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Meeting Paper

Vibrations and Free Oscillations in Salt Caverns

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VIBRATIONS AND FREE OSCILLATIONS IN SALT CAVERNS

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ABSTRACT

The fluids (brine, oil or gas) stored in a cavern, as well as the cavern itself, behave elastically. This signifies that salt caverns are the sites of natural vibrations whose periods are long enough (several seconds to several minutes) to be easily observed as soon as the cavern are opened to the atmosphere or are closed but contain a small amount of gas. These vibrations can be recorded at a very low cost and provide useful information on cavern compressibility ; in some cases, they allow us to determine the cavern volume and the brine/stored products ratio or to detect gas pockets trapped in the caverns.

Examples of recorded vibrations of different caverns will be presented and discussed.

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INTRODUCTION

The fluid(s) contained in an underground cavern and access well as well as, the cavern and the well, are elastic bodies. This means that when the fluid(s), the cavern or the well are affected by small changes in pressure or shape, these bodies vibrate according to their mechanical properties, sizes and shapes, and according to their mechanical interactions. These vibrations constitute a source of information that is rarely used, even when the cost of this information is minimal, since all that is needed is to record the development of the fluid pressure at the well-head.

Holzhausen and Gooch (1985), for instance, have analyzed the effects of hydraulic fracture growth on the period of the free vibrations in a closed well ; a very similar method has been applied to the same problem by Berest (1985). Hsu (1975) had derived a theoretical relation between the oscillation period and the radius of a penny-shaped fracture.

For cased wells opening into a salt cavern, Berest and Habib (1983) and Berest (1986) have proven that, when a cavern well is opened to the atmosphere, long period waves take place in response to a small pressure drop in the cavern and can be easily measured, which allow evaluation of the cavern volume through simple calculations.

In the present paper, we will consider several types of acoustic waves that can easily be measured and discuss their relations with salt cavern properties ; typical records will be presented.

TUBING WAVES

The first type of wave observed in salt caverns is a tubing wave, whose period is of the order of one to a few seconds. When a rapid change in pressure and/or fluid flow rate takes place in a fluid-filled tubing (for instance, when a valve is suddenly closed or opened), this change generates an acoustic wave that travels in the fluid along the tubing.

If the tubing were perfectly stiff, the wave celerity would be given by the simple formula

$$\beta_F \ \rho_F \ c_F^2 = 1$$

where c_F is the acoustic wave celerity, β_F is the fluid isentropic compressibility and ρ_F is the fluid density. With standard temperature and pressure conditions, typical values of the wave celerity are :

soft water	: C_W	= 1400 m/s
air	: C_A	= 340 m/s
saturated brine	: C_B	= 1800 m/s

As a matter of fact, a steel tubing is also a compressible body ; if the fluid pressure rapidly changes by $\dot{P}$, then the tubing cross section, S, will change by $\dot{S} = S\dot{P} / \left(\rho_0 c_T^2\right)$ where $1/\left(\rho_0 c_T^2\right)$ is the tubing compressibility which depends on steel properties, tubing width/radius ratio, and mechanical properties of the annular space, casing and rock mass.

As a whole, the speed, c, of the wave traveling through the fluid in the tubing will be given by

$$\frac{1}{c^2} = \frac{1}{c_F^2} + \frac{1}{c_T^2}$$

which means that this speed is smaller than the acoustic waves speed, c_F, in the fluid. As emphasized above, the exact figure depends on several factors and must be calculated or, more realistically, measured in each case. A typical value for water or brine in a tubing will be

$$c = 1000 \text{ m/s}$$

which means that if, for instance, brine injection in a well is interrupted by the rapid closure of a surface valve, the generated wave will reach a point located 1 km below ground level in one second.

In this example if the tubing cross-section were S = 250 cm^2 (7"5/8) and the brine flow rate before closing the valve were Q = 36 m^3/h, the brine speed would be $v = Q/S$ = 0.4 m/s and would suddenly vanish to zero ; the pressure increase due to the sudden valve closure would be

$$\Delta P = \rho c v$$

or, in our case, ΔP = 0.48 MPa or 68 psi. Such a phenomenon can be called a "water-hammer".

When the wave reaches the cavern at the bottom of the well, a reflected wave traveling upward is generated ; it will reach the well head and then, in turn, generate a backward wave. After a short time, these waves combine to form a simple stationary wave : at any point, pressure and fluid speed can vary according to a dampened sinusoidal function. At a given instant, the pressure distribution can exhibit one of the following behaviors (fig. 1) :

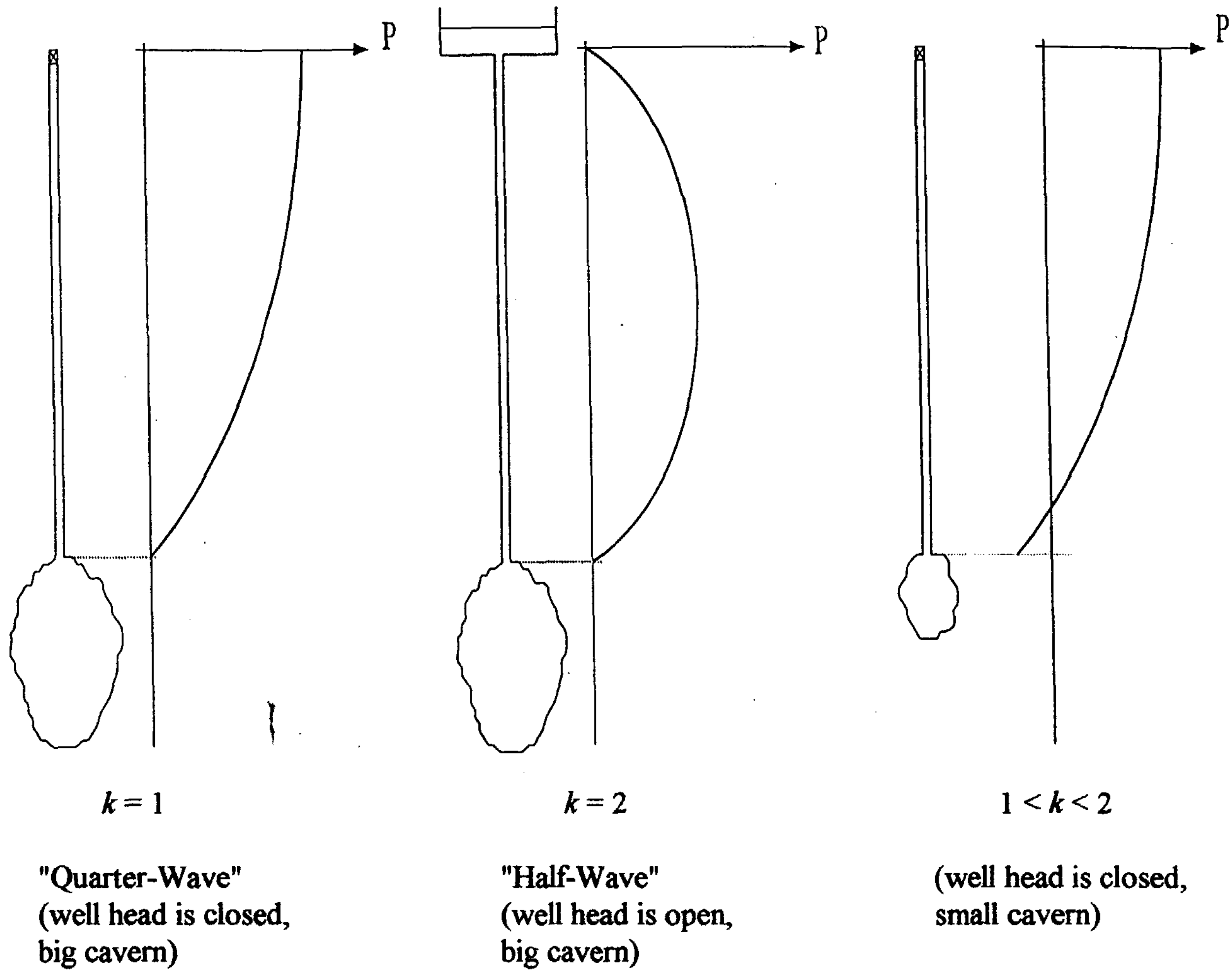


Figure 1 : ***Stationary waves in cavern wells. (The volume of a "small cavern" is of the same order of magnitude as the volume of the well itself).***

