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MEETING
PAPER

BEHAVIOR OF SEALED SOLUTION-MINED CAVERNS

by

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ABSTRACT

Solution-mined caverns will be one day sealed and abandonned. Due to an increasing concern in environmental and safety issues, the long term behavior of brine bubble initially enclosed in the cavern has been analyzed by several authors, who lay emphasis on the fracturation risk due to the progressive pressure build up in the cavern caused by brine heating and cavern creep. In this paper we suggest to take into account the rock salt permeability : even if small, it allows some pressure release and leads to a final equilibrium pressure which is substantially lower, in many cases, than the lithostatic pressure.

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

The fluid pressure builds up if we take into account the brine expansion due to geothermal heating and the 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, Wallner, Wassmann (1984) have shown that pressure build up will in many cases 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 fastly moving upwards can be expected.

The former analysis disregards the favourable effect of salt permeability, which allows some release of brine out of the cavern. We will prove that this release can lower by a significant amount the final pressure reached in the cavern.

In a first part, we discuss the main physical factors playing a role in cavern pressure build up :

- Brine heating and thermal expansion
- Cavern compressibility
- Brine percolation
- Creep

Then we will discuss successively the effects of :

- Creep in a closed cavern
- Creep and percolation
- Creep, percolation and brine heating

This analysis allows for an interpretation of several in situ tests (measurement of pressure build up in closed caverns). As a conclusion we suggest procedures able to mitigate pressure build up rate and maximum value.

Brine heating

Solution Mining uses relatively cold brine (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 distribution is T(°C) = 12 + 0,03 z (metres) where z is the cavern depth ; it means that T = 42°C (108°F) at a depth of 1000 metres.

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 to the heat conduction through the rock mass towards the cavern. The thermal balance is intricated, because dissolution is an endothermal process (the reaction needs some heat) ; it depends on the injection - withdrawal rate. As a conclusion, the average temperature in the cavern at the end of leaching is intermediate 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 and tend to reach an equilibrium with the rock mass temperature.

For simplified assumptions a simple computation of the temperature evolution is possible. Those assumptions are essentially the following :

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

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

Then, It is easy to estimate the characteristic time of the brine heating process (the "characteristic time" means here the time after which approx. 75 % of the initial temperature gap has vanished) ; this time is

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

where V is the cavern volume (in m^3) and k the thermal diffusivity (in m^2/s). For a 8 000 m^3 cavity, the characteristic time is t_c = 1 year ; for a 500 000 m^3 cavity, 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 consequences (pressure build up, if the cavern is closed, or brine flow at ground level, if the well head is left open) can be accurately observed. These points will be discussed in the following paragraph ; an example of a direct measurement is described on figure 1.

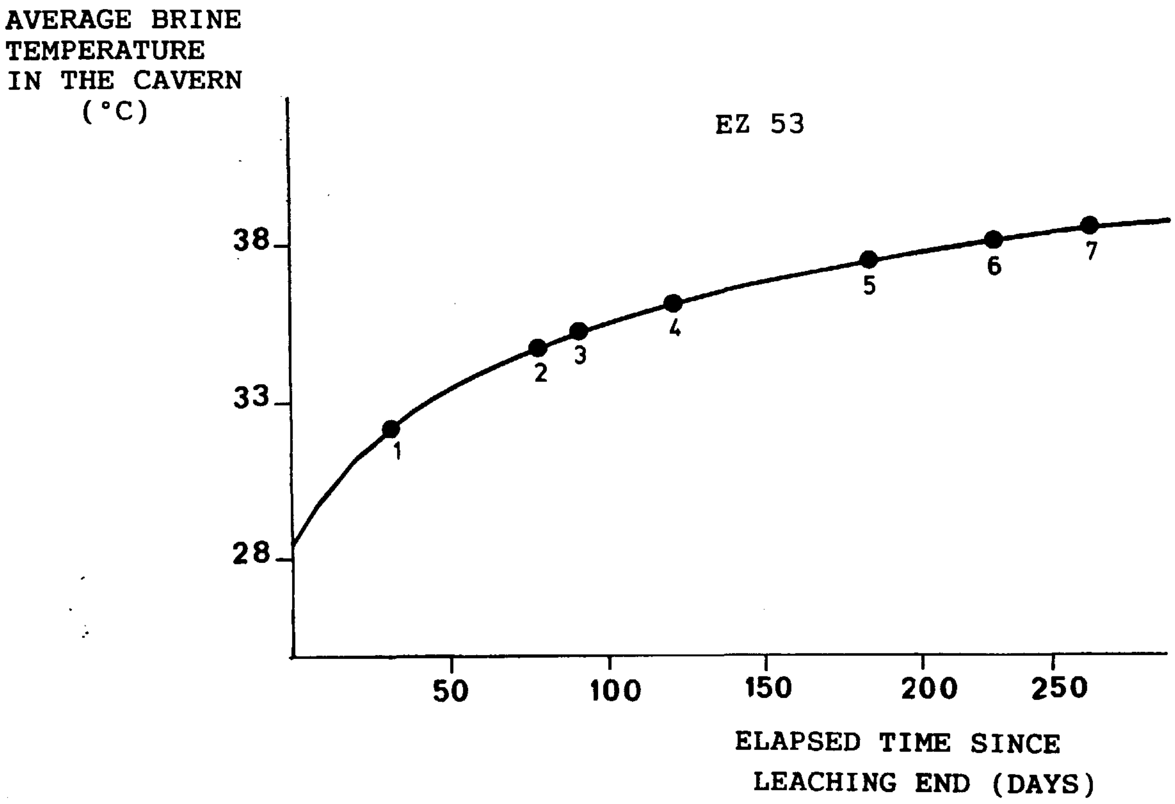

Figure 1 - Temperature evolution (as measured) in the Ez 53 cavern.

