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In Situ Tests in Salt Caverns

Pierre Berest[1] and Pierre Antoine Blum[2]

[1]*Laboratoire de Mécanique des Solides, Centre Commun X, Mines, Ponts URA 317, Ecole Polytechnique*
[2]*Institut de Physique du Globe de Paris.*

ABSTRACT

Three original *in situ* tests performed on salt caverns are described and discussed. The first is the measurement of the natural vibrations of the brine mass contained in the cavern and tubing. It is proved that their period is of the order of one minute and is related only to the cavern volume, therefore the estimation of cavern volume is a very simple procedure. The second test consists of measuring the dips induced at ground level by a sudden pressure variation in a deep salt cavern. The average elastic properties of the ground at a very large scale can be deduced from these measurements, which are recorded by a high resolution tiltmeter.

The last test is the measurement of the volume rate of brine naturally expelled from a salt cavern. The interpretation is difficult, for many phenomena play a role in the expulsion of brine. Slowly-varying phenomena are brine heating, cavern creep and brine percolation. These three phenomena can be quantified; their relative importance is variable during the whole test, which lasted nine years. Atmospheric pressure and temperature at ground level vary widely even during one day. When these phenomena are taken into account, the effects of the daily earth tides, in spite of being extremely small, can easily be observed.

PART I. CAVERN VOLUME MEASUREMENT

INTRODUCTION

Access to a salt cavern is attained only through tubing; information on the volume or shape of the cavern is generally obtained through sophisticated devices. In this part, we suggest the innovative use of free information, namely the period of the natural vibration of the fluid which can be measured easily at the well head. From this period can be deduced the volume of a brine-filled cavern or, in the case of oil storage, the brine–oil volume ratio.

BASIC HYPOTHESIS

In a salt cavern, we must distinguish between:

– The volume of the cased and cemented borehole which links the cavern to ground level; in our case, the cross-sectional area is 250 cm^2 (diameter: 7⅝ inch), and the height is 1000 m, which means that the volume of brine contained in the casing is 25 m^3.

– The volume of the cavity proper (V_0), which is much larger than the volume of the casing, and may reach several hundred thousand cubic metres.

The system previously described is completed by connecting the cavern with a container of cross-section $\Sigma >> S$ (Fig. 1). The advantage of this device will be explained later.

PRINCIPLE OF THE METHOD

Let P be a slight variation of pressure, uniform throughout the cavern. If P is positive, the cavern will contain a small excess of fluid and the free surface in the container will be below the equi-

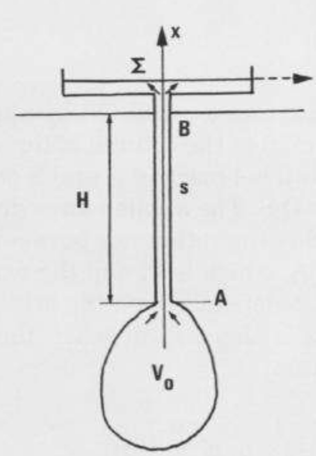

Fig. 1. Cavern, casing and container. H: depth; V_0: cavern volume; s: borehole cross-sectional area; Σ: container cross section.

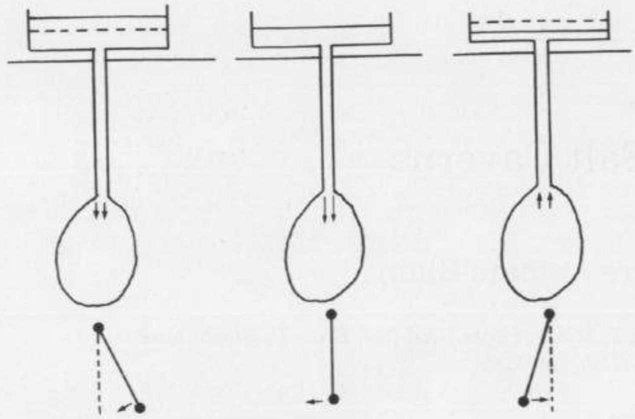

Fig. 2. Natural small movements in the cavern.

librium level. Brine will flow out of the cavern in order to restore equilibrium, and the free surface will rise in the container over the equilibrium level (Fig. 2); then brine will flow downwards, etc. Let Q be the flow rate in the tubing, crossing the section at the cavern top marked A on Fig. 1. Any variation of the brine mass in the cavern must be balanced by the mass of brine crossing the cavern top

$$\frac{d}{dt}(\varrho V) + \varrho Q = 0$$

To solve this equation, one must take into account the brine compressibility, $\varrho = \varrho_0 (1 + \beta_1 P)$ and the cavern compressibility $V = V_0 (1 + \beta_2 P)$. The coefficient β_1 is related to the speed of sound C in the brine, $\varrho_0 \beta_1 C^2 = 1$. The constant β_2 depends both on the elastic properties of the rock mass and on the shape of the cavern. In a cavern of regular shape, β_2 is smaller than β_1. Then setting $\beta = \beta_1 + \beta_2$, the brine mass balance can be written

$$\beta V_0 \dot{P} + Q = 0 \quad (1)$$

A second equation is obtained by applying Newton's law (F = m a) to the column of liquid contained between the sections marked A and B on Fig. 1; $m = \varrho_0 H S$ and $a = \dot{Q}/S$. The applied force divided by the cross-section S is the difference between the excess of pressure in A, which is P, and the excess of pressure in B, which depends upon the brine level in the container. If t_0 is the instant when the system departs equilibrium:

$$\varrho_0 H \dot{Q} = S \left[P - \int_{t_0}^{t} \varrho_0 g \frac{Q(\tau)}{\Sigma} d\tau \right] \quad (2)$$