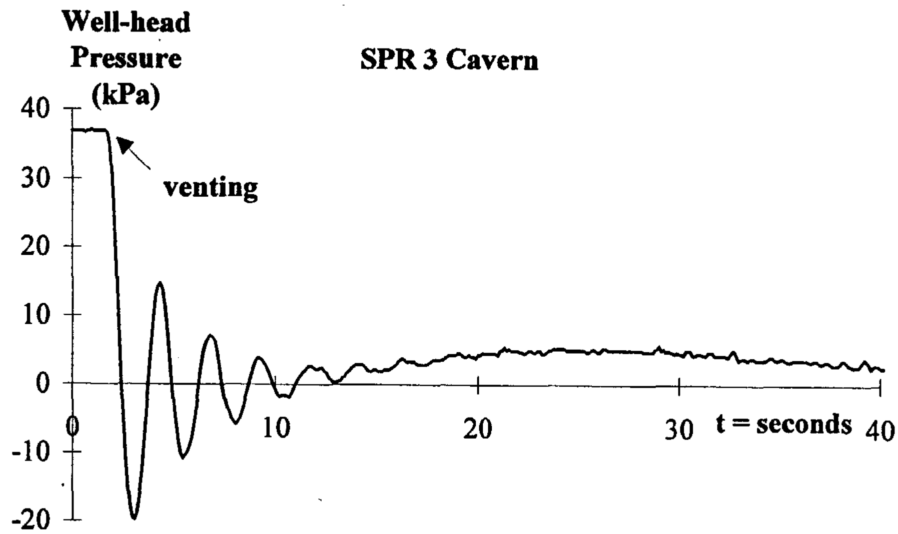
The exact form of the wave depends upon conditions reigning at the two ends of the tubing ; the period of the stationary wave is

$$T = 4\, h/(kc)$$

where h is the tubing length, c is the wave speed as evaluated in last paragraph and, k is a constant laying between 1 and 2. For a "quarter-wave" (see fig. 1) and a 1000-meters deep cavern, the period is $T = 4$ seconds.

Such waves can very easily be observed in underground salt caverns, provided that an appropriate pressure recording device is set at the well head. Two examples are given below. This type of wave does not provide very useful information, but it can provide a measurement of wave speed in the tubing.

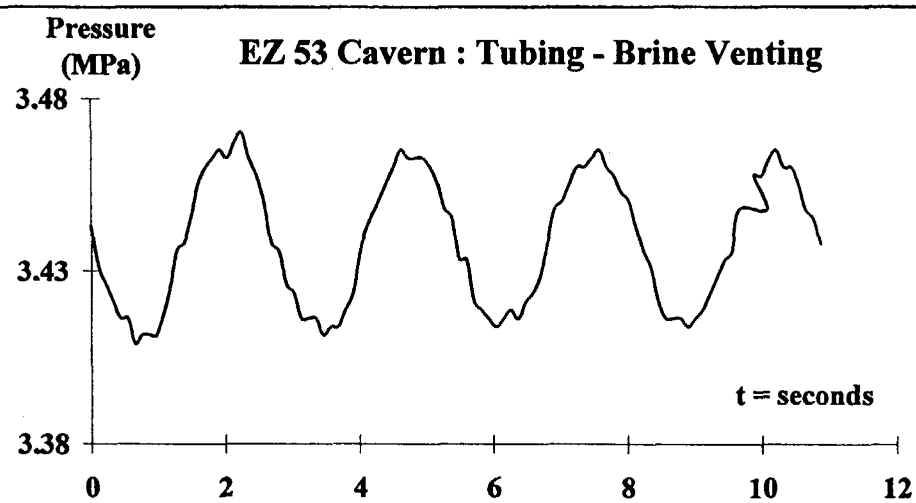
EXAMPLE 1 : THE JULY 1995 CARRESSE TEST (ELF-AQUITAINE)



A venting on SPR3 cavern ; pressure variation versus time.

The test was performed in July 1995 on the Carresse SPR3 cavern operated by Elf-Aquitaine. (Carresse is located 8 miles west of Salies-de-Béarn in South-West France.). The cavern is filled with brine ; its volume, as estimated by sonar, is 4600 m^3, and the cavern top is 692 meters deep. The observed vibrations are triggered by venting of the cavern, during which the well-head pressure suddenly drops from 0.4 MPa to zero. Oscillation period is T = 2.5 seconds, which means that $c = 4h/T = 4 \times 692/2.5 \cong 1100$ m/s.

EXAMPLE 2 : THE FEBRUARY 1995 ETREZ TEST (GAZ DE FRANCE)



Well head pressure variations during a pressurization phase.

The test was performed in February 1995 on the Etrez 53 cavern operated by Gaz de France, as a part of the full test program described by Berest et al., (1996). The cavern volume was $V \simeq 7500$ m^3, and the tubing length, h = 930 meters. The vibrations were observed at the end of a venting phase. The period is approximately $T \cong 2.7$s, which means that sound speed is $c = 4h/T \cong 1350$ m/s

BRINE-FILLED CAVERN ; TUBE OPENING IN A CONTAINER

In the first paragraph we considered waves generated by small displacements of the fluid contained in the tubing and traveling through the tubing. We now consider longer period oscillations generated by large displacements of the fluid through the tubing. During such movements, the brine in the tubing is considered as a *rigid body* moving up and down in the well. In other words, the shorter period movements described before will not be taken into account. During a real test, the two types of waves co-exist.

Consider, first, the simple example consisting of a cavern and a central tube filled with brine and opened to the atmosphere in a container whose cross-section (Σ) is larger than the cross section (S) of the tube (fig.2).

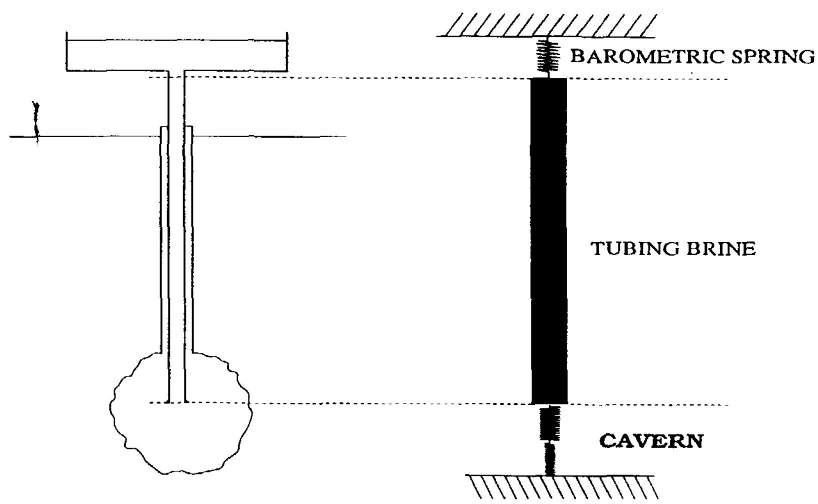


Figure 2 : ***A salt cavern, considered as a mass and spring set.***

Cavern compressibility, or the "lower spring"

Both brine in the cavern and the cavern itself behave as springs, in the sense that both are compressible : a $\dot{P}$ pressure-variation rate in the cavern leads to a brine inflow rate through the cavern top, Q, such that :

$$(\beta_c + \beta_b)V\dot{P}_1 + Q = 0$$

where V is the cavern volume and β_c and β_b are the cavern and brine compressibilities, respectively. Brine compressibility is in the range $\beta_b = 2.7\ \ 10^{-4}\, MPa$ (Boucly, 1982 ; Crotogino, 1981) ; cavern compressibility obviously depends upon both rock-salt elastic properties and cavern shape.

A typical value, according to Boucly, is $\beta_c = 1.3 10^{-4} MPa^{-1}$ and, as a whole, $\beta_c + \beta_b = 4 10^{-4} MPa^{-1}$. These figures can be modified drastically if the cavern has an irregular shape (e.g., if its height is much smaller than its diameter) or if the cavern contains other fluids, especially gases, as will be seen later.

The "stiffness" of the brine-filled cavern or "lower-spring", (i.e., the ratio between brine flow and the pressure build-up rate) is $1/\left[(\beta_c + \beta_b)V\right]$; for a 100,000 m^3 cavern, this ratio is

$$\frac{1}{(\beta_c + \beta_b)V} = 2.5\,10^{-2} MPa / m^3$$

In other words, it is necessary to force a 40 m^3 volume of brine into the cavern to increase its pressure by 1 Mpa. This stiffness, or $\Delta V / \Delta P = 1/\left[(\beta_c + \beta_b)V\right]$, is sometimes called *apparent compressibility* by cavern operators.

Brine in the tube, or the "mass"

The brine contained in the central tube will appear, by comparison, as an extremely stiff body. The (brine plus steel tube) compressibility may not be very different from the (brine plus cavern) compressibility, but the tube volume is smaller by 3 or 4 orders of magnitude than the cavern volume resulting in a much larger stiffness. As a whole, the brine in the tube can be considered as a rigid body whose mass is $M = \rho S h$ where h is the cavern depth (h = 1000 m is typical), S is the tube cross-section (S = 25 liters per meter is typical) and ρ is the brine density (ρ=1200kgm^{-3}). In this example, the tube volume is 25 m^3, and the brine mass is 30,000 kg.

