BEHAVIOR OF SEALED SOLOUTION-MINED CAVERNS

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ABSTRACT

Solution-mined caverns are designed to be sealed and eventually abandoned. Due to increasing concern for environmental and safety issues, the long-term behavior of brine bubble initially enclosed in a cavern has been analyzed by several researchers 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.

INTRODUCTION

In recent years, the thermo-mechanical behavior of sealed solution-mined caverns has gained much attention. This interest can be explained both by the growing concern in environmental issues and by new projects in which underground caverns are used as chemical-waste disposals. Among many others, Langer et al. (1984), Wallner (1984), Cauberg et al. (1986), Berest (1990), Ehgartner and Linn (1994), You et al. (1994), Fokker (1995) and Veil et al. (1995) have contributed to this discussion.

The fluid pressure in a cavern builds up if we take into account brine expansion due to geothermic heating and cavern shrinking due to salt creep. Ehgartner and Linn (1994) have convincingly shown that salt dissolution, due to changes in brine concentration related to pressure and temperature evolutions, must be taken into account for a correct evaluation of the magnitude and rate of fluid pressurization. Langer et al. (1984) or Wallner (1984) have shown that, in many cases, pressure build-up will lead to an unstable final situation in which the fluid pressure at the top of the cavern exceeds the lithostatic pressure by a substantial amount. In such a situation, the opening of a fracture moving upward can be expected.

The former analysis disregards the favorable effect of salt permeability, which allows some release of brine out of the cavern. We will prove that this release can lower the final pressure reached in the cavern by a significant amount.
First, we discuss the main physical factors that play a role in cavern pressure build-up: brine heating and thermal expansion, brine percolation, cavern compressibility and creep. Then we will discuss step by step the effects of: creep in a closed cavern, creep and percolation, and creep, percolation and brine heating. This analysis allows for interpretation of several in-situ tests (e.g., measurement of pressure build-up in closed caverns). In conclusion we suggest procedures to mitigate the pressure build-up rate and the maximum value of the fluid pressure.

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BRINE HEATING

Solution mining uses relatively cold water (12°C or 52°F) pumped out from near-surface aquifers. The temperature of the salt mass is larger and increases with depth. A typical temperature is T = 45°C (113°F) at a depth of 1000 meters (3280 ft).

During the leaching process, the soft water pumped into the cavern leaches the rock mass, and its temperature increases due to the dissolution of hot salt and heat conduction through the rock mass toward the cavern. The thermal balance is intricate, because dissolution is an endothermal process ; it depends on the injection-withdrawal rate. Thus, the average temperature in the cavern at the end of leaching lies between the soft-water temperature and the rock mass temperature. After leaching, if the produced brine remains in the cavern, its temperature will gently increase, tending to reach equilibrium with the rock mass temperature. A similar conclusion would be true if a hydrocarbon storage cavern were filled with brine just before abandonment.

A simple computation of the temperature evolution is possible, but the following assumptions are required:

1. Heat is transported by thermal conduction through the rock mass according to Fourier's law. Typical values of the thermal conductivity and the thermal diffusivity of rock salt are $\overline{K}$ = 6 Watt/m/°C and k = 3 10^{-6} m^2/s, respectively.

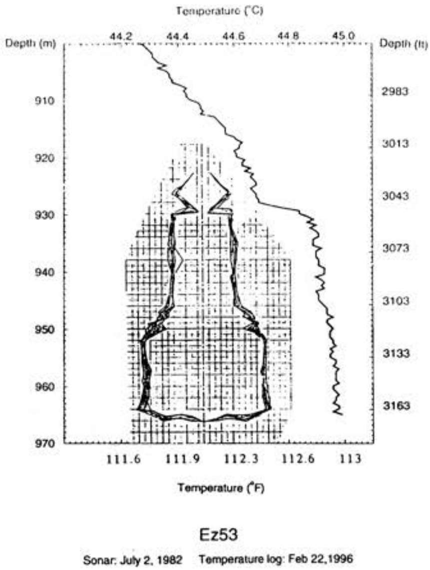
2. The temperature in the cavern is roughly uniform. The main argument supporting this statement is the existence of a geothermal vertical temperature gradient that generates natural heat convection and, therefore, stirs up the brine even if the difference between the average brine temperatue and the rock mass temperature is low (see Figure 1).

It is then easy to estimate the characteristic time of the brine-heating process when no brine is pumped into or from the cavern. Here, the "characteristic time" means the time after which approximately 75% of the initial temperature difference has vanished. This characteristic time is

$$t_c = V^{2/3}/(4k) \qquad (1)$$

where V is the cavern volume (in m^3). For a 8000 m^3 cavity (50,000 bbls), the characteristic time is t_c = 1 year; for a 512,000 m^3 cavity (3,220,000 bbls), t_c = 16 years. This last figure is important: it proves that, for a large cavern, the heating process is relatively slow.

In general, the temperature changes are not directly measured, but their effects (pressure build-up if the cavern is closed, or brine flow at ground level if the well head is left open) can be observed accurately. These points will be discussed below; an example of a direct measurement is shown in Figure 2. Gaz de France has measured the brine temperature at different times after the end of the leaching process by lowering a thermometer into the cavern (Hugout, 1988). The cavity, called Ez 53, has a volume of 8000 m^3 (50,000 bbls) and a depth of 950 m (3100 ft). Immediately after leaching, the brine temperature was 28°C (82°F), compared to the rock mass temperature (45°C or 113°F) and to the soft-water temperature (12°C or 54°F). In this (small) cavern, 60% of the initial temperature difference has been resorbed after 8.5 months, which is consistent with our previous estimation (75% resorbed after t_c=12 months).