This equation disregards the damping forces which will be dealt with later. By deriving (2) with respect to time and combining with (1), one may obtain:

$$\ddot{Q} + \omega_0^2 Q = 0, \quad \omega_0^2 = (1/\varrho_0 \beta V_0 + g/\Sigma) S/H \quad (3)$$

ORDER OF MAGNITUDE OF THE PERIOD

A test, which will be described later, has been performed in a cavern on the Gaz de France storage site at Etrez, Ain, France. The following numerical values have been obtained:

$H = 930$ m; $S = 2.5\ 10^{-2}$ m^2; $\varrho_0 = 1200$ kg m^{-3}; $\beta = 4\ 10^{-10}$ Pa^{-1}; $V_0 = 7500$ m^3

The coefficient β is the sum of the brine compressibility, $\beta_1 = 2.7\ 10^{-10}$ Pa^{-1}, and of the cavern compressibility, $\beta_2 = 1.3\ 10^{-10}$ Pa^{-1}. It was estimated by using a large number of *in situ* compressibility tests (Boucly, 1982). The volume V_0 was obtained through a sonar measurement, and corrected to take into account the volume of brine contained in the sump.

It is easy to check that $(\varrho_0 \beta V_0)^{-1} = 278$ m^{-1} s^{-2} is much larger than g/Σ when Σ, the container horizontal cross-section, is a few square meters. If this container had not been used, it would be necessary to replace Σ by S in (3); then $(\varrho_0 \beta V_0)^{-1}$ and g/S would be of the same order of magnitude. In a very large cavern, $(\varrho_0 \beta V_0)^{-1}$ may be disregarded and the system would behave like a simple pendulum of the same length as the tubing.

Due to the existence of the container, we can disregard g/Σ in (3) and then

$$T = 2\pi/\omega_0 \sim 72.5 \text{ seconds}$$

This period is long enough for the phenomenon under consideration to be easily distinguished from other oscillations, such as stationary waves in the cavity. These latter show a fundamental pulsation $\omega = c/l$, if l is a characteristic dimension of the cavern. Because $V_0 \sim l^3$ and $C \sim 1/\sqrt{\varrho_0 \beta}$ we can write $\omega_0/\omega \sim \sqrt{S/(Hl)}$ which is on the order of 10^{-3}, thus it is reasonable to assume that the pressure variation P is uniform throughout the whole cavern at every instant. The same assumption is not completely correct when applied to the brine column in the tubing; this point will be discussed later.

HEAD LOSS

The damping forces must be evaluated to define the optimum operational conditions. The loss of head in the tubing accounts for an important part of this damping; it can be estimated using the Poiseuille formula when the movement is laminar; if ν is the kinematic viscosity of the brine, (3) becomes:

$$\ddot{Q} + 2\lambda\dot{Q} + \omega_0^2 Q = 0 \text{ with } \lambda = \frac{4\nu\pi}{S} \quad (4)$$

Since ν is about $2.10^{-6}\ \mathrm{m^2\,s^{-1}}$, we have $\lambda \approx 10^{-3}\ \mathrm{s^{-1}}$, and λ is small compared with ω_0. However, this formula only applies to laminar flow, that is to say for a Reynolds number given by:

$$R = \frac{2\,Q}{\nu\sqrt{\pi S}} < 2000$$

It is therefore necessary that Q be less than 0.6 $10^{-3}\ \mathrm{m^3/s}$. The maximum flow rate is linked to the maximum pressure amplitude by $Q_{max} = \beta\ V_0\ \omega_0\ P_{max}$; hence the brine flow is laminar for pressure amplitudes below 2000 Pa (that is, 20 millibars). In practice, experiments are undertaken by inducing an initial disequilibrium of pressure greater than 20 millibars. It must be remembered that equation (4) is then ill-adapted for use with the first oscillations.

APPLICATION OF THE METHOD TO A SALT CAVERN

The main characteristics of the cavern have been described above.

The initial disequilibrium in pressure was achieved by closing the central tubing by means of a valve placed at the head of the pipe, then forcing about 60 l of brine into the 7⁵/₈ inch tubing, so as to obtain an excess pressure of about 20,000 Pa, that is, 200 millibars. The opening of the valve started the system oscillating (see Fig. 3).

The container was a drum linked to the shaft head by a 3 inch diameter flexible tube.

Pressure change was measured by taking advantage of certain favourable circumstances: for reasons having to do with the solution process, the drill hole consisted of a central tube filled with brine and a ring element filled with fuel oil. Since the fuel oil is lighter than the brine, its pressure at the well head is quite high (about 3.93 MPa during the test), so that the ring element must be kept closed by a valve. The fuel oil contained will thus not participate in the periodic movement, but it transmits to the well head the pressure variations of the brine contained in the cavity. It is therefore in the ring element filled with fuel oil that the pressure is measured by means of a Digiquartz pressure meter.

The pressure values were recorded on automatic data equipment about every 1.5 seconds; that is, 1/50 of the oscillation period.