Gaz de France has measured the brine temperature at different instants after the end of the leaching process by lowering a thermometer into the cavern. The cavity is called Ez 53 ; its volume is 8 000 m^3, its depth is 950 m. Immediately after leaching, the brine temperature was 28°C, to be compared to the rock mass temperature (45°C) and to the soft water temperature (12°C). The brine warms up as follows (the bracketed figure is the number of days after the leaching has ended) :

32.03°C (31), 34.88°C (81), 35.22°C (94), 36.09°C (123),
37.55°C (185), 38.20C (226), 38.7°C (255)

In this (small) cavern 60 % of the initial temperature gap has been resorbed after 8.5 months.

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 $\alpha = 4.4\ 10^{-4}/^{\circ}C$, so that the flow which would be expelled from the cavern can be expressed as :

$$Q_{th} = \alpha V \dot{T}$$

where $\dot{T}$ is the derivative of temperature with respect to time. For instance Hugout (1988) has observed the flow expelled from the Ez 53 cavern (see Figure 2) during days α 50 to 90 and 263 to 360 after the leaching has ended ; the brine outflow is a little bit larger than would have been expected from temperature measurements (the reason of such a discrepancy is the cavern skrinkage due to salt creep)

The brine flow, at first sight, 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 power 1/3 of the cavern volume

$$Q_{th} \approx V^{1/3} \Delta T$$

Where ΔT is the initial temperature gap. In other words, when the flow is 200 litres/day in a 8 000 m^3 cavern, its value will be 200 x 4 = 800 litres/day in a 512 000 m^3 cavern which is 64 times bigger than the smaller cavern ; however, such a flow will decrease much more slowly in the bigger cavern.

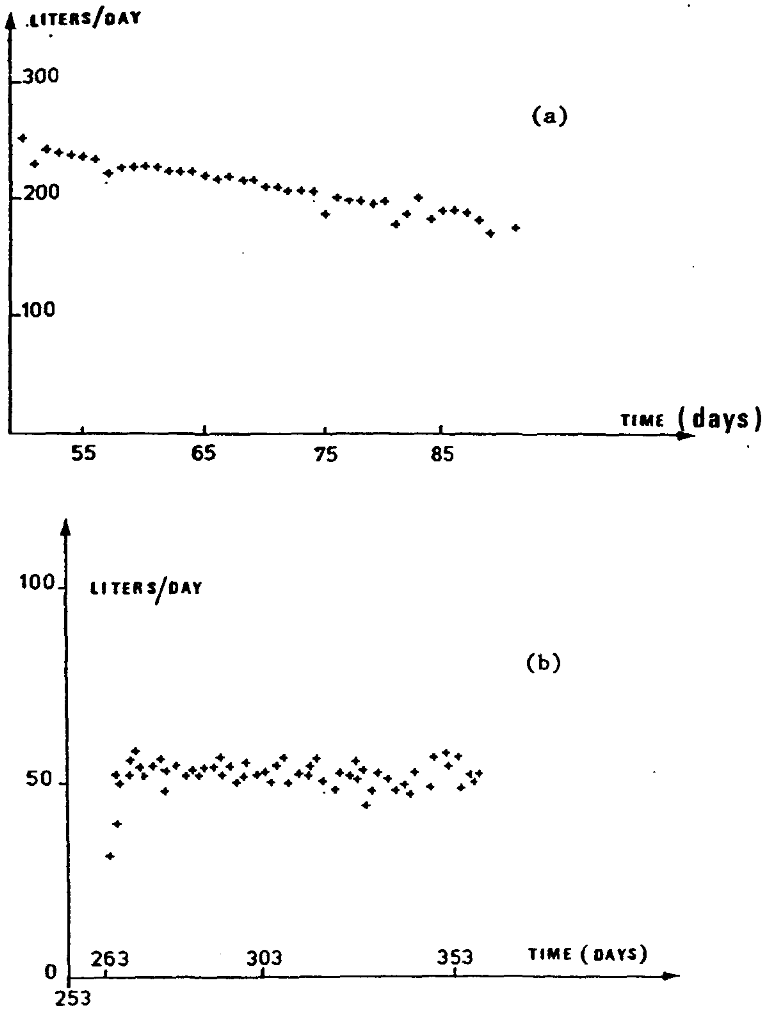

Figure 2 - Brine Flow expelled from an open cavern.

Cavern compressibility

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

$$\Delta V + \beta \ V \ \Delta P_i = 0$$

where V is the cavern volume and β is the "compressibility factor", which is the sum of the brine compressibility (approx. 2.7 $10^{-10} Pa^{-1}$) and the cavern compressibility (1.3 $10^{-10} Pa^{-1}$ for a cavern of regular shape). A typical value is $\beta = 4.10^{-10} Pa^{-1}$ (Boucly, 1982) ; it means that, in a 500 000 m^3 cavern, the injection of 1 m^3 of additional brine in a salt cavern leads to a 5 kPa pressure build up.

In Colin, You (1990) a slightly higher compressibility coefficient, $\beta = 5.10^{-10} Pa^{-1}$ is proposed for the salt caverns of the Manosque site (France).

Brine percolation

Rock salt exhibits very low permeability. A typical value of the intrinsic permeability as measured in laboratory, for a pure and intact salt is $K = 10^{-22}$ m^2.

Generally, salt is mixed up with small amounts of other minerals (clay, anhydrite, limestone) so that the global average permeability strongly depends upon the relative proportion and arrangement of the different components. The permeability is also strongly influenced by the stress path to which the salt has been submitted. For instance, L. Thorel and M. Ghoreychi (1993) suggest a distinction between the contractant domain (small deviatoric stresses, large mean pressure) in which the viscoplastic creep is of the associated type -i.e. with no volume change-, and a dilatant domain (large deviatoric stresses) in which large irreversible volume changes occur, along with a drastic increase of the permeability (several order of magnitudes). One must add that some physico-chemical interactions between brine and rock salt can take place : the salt concentration in a saturated brine is a function of both temperature and pressure ; then an upward brine percolation in the rock mass can lead to a gradual crystallisation along the brine path and to a correlated reduction in permeability. One must recognize the lack of field evidences of such phenomena.