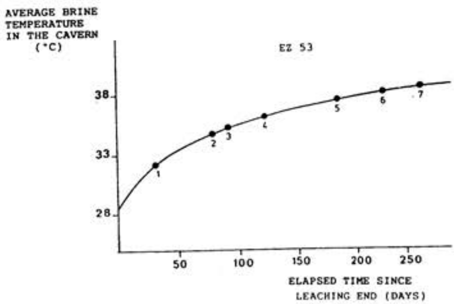


Figure 1 - Temperature Distribution in the Ez 53 cavern in 1996

Figure 2 - Temperature Evolution (as measured) in the Ez 53 cavern in 1982.

THERMAL EXPANSION

If the cavern is opened at the well head, brine heating will produce a thermal expansion of the brine, and some flow will be expelled from the cavern. The thermal expansion coefficient of brine is $\alpha \approx 4.4\ 10^{-4}$ /°C $\approx$ 2.4 10^{-4} /°F; thus, the flow to be expelled from the cavern can be expressed as

$$Q_{th} = \alpha \cdot V \cdot \dot{T} \qquad (2)$$

where $\dot{T}$ is the derivative of the average brine temperature in the cavern with respect to time. For instance, Hugout (1988) has observed the flow expelled from the Ez 53 cavern (see Figure 3) between 50 to 90 days and 263 to 360 days after leaching end and found that the brine outflow is a bit larger than what was expected from temperature measurements (see Figure 2). (The reason for such a discrepancy is the shrinkage of the cavern due to salt creep.)

At first sight, the brine flow seems to be proportional to the cavern volume. In fact, the temperature change rate ($\dot{T}$) is inversely proportional to the characteristic time (t_c), so that the flow varies as the 1/3-power of the cavern volume:

$$Q_{th} = V^{1/3}\left[T_R - T_i(0)\right]\frac{d\varphi}{du}(u)/tc \quad ; \quad u = t/t_c \qquad (3)$$

where $T_R - T_i(o)$ is the difference between the rock mass temperature and the initial brine temperature, and φ is a function such that $\varphi(1) = 25\%$, which can easily be determined if the cavern shape is spherical (Berest et al., 1979). In other words, when the flow is 200 liters per day (1.3 bbls/day) in a 8000 m^3 cavern (50,000 bbls), its value at the same dimensionless time $u=t/t_c$ after the end of leaching will be 200 x 4 = 800 liters per day (5 bbls/day) in a 512,000 m^3 cavern (3,220,000 bbls), which is 64 times larger: however, such a flow will decrease much more slowly in the case of the largest cavern at the same dimensionless time.

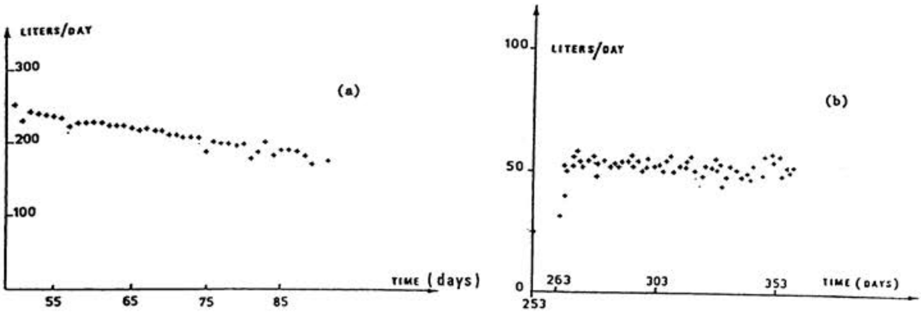


Figure 3 - Brine flow expelled from open cavern EZ53 [Hugout, 1988].

CAVERN COMPRESSIBILITY

Both brine and rock salt exhibit compressibility. When a brine volume, ΔV, is injected into a closed cavern, it results in a pressure build-up, ΔP, in the cavern:

$$\Delta V = \beta . V . \Delta P \qquad (4)$$

where V is the cavern volume, and β is the cavern compressibility, which is the sum of the brine compressibility (approximately $2.7\ 10^{-10}\ Pa^{-1}$; i.e. $1.9\ 10^{-6}\ psi^{-1}$) and the rock mass compressibility ($1.3\ 10^{-10}\ Pa^{-1}$; i.e. $9.0\ 10^{-7}\ psi^{-1}$ for a cavern of regular shape); hence, a typical value is $\beta = 4.10^{-10}\ Pa^{-1}$; i.e. $2.8\ 10^{-6}\ psi^{-1}$ (Boucly, 1982). This means that in a 500,000 m^3 cavern (3,145,000 bbls), the injection of 1 m^3 (0.06 bbls) of additional brine leads to a 5 kPa (0.76 psi) pressure build-up.
Note that when estimating the values of the coefficients α and β, the influences of temperature and pressure, as well as brine saturation concentration, must be taken into account. A discussion on this can be found in Ehgartner and Linn (1994).