The air/brine interface, or the "barometric string"

The brine in the container at ground level also behaves as a "spring" in the following sense : if a brine flow, Q (in m^3 per second), is expelled from the cavern, it will result in a Q/S uprise of the air/brine interface at the well-head which, in turn, determines a pressure build-up in the cavern :

$$\dot{P}_2 = \rho g Q / \Sigma$$

The barometric stiffness due to gravity forces, or the ratio between the expelled brine flow and pressure build-up in the cavern, in the case of a $\Sigma = 1m^2$ container cross-section, is

$$\frac{\rho g}{\Sigma} = 10^{-2} MPa / m^3$$

This stiffness is larger when the container cross-section is small (fig.3). For example, if there is no container, and the air/brine interface is located inside the tubing itself, the barometric stiffness due to gravity forces will be $\rho.g / S = 40 10^{-2} MPa / m^3$. In this case, the "upper string" would be much stiffer than the "lower string" constituted by the cavern.

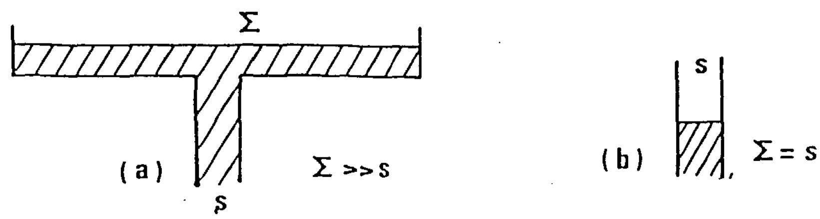


Figure 3 : *Upper string stiffness, as a function of container cross section.*

A very large harmonic oscillator

The differential equation satisfied by the flow-rate Q is simply reached by considering that brine in the tubing, with mass $M = r\ S\ h$ and acceleration $a = \dot{Q}/S$, is pushed upward by the cavern pressure excess (when compared to static pressure distribution at rest) and pushed downward by the pressure at the bottom of the container, both pressures acting through the tubing cross-section

$$(\rho.Sh)(\ddot{Q}/S) = S(\dot{P}_1 - \dot{P}_2)$$

Some straightforward algebra allows elimination of P_1 and P_2

$$\ddot{Q} + \left\{\frac{S}{\rho.hV(\beta_c + \beta_b)} + \frac{gS}{\Sigma}\right\} Q = 0$$

The solution of such a differential equation is a sine function, whose period is

$$T = 2\pi / \omega_0 \quad , \quad \omega_0^2 = \frac{S}{\rho h V(\beta_c + \beta_b)} + \frac{gS}{\Sigma h}$$

The following two limit cases can be examined :

1 - The cavern volume, V, is small (10,000 m^3 for instance), and the container cross-section, S, is very large (several m^2) ; thus $(g\ S)/(S\ h)$ is negligible when compared to the first term $S/(\rho h \beta V)$. In other words, the cavern is a much stiffer spring than the air/brine interface. In such a case, the period of oscillation is in the range of one to two minutes (see example below) :

$$T = 2\pi \sqrt{\frac{\rho h \beta V}{S}}$$

2 - The cavern volume is very large and there is no container (The air/brine interface is located in the tubing). Then $S = \Sigma$ and the oscillations are governed by the upper spring :

$$T = 2\pi\sqrt{h/g}$$

In other words, the system behaves as a simple pendulum, the length of which is equal to the brine column height. A typical period, for h = 1000 meters, g = 10 m/s^2 , is T = 63 seconds (fig.4).

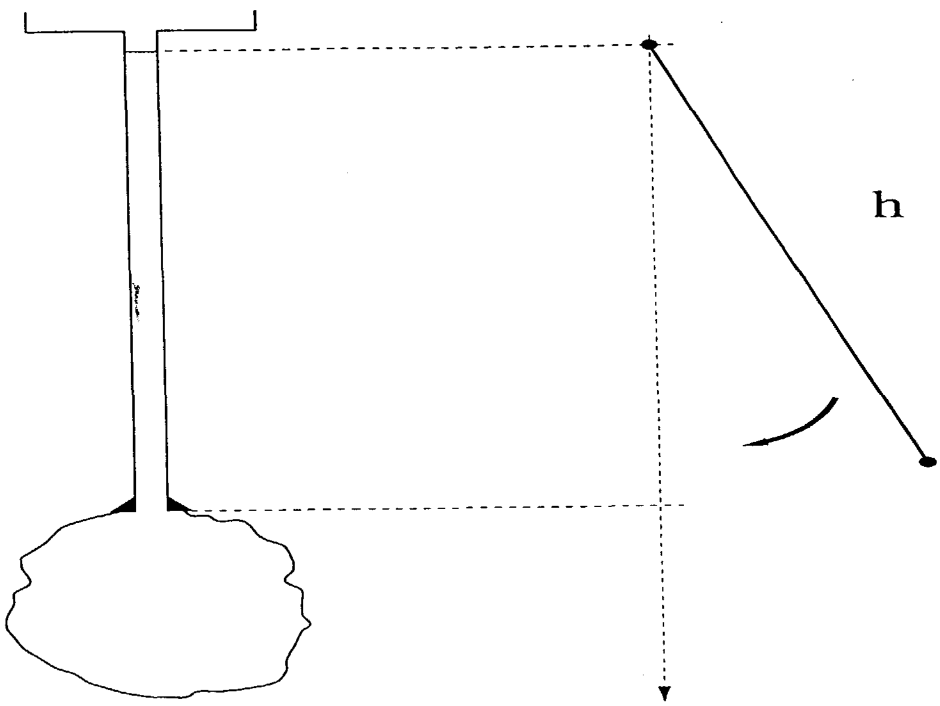
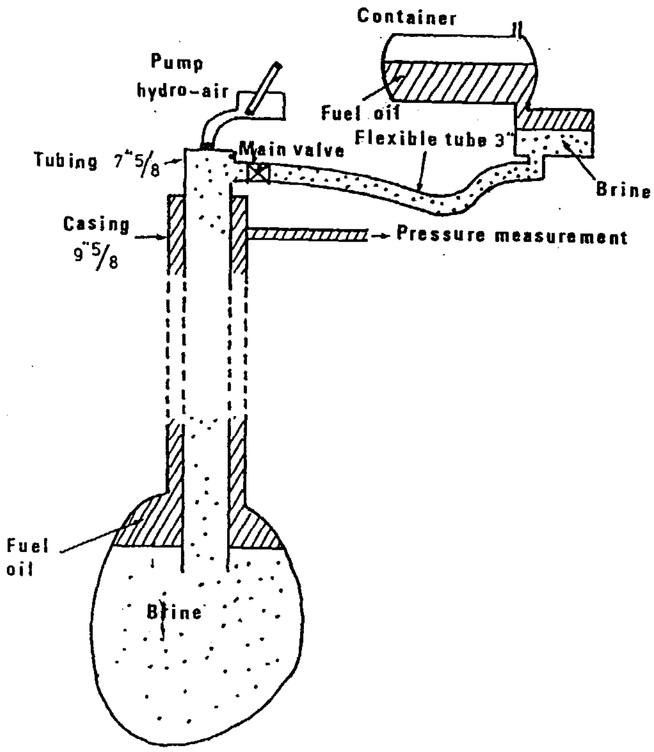
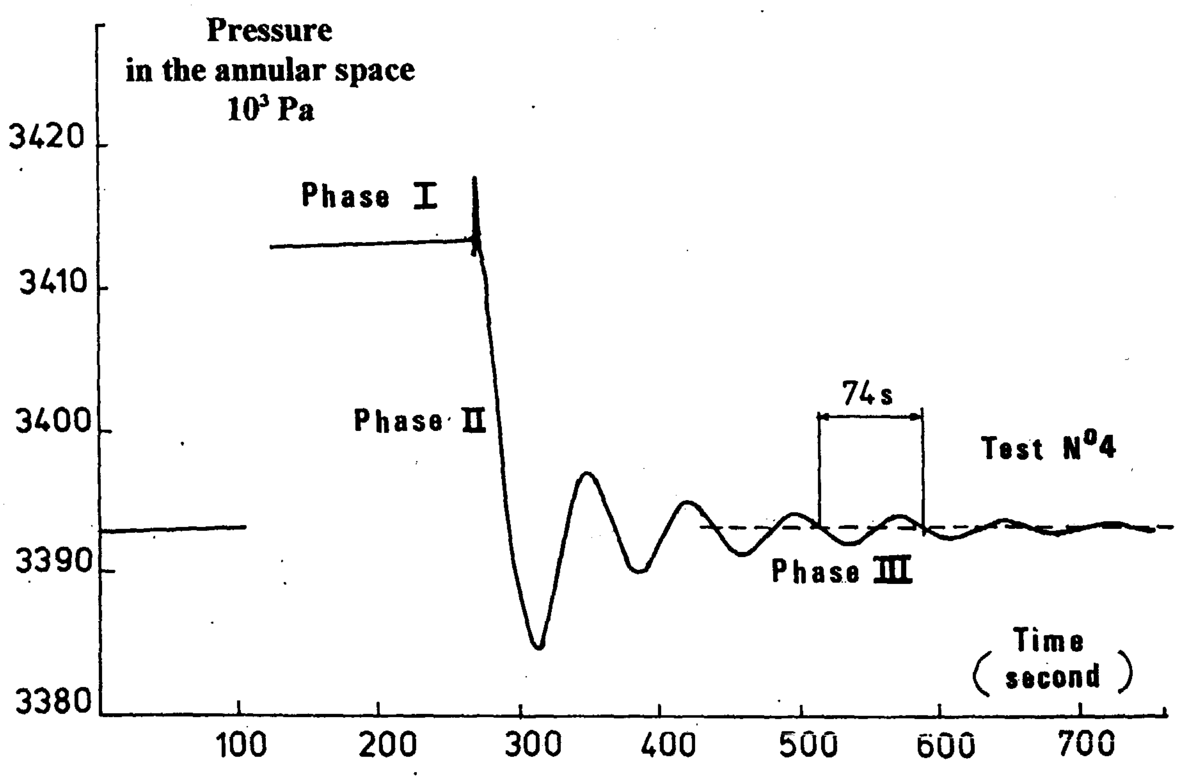