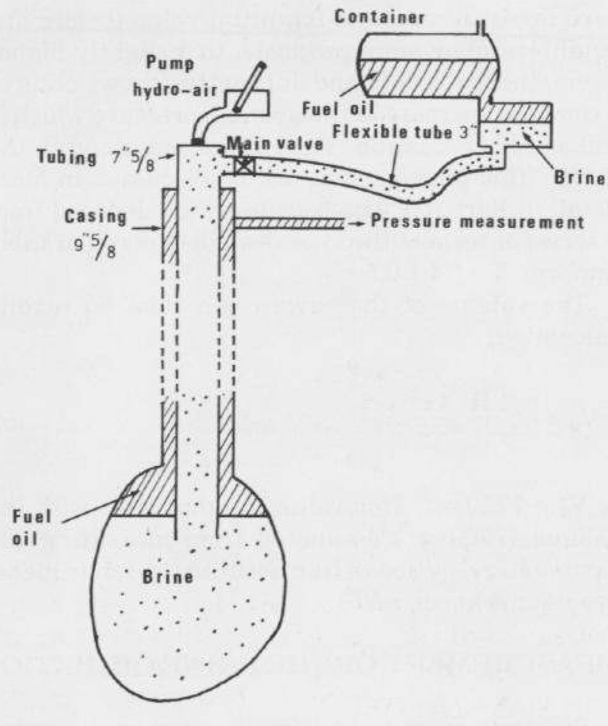

Fig. 3. A schematic diagram of the cavity during a test.

Figure 4 shows the curve recorded during a test. Phase I represents the setting up of the initial disequilibrium of 200 millibars. Phase II begins with the opening of the valve at the well head. At the beginning of this phase, small-period vibrations in the brine-filled tubing can be observed. Those small vibrations are due to waves running upwards and downwards in the tubing. The speed of these waves is, roughly speaking, $C \approx 1750$ m/s if the compressibility of the tubing is neglected; the apparent period is then $T' = 2\ H/C \approx 1$ s. Due to their rather high frequency, those waves vanish rapidly. During phase III the movement in the central tube can be considered laminar. At the end of this phase, the pres-

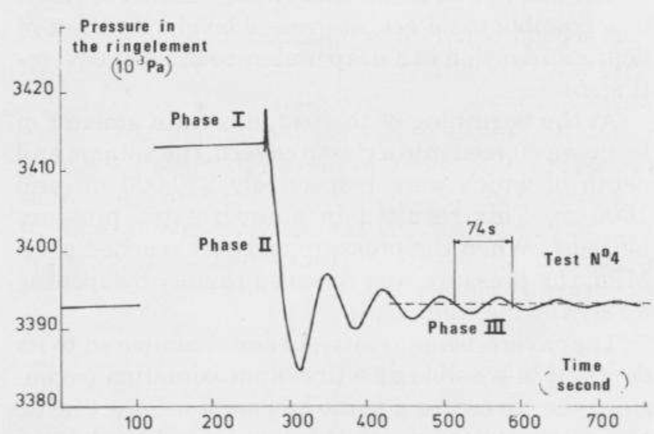

Fig. 4. Development of pressure as a function of time during a test on a 7500 m³ salt cavern (Etrez, Gaz de France).

sure tends to return to its initial value (before disequilibrium) or more precisely, to a slightly higher value. Indeed, before and during the test we observe a constant increase of the average pressure which is linked to the heating of the brine contained in the cavity (this phenomenon will be discussed in more detail in Part III). The pseudo-period deduced from a series of tests of the type described is remarkably uniform: T = 74 ± 0.5 s.

The volume of the cavern can then be readily calculated:

$$1/V_0 = \frac{\varrho_0 \beta H}{s} \frac{4\pi^2}{T^2} \qquad (5)$$

or $V_0 = 7750\ m^3$. This value is comparable with the volume (7500 m^3) estimated from measuring the cavity shape by sonar (the accuracy of sonar measurement is about ± 5%).

MEASUREMENT OF THE BRINE/OIL RATIO

Storage caverns for oil are operated by the "brine compensation" method: as oil is withdrawn, an equivalent amount of brine is injected through the central tube. If x is the oil/brine volume ratio, and β_0 the oil compressibility, the coefficient $\beta = \beta_1 + \beta_2$ which had been introduced before must be replaced by $\beta = x\beta_0 + (1 - x)\beta_1 + \beta_2$. In other words, the oscillation period is related to x by:

$$T(x) = 2\pi \sqrt{\varrho_0 V_0\{x\beta_0 + (1-x)\beta_1 + \beta_2\} H/s}$$

PART II. MEASUREMENT OF THE ELASTIC PROPERTIES OF A ROCK MASS

The aim of this test was to check whether or not it was possible to detect, at ground level, the effect of depressurization in a deep underground salt cavern. (Fig. 5).

At the beginning of the test, a certain amount of brine was forced into a closed cavern, the volume and depth of which were respectively 230,000 m^3 and 1300 m. This resulted in a progressive pressure build-up. When the pressure increase reached p = 5 MPa, the pressure was released rapidly by opening a valve at the well head.

The cavern being relatively small compared to its depth, it is possible as a first approximation to consider the cavern as a point in a semi-infinite elastic space, located at a depth H below ground level. If p = 5 MPa is the pressure increase, and r_0 = 40 m the

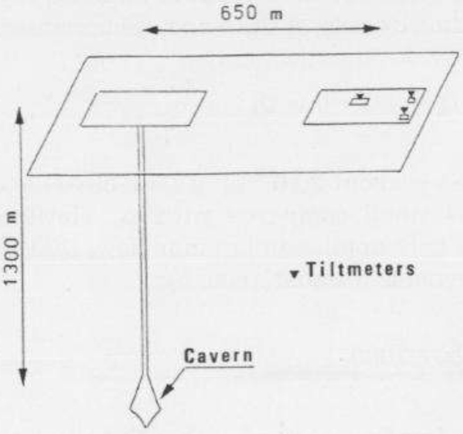

Fig. 5. Schematic view of the test site.

equivalent radius of a sphere whose volume is equal to the volume of the cavern, then the theoretical dip at ground level will be

$$\frac{\partial u_z}{\partial r} = \frac{3pr_0^3(1-\nu)Hr}{\mu(H^2 + r^2)^{5/2}}$$

where ν is Poisson's ratio, μ the shear modulus, and r the horizontal distance between the well head and the considered point. It is clear that the maximum dip will be reached when r = H/2, at a distance of 650 m from the well head. This will be the best location for the tiltmeters. A value of μ ~ 10,000 MPa was expected, which means that the observed dips were to be of the order of magnitude of 10^{-8} (or a slope of 1 mm to 100 km), which is quite small.