BRINE PERCOLATION

Rock salt has long been considered an impermeable rock and, as a matter of fact, its permeability is extremely low. It is common to define the impermeability of soils and rocks by the inequality $K<10^{-17}\ m^2$, where K is the intrinsic permeability. A pure and intact salt can satisfy $K = 10^{-22}\ m^2$; for a salt formation at large scale, $K = 10^{-21}\ m^2$ to $K = 10^{-19}\ m^2$ is typical.

In the laboratory, thorough testing is necessary — e.g., sampling, transport and cutting can damage rock salt and increase its permeability by several orders of magnitude. Recent advances in laboratory experiments (Spiers et al., 1987; Peach, 1991) help to achieve a full understanding of the rock-salt permeability models.

In the present paper, we adopt a more empirical perspective 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 in one-month long increments. His main conclusions are as follows:

(i) 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. (In the following, we will say that the "halmostatic hypothesis" is satisfied.)

(ii) The global intrinsic permeability is $K \approx 6.10^{-20}$ m².

It would be dangerous to infer from these global statements that conclusions relative to the local properties of salt can be deduced :

- the amount of impurities (clay, anhydrite) in the Etrez rock salt is of the order of 10%, and some of the impurities are horizontally bedded. It is possible that a large part of the observed brine flow takes place in these specific beds.

- on the other hand, rock-salt permeability is strongly influenced by the stress path to which the salt has been subjected. Cosenza and Ghoreychi (1993) or Cristescu and Hunsche (1993) suggest that a domain of confinment (small deviatoric stresses, large mean pressure) in which viscoplastic flow is of the associated type (i.e., with no volume change), and a dilatant domain (large deviatoric stresses) in which significant irreversible strains and drastic increases (several orders of magnitude) of permeability must be distinguished. The permeability of the open hole probably results from deviatoric stresses due to excavation and is much larger in the neighborhood of the walls than in the virgin salt mass.

However, several uncertainties do exist. In the following, we will assume the "practical" notion of a Darcy permeability and suppose that it can vary typically in the range of 10^{-22} m² to 10^{-20} m².

Percolation can be roughly estimated by assuming that the cavern behaves as a spherical cavern of radius R (i.e., $V = 4\pi R^3/3$) 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., $P=P_i.R/r$), and the relative loss of brine from the cavern will be defined as (see Berest and Brouard, 1995):

$$\dot{\varepsilon}_{perc} = -3K(P_i - P_0)/(\eta R^2) \qquad (5)$$

where P_i is the cavern brine pressure, R is the cavern radius, η is the brine viscosity which is a decreasing function of temperature ($\eta \approx 1.2\ 10^{-3}$ Pa.s at 45°C and $0.6\ 10^{-3}$ Pa.s at 100°C), and P_0 is the natural brine pore pressure. In many cases, it is reasonable to assume that this pressure is equal to the initial brine pressure when the cavern is opened (i.e., $P_o=P_i(0)=0.012$ z in MPa if z is the cavern depth, in meters, according to the "halmostatic hypothesis").

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 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., 212°F) (Vouille, personnal communication).

If one considers the behavior of caverns filled with brine and open to the atmosphere, the two effects are combined. At a depth of 1000 meters (3280 ft), the lithostatic pressure is 22 MPa (3190 psi), the brine *halmostatic* pressure is 12 MPa (1740 psi) and the rock temperature is 45°C (113°F). The steady-state volume-change rate will typically be $2.5\ 10^{-4}$ 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, 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:

$$\dot{\varepsilon}_{cr} = A\left[\left(P_R - P_i\right)/10\right]^m \exp\left[\gamma(T-45)\right] \qquad (6)$$

where P_R is the overburden pressure in MPa (approximately $P_R = 0.022$ z), P_i is the cavern pressure in MPa (approximately $P_i = 0.012$ z if the hole is filled with brine and open to the atmosphere), and z is the cavern depth (in meters). Thus, reasonable parameters values are:

$\gamma = 4.5\ 10^{-2}\ °C^{-1}$
m = 3
$A = 2.5\ 10^{-4}\ (MPa)^{-m}.(year)^{-1}$
$T(z) = 45°C + 0.55.(z-1000)$

This means that cavern creep in an open cavern [$2.5\ 10^{-4}$ per year at a depth of 1000 m (3280 ft), where the temperature is 45°C] is equal to $2.5\ 10^{-2}$ per year at a depth of 2000 m (6560 ft) if the temperature is 100°C (212°F). Increased pressure and temperature differences result in eight-fold and twelve-fold increases in creep rate, respectively.

THE EFFECT OF CREEP IN A CLOSED CAVERN WHEN THERMAL EXPANSION AND BRINE PERCOLATION CAN BE DISREGARDED

Thermal expansion can be disregarded if brine has been left at rest in the cavern during a longer time period than the "characteristic time" $t_c = V^{2/3}/(4k)$; i.e., if the brine temperature in the cavern is not very different from the rock mass temperature.