Figure 4 : ***Air/gas interface located below ground level (the system behaves as a simple pendulum)***

EXAMPLE 3 : THE 1982 ETREZ TEST (GAZ DE FRANCE)



The test was performed in July1982 on the Etrez 53 cavern operated by Gaz de France. Cavern volume was $V \simeq 7500\ m^3$, tubing length, h, was 30 meters,and the tubing cross-section S, was 250 cm^2. At the beginning of the test the main valve was closed and brine was forced into the cavern through the hydro-air pump to increase the cavern pressure. Then the main valve was opened (end of Phase I) and a long period oscillation (T = 74 s) took place. Measuring the pressure variations through the fuel-filled annular space was an easy process.



A CAVERN CONTAINING TWO DIFFERENT FLUIDS

Consider, now, the case of a cavern containing two fluids with different compressibilities. One of the two fluids is brine, whose compressibility is

$$\beta_b = 2.7\,10^{-10}\,Pa^{-1} \quad \text{(brine)}$$

The other fluid can be a stored hydrocarbon. For instance propane, when stored in a 700-meter deep cavern under a temperature of 35°C and a pressure of 8 MPa, has a compressibility of the order of

$$\beta_f = 4.5\,10^{-9}\,Pa^{-1} \quad \text{(propane)}$$

i.e., one order of magnitude larger than brine compressibility. Of course such a figure can vary with cavern temperature and pressure.

If the other fluid is a gas, (for instance nitrogen), its compressibility will be much larger still, of the order of $\beta_f = 1/(\gamma.P)$ where g is a constant $(\gamma \approx 1.4)$ and P is the gas pressure, $P \approx 8 MPa$ if h = 700 meters, thus,

$$\beta_f = 8.9\,10^{-8}\,Pa^{-1} \quad \text{(nitrogen)}$$

Let xV be the fluid volume and, $(1 - x)\,V$ be the brine volume : x is the fluid-volume/cavern-volume ratio. Then the cavern and the two fluids (brine and hydrocarbon) in the cavern can be considered as a set of three different springs, whose compressibilities are $\beta_c, x\beta_f, (1-x)\beta_b$ respectively ; the overall cavern compressibility is

$$\beta = \beta_c + x\,\beta_f + (1-x)\,\beta_b$$

Because β_f and β_b are different, the period of the oscillations

$$T = 2\pi / \omega_0 \qquad \omega_0^2 = \frac{S}{\rho h V \beta} + \frac{gS}{\Sigma h}$$

will be strongly affected by the fluid/brine ratio.

If we suppose that the container cross section Σ is extremely large, $gS/(\Sigma h)$ is negligible in the last formula. Let T_{min} be the period of oscillation when there is no propane in the cavern (in other words, the cavern is filled with brine, or $x = 0$). The period of oscillation when the hydrocarbon volume in the cavern is xV will be :

$$T = T_{min}\sqrt{\frac{\beta}{\beta_c}} = T_{min}\sqrt{1 + 10.6x}$$

In other words, the period will be multiplied by 3 when the cavern contains 80% propane (fig.5).

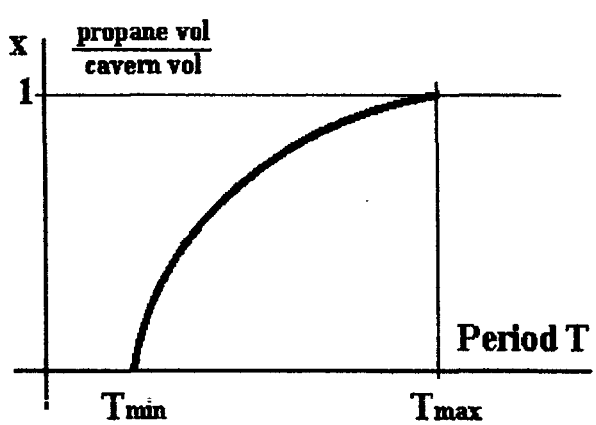
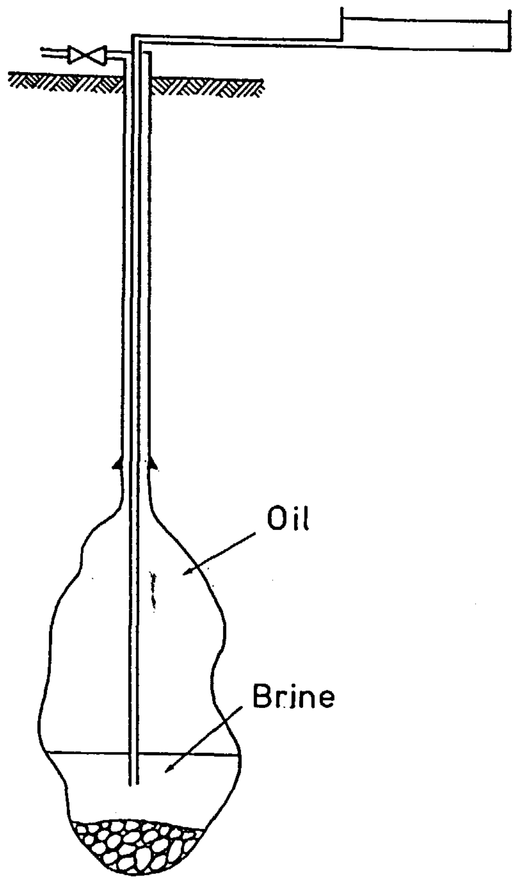


Figure 5 : ***Oscillation period as a fonction of propane volume.***

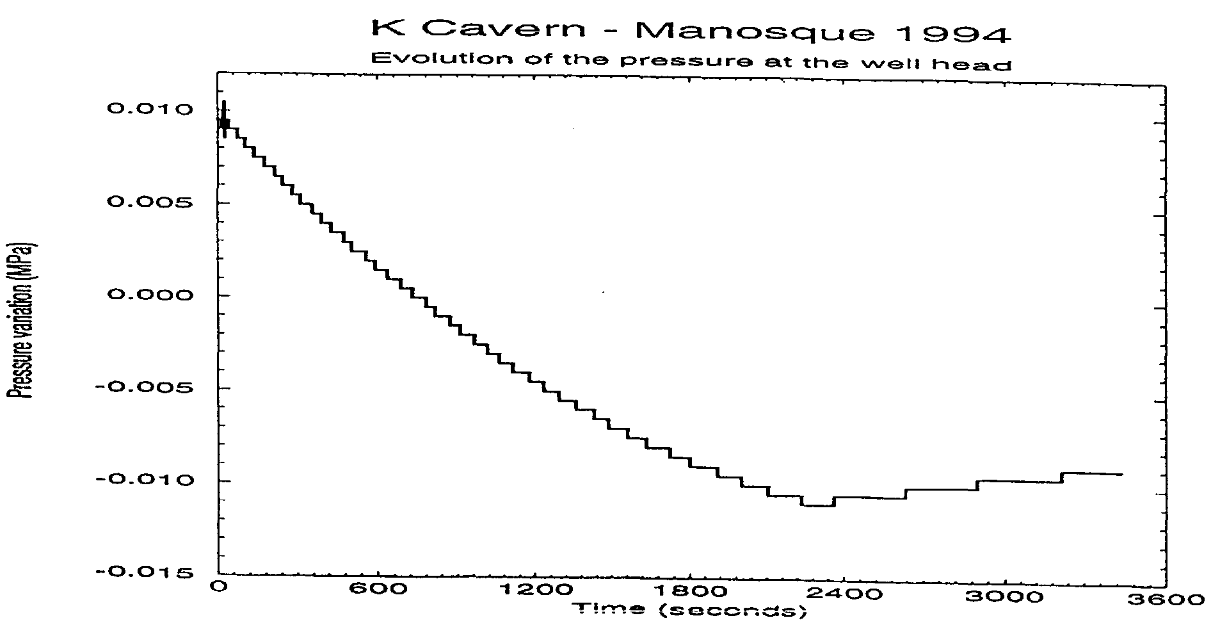
EXAMPLE 4 : THE 1994 MANOSQUE TEST (GEOSTOCK)



The test was performed in July 1994 on the Manosque K cavern operated by Geostock. Cavern volume was $V \simeq 375{,}000\ m^3$, the tubing length, h was 600 meters, and the tubing cross section, S, was 700 cm^2. The volume of oil in the cavern was 220,000 m^3 The pressure build-up at the beginning of the test was approximately 100 mbars. As can be seen below the test partly failed because :

(1) the measurement-system resolution was probably not sufficient, and

(2) head losses were much higher than during the 1982 Etrez test.