Several in situ tests have been performed in order to determine the in situ permeability of rock salt. For instance in the Etrez site, described above, G. Durup (1994) has performed a one year test in a 1 000 metres deep hole ; the average impurity content of the Etrez salt is 10 % and the measured permeability in the 100 metres high open hole is $K = 6.10^{-20}$ m^{2}·. From now on, we assume that a value of 10^{-20} m^{2}· to 10^{-22} m^2.is a reasonable range of variation for the overall permeability of a cavern.

Creep

Many works have been devoted to the rheology of rock salt and the subject does not seem to be exhausted, by far. Nevertheless many authors (see Proceedings of the First and Second Conf. The Mechanical Behaviour of Salt, R. Hardy and M. Langer Editors) agree on several main features of rock salt constitutive behaviour. First, salt behaves like a fluid, in the sense that it flows even under small deviatoric stresses ; salt is a non-newtonian fluid, which means that its strain rate is proportional to a rather high power of the 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 is increased by 100°C).

The two effects will combine if one considers the behaviour of caverns filled with brine and open to atmosphere. At a depth of 1 000 metres, the lithostatic pressure is 22 MPa, the brine pressure is 12 MPa, the rock temperature is 45°C ; the steady state volume change rate will typically be 2.5 10^{-4} per year (this figure has been measured by P. Berest, P.A. Blum, 1992, in the Ez 53 cavern quoted above, eight years after the leaching has ended). At a depth of 2 000 metres, this rate would probably increase by a factor of at least 100, due to both larger temperature and overburden pressure.

In order to make some tentative calculations, we will assume in the following that in the steady state regime the volume change rate can be described as follows

$$\dot{V} / V = A\left[(P_R - P_i)/10\right]^m \exp\left[\gamma(z-1000)\right]$$

where P_R is the overburden pressure, in MPa (approx. P_R = 0.022 z), P_i is the cavern pressure in MPa (approx P_i = 0.012 z if the hole is filled with brine and open to atmosphere) and, z is the cavern depth (in metres). A reasonable set of parameter values is :

$\gamma = 2.5 \ 10^{-3}$ (metre)$^{-1}$
m = 3
A = 2.5 10^{-4} (year)$^{-1}$

it means that at 1 000 metres deep, cavern creep is 2.5 10^{-2} per year at a depth of 2 000 metres.

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 time much larger than the "characteristic time" $t_c = V^{2/3}/(4k)$, or in other words, if the brine temperature in the cavern is not very different from the rock mass temperature.

If percolation too can be disregarded, pressure will slowly increase in a closed cavern. For the sake of simplicity, we assume that a steady state creep is reached at any instant (this assumption is reasonable as long as the process is slow, as will appear later), then the volume change rate can be written

$$\dot{V}/V = B\left(P_R - P_i\right)^m$$

where $B(z) = A(10)^{-m}\exp\left[\gamma(z-1000)\right]$. On the other hand, due to brine compressibility, we have:

$$\dot{V}/V + \beta\,\dot{P}_i = 0$$

and, by combining the former relationships, we get the evolution with respect to time of the average fluid pressure in the cavern :

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

with m = 3, β = 4 10^{-4} MPa^{-1}. The initial pressure build up rate will be 0.625 $\mathrm{MPa(year)}^{-1}$ in a 1 000 metres deep cavern, for which B = 2.5 10^{-7} $\mathrm{(MPa)}^{-m}\mathrm{(year)}^{-1}$ and the initial difference between overburden pressure and internal pressure is $P_R - P_i(o) = 10\,MPa$. At such a depth, this difference will be divided by two after 8 years and divided by ten after 8 centuries approximately.

Things are a little bit different in a 2 000 metres deep cavern, for which $B = 3.10^{-6}\,(MPa)^{-m}(year)^{-1}$ and $P_R - P_i(o) = 20\,MPa$; time scale will be reduced by a factor slighly smaller than 50, which means that the gap between overburden pressure and internal pressure will be 10 MPa after two months, and 2 MPa 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 much more pronounced yet if the exponent "m" in the creep constitutive equation was taken equal to 4 or 5, which can be realistic in many cases.

Thermal expansion and brine percolation have been disregarded and will be considered in the following ; but first we will discuss the nature of the final state reached at the end of the pressure build up.

In the former paragraph, we have seen that the average brine pressure tends towards equilibrium with the lithostatic pressure. In fact, equilibrium cannot be reached as observed by many authors, for instance Langer, Wallner, Wassmann (1984) and Ehgartner, Linn (1994).

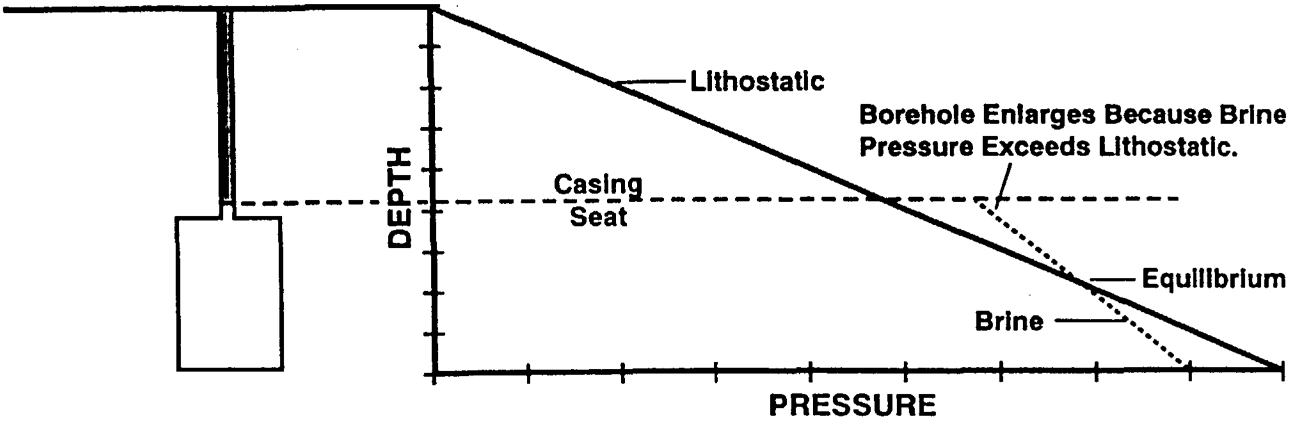

Figure 3 - Illustration of Pressure Differential between brine and lithostatic pressure at the casing seat.(after Ehgartner and Linn, 1994).