1. The daily variations of temperature at ground level induced dips much larger than those which were expected. The temperature near the tiltmeters was measured in order to establish a correlation between its changes and the indications of the tiltmeter. Favourable weather conditions were selected (foggy weather, which ensures a slowly varying temperature); nevertheless the temperature variations appear as the most disturbing factor. A simple way of avoiding its effect is to conduct relatively short tests, during which the temperature change rate can be considered as constant. That is the reason why the test was performed during depressurization, which can be carried out much faster than pressure build-up.

2. The tiltmeters must be of very high resolution. Those we used were designed by Blum, 1963 (see also Aste et al., 1986), and the operating principle is as follows: a moving part can rotate around an axis; its centre of gravity is thrown off centre, so that if the axis deviates from vertical, the centre of gravity will

be in the plane common to vertical and rotation axis. An optical system allows for measuring the deviation. The tiltmeter is a single silica block, which avoids solid friction and reduces the effects of temperature change. The theoretical resolution of the tiltmeter is smaller than 10^{-8}.

3. The tiltmeter has a preferential measurement direction; the measured dip is the projection of the actual dip in this preferential direction. For this reason, a pair of tiltmeters whose preferential directions are orthogonal was set in each emplacement.

4. In order to evaluate the influence of the coupling between the tiltmeter and the ground, three different systems have been tried, each of them including two tiltmeters as previously described (Fig. 6). The first system consisted of a concrete-walled cubic hole ($2 \times 2 \times 2\ m^3$) at the bottom of which a small concrete slab ($0.6 \times 0.6 \times 0.3\ m^3$) was linked to a vertical pile, 5 m long, in order to make the slab solid with the ground. The tiltmeter was set upon the slab, the concrete walls were covered by a 10 cm thickness of polystyrene, and the hole was covered by an insulated hood.

The second system was similar, except that there was no pile.

The third system was set on the walls of a preexisting vault, 4 m deep.

The first system proved to be the best during the preliminary tests which consisted of recording the effect of a car or a pedestrian passing near the tiltmeters (incidently, those tests proved to be a very efficient way to back-calculate the Young's modulus of the ground).

RESULTS OF THE TEST

Five tests, each of them including a pressurization-depressurization of the cavern and lasting five hours, have been performed. The quality of the results are variable; Figure 7 displays a test which proved to be satisfactory. The dip is affected by a drift, very probably of thermal origin; but a clear change in the curve slope can be noticed at the beginning of the depressurization. From this record an average Young's modulus of 15,000 MPa can be deduced. Such a figure may seem to be very high for large volumes of sedimentary rocks, which are often affected by some scale effect. But here the cavern is overcome by 600 m of rock salt, above which can be found limestones, sandstones and marls. Then the rock salt layers play a pre-eminent role in the whole mechanical behaviour; rock salt is a rather stiff material (when rapid loadings are considered) which is rarely weakened by fractures.

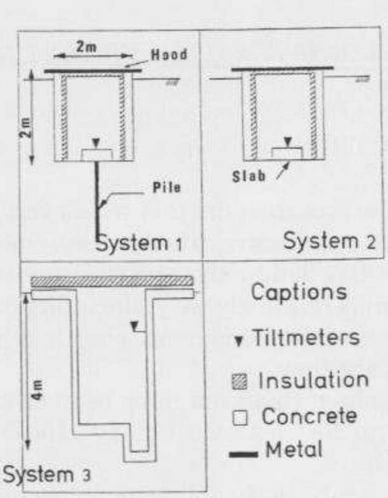

Fig. 6. Vertical cross-section of the tiltmeter emplacements.

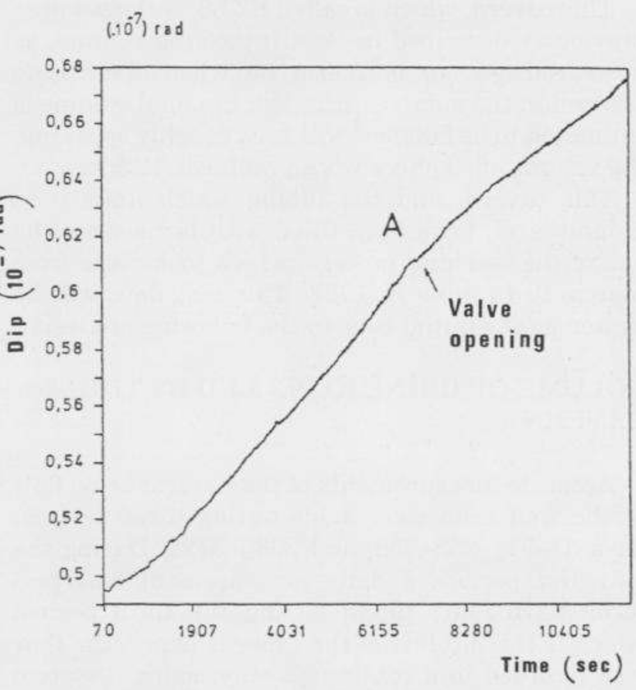

Fig. 7. Observed dips during cavern loading and unloading.