If percolation can also be disregarded, which can be done in a site where permeability is small and the cavern size is large, pressure will slowly increase in the closed cavern. For the sake of simplicity, we assume that steady-state creep is reached at any instant. (This assumption is reasonable as long as the process is slow, as will be shown later). The volume change rate can then be written as:

$$\dot{\varepsilon}_{cr} = B(T)\left[P_R(z) - P_i(t)\right]^m \qquad (7)$$

where $B(T) = A.10^{-m}.\exp\left[\gamma(T-45)\right]$. On the other hand, due to cavern compressibility, we have

$$\dot{V}/V = \beta\ \dot{P}_i \qquad (8)$$

By combining the two former relations, we obtain the evolution with respect to time of the average fluid pressure in the cavern:

$$\frac{P_R - P_i(t)}{P_R - P_i(o)} = \left\{1 + (m-1)\,B\left[P_R - P_i(o)\right]^{m-1} t/\beta\right\}^{\frac{1}{1-m}} \qquad (9)$$

with m=3 and $\beta = 4\ 10^{-4}\ MPa^{-1}$.

The initial-pressure build-up rate will be 0.625 $MPa.(year)^{-1}$ in a 1000-meter (3280 ft) deep cavern, for which $B = 2.5\ 10^{-7}\ (MPa)^{-m}.(year)^{-1}$ and the initial difference between overburden pressure and internal pressure is $P_R - P_i(0) = 10$ MPa. At such depth, this difference will be divided by two after eight years, and by ten after approximately eight centuries.

Things are a bit different in a 2000-meter deep cavern (6560 ft), for which $B = 3\ 10^{-6}\ (MPa)^{-m}.(year)^{-1}$ and $P_R - P_i(0) = 20$ MPa. The timescale will be reduced by a factor slightly smaller than 50, which means that the difference between overburden pressure and the internal pressure will move from 20 MPa (2900 psi) to 10 MPa (1450 psi) after two months, and to 2 MPa (290 psi) after 16 years.

In a closed and perfectly impervious cavern, pressure build-up due to creep considerably slows down with time but is a much faster phenomenon at great depth.

Note that those conclusions are not affected by cavern size: they would be more pronounced if the exponent "m" in the creep constitutive equation were taken equal to 4 or 5, which is realistic in many cases.

Thermal expansion and brine percolation have been disregarded and will be addressed in the following; first, however, we will discuss the nature of the final state, reached at the end of pressure build-up. We have seen that the average brine pressure tends toward equilibrium with lithostatic pressure. In fact, equilibrium cannot be reached, as observed by many authors (e.g., Langer et al. (1984), Wallner (1984), Ehgartner and Linn (1994)).

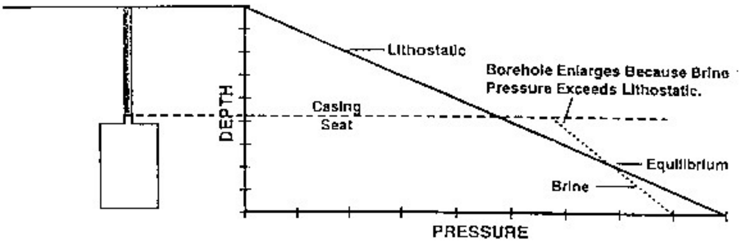


Figure 4 - Illustration of pressure differential between brine and lithostatic pressures at the casing seat [after Ehgartner and Linn, 1994].

It is reasonable to assume that *average* brine pressure will reach *average* rock-overburden pressure after some time, but, brine density (1,200 kg/m^3 or 420 lbs/bbl) is notably different from rock mass density (2,200 kg/m^3 or 770 lbs/bbl). As a result, mechanical equilibrium (which implies a hydrostatic stress-state both in the brine and in the rock salt) cannot be reached between brine and salt along a high vertical wall. This means that brine pressure exceeds rock pressure at the top of the cavern, with the inverse true at the bottom.

Of serious concern is the risk of fracture. Salt tensile strength is small, and fracture can occur when brine pressure exceeds rock lithostatic pressure even by a small amount. [For a description of an in-situ slow-fracture test, see Durup, (1994).]

In a perfectly homogeneous salt, fracture presumably occurs first at the top of the cavern and progresses upward, with the driving force increasing as the total height (cavern plus fracture) of the brine column becomes larger. In bedded salt, fracture presumably progresses toward a weaker horizontal bed.

THE EFFECT OF CREEP AND BRINE PERCOLATION IN A CLOSED CAVERN WHEN THERMAL EXPANSION CAN BE DISREGARDED

If brine percolation is taken into account, pressure build-up reaches much lower levels, as indicated by Berest (1990), Cosenza and Ghoreychi (1993) and Berest and Brouard (1995). The equilibrium will be reached when cavern loss of volume rate due to creep exactly equals the brine leakage due to percolation toward the rock mass:

$$3K(P_i - P_0) / (\eta R^2) = B(T)(P_R - P_i)^m \qquad (10)$$

If we set $1/a=\eta(T)B(T)R^2(P_R-P_o)^{m-1}/(3K)$ and $y=(P_R-P_i)/(P_R-P_o)$, this relation can be written : $y^m-a(1-y)=0$, where y is the ratio between the initial and final difference between lithostatic and brine pressures. When y is close to zero, the risk of fracture exists.