HEAD LOSSES

The previous analysis failed to take into account head losses, which are due to the viscosity of brine flowing through the tubing, the well-head and the flexible tubings at ground level. They bring some dampening of the oscillations which (fig.6), in some cases, become very difficult to record.

In the following, we assume that brine flow in the tubing is slow enough for the flow to be laminar ; then the head losses can be computed according to the classical Poiseuille formula (In other words, we assume that head losses are linearly proportional to flow rate. In some cases, however, this approximation is too rough.) :

$$\lambda = \frac{4\nu\pi}{S}$$

where ν is the kinematic viscosity of brine ($\nu = 2 10^{-6} m^2 / s$ for brine at a temperature of 20 °C) and S is the tubing cross-section. In fact, this formula applies for a clean smooth tube, which a brine tube in a deep hole is definitely not ; so some corrective factor namely, f must be used, and the actual head-losses coefficient is $\lambda . f$. When head losses are taken into account, the differential equation satisfied by brine flow rate must be modified as follows

$$\ddot{Q} + 2f.\lambda.\dot{Q} + \omega_0^2 Q = 0$$

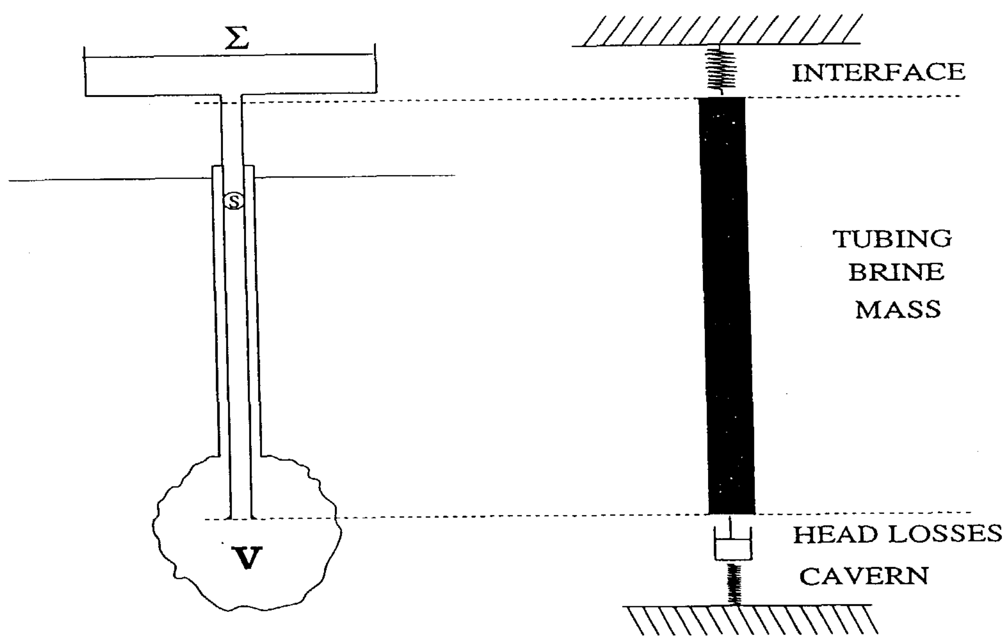


Figure 6 : ***Head losses in the tubing and well head.***

The solution of such an equation can be written (fig.7) :

$$Q = Q_0\, e^{-\beta t}\, \cos\left(\sqrt{\omega_0^2 - \lambda^2 f^2}\, t\right)$$

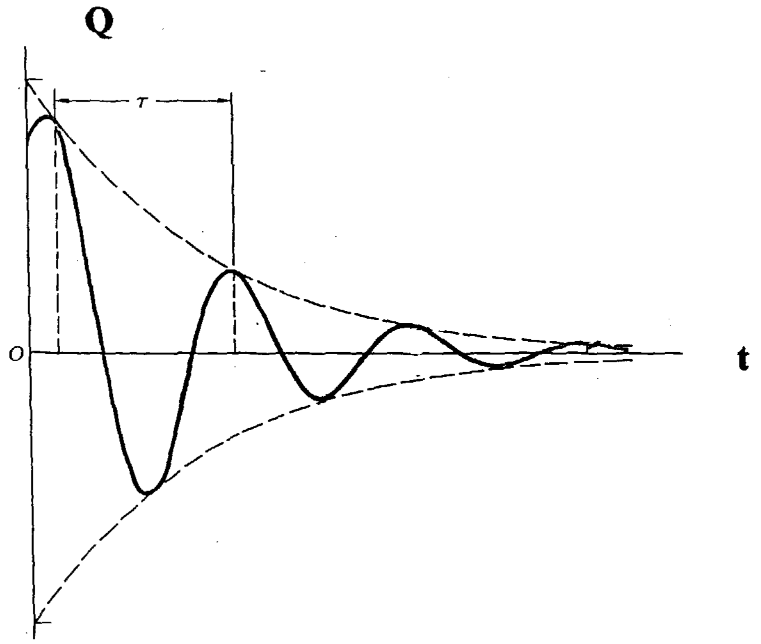
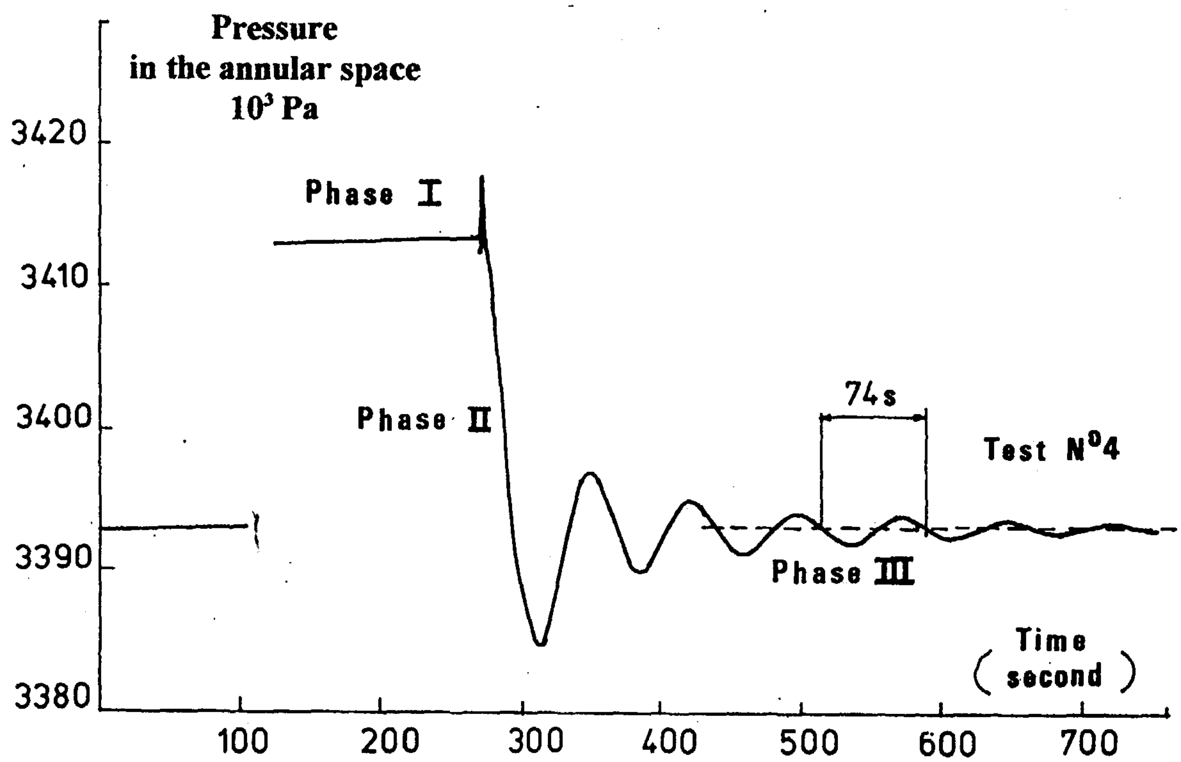


Figure 7 : ***Dampen vibrations***.