CONCLUSIONS

This test can be considered as relatively successful. Nevertheless the considered depth (1300 m) is probably the upper limit for such a method, which is much more suitable for more shallow depths.

The system involving a pile which gives a good coupling between tiltmeter and ground has proved to be the more efficient.

PART III. A LONG-TERM CREEP TEST IN A CAVERN

INTRODUCTION

The simplest mechanical test which can be made in a brine-filled open cavern is a measurement of the flow of brine expelled by the cavern. However, if the measurement is relatively easy, the interpretation is difficult, for many phenomena play a role in the formation of the flow.

Several tests of this kind have been described in the literature; for instance Boucly (1982) or Crotogino (1981).

We will describe in the following a test which was performed nine years after the end of the cavern leaching; we will refer to other tests performed on the same cavern just after leaching (Hugout, 1988).

This cavern, which is called EZ 53, is the same as previously described in Part I; the free volume, as measured by sonar, is 7500 m^3 but when all the brine trapped in the sump is included, the total volume is estimated to be 8000 m^3 which is, roughly speaking, the volume of a sphere whose radius is 12.5 m.

This cavern, and the tubing which links it to ground level, have been filled with brine since the end of the leaching process, which took place from March 19 to June 6, 1982. This last date will be chosen as the initial time in the following analysis.

VOLUME OF BRINE EXPELLED BY THE CAVERN

Accurate measurements of the natural brine flow at the well head were made during three periods: days 37–91, 253–358, and 3086–3122. During the two first periods a daily measurement was performed (Hugout, 1988); during the third period, which is the interest of the present paper, the flow was recorded in a continuous way, using a system described below. The main results are displayed in Fig. 8, which gives the daily flow rate versus time.

CAVERN HISTORY

It should be noted that two other tests were performed on the same cavern during the considered period (Hugout, 1988). First, from day 93 to day 252, the tubing was filled with fuel oil, resulting in a lowering by 3.4 MPa of the internal pressure in the cavern (8 MPa instead of 11.4 MPa). During that period, the brine flow was considerably larger; it was more than 500 l per day at the beginning of the test (day 94), 200 l/d on day 145, and still 120 l/d on day 250. Second, from day 361 to day 585 the cavern was

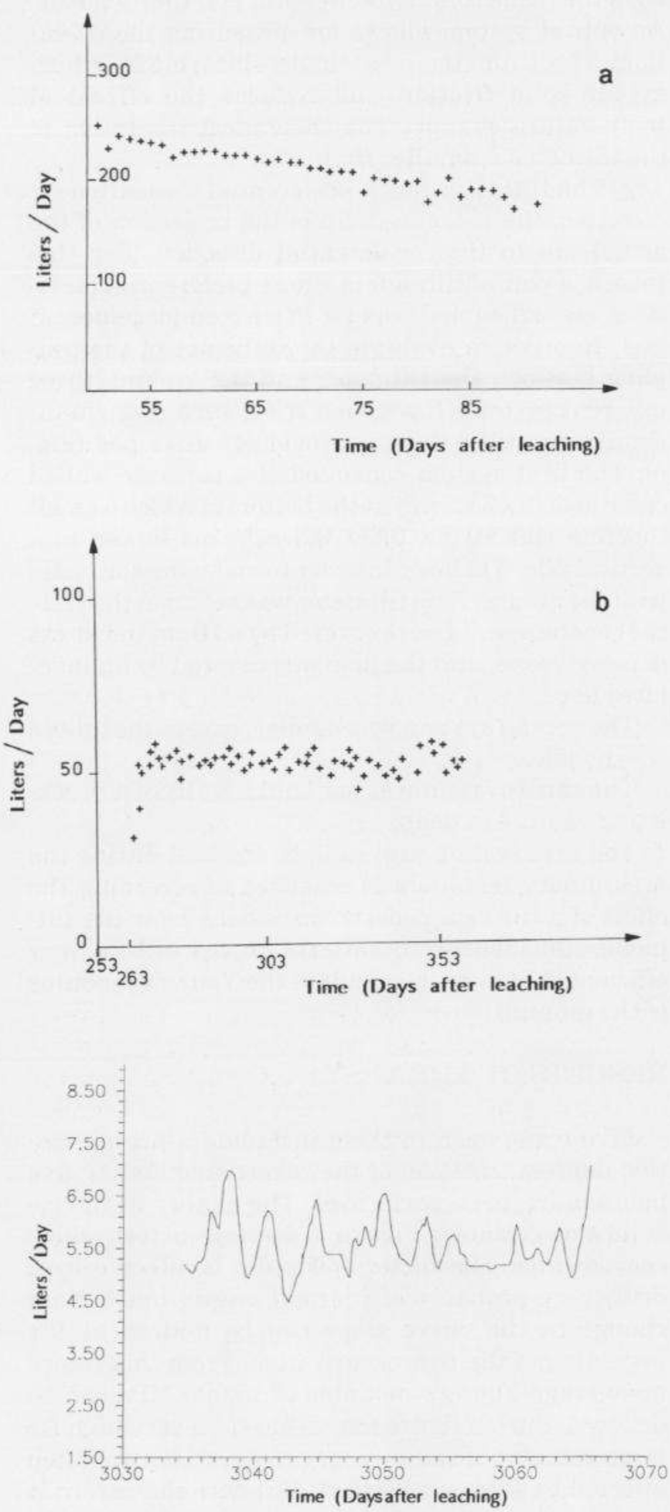

Fig. 8. Flow rate during the three tests (a, b: after Hugout, 1988).

closed, bringing a natural pressure increase in the cavern from 11.4 MPa to 12.6 MPa. After this period the pressure was released and the cavern was closed again, the pressure increasing from 11.4 MPa to 13.1 MPa between days 604 and 997. From this last date to the beginning of the last test (day 3086), the pressure in the cavern was kept constant and equal to 11.4 MPa.