First, consider the case of a cavern (V = 225,000 m^3 =1,415,000 bbls, R=26 m=85 ft) at shallow depth (z=1000 meters=3280 ft). We assume the halmostatic hypothesis (P_o= 12

MPa=1740 psi), and the overburden pressure as 22 MPa (3190 psi). Brine viscosity is assumed equal to $\eta=1.2\ 10^{-3}$ Pa.s^{-1}, and the rock-salt mechanical properties are defined by the following parameters:

$$m = 3$$
$$A = 2.5\ 10^{-4}\ (\text{year})^{-1}$$
$$B(T=45°C) = 2.5\ 10^{-7}\ (\text{MPa})^{-m}\ (\text{year})^{-1}$$

The salt permeability is assumed equal to $K=6\ 10^{-20}\ m^2$, then $1/a = 3.75$, $y \cong 0.5$, and the final pressure in the cavern will be 17 MPa (2465 psi); i.e., half way between the lithostatic pressure and the initial brine pressure. In this example, it is clear that *the risk of fracturing due to high internal brine pressure vanishes*. This conclusion is true for a smaller cavern, but still holds for very large caverns (one million cubic meters).

At greater depth, the conclusions are different because parameter a is strongly influenced by depth. The salt creep rate increases with increasing temperature (coefficient B), and with a larger difference in initial pressure (P_R-P_o=0.01 z) even if, with opposite effects, the brine viscosity is lowered when the temperature increases. For instance, at a depth of 2000 meters (6560 ft), the coefficient $1/a$ is multiplied by 50 and y is divided by 5. The initial pressure difference is 20 MPa (2900 psi), but will be reduced to 4 MPa (580 psi) when final equilibrium is reached.

These figures are strongly influenced by the permeability value. Until now, we have selected a rather high permeabiliy ($K = 6\ 10^{-20}\ m^2$). If a value of $K = 10^{-22}\ m^2$ is chosen, the final difference between lithostatic pressure and brine pressure will be reduced to 0.7 MPa (101 psi), instead of 5 MPa (i.e., 725 psi), for a 1000-meter (3280 ft) deep cavern.

These results prove that when brine percolation is taken into account, the final pressure in the cavern can remain far below the lithostatic pressure: thus, the risk of fracture vanishes for all practical purposes. This statement is incorrect, however, (as the next paragraph will demonstrate), if thermal expansion due to brine heating cannot be disregarded.

EFFECTS OF CREEP, BRINE PERCOLATION AND THERMAL EXPANSION

We have seen that temperature increase leads to thermal expansion according to the relation $Q_{th} = \alpha V \dot{T}$. If the cavern is closed, this expansion produces a pressure build-up according to the elastic relation:

$$\beta \cdot \dot{P} = \alpha \cdot \dot{T} \qquad (11)$$

As a rough estimate, a 1°C (1.8°F) increase in temperature leads to a 1.1 MPa (160 psi) increase in pressure.

The initial difference (before sealing) between overburden pressure and brine halmostatic pressure is P_R-$P_i(0)$=0.01 z, (units are MPa and meters, respectively). There is a risk of fracture if the initial difference between rock temperature and brine temperature is larger than T_R-$T_i(0)$=0.01 z (units are Celsius degree and meter, respectively), or 10°C at a depth of 1000 meters and 20°C at a depth of 2000 meters. This statement is a bit rough, for it does not take into account the additional effects of creep and percolation. If the three phenomena are considered together, two main types of evolution can be distinguished depending upon the cavern depth, namely:

1- In a shallow cavern (1000 meters, 3280 ft, deep, for instance), initial creep is very slow ($2.5\ 10^{-4}$ per year is typical,if the cavern is opened to atmosphere -or a pressure build-up of 0.625 MPa (91 psi) per year in a closed cavern).

For a very permeable cavity, if there is no thermal expansion, brine presure in the cavern reaches a relatively low value (see the dashed line on Figure 5a) especially if the cavern is very small (8,000 m^3 in this example). On the other hand, the thermal expansion is predominant during a period that is short compared to the characteristic time $t_c = (V)^{2/3}/(4k)$. At this time, the flow due to brine heating is about 200 liters per day - that is, a 2.5 10^{-5} per day strain rate. The pressure build-up is almost proportional to the temperature increase during this first step. When brine pressure reaches a high level, brine percolation is no longer negligible when compared with vanishing thermal expansion. Thus, 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 determine whether the brine pressure can reach and exceed the lithostatic pressure during the transient period. Figure 5b shows the importance of cavern size: the larger the cavern, the less effective the percolation. Similar conclusions can be drawn when the permeability is smaller than in this example.

2- In a deeper cavern (2000 meters, 6560 ft, for instance), the initial differences 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 reaches the overburden pressure (see Figure 5b), creep vanishes but thermal expansion leads the pressure to exceed the overburden pressure. In a small cavern (8,000 m^3 instead of 512000 m^3, 50,000 bbls instead of 3,220,000 bbls), the evolution is similar, but the thermal transient period is shorter: thus, the equilibrium between creep and percolation is reached relatively quickly. Even in this case, however, the decisive period is transient.

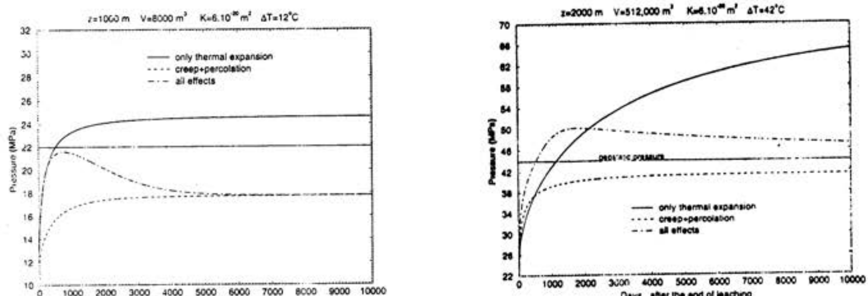


Figure 5 - Pressure build-up in a small, shallow cavern (a) or a large, deep cavern (b).