As a matter of fact, brine density (1 200 kg/m^3) is notably different from rock mass density (2 200 kg/m^3) ; then a mechanical equilibrium (which implies hydrostatic state of stress) cannot be reached between brine and salt along a vertical interface. It means that brine pressure exceeds rock pressure at the top of the cavern, the inverse being true at the bottom : the cavern enlarges at its top and shrinks at its bottom, resulting in a global upwards movement of the cavern.

This movement is probably small, since the driving pressures are low (their magnitude is given by the differences in pressure between two columns of salt and brine resp., whose height is equal to cavern height, for instance $\Delta P = 5\,MPa$ in a 500 metres high cavern).

Of much more serious concern is the risk of fracturation. Salt tensile strength is small, and fracturation can occur when brine pressure exceeds by a small amount rock lithostatic pressure (for a description of an in situ slow fracturation test, see Durup 1994). Fracture will presumably occurs first at the top of the cavern trac and will progress upwards, the driving force increasing as the total height (cavern plus fracture) becomes larger.

Note also that thermal equilibrium cannot be reached due to geothermal gradient : rock temperature being lower at cavern top, convective flow will take place in the cavern, hot brine moving upwards along cavern walls, crystallizing some salt on the cold top of the cavern, then flowing downwards along the cavern axis. Dissolution (at the bottom) and crystallisation (at the top) will produce a global apparent downwards movement of the cavern, whose rate will probably be very slow.

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 will reach much lower levels, as indicated by Berest (1990) and Ghoreychi, Cosenza (1993). The equilibrium will be reached when cavern loss of volume, due to creep, exactly balances brine leak due to percolation towards the rock mass. Percolation can be roughly estimated in assuming that the cavern behaves as a spherical cavern of radius R such as $V=4\pi R^3/3$, in a porous rock mass which satisfies Darcy law. In the steady state regime, pressure distribution in the rock mass will be an harmonic function and the relative loss of brine from the cavern will be (see Berest, 1995) :

$$Q/V=3K(P_i-P_o)/(\eta R^2)$$

where K is the salt intrinsic permeability, which typically ranges from $K=10^{-20}\,m^2$ to $K=10^{-22}\,m^2$, P_i is the cavern brine pressure, R the cavern radius, η the brine viscosity (which is a decreasing function of temperature, $\eta=1.2\;10^{-3}\,Pa.s^{-1}\;at\;45°C\;and\;0.6\;10^{-3}\,Pa.s^{-1}\;at\;100°C$, and P_o is the natural brine pore pressure. In many cases it is reasonable to assume that this pressure is equal to the brine pressure in a cavern open to atmosphere (i.e. $P_o=P_i(o)=0.012z$ if z is the cavern depth). In the following this assumption will be called the "hydrostatic hypothesis".

A balance between cavern creep and brine leak will be reached when

$$3K(P_i-P_o)/(\eta R^2)=B(z)(P_R-P_i)^m$$

If we set $1/a=\eta(z)B(z)R^2(P_R-P_o)^{m-1}/(3K)$ and $x=(P_R-P_i)/(P_R-P_o)$, this relationship can be written $x^m-a(1-x)=0$; x is the ratio between the final gap and the initial gap between lithostatic pressure and brine pressure ; when x is close to zero, a risk of fracturation exists.

First consider the case of a cavern (225 000 m^3, R = 26 metres) at shallow depth (z = 1 000 metres). We assume the hydrostatic hypothesis (P_o = 12 MPa), the overburden pressure is 22 MPa ; brine viscosity is taken equal to $\eta=1.2\;10^{-3}\,Pa.s^{-1}$; rock salt properties are m = 3 and A = 2.5 10^{-4} (year)$^{-1}$, B = 2.5 10^{-7} (year)$^{-1}$. The salt permeability is taken equal to $K=6\;10^{-20}\,m^2$, then 1/a = 3.75, x ≅ 0.5 and the final pressure in the cavern will be 17 MPa (i.e., half way between lithostatic pressure and initial brine pressure). In this example, it is clear that <u>the risk of fracturation due to high internal brine pressure vanishes</u>. This conclusion will be enforced for a smaller cavern and still holds for very big caverns (one million cubic metres).

At greater depth, the conclusions are different because the parameter a is strongly influenced by depth : salt creep is fastened by higher temperature (coefficient γ), the initial gap of pressure is larger ($P_R - P_o = 0.01z$) but, with opposite consequences, the brine viscosity is lowered when the temperature increases. For instance, at a depth of 2 000 metres, the coefficient 1/a is multiplied by 50 and x is divided by 5. The initial gap is 20 MPa but will be reduced to 4 MPa when final equilibrium is reached.

Those figures are strongly influenced by the permeability value. Up to 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 gap between lithostatic pressure and brine pressure will be reduced to 0.7 MPa (instead of 5 MPa) for a 1 000 metres deep cavern.

Those 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 fracturation practically vanishes. This statement is incorrect, as will be seen in the next paragraph, if thermal expansion cannot be disregarded.