FLOW RATE EVOLUTION

The curves of daily flow rate versus time are relatively smooth. Their interpretation is difficult, for many phenomena play a role in the formation of the flow. One must distinguish on one hand the phenomena whose effects vary relatively slowly with respect to time or, more precisely, are practically constant on a daily basis, and, on the other hand, the fluctuations of a smaller period.

SLOWLY VARYING PHENOMENA

Percolation through the rock mass

Percolation of the brine from the cavern towards the rock mass, although weak, does exist. A long term permeability test, performed on an open hole on the same site (Durup, 1991), has proved that the percolation can be described by means of Darcy's law, the permeability being $6\ 10^{-5}$ millidarcy or $K = 6\ 10^{-20}\ m^2$. If we consider the salt porosity to be ϕ = 1%, the brine viscosity $\eta = 1.2 \times 10^{-3}$ Pa s, and the compressibility $\beta = 4 \times 10^{-10}\ Pa^{-1}$, then the hydraulic diffusivity is $a = 1.5 \times 10^{-5}\ m^2\ s^{-1}$, and the characteristic time for the percolation phenomenon is $R^2/a \sim 10^7$ s ~ 4 months. In other words, nine years after leaching, steady state has been reached. This steady state is characterised by the difference between the internal pressure in the cavern (11.4 MPa) and the natural interstitial brine pressure — which is unfortunately unknown. This difference is presumably low and even considered nil in Durup (1991). In any case, one can check that the flow rate crossing the cavern wall would be 0.8 l per day per MPa of difference between those two pressures. In other words, brine percolation after nine years is probably constant and small.

Brine heating

The fresh water which was used for leaching the salt was at surface temperature, i.e. 12°C, compared to the rock salt temperature which was 45°C at a depth of 950 m. The thermal balance during the leaching process was complex; the average temperature of the brine at the end of leaching was approximately 28°C.

The subsequent heating was relatively slow; thermal measurements carried out along the cavern axis gave the following figures: 32.03°C (31), 34.88°C (81), 35.22°C (94), 36.09°C (123), 37.75°C (185), 38.2°C (226), 38.7°C (255), where the figures between brackets refer to the number of days after the end of leaching. It is easy to model the heating phenomenon: we suppose that, after the end of leaching, the uniform temperature of a perfectly conducting brine enclosed inside a spherical cavern increases under the effect of heat conduction through the rock mass. In other words, the Fourier equation, $\partial T(r,t)/\partial t = k\ \Delta T(r,t)$, where k is the thermal diffusivity, is satisfied. At the cavity wall, r = R, the heat balance can be written

$$\frac{4}{3}\pi R^3\ \varrho_F\ C_F\ \partial T/\partial T = 4\pi R^2\ k\varrho_M\ C_M\ \partial T/\partial r$$

where ϱC is the volumetric specific heat of the fluid (F) or of the rock mass (M). The whole phenomenon is then governed by two time constants; the first characterizes heat conduction in the rock mass, $t_1 \sim R^2/k$; the second is relative to heat exchange at the wall $t_2 \sim t_1\ \varrho_F\ C_F/\varrho_M C_M$. Those two characteristic times are of the same order of magnitude, $t_2 \sim t_1 \sim 1.5$ year, which means that brine heating is relatively slow (and it would be much slower for a bigger cavern, for those times are proportional to the square of the radius, or to $V_0^{2/3}$ if V_0 is the cavern volume).

A satisfactory fitting of the measured temperature can be achieved with such a model (Berest et al., 1979), but the most difficult point is to determine the initial temperature distribution at the end of leaching. The simplest way is to select the time origin and the initial temperature in order to match the measured temperatures; in any case we are mainly interested in the thermal behaviour after several years, which is relatively independent of the initial fit. If $k = 2.84\ m^2\ s^{-1}$, $\varrho_M\ C_M = 2\ 10^6\ J/°C/m^3$ $\varrho_F\ C_F = 4.8\ 10^6\ J/°C/m^3$, the heating rate is approximately 0.14°C per year after 2000 days; 0.06°C after 3000 days; 0.045°C after 4000 days. These values, deduced from the simplified model, are probably over-estimated; the brine temperature in the cavern can be considered as homogeneous only if thermal convection is effective, which is less and less true when the temperature gradients become smaller and smaller. After a long time, the thermal exchange in the brine is probably mainly of a conductive nature. The brine is less conducting than the rock mass; therefore the initial model is probably false and heat exchange becomes slower and slower.

Heating of the brine induces thermal expansion. The thermal expansion coefficient can be estimated from *in situ* experience. Boucly (1982) suggests $\alpha = 4.4 \times 10^{-4}\ °C^{-1}$ and Crotogino (1981) proposes $4.5 \times 10^{-4}\ °C^{-1}$. If we use the first value, the average flow rate between days 31 and 81 due to thermal expansion would be $\alpha V_0 \dot{T}$ = 200 l per day, i.e. 80% of the observed value. Similarly, if the simplified thermal model is correct, this flow rate will only be 0.6 l per day after 9 years, i.e. 12% of the observed value.