First example : Hauterives

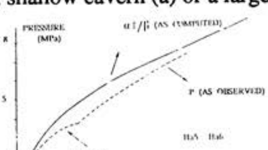


Figure 6 - Pressure build-up in a closed dual cavern at Hauterives (Ha 5 + Ha 6).

This example concerns the brine-production caverns operated by Rhône Poulenc, near Hauterives in Drôme, France (see, for instance, George and Laporte, 1976). In fact, the example concerns a pair of caverns, Ha 6 (a very small cavern) and Ha 7 (a large cavern) linked together by an underground connection 250 meters (820 ft) long. The global volume at test time was 460,000 m^3 (2,900,000 bbls); the caverns were located at a depth between 1,550 meters (5100 ft) and 1,650 meters (5400 ft). The natural rock temperature at that depth is approximately 61°C, and the brine temperature is estimated to be 26°C at the time when the caverns are closed. The pressure increase versus time curve (as measured at the well head) is not very different from the value calculated according to the $\dot{P}=\alpha\cdot\dot{T}/\beta$ rule. (Difficulties have been encountered during the test due to leaks at the well head). This evolution can be considered an example of the "shallow-cavern" type: during the measurement period, neither percolation nor creep plays a pre-eminent role; this role belongs to thermal expansion.

Second example : Etrez

This test concerns the Ez 53 cavern, which is a part of the Etrez site operated by Gaz de France in the north of Lyon (France). This cavern, located at a depth of 950 meters (3120 ft), has a volume of 8000 m^3 (50,000 bbls).

Various in-situ tests had been performed in this cavern or in holes at same depth and in the same site (Boucly, 1982; Berest, 1986; Hugout, 1988; Durup, 1991). The following useful conclusions resulted from this tests:

- The halmostatic hypothesis that the initial pore pressure is equal to the brine pressure in the opened cavern is reasonable and salt permeability is in the range of $K = 6.10^{-20}$ m^2.

- One year after the leaching has ended, thermal expansion is still active and can be considered responsible for 80% - 90% of the observed brine outflow.

- Cavern creep, measured 7 and 13 years after the described test, when thermal expansion is much smaller, is 5 liters per day (0.03 bbls/day).

The cavern was closed 361 days after the leaching had ended and was kept closed for 224 days (7.5 months). A few days before closing, the cavern was opened to the atmosphere, and a 50-liter/day (0.31-bbl/day) brine outflow was observed for a hundred days. For the sake of simplicity, we assume that thermal expansion generates a 40-liter/day (0.25-bbl/day) brine flow; the rest (10 liters/day = 0.06 bbls/day) is due to slowly decreasing cavern shrinkage. Thus the pressure build-up rate, $\dot{P} = \dot{V} / (\beta V)$, in a closed cavern can be expected to be in the range 4.5 to 6.25 MPa/year; i.e., to 900 psi/year. The observed value is smaller than expected (see Figure 6), which may be partly due to experimental problems.

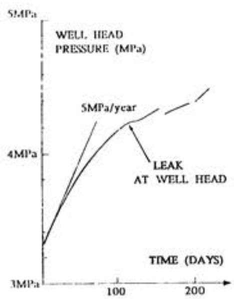


Figure 7 - Pressure build-up in a closed cavern at Etrez (Ez 53).

Third example : Vauvert

The caverns of this site are much deeper; salt rock lays between 1,800 meters (5900 ft) and 2,500 meters (8200 ft). The insoluble amount is large, about 50%. The natural temperature of the rock is higher than 100°C (212°F). The caverns Pa1, Pa2, Pa6 are linked together; soft water is injected into one hole and withdrawn from another. The Pa1-Pa2 pair has produced 292,000 metric tons (643 10^6 lbs), and the Pa1-Pa6 pair 68,000 metric tons (150 10^6 lbs). The volume of each cavern is approximately Pa6, 16,000 m^3, Pa2, 68,000 m^3, and Pa1, 84,000 m^3. The Pa3 cavern has remained isolated.

The very steep slope of the curves (pressure build-up) versus (time) for the 3 caverns (Pa1, Pa2, Pa6) is typical of deep caverns. Just after the well-head closure, cavern creep is larger than thermal expansion, up to the point at which the difference between the lithostatic and brine pressures becomes smaller than 7 MPa (1015 psi). Creep is then ineffective, and thermal expansion becomes the first contributor to pressure build-up. When the well-head pressure is larger than 20 MPa, i.e., 2900 psi (and more for Pa6), the geostatic pressure at cavern depth is reached: hydrofrac and reopening of the links between caverns prevent any further increase in brine pressure.

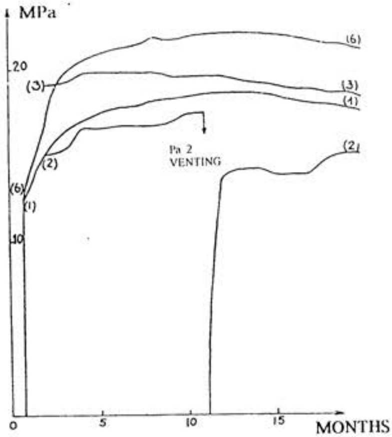


Figure 8 - Pressure build-up in closed caverns at Vauvert (Pa1, Pa2, Pa3, Pa6).