Effects of creep, brine percolation and thermal expansion

We have seen that temperature increase leads to a thermal expansion

$$Q / V = \alpha \dot{T}$$

If the cavern is closed, this expansion will produce a pressure build up according to the elastic relationship

$$\beta \dot{P} = \alpha \dot{T}$$

where β is the brine plus cavern compressibility and α is the thermal expansion coefficient. When estimating the values of the coefficient β and α, one must take into account the influence of temperature, pressure, but also brine saturation concentration (a change in pressure or temperature, inside the cavern, brings to additional dissolution or crystallisation which modifies the apparent compressibility). A discussion can be found in Ehgartner and Linn, 1994). As a rough estimation, a 1°C increase in temperature leads to a 1 MPa increase in mesure. The initial gap (before sealing) between overburden pressure and brine pressure being $P_R - P_i(o) = 0.01z$ (units are : MPa and metre, respectively) there is a risk of fracturation if the initial gap between rock temperature and brine temperature is larger than $\Delta T = 0.01z$ (units are : Celsius degree and metre, respectively) or 10°C at a depth of 1 000 metres and 20°C at a depth of 2 000 metres.

This statement happens to be a little bit too 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 temperature.

In a rather shallow cavern (1 000 metres deep for instance) creep is very slow ; for times small when compared to the critical time $t_c = (V)^{2/3} / (4k)$, pressure build up versus time is practically proportional to temperature increase, $\beta \dot{P} = \alpha \dot{T}$. On figure 4(a) the dashed line represents the pressure build up in a cavern in absence of percolation and creep. When percolation is taken into account, we get a slightly lower or upper curve which differs from the former one when the temperature increase slows down ; after a long time, it will reach the equilibrium value, when creep exactly balances percolation.

The key question is to check whether the brine pressure can reach or not the lithostatic pressure. A precise calculation must be performed in each practical case.

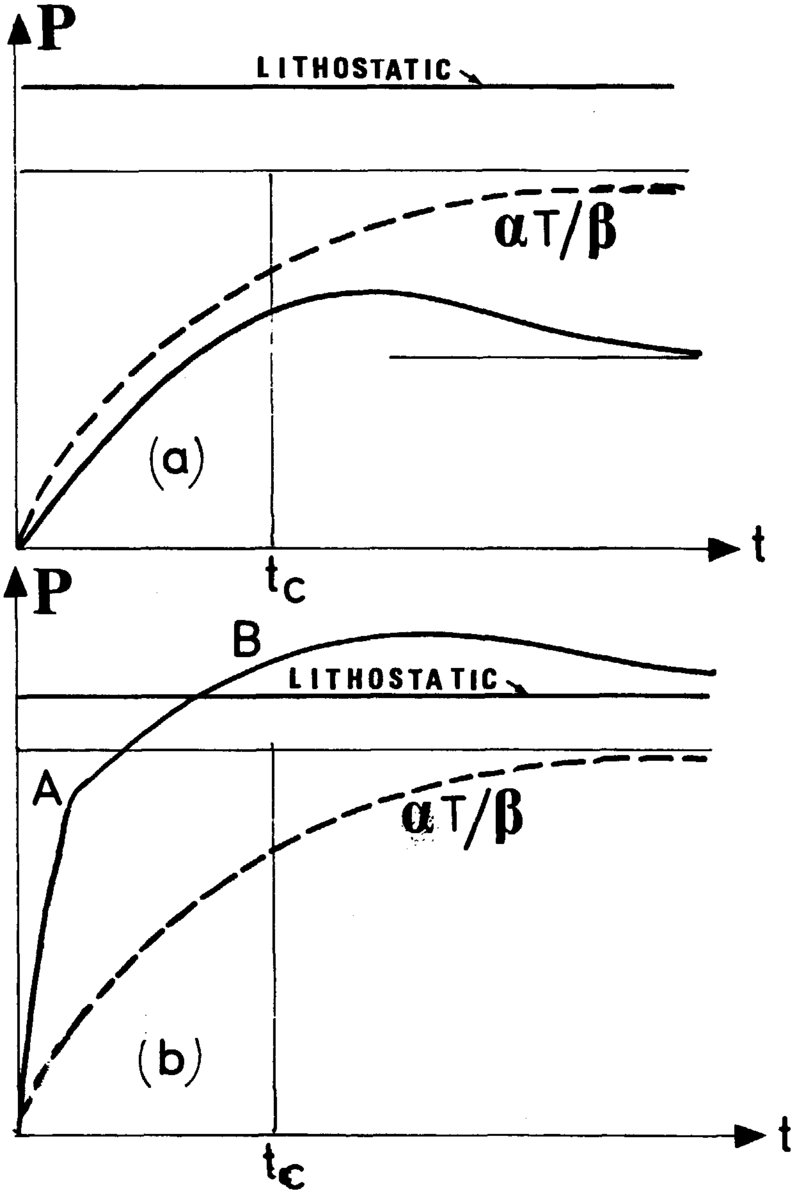

*Figure 4 - Pressure build up in a shallow (a)
or deep (b) closed cavern*

In a deep cavern (2 000 metres for instance), creep will be the preeminent phenomenon (initial pressure build up rate due to creep is :
$\dot{P}(o)=\frac{1}{\beta}A\left\{\left[P_R-P_i(o)\right]/10\right\}^m\exp\left[\gamma(z-1000)\right]=(2.4\;10^{-2}\,year^{-1})/4\;10^{-4}\;MPa$
or 60 MPa/year) ; if the initial gap in temperature is $\Delta T=40°C$, the pressure build up rate due to thermal expansion is $\frac{\alpha}{\beta}\frac{\Delta T}{t_c}\cong\frac{\Delta T}{(0.08R)^2}$ if R is the radius (in metres) of a sphere whose volume is equal to the cavern volume. For a 50 metres radius (V = 500 000 m^3) the initial pressure build up rate is approximately 0.625 MPa/year, negligible when compared to creep.

After a relatively short time (point A on figure 4b), creep will drastically slow down, for the difference between overburden pressure and cavern pressure, which is the creep driving force, is considerably lowered. Then temperature increase will become preeminent, as in the first case, and the curve pressure versus time will be parallel to the $\alpha T/\beta$ curve (point A to point B). When temperature changes vanish, the pressure will tend towards a smaller value, which is defined by the exact balance between creep and percolation.

