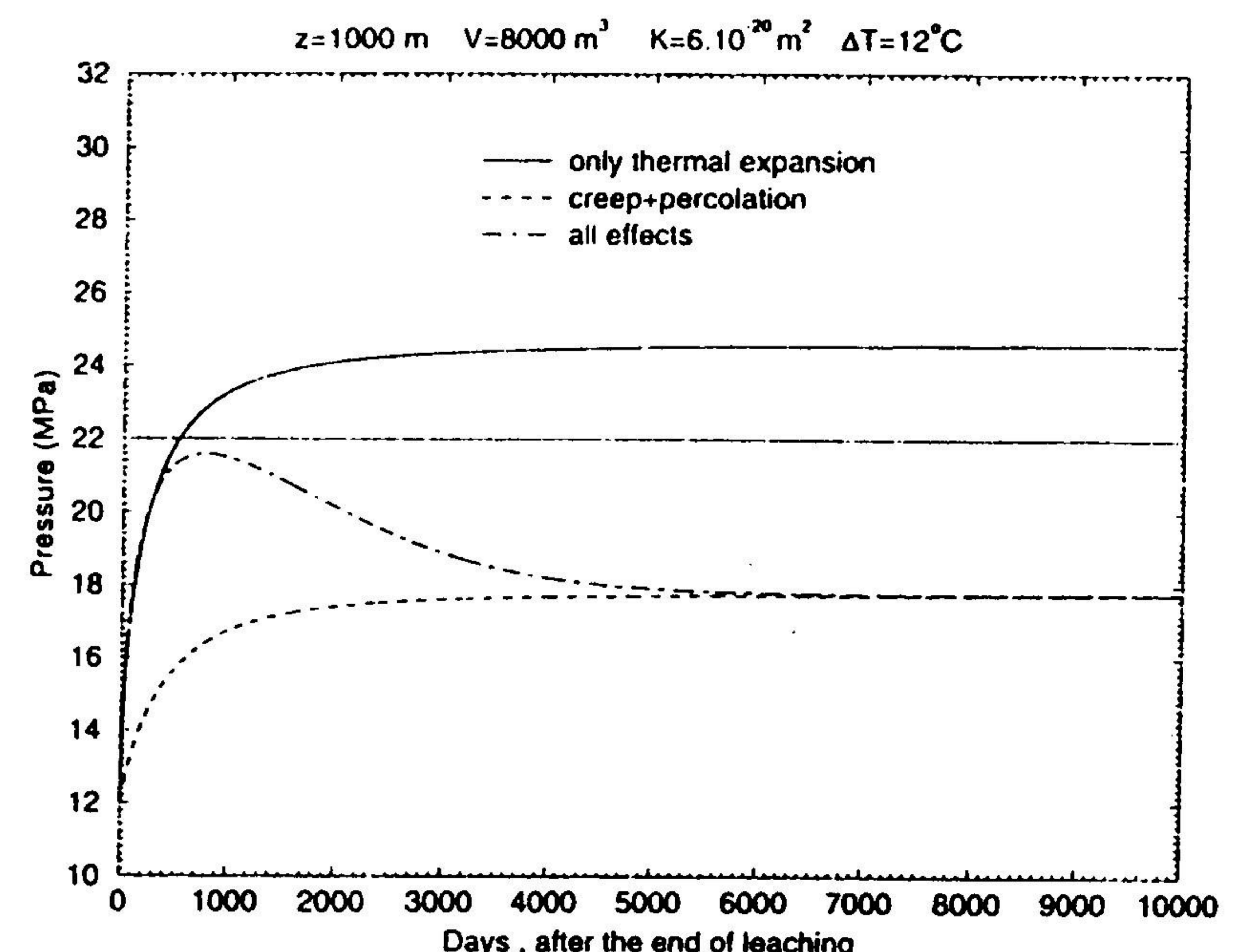


Figure 3 - Pressure build-up in a small and shallow cavern (a) or deep and big cavern (b).

8 CONCLUSIONS

The pressure build-up in a sealed cavern, generated by salt creep and brine heating, leads to a *final* equilibrium pressure that is smaller than the lithostatic pressure, provided that the rock-salt exhibits some permeability ; but in many cases it will not be sufficient to avoid a transient period, mainly due to brine thermal expansion, during which the pressure in the cavern exceeds the lithostatic pressure.

Several solutions to this problem can be suggested :

1. Delayed installation of the plug allows the salt to heat the brine (Ehgartner and Linn, 1994, You and Valette, 1994). The major drawback is that the delay can be long, especially for a big cavern ; then the difficult problem of responsibility transfer must be solved -will the company still exist in 20 or 30 years ? if not, who will pay for cavern plugging ?.

2. It is possible to increase the creep rate by lowering the brine pressure in the cavern (for instance, with an immersed pump) ; then, before sealing, the cavern volume can be significantly reduced. This method can be an efficient solution for deep caverns (deeper than 1500 meters i.e. 5000 ft). A too-stiff pressure drop in the cavern can lead to severe disorders, and must be avoided ; subsidence is unavoidable and must be carefully evaluated. A specific example is described in Fokker (1995).

3. Gas (nitrogen, for instance) can be injected in the cavern before sealing, as suggested by Legait, in order to lower the compressibility of the cavern : $\beta \approx 4 \cdot 10^{-10} \cdot (1-x) + x/P_i$ (in Pa⁻¹) if x is the cavern-volume fraction occupied by the gas. A very small amount of gas trapped in the cavern leads to a drastic increase in compressibility.

In any case when discussing the occurrences of the risks, site-specific geological and geographical contexts must be taken into account.

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