CONCLUSIONS

We have proven that 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 in the cavern surroundings exhibits some permeability. In many cases the favorable effects of salt permeability will not be sufficient to avoid a *transient* period during which, especially in deep caverns, the pressure in the cavern exceeds the lithostatic pressure. This is mainly due to brine thermal expansion.

Several solutions to this problem can be suggested:

1. Delayed installation of the plug allows the salt to heat the brine (see, for instance, Ehgartner and Linn, 1994). The major drawback is that the delay can be long (several times the characteristic time, t_c); thus, except possibly in the case of state-owned companies, the difficult problem of responsability 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 immerged pump). Then, before sealing, the cavern volume and, therefore, the brine bubble can be significantly reduced. An interesting, but somewhat specific, example is given by the Veendam brine-production caverns, which have been described by Fokker (1994). The top of the evaporitic formation lays at a depth of 1500 meters (4920 ft). The leached-out layers are magnesium salt-bearing strata (carnalite, bischofite, kieserite), which are much more soluble than halite (or rock salt). The total volume of the cavern is half a milion m^3. Magnesium salts creep at a very high rate (higher, by one or two orders of magnitude, than rock-salt creep). For this reason, leaching is processed with a high well-head pressure (15 MPa (2200 psi) is typical in the Veendam site.), in order that the difference between overburden pressure and cavern brine pressure, which is the creep-driving force, be as small as possible (2 MPa or 290 psi in the Veendam example).

In this case, by simply lowering the additional pressure at the well head, it is possible to drastically increase the cavern creep. It was decided in the Veendam case, to lower the well-head pressure to 3 MPa (435 psi) so that the difference between the overburden pressure and the cavern brine pressure would increase to 14 MPa (2030 psi). During the test, the total duration of which was approximately 65 weeks, the average brine flow was 2500 m^3 (15,700 bbls) per week, resulting in a 150,000 m^3 (940,000 bbls) cavern shrinkage (Fokker, 1994). In order to transpose such an experience to the case of an ordinary rock-salt cavern, in which the creep rate is (relatively) much smaller, it is necessary to lower the brine column inside the borehole with an immerged pump. This triggers a large transient creep which will converge to a steady-state creep. In order to estimate orders of magnitude, we use the same creep law as before.

- For an open cavern at a depth of 1000 meters (3280 ft), the steady-state creep rate is 2.5 10^{-4} per year for a pressure difference of 10 MPa (1450 psi). By lowering the air-brine interface by 750 meters (2460 ft), the difference increases by 9 MPa (1300 psi) and the creep rate is multiplied by a factor smaller than 8. This rate is still too slow to make the method very efficient.

- For an open cavern at a depth of 1500 meters (4920 ft), the creep rate is 3 10^{-3} per year for a 15 MPa (2175 psi) pressure difference. If the air-brine interface is lowered by 1250 meters (4100 ft), the difference is doubled, and the cavern creep rate becomes 2.4 10^{-2} per year which is better, yet not extremely effective. However, this order of magnitude can be strongly influenced by many factors, such as geothermal gradient and rock salt quality. The following problems must then be tackled:

(i) A too-stiff pressure drop in the cavern can lead to severe disorders. A good example is provided by the Kiel cavern, described by Kuhne et al. (1973) and by Baar (1977). The cavern depth was between 1300 meters (4270 ft) and 1500 meters (4920 ft); its volume, as measured by sonar, was 39,600 m^3 = 249,000 bbls. (53,000 m^3, i.e. 333,000 bbls, of salt had been leached out ; the difference can be explained by the sump volume). During the first step, the interface was lowered to a depth of 550 meters (1800 ft) in 23 hours. The expelled flow (18.6 m^3/h = 0.12 bbls/h) exactly equaled cavern creep, the interface being still. A powerful pump then lowered the interface to a depth of 1260 meters (4130 ft) after 6.5 days. The total expelled volume was then 2500 m^3 (15,700 bbls), and the cavern roof broke.

(ii) Creep-rate increase leads to cavern-volume shrinkage, which results in delayed repercussions at the ground level. In the case of the Veendam site, there are concerns about the effects of subsidence, since the phreatic level is at shallow depth and an important test objective was to evaluate the subsidence generated by a faster creep.

In conclusion, creep-rate increase can be an efficient solution for deep caverns (deeper than 1500 meters or 5000 ft, at least). It may be wise to slowly lower the brine interface in an experimental phase designed to correlate cavern volume loss and ground-level subsidence.

3. Gas (nitrogen, for instance) can be injected into the cavern before sealing in order to lower the compressibility, β, of the cavern as suggested by Abouaf and Legait (1978). If x is the cavern-volume fractional part occupied by the gas and P is the cavern pressure (in Pa), the overall cavern compressiblity is β (in Pa^{-1}) = 4 10^{-10}.(1-x) + x/P : a very small amount of gas trapped in the cavern leads to a drastic increase in compressibility —for instance, for a 1000-meter deep cavern (3280 ft), P = 12 MPa (1740 psi). If x = 0.6%, we obtain β = 0.5 10^{-7} Pa^{-1} = 3.4 10^{-4} psi^{-1} and the effects of thermal expansion decrease by two orders of magnitude. Nonetheless, it will be necessary to verify that the injected gas does not permeate too rapidly into the rock mass.