EXAMPLE 5 : THE 1982 ETREZ TEST (GAZ DE FRANCE)



EZ 53 - Oscillations Test

In the case of the Etrez test described above it can be estimated that

$$T\lambda f = \sqrt{T^2\omega_o^2 - 4\pi^2} \approx 1.19$$

from which λ f = 1.6 $10^{-2}s^{-1}$ (It is noticeable that $f \approx 16$ if $\lambda \approx 10^{-3}s^{-1}$, which proves that head losses are underestimated by the formula taken from the book. The reasons for this are :

(1) the brine tubing internal surface is not smooth, and

(2) at ground level, the container was linked to the well head by a 3" flexible tube which, even if relatively short, brought large additional head losses).

CLOSED CAVERNS, GAS-FILLED TUBING OR ANNULAR SPACE

We now consider the case of a brine/gas interface lowered at a depth $(H - h)$ below ground level. Such a configuration can be found during the so-called mechanical integrity test (M.I.T.). As long as the oscillations are relatively rapid, the gas pressurizations/depressurizations can be considered as adiabatic -i.e., gas pressure, P_g, and gas column height, $(H - h)$, are related by the adiabatic relation, $P_g(H-h)^\gamma = Constant$, where γ is the adiabatic constant. In other words

$$\dot{P}_g = \gamma . P_g \dot{h} / (H-h) = \gamma . P_g Q / [\sigma (H-h)]$$

where σ is the annular cross section. Brine in the annular space is now pushed downward by a double spring, a "barometric spring" and a spring associated with the gas compressibility (fig.8)

$$\dot{P}_2 = \rho g Q / \sigma + \gamma . P_g Q / [\sigma (H-h)]$$

The differential equation satisfied by brine flow is

$$(\rho g h)(\ddot{Q}/\sigma) + \left[\rho g + \gamma . P_g / (H-h) + \frac{\sigma}{\beta . V}\right] Q = 0$$

or

$$T = 2\pi / \omega_0 \qquad \omega_0^2 = \frac{g}{h} + \frac{\sigma}{\beta V \rho h} + \frac{\gamma P_g}{\rho h (H-h)}$$

The period clearly depends upon the gas column height and vanishes both when the column is very long or very short (fig.9).

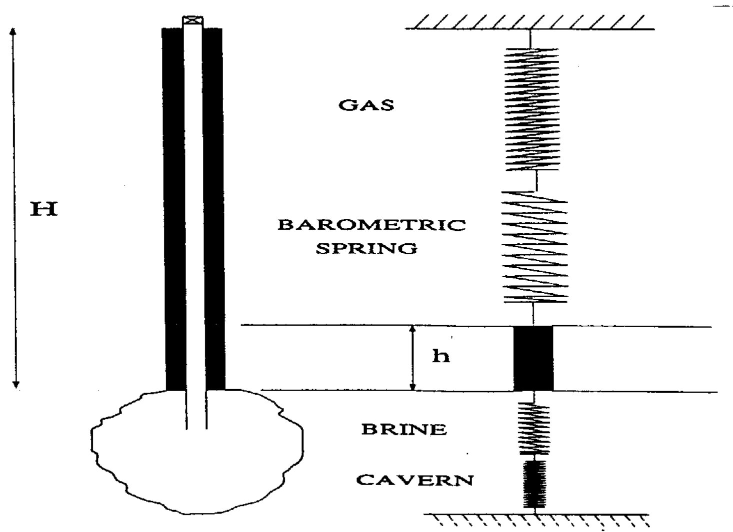


Figure 8 : ***Mass and spring system for the case of a gas-filled annular space.***

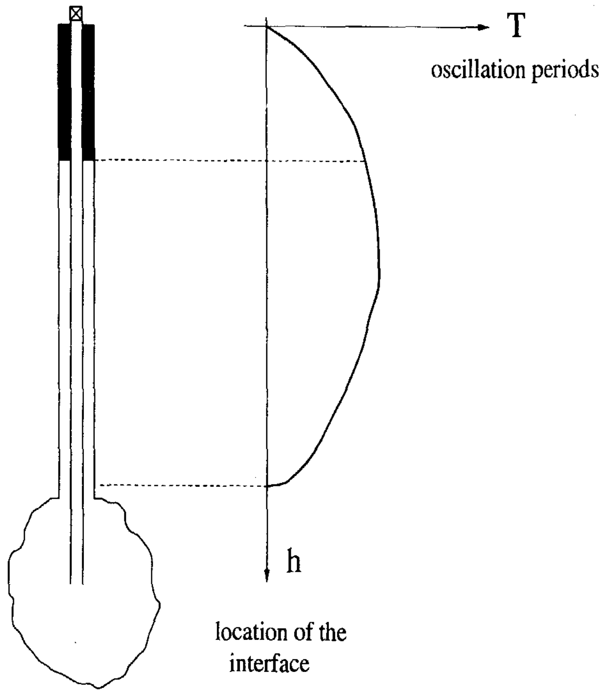


Figure 9 : ***Oscillation period as a function of gas column height***

The case $h \to 0$ does not have a clear physical meaning because, in many cases, the well opens at its bottom in a neck that gradually enlarges before reaching the cavern itself. The case $h \to H$ (The amount of gas in the annular cross-section is small) is much more interesting, especially for the case in which gas pressure is small.

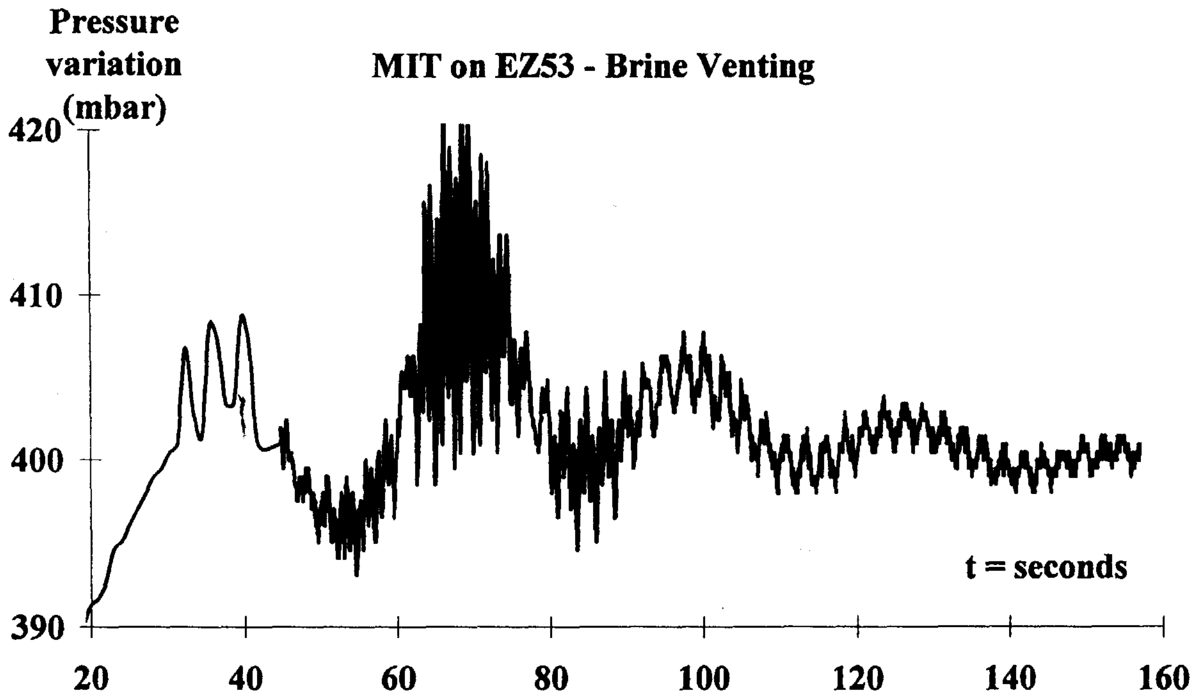
The gas pressure variations, as measured in the annular space, and the brine pressure variation, as measured in central tube, are respectively :

$$\dot{P}_g = \frac{P_g \gamma}{\sigma(H-h)} Q$$

$$\dot{P}_c = -\frac{1}{V\beta} Q$$

Their amplitudes can be, in some cases, notably different and their signs are opposite.

EXAMPLE 6 : THE FEBRUARY 1996 ETREZ TEST (GAZ DE FRANCE)



At the beginning of this phase of the test performed on the Etrez 53 cavern, 1.3 m^3 of brine was withdrawn from the central tube, resulting in a pressure drop from 4.7 MPa to 4.43 MPa in the annular space which was filled partly with nitrogen (the tube length is 930 meters). Three different oscillation periods can be observed on the (gas pressure-versus-time) curve:

(1) a short period (smaller than one second) that is associated to half-waves in the gas column ;

(2) an approximately 2.5 second period, probably associated with quarter-waves in the annular-space brine column, and

(3) a 30-second period, which was described in the previous paragraph.