Once again, those statements are correct if the overburden pressure is not exceeded by a too large amount. At large depth this assumption is optimistic, as will be seen in the examples.

First example : Hauterives

This example concerns brine production caverns operated by Rhône Poulenc, near Hauterives (Drôme, France), see for instance George, Laporte, 1976. In fact the example concerns a pair of caverns, Ha 6 and Ha 7, a very small and a big one, linked together by an underground connection. The global volume at test time was 460 000 m^3 ; the caverns were located at a depth between 1 550 metres and 1 650 metres. The natural rock temperature at that depth is approx. 61 °C and the brine temperature was estimated to be 26°C when the cavern was closed.

The pressure increase versus time, as measured at the well head, is not very different from the value calculated according to the $\dot{P}=\alpha\dot{T}/\beta$ rule (difficulties have been encountered during the test due to leaks at the well head) ; this evolution can be considered as an example of the "shallow cavern" type : during the measurement period, both percolation and creep do not play the preeminent role, which is devoted to thermal expansion.

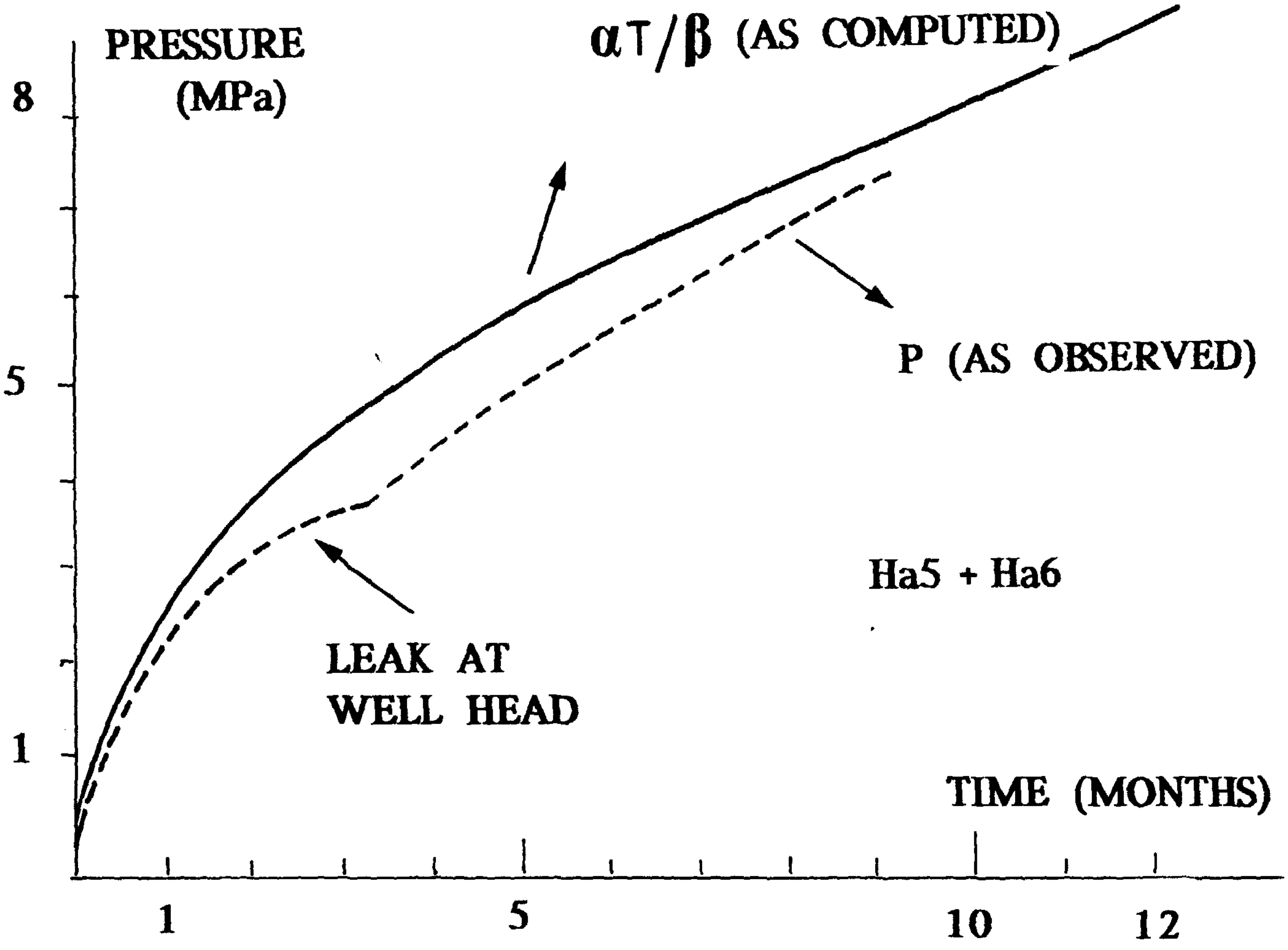

Figure 5 - Pressure build up in a closed cavern at Hauterives (Ha 5 + Ha 6)

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 metres, has a $8000\,m^3$ volume. The cavern was closed 361 days after the leaching had ended and kept closed during 224 days (7.5 months). A few days before closing, the cavern was opened to atmosphere and a 50 litres/days brine outflow was observed for a hundred days.

Various in situ tests had been performed in this cavern, or in holes at same depth and small distance (Boucly, 1982 ; Berest, 1986 ; Hugout, 1988 ; Durup, 1991). From these tests resulted some useful conclusions

- The hydrostatic hypothesis (the initial pore pressure is equal to brine presure) is reasonable and salt permeability is in the range of $K = 6.10^{-20}$ m^2
- Thermal expansion, one year after the leaching has ended, is still active and can be considered as responsible of 80 % - 90 % of the observed brine outflow.
- Cavern creep, as measured 7 years after the described test (thermal expansion is then much smaller) is 5 litres per day.