In conclusion, brine heating manifestly explains the larger part of the observed flow rate during the first years after the end of leaching; this statement does not hold after a longer period.

Cavern creep

Cavern convergence results from overburden pressure, the value of which is approximately 21 MPa at the cavern depth, and which is not completely balanced by the internal pressure, i.e. 11.4 MPa. This discrepancy brings a progressive closure of the cavern. Such closure has been observed in many caverns: for instance in the Tersanne site (France) the closure rate reaches 3% per year (Boucly, 1982) but for much more severe conditions (difference of 22 MPa) and a more ductile salt. The creep law being highly non-linear, very slow cavern creep can be expected during our test.

The exact form of the constitutive law for rock salt is a very controversial matter. Gaz de France (Hugout, 1988) has fitted a so-called "Lemaitre law" whose simplified expression for uniaxial compression test can be written:

$$\varepsilon = 10^{-6} \left(\frac{\sigma}{K}\right)^{\beta} t^{\alpha}.$$

This back fitting has used both laboratory data and data from the *in situ* tests described in this paper (except for the last test, for which results were not available at the time of writing).

Generally speaking, those tests were a few months long; therefore their predictive power for longer periods was questionable. In fact two sets of parameters have been suggested by Gaz de France. The first, K = 0.85 MPa, β = 2.98, α = 0.36 was fitted from numerous tests performed on a relatively deeper salt layer of the same site; the second, K = 1.1 MPa, β = 2.98, α = 0.36 was deduced from the first tests performed on the EZ 53 cavern. Those two sets respectively predict a 7.5 l per day and a 2.2 l per day flow rate after a period of 3000 days under constant internal pressure. It is consistent that these two predicted values bracket the observed figure (approx. 5 l per day).

In conclusion, the flow rate is governed by brine heating during the first years (during a period of approximately $T \sim V_0^{2/3}/k$, if V_0 is the cavern volume and k the salt thermal diffusivity, $k \sim 3\ 10^{-6}\ m^2\ s^{-1}$). For longer periods, cavern creep becomes the predominant phenomenon.

PHENOMENA OF SHORTER PERIOD

Introduction

The larger part of the brine mass is enclosed in the cavern, at a depth of 1000 m, in an environment where, except for the *sui generis* phenomena described below, temperature and stress state vary very slowly, even on a monthly scale. Generally speaking, the perturbations of seismic origin are random, brief, and of small amplitude. The fluid mass can be excited by vibrations whose period is approximately one minute (described in the first part of this paper), but these oscillations dampen if they are not sustained by external causes. Such excitations were observed during the test, and caused some concern, even though they were of small amplitude.

The two quantities which change substantially during a period of time of one day are the atmospheric pressure and the temperature.

Atmospheric pressure

Taking the casing shoe as the origin of the vertical axis, the pressure at this particular point is:

$$P = P_a(t) + \int_0^{h(t)} \varrho(P,T)\, g(t)\, dz$$

The following points are important:

1. The atmospheric pressure, $P_a = P_a(t)$ fluctuates around its average value with a variance which is typically 10 millibars, or 10^3 Pa. The compressibility of the cavern is approximately $\beta = 4 \times 10^{-10}\ Pa^{-1}$ (as seen in Part I), but is lowered to $1.25 \times 10^{-10}\ Pa^{-1}$ in the case of the atmospheric pressure, transmitted both through the column and the rock mass.

2. The gravity intensity, g = g(t), does vary, especially due to earth tides, but the induced relative variations are of the order of 10^{-8}, very small when compared, for instance, to the effect of atmospheric pressure variations.

3. The height of the brine column, h = h(t), can vary substantially if the brine can move upwards freely inside the tubing. Let q be the brine flow which would be expelled from the cavern if the brine level were kept constant inside the tubing, and let S be the tubing cross-section. An upwards rise $\dot{h}$ of the brine–air interface would increase the pressure in the cavern by $\varrho g \dot{h}$, therefore $S\dot{h} = q - \beta V \varrho g \dot{h}$; then the apparent flow deduced from an upwards movement of the brine–air interface in the tubing would be 2.5 times smaller than the actual flow rate. One can understand the importance of a constant level procedure.

Temperature change

The last significant phenomenon is the daily variation of the ground level temperature, which can be of the order of $\Delta T = 10°C$. These variations will affect the surface part of the system, the total length of which, between the well head and the measurement shack, is $h_1 = 3.5$ m approximately. Over this length, the difference in altitude between the lower and the higher points is $h_2 = 1.5$ m. The cross-sectional area of the surface tubing is $\sigma = 81\ cm^2$, the brine volume variation is $v_1 = \alpha \Delta T\, h_1\, \sigma = 0.12$ l; thus weight of the brine column is reduced by $\varrho g\, h_2\, \alpha\, \Delta T$, or approximately 80 Pa, which brings an additional expulsion of 0.25 l.

Earth tides

The moon exerts gravity forces on the earth. Those forces vary with respect to time, due to variation of the mutual positions of the two planets. An evident consequence of this variation is the ocean tides; but they induce also some deformation of the earth itself. The order of magnitude of the induced strains is 10^{-8}, which means that a 8000 m^3 cavern will see its volume change twice a day by a small quantity, the order of magnitude of which will be a few tenths of a litre. This oscillation is quite small but not unmeasurable; furthermore its period is faithful (approximately 12 h and 25 min), which helps in its identification.