CLOSED CAVERNS, SMALL AMOUNT OF GAS IN THE TUBING OR ANNULAR SPACE

The following calculations are very similar to those discussed in the previous paragraph but, here, we suppose that a very small amount of gas is trapped at the top of the annular space (In other words, $(H - h)$ is very small when compared to H.). Furthermore we suppose that the equilibrium gas pressure (P_0) is small (of the same order as atmospheric pressure).

With these conditions even small water hammers generated by the closing of a valve will trigger *large* changes in gas pressure. Instead of the linear relation between gas pressure rate $(\dot{P}_g)$ and brine flow (Q) we must use the exact adiabatic relation

$$P_g(H-h)^\gamma = P_g^1(H-h^1)^\gamma$$

where P_g^1, h^1 holds for the equilibrium static value. The equation satisfied by the interface level is now

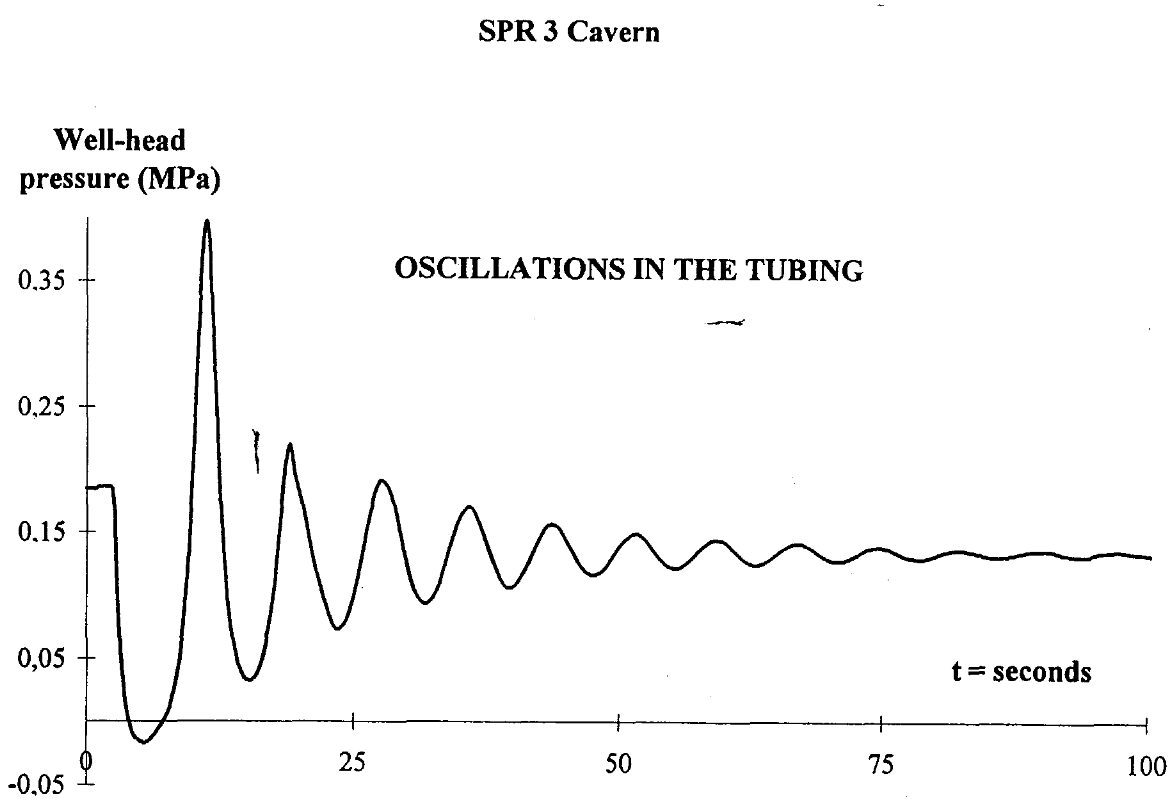
$$\rho.h\ddot{h} + P_g^1\left[\left(\frac{H-h_1}{H-h}\right)^\gamma - 1\right] + \left(\rho.g + \frac{\sigma}{\beta.V}\right)(h-h_1) = 0$$

This differential equations is a non linear one, which means that the observed oscillations will exhibit several new characteristic features, as described below

- The oscillations are an-harmonic, which means that the (pressure-versus-time) curve will no longer be symmetric with respect to the time axis : maxima are spiky and minima are rounded. The reason for this is that the gas pocket trapped at the top of the annular space behaves as a non-linear spring.

- The period of the movements is strongly influenced by the initial value of the gas pressure (P_g^1), which can easily be modified by pre-pressurization via a small brine injection through the brine tubing.

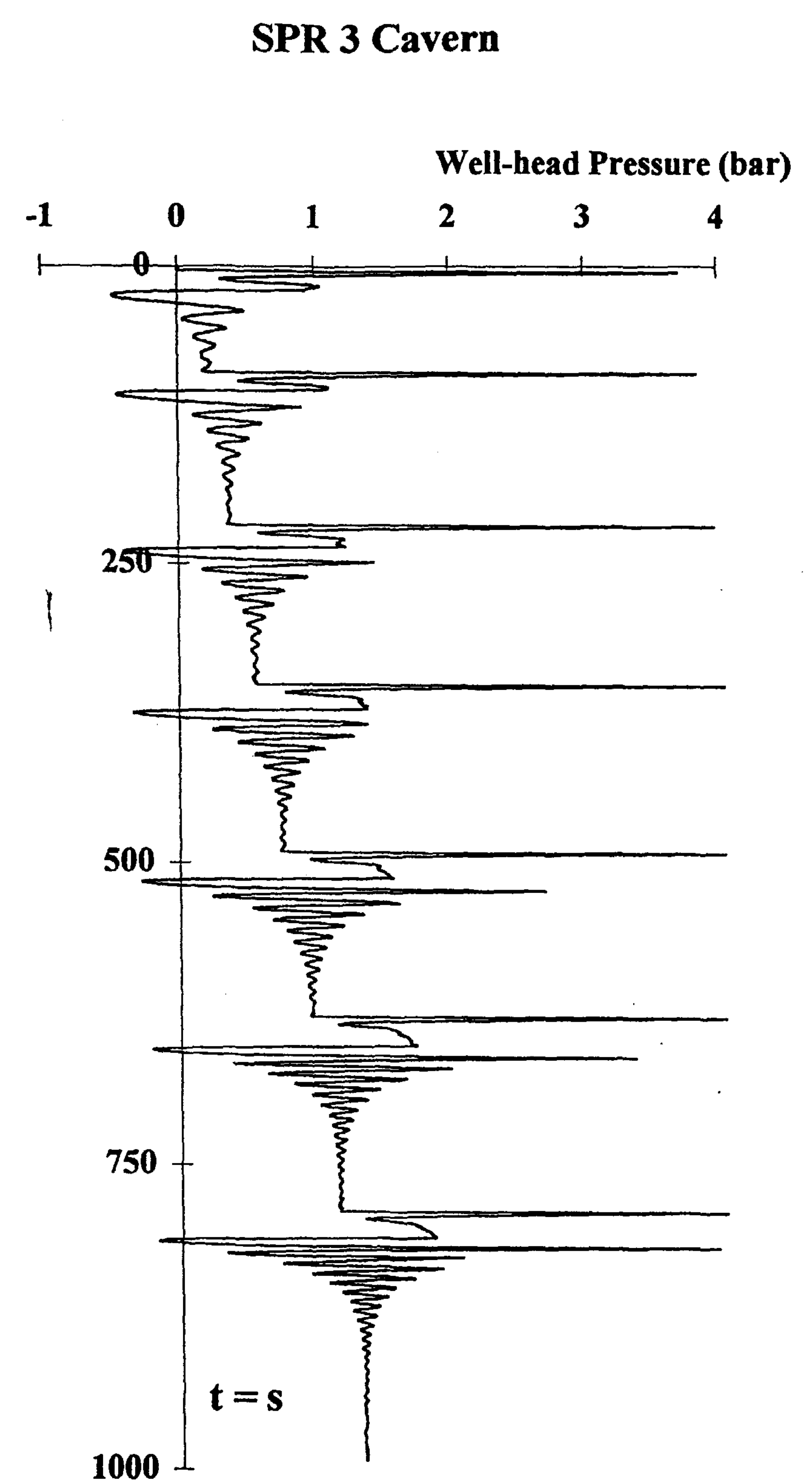
EXAMPLE 7 : THE JULY 1995 CARRESSE TEST (ELF-AQUITAINE)



This test was performed in the SPR 3 cavern previously described in Example 1. The curve shown was recorded at the end of a brine injection phase : the oscillations are triggered by stopping the injection rate. During the first "periods", the oscillations are extremely an-harmonic, due to drastic changes in gas-pocket stiffness with respect to the gas/brine interface location. The an-harmonic features vanish when the pressure-variation amplitude becomes smaller.