If we assume for the sake of simplicity that thermal expansion generates a 40 litres/day brine flow, the rest (10 litres/day) being related to a slowly decreasing cavern shrinking, then the pressure build up rate , $\dot{P} = \dot{V} / (\beta V)$ in a closed cavern can be expected to lay in the range 4.5 to 6.25 MPa/year. The observed value is rapidly smaller than expected (see Figure 6) which may be partly due to experimental problems.

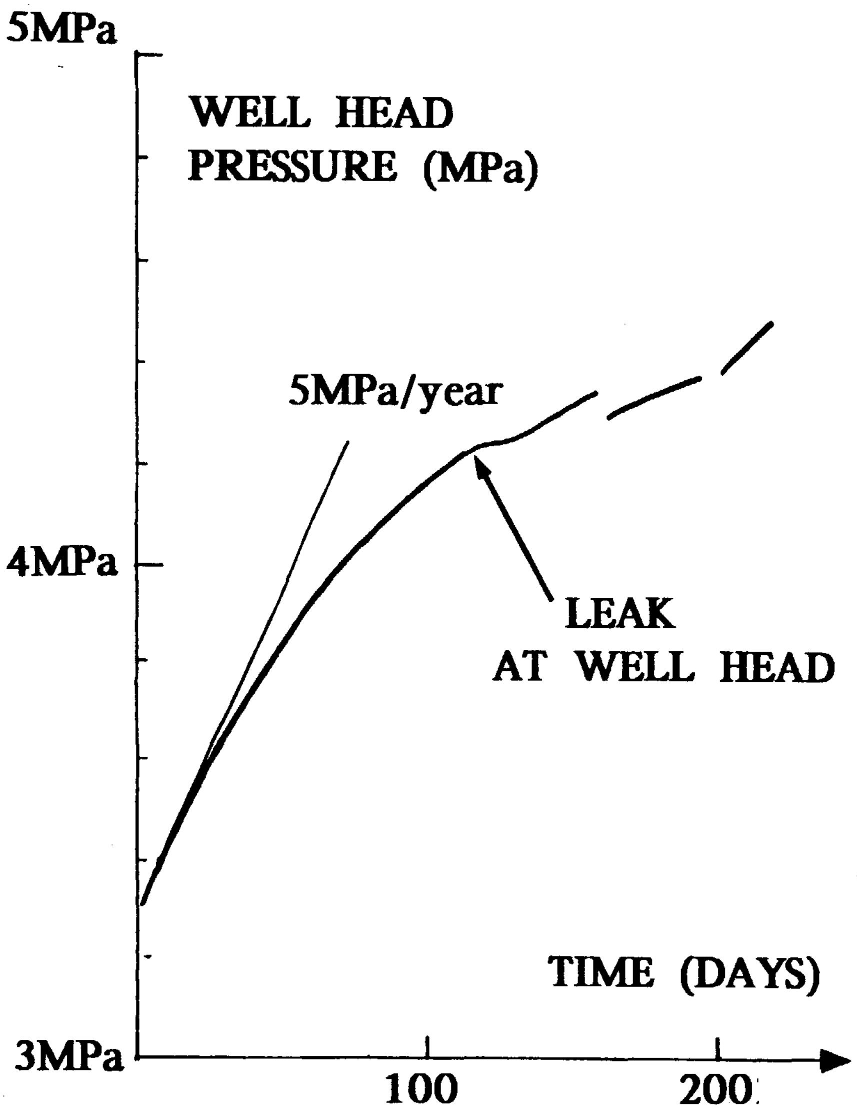

Figure 6 - Pressure build up in a closed cavern at Etrez (Ez 53)

Third example : Vauvert

The caverns of this site are much deeper ; salt rock lays between 1 800 metres and 2 500 metres. The insoluble amount is large, not far from 50 %. The natural temperature of rock is higher than 100°C (210°F). the caverns Pa1, Pa2, Pa6 are linked together ; soft water is injected in one hole and withdrawn from another. The Pa1 - Pa2 pair has produced 292 000 tonnes, and the Pa1 - Pa6 pair 68 000 tonnes. The volume of each cavern is approximately the following : Pa6, 16 000 m^3 (R = 16 metres), Pa2, 68 000 m^3 (R = 25 metres), Pa1, 84 000 m^3 (R = 27 metres). The Pa3 cavern has remained isolated.

The very stiff slope of the curves (pressure build up) versus (time) for the 3 caverns Pa1, Pa2, Pa6 is characteristic of deep caverns : just after the well head closure, cavern creep is much more important than thermal expansion, up to the point when the gap between lithostatic and brine pressures has become smaller than 7 MPa. 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 (and more for Pa6) the geostatic pressure at cavern depth is reached ; hydrofrac and reopening of links between caverns stop any further increase in brine pressure.