TEST INTERPRETATION

The well head is linked by a flexible tube to a central cabin. A servo-controlled system allows the brine level to be kept constant in the tube; a step motor draws off the brine from the tube. The fault of such a system is that the effect of atmospheric pressure variations is not corrected. Furthermore, thermal insulation of the surface parts did not prove to be completely effective as shown above.

Figure 8 gave the flow rate versus time. Except for some brief failures of the measurement system (marked by a dot) the observed curve is relatively smooth. The average value of the flow rate is the sum of the effects of cavern creep, brine heating, and brine percolation (if any) in the rock mass. These phenomena have practically constant effects during that period. When subtracting from the curve its average value, one obtains Fig. 9 on which the evolution of atmospheric pressure versus time is plotted. The existence of a correlation is obvious, as expected. An empirical correlation relationship has been computed; when the pressure effect is subtracted, Fig. 10 is obtained with its plot of the evolution of the temperature at ground level. In fact, the temperature was measured in the central cabin and is probably not fully representative of the brine temperature in the surface part of the tubing. When subtracting again the better empirical correlation, Fig. 11 is obtained. The order of magnitude of the remaining volume variations is a few tenth of a litre, and their period is a little bit larger than 12 hours, which means that the earth tides have been clearly displayed.

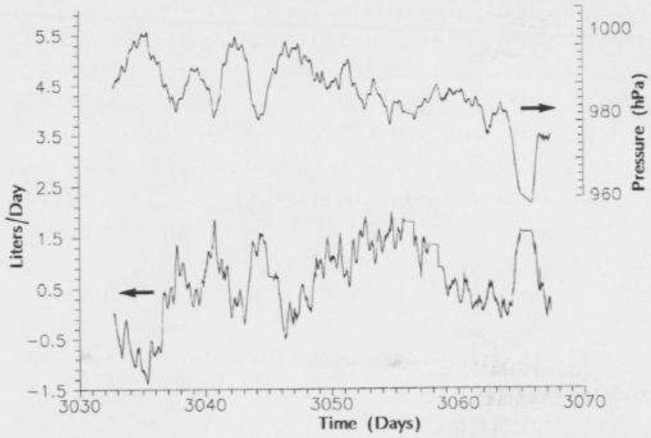

Fig. 9. Flow rate fluctuations and atmospheric pressure versus time.

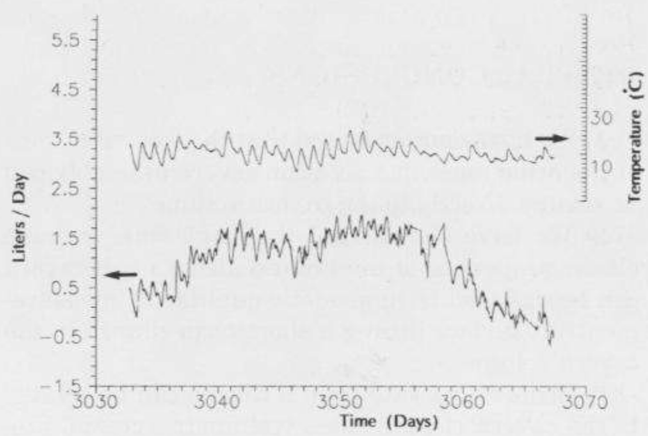

Fig. 10. Flow rate fluctuations, minus atmospheric pressure effect.

Conclusions

It has been proved that the action of the moon on an underground cavern can be observed, in spite of being extremely small (the associated displacement of the cavern walls is smaller than one thousandth of a millimeter). At the time when the present paper was written (autumn 1991) the test was going on but a better measurement system has been designed in order to reduce parasite effects; a very precise measurement of earth tides is expected from the test.

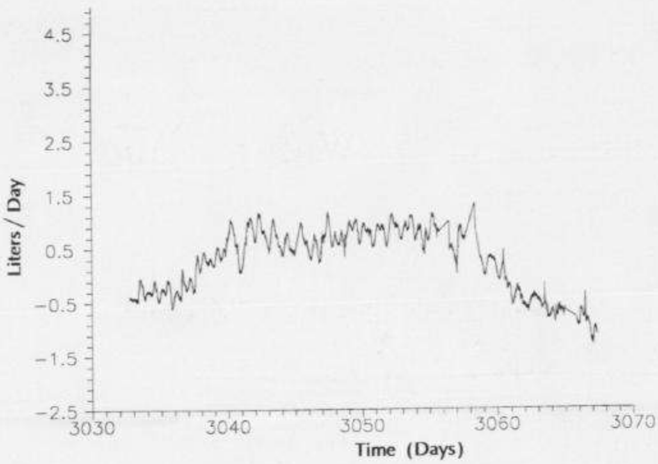

Fig. 11. Flow rate fluctuations, minus atmospheric pressure and temperature effect.

GENERAL CONCLUSIONS

1. We have demonstrated that the free vibrations of the brine mass in a solution cavern assembly can be related directly to the cavern volume.

2. We have shown that the large-scale average elastic properties of the ground above a salt cavern can be deduced from geodetic-quality tilt measurements at surface during a short-term change in the cavern volume.

3. Brine efflux rate from a cavern can be related to the cavern closure rates (volumetric creep), provided that a number of corrections are implemented: long-term effects include temperature changes and brine percolation into the strata; short-term effects include atmospheric pressure variations, low frequency seismic excitations, and earth tides. In fact, we can easily measure the effects or earth tides because of their consistent period.

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