REFERENCES

Abouaf, M., and Legait, B., [1978], "Les différentes utilisations du sel souterrain et leurs conséquences à long terme", Internal report. Ministry of Industry, France.

Baar, C.A., [1977], "Applied Salt Rock Mechanics I", Developments in Geotechnical engineering, 16-A, Elsevier.

Berest, P., [1990], "Les problème soulevés par l'abandon des cavités de dissolution profondes dans le sel gemme", Stockage en souterrain, pp. 115-130, Presses des Ponts et Chaussées, Paris.

Berest, P., and Blum, P.A., [1992], "In situ tests in salt caverns", Proc. 7th Int. Symp. on Salt, Kyoto.

Berest, P., Ledoux, E., Legait, B., and de Marsily, G., [1979], "Effets thermiques dans les cavités en couche salifère", 4th Int. Congress ISRM, Montreux, Vol. 1, pp. 31-35, Balkema.

Boucly, P., [1982], "Expériences in situ et modélisation du comportement des cavités salines utilisées pour le stockage de gaz", Revue Française de Géotechnique, n° 18, pp. 49-57.

Cauberg, H., Kuilman, B.,Valkering, B., and Walters, J.V., [1986], "Rock mechanical behavior and sealing aspects of a closed-in salt cavity filled with brine", SMRI Autumn Meeting Sept. 21-24, Okura Hotel, Amsterdam.

Colin, P., and You, Th., [1990], "Salt Geomechanics seen through 20 years experience at the Manosque Facility", SMRI Fall meeting.

Cosenza, Ph., and Ghoreychi, M., [1993], "Coupling between mechanical behavior and transfer phenomena in salt", 3rd Conf. Mech. Behavior of Salt, Palaiseau., Ghoreychi, Berest, Hardy and Langer ed., pp. 287-307, Tran. Tech. Pub.

Cristescu N., Hunsche U., [1993], "A comprehensive constitutive equation for rock salt-determination and application", 3rd Conf. Mech. Behavior of Salt, Palaiseau, Ghoreychi, Berest Hardy and Langer ed., pp. 191-205, Trans. Tech. Pub.

Durup, G., [1994], "Long term tests for tightness evaluations with brine and gas in salt", SMRI Fall Meeting, Hannover, Germany.

Ehgartner, B.L., and Linn, J.K., [1994], "Mechanical Behavior of Sealed SPR Caverns", SMRI Spring meeting, April 25-27, Houston Texas.

Fokker, P.A., [1995], "The Behavior of Salt and Salt caverns", Ph. D. Thesis, Delft University of Technology.

George, B., and Laporte, P., [1976], "Exploitation de sel par dissolution à "Hauterives" (France)", Revue de l'Industrie Minérale, Nov. 76.

Ghoreychi M., Berest P., Hardy H.R., Langer M., [1996], Proceedings of the Third Conference on the Mechanical Behavior of Salt, Trans Tech Publications.

Hardy H.R., Langer M., [1984,1988], Proceedings of the First and Second conferences on the Mechanical Behavior of Salt. Trans. Tech. Publications.

Hugout, B., [1988], "Mechanical Behavior of salt cavities -in situ tests- model for calculating the cavity volume evolution", 2nd Conf. Mech. Behavior of Salt, Hannover, Hardy and Langer ed., pp 291-310, Trans. Tech. Pub.

Kuhne, G, Rhor, W.U., and Sasse, W., [1973], "Kiel gas storage facility, the first city gas cavern in Germany", Proc. 12th Int. Gas Congress, Nice.

Langer, M., Wallner, M., and Wassmann, W., [1984], "Gebirgsmechanische Bearbeitung von Stabilitäts fragen bei Deponiekavernen im Salzgebirge", Kali und Steinsaltz, S66/76, Verlag Glückhauf.

Peach, C.J., [1991], "Influence of deformation on the fluid transport properties of salt rocks", Thesis, Univ. of Utrecht, Holland.

Spiers, C.J., Peach, C.J., Brzesowsky, R.H., Schutjens, P.M.T.M., Liezenberg, J.L., and Zwart, H.J., [1987], "Long term rheological and transport properties of dry and wet salt rocks", Final report, aims 1-3 HPT Laboratory Dept. of Geology, Inst. of Earth Sciences; University of Utrecht, The Netherlands.

Veil,.J., Elcock, D., Raivel, M., Caudle, D., Ayers, R.C., and Grunewald, B., "Preliminary Technical and Legal Evaluation of Disposing of Nonhazardous Oil Field Waste into Salt Caverns", Argonne National Laboratory . US Department of Energy. To be published in 1996.

Wallner, M., [1984], "Frac-Pressure Risk for Cavities in Rock Salt", 2nd Conf. Mech. Behavior of Salt, Hannover, Hardy and Langer ed., pp. 645-658, Trans. Tech. Pub.

You, Th., Maisons, Ch., and Valette, M., [1994], "Experimental procedure for the closure of the brine production caverns on the "Saline de Vauvert" site", SMRI Fall Meeting, Hannover, Germany.