The influence of the (average) gas pressure is clearly illustrated with the second curve. Each oscillations phase is triggered by the end of a (small) brine injection period during which the pressure is increased by a fraction of a bar (2 or 3 psi). The "period" of the oscillation is divided by approximately two when gas pressure is increased by 1.3 bar.

EXAMPLE 7 : THE JULY 1995 CARRESSE TEST (ELF-AQUITAINE)-SSQ



Pressure buildup ; brine is injected step by step

CLOSED CAVERN, TUBING AND ANNULAR SPACE ARE GAS FILLED

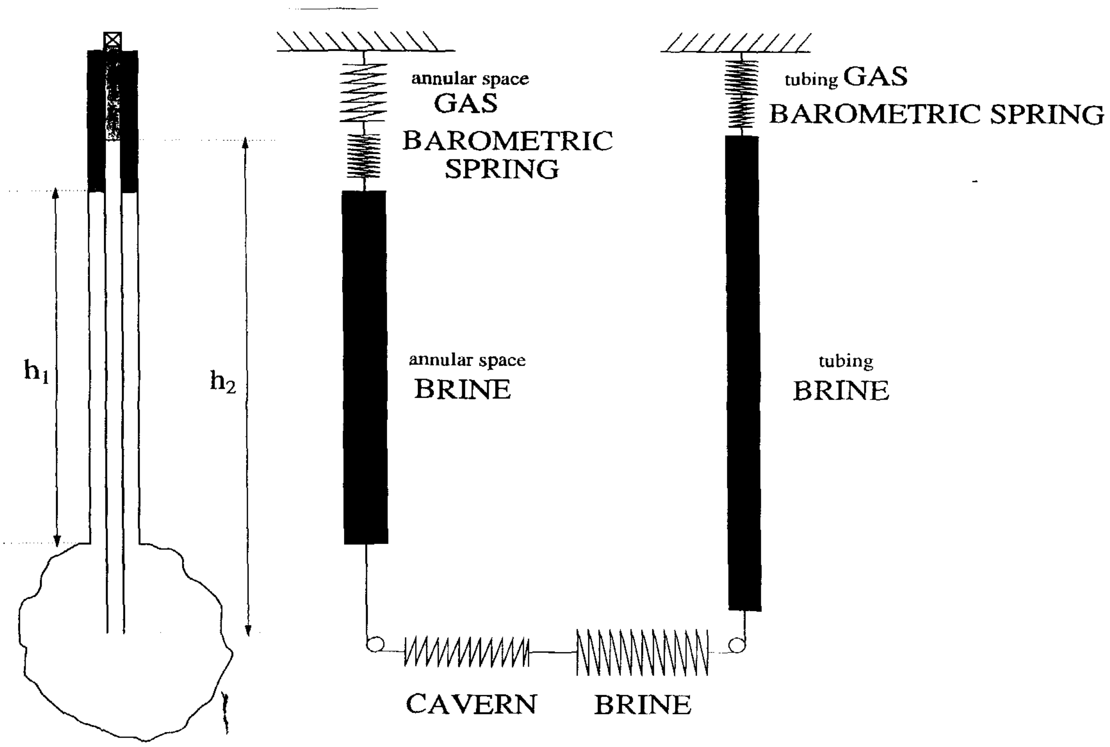


Figure 10 : ***Gas in the annular space and in the tube.***

In this case, both the annular space (cross-section σ) and central tubing (cross-section S) contain some gas (fig.10). The whole system consists of two masses (The brine masses are contained in the annular space, $\rho\ \sigma\ h$, and in the central tubing, $\rho\ S\ h_2$, respectively) whose oscillations are coupled through a set of elastic springs :

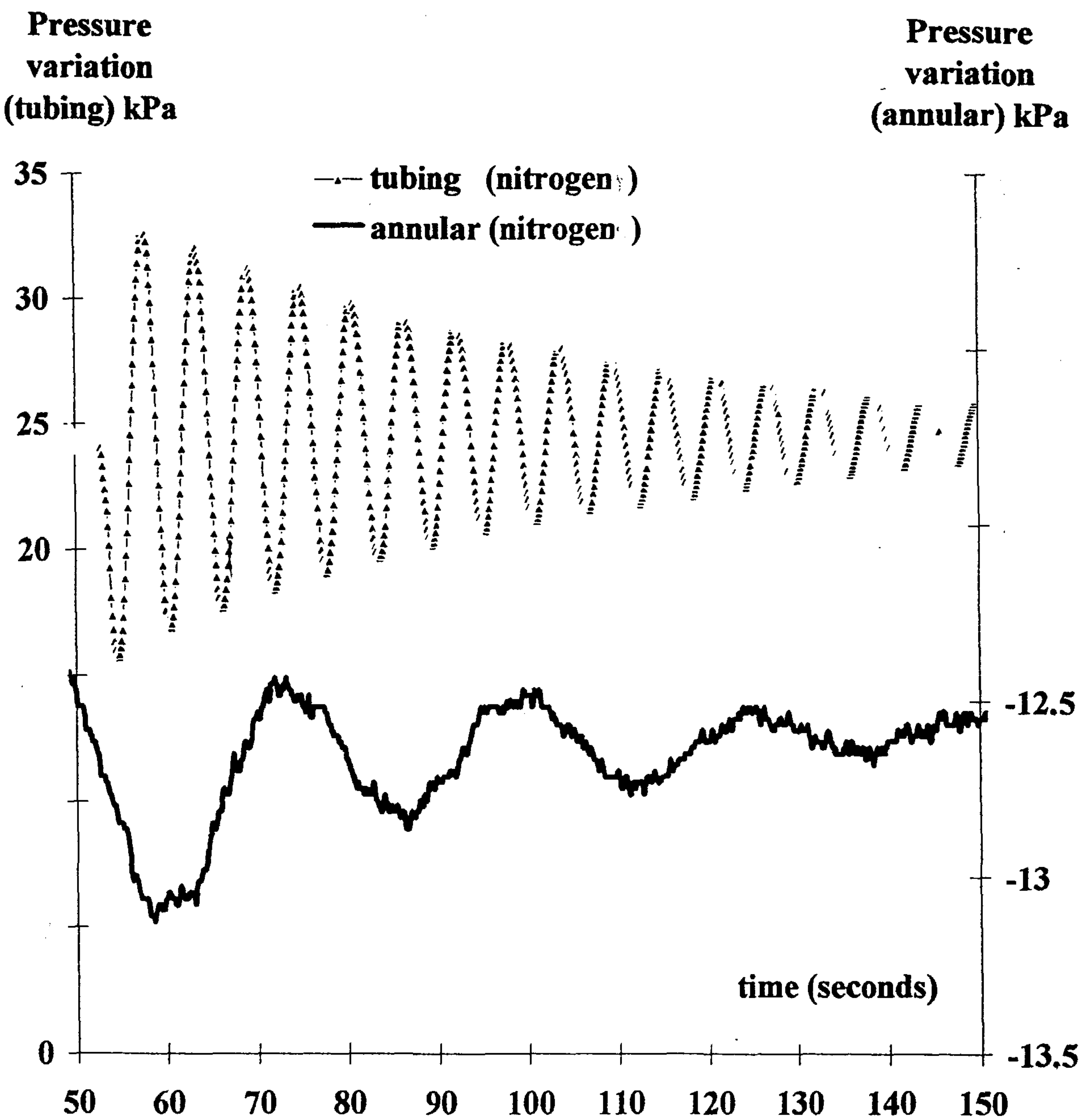
$$(\rho.\sigma.h_1)(\ddot{Q}_1/\sigma) = \sigma\left(\dot{P} - \gamma.P_g^1 Q_1/[\sigma(H-h_1)] - \rho g Q_1/\sigma\right)$$
$$(\rho.Sh_2)(\ddot{Q}_2/S) = S\left(\dot{P} - \gamma.P_g^2 Q_2/[S(H-h_2)] + \rho g Q_2/S\right)$$
$$\beta V\dot{P} + (Q_1 + Q_2) = 0$$

The initial (or static) gas pressures, P_g^1 and P_g^2, are related by

$$P_g^2 + h_2\rho g = P_g^1 + h_1\rho g$$

The system is characterized by two distinct periods ; the real pressure variations are a certain combination of two basic oscillations (eigenmodes).

EXAMPLE 8 : THE FEBRUARY 1996 ETREZ MIT TEST (GAZ DE FRANCE)



The test was performed on the Etrez 53 cavern (see example 2). A nitrogen column was lowered approximately 400 meters below ground level in the annular space. Unexpectedly, the tubing became leaky, and some gas entered the central tubing. Pressure variations at the well-head have been recorded during venting of the tubing gas. The gas/brine interface is much higher in the central tubing and its oscillations period much shorter.

CONCLUSIONS

Much useful information can be inferred from recording the pressure oscillations that are triggered when brine injection or withdrawal stops, for instance, the volume of a salt cavern, the LPG-volume/brine-volume ratio in an LPG storage cavern, and the existence of small gas prockets trapped in the well-head. A further advantage is that information can be obtained for relatively *little cost*.

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