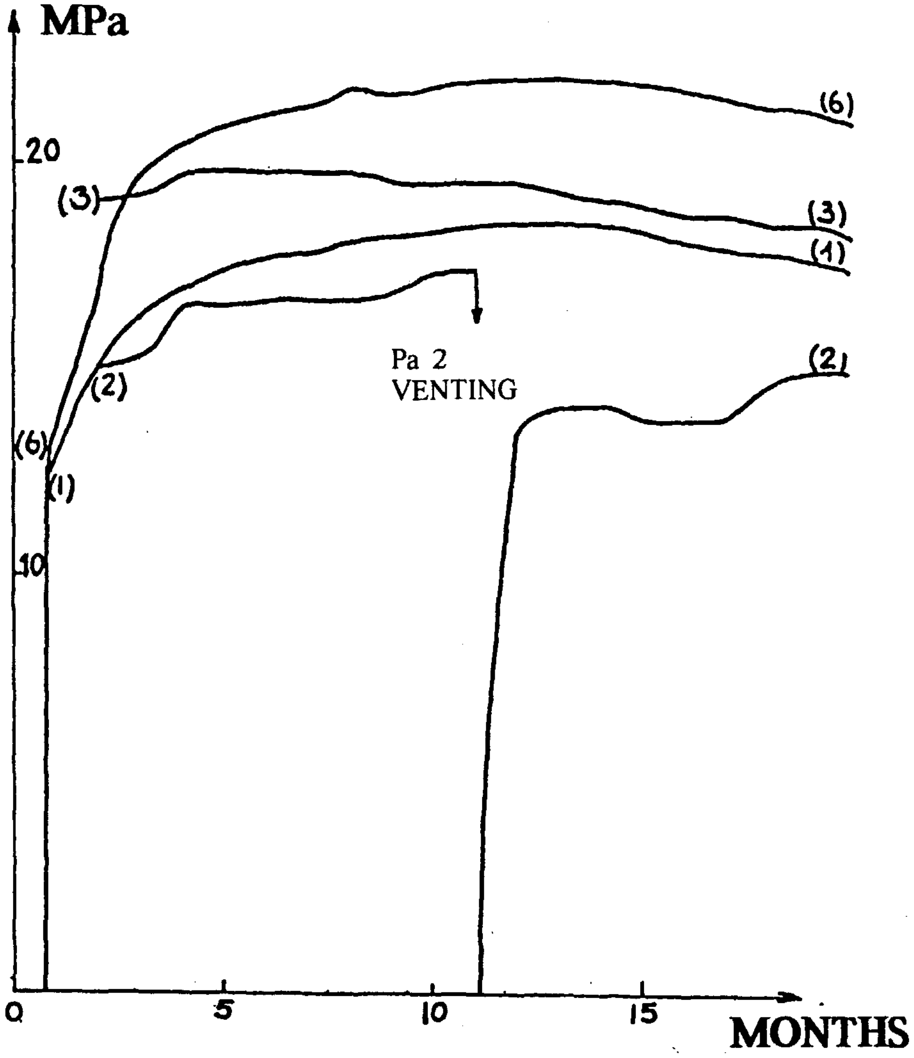

Figure 7 - Pressure build up in closed caverns at Vauvert (Pa1, Pa2, Pa3, Pa6)

CONCLUSIONS

We have proved that pressure build up in a sealed cavern, generated by salt creep and brine heating, lead to a final equilibrium pressure which is smaller than lithostatic pressure, provided that rock salt in the cavern surroundings exhibit some permeability.

Our first recommendation, in a real site, is to take advantage of open holes, before leaching, to perform accurate in situ pressurization tests in order to evaluate the field permeability. This figure is essential for further estimations.

The favourable effects of salt permeability will not be sufficient, in many cases, to avoid a transient period during which, mainly due to brine thermal expansion, the pressure in the cavern exceeds the lithostalic pressure (especially in deep caverns).

Several solutions to this problem can be suggested :

1. Delay installation of the plug allow the salt to heat the brine (for instance, Ehgartner, Linn 1994). The major drawback is that the delay can be long (several times the characteristic time, t_c) and then, except maybe in the case of state-owned companies, a difficult problem of responsability transfer must be solved [will the company still exist in 20 or 30 years ? if not, who whill pay for cavern plugging ?].

2. Accelerate cavern creep, for instance by setting an immerged pump at the bottom of the hole, as performed with partly unexpected consequences in a Kiel cavern in Germany (Kuhne, Rhor, Sasse 1973). Such a solution has been suggested, in a special context which makes the idea attractive, by Fokker (1994).

3. Inject some gas (nitrogen or air) in the cavern, prior to plugging, in order to lower cavern compressibility and reduce pressure build up rate. Such a solution has been suggested by Abouaf, Legait (1978) and can provide an ingenious way of mitigating thermal expansion effects.

REFERENCES

Alla N., Berest P., Blum P.A., Durup G., (1993), *In situ test in brine filled caverns,* 3rd Conf. Mech. Behaviour of Salt, Palaiseau.

Kuhne G, Rhor W.U., Sasse W., (1973), *Kiel gas storage facility, the first city gas cavern in Germany,* Proc. 12th Int. Gas Congress, Nice.

Berest P., (1990), *Les problème soulevés par l'abandon des cavités de dissolution profondes dans le sel gemme,* in stockage en souterrain, pp. 115-130, Presses des Ponts et Chaussées, Paris.

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

Berest P., (1986), *A simple method for evaluating the volume of underground cavities,* SMRI Autumn Meeting, Sept. 21-24, Okura Hotel, Amsterdam.

Berest P., Blum P.A. (1992), *In situ tests in salt caverns*, Proc. 7th Int. Symp. on Salt, Kyoto.

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.

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

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

Abouaf M., Legait B., (1978), *Les différentes utilisations du sel souterrain et leurs conséquences à long terme,* Internal report, Ministry of Industry, France.

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

Langer M., Wallner M., Wassmann W., (1984)), *Gebirgsmechanische Bearbeitung von Stabilitäts fragen bei Deponiekavernen im Salzgebirge,* Kali und Steinsaltz, S66/76, Verlag Glückhauf.

Ehgartner B.L., Linn J.K., (1994), *Mechanical Behavior of Sealed SPR Caverns, SMRI Spring meeting,* April 25-27, Houston Texas.

Cosenza Ph., Ghoreychi M., (1993), *Coupling between mechanical behavior and tansfer phenomena in salt,* 3rd Conf. Mech. Behaviour of Salt, Palaiseau.

Durup G., (1994), *Long term tests for tightness evaluations with brine and gas in salt,* SMRI Fall Meeting, Hannover.

Fokker P.A., (1995), *The behaviour of Salt and Salt caverns,* Ph. D. Thesis, Delft University of Technology.

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

Berest P., (1995), *Some studies related to the closure of solution mined caverns,* (in french) to be published in the Proc. of the Kyoto ISRM Congress, Sept. 1995.

Colin P., You Th., (1990), *Salt Geomechanics seen through 20 years experience at the Manosque Facility,* SMRI Fall meeting.

Boucly Ph., Legreneur J., (1980), *Hydrocarbon storage in cavities leached out of salt formations,* Proc. Int. Symp. Subsurface Space, Stockholm, Vol.1, pp 251-258.