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MEETING PAPER

SOME COMMENTS ON THE MIT TEST

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ABSTRACT

We discuss several aspects of the so-called MIT test which is performed by lowering a nitrogen/brine interface in the annular space of a salt cavern hole.

1. In case of a gas leak, the leak rate is underestimated by a factor comprised between 1 and 2 when multiplying the annular cross section by the interface rise rate.

2. The interface level, as measured by a logging equipment, can be checked by :

   i. Comparing the brine and gas pressures as measured at the well head.
   ii. Measuring the cavern compressibility and brine pre-pressure.
   iii. Measuring the nitrogen injected mass.

3. Several factors, like thermal expansion, steady state and transient creep, brine percolation can modify the interface rate even in the case of absence of leak. The effect of some of those factors can be precisely estimated.

4. A thoroughful examination of brine and gas pressure at ground level allow for estimating the gas leak.

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NOTATIONS

s : horizontal cross section of the annular space filled with gas

Σ : horizontal cross section at the brine-gas interface

h : distance from the well head to the interface

z : depth from well head

p(z) : pressure distribution in the columns

T(z) : temperature distribution in the columns

P_b : brine pressure at the well head

P_g : gas pressure at the well head

P_t : test pressure

P_{geo} : geostatic pressure

P_{pore} : pore pressure

ρ_b : brine density

ρ_g : gas density

r : constant of perfect gas ($r=296.6$ Pa.m^3.kg^{-1}°C^{-1})

Z : compressibility factor ($Z \approx 1$)

g : gravity constant

A : geothermal gradient

T_o : temperature at the well head

ρ_o : reference density for brine at 1 atm (14.696 psi) and 25°C (77°F).

a_s : saturated brine compressibility at 25°C and 1 atm

β_b: saturated brine compressibility at another temperature and pressure

b_s : saturated brine thermal expansion coefficient at 25 °C and 1 atm

α : saturated brine thermal expansion coefficient at another temperature and pressure

P_0^{ref} : pressure reference for brine density (P_0^{ref}=1 atm=1.01325 MPa=14.696 psi)

T_0^{ref} : temperature reference for brine density (T_0^{ref}=25°C=77°F)

V : cavern volume after leaching

R : cavity radius (cavern as a sphere)

β : sum of brine and cavern compressibilities

K_{cr} : constant for the calculation of cavern creep

m : mass of injected gas or parameter of cavern creep

n : parameter of cavern creep

K : salt intrinsic permeability

ϕ : salt porosity

η : brine kinematic viscosity

k : hydraulic diffusivity

PART I REAL versus APPARENT LEAK : the barometric effect

I.1 - Introduction

The MIT test basically consists in injecting some pressurized gas (nitrogen, in many cases, for this gas is inert and cheap) in a closed brine filled cavern and forcing the brine gas interface down to a level slightly lower than the casing shoe. In general, the volume of the gas is contained in a annular space between the casing and a central tubing which is filled with brine.

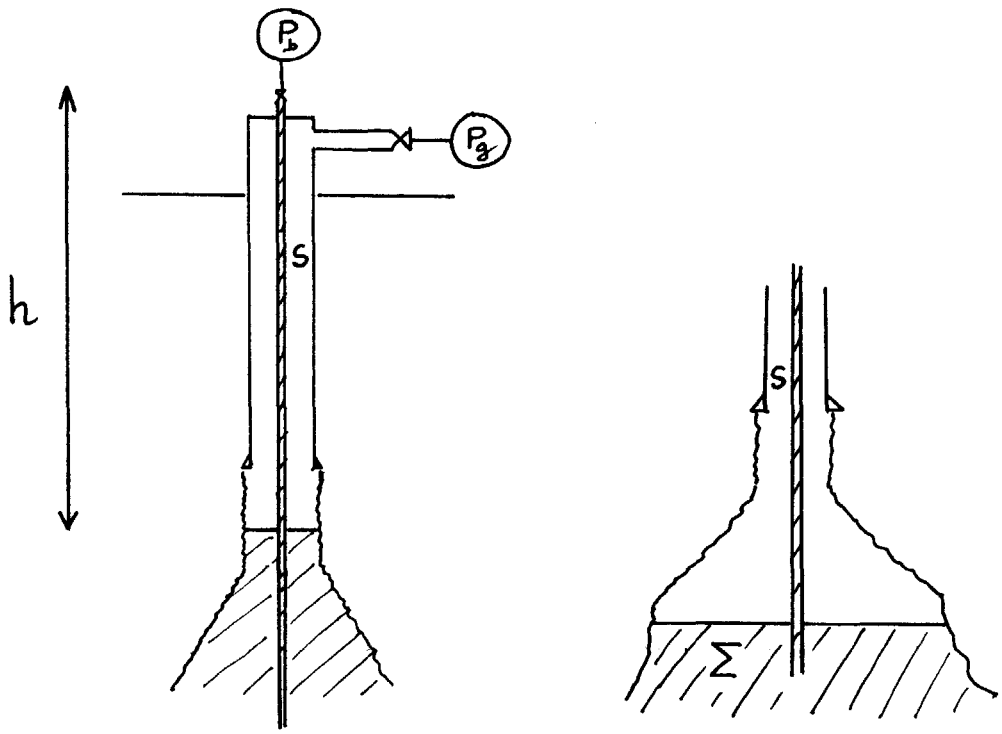

Figure 1 : Principle of a MIT test.

In some cases, the hole opens into a wider neck just below the casing shoe ; then the area of the horizontal cross section Σ at the brine - gas interface can be significantly larger than the area s of the annular space filled with gas. Anyway the volume of the gaz will be $v = h.s$ where h is exactly the interface depth if $\Sigma = s$ and is slightly higher in the case when the interface is located in a neck. In any case, a gas volume change will be $\Sigma \dot{h}$ ($s\dot{h}$ if there is no neck).

The interpretation of the MIT test sets the problem of linking the movements of the interface (namely, the value of the interface rate, $\dot{h}$) to a loss of gas due to a leak.

I.2 - Pressure in the brine column

It is reasonable to assume that brine density is constant in the column. Then the pressure distribution in the brine column will be : $p(z) = P_b + \rho_b g z$

where P_b is the brine pressure at the well head, z the depth under the well head, $\rho_b g$ is the so called "brine gradient", approximately 0.012 MPa per m or 0.53 psi per foot.

A better approximation is useless in many cases. Nevertheless, if we assume the rock temperature to be a linear function of depth, $T(z) = T_0 + Az$, where T_0 is the ground level temperature and A is the geothermal gradient (0.03 °C/m or 0.01 °F/ft is typical), then the brine state equation can be written :

$$\rho_b = \rho_0\left[1 + a_s\left(P - P_0^{ref}\right) - b_s\left(T - T_0^{ref}\right)\right]$$

where $a_s = 3.16\ 10^{-10}\ Pa^{-1}$, $b_s = 3.76\ 10^{-4}\ °C^{-1}$

$\rho_0 = 1198\ kg/m^3$; $P_0^{ref} = 1$ atm and $T_0^{ref} = 25$ °C.

it can be deduced :

$$p(z) = \rho_0 b_s + \frac{b_s A}{a_s} + \frac{1}{a_s}(1 + a_s\left(P_b - P_0^{ref}\right) - b_s\left(T_0 - T_0^{ref}\right) - \frac{b_s A}{\rho_0 a_s g}\left[exp(\rho_0 a_s g z) - 1\right])$$

One can notice that the further values used for the brine compressibility and the brine thermal expansion are different, indeed those quantities depend on the brine concentration in the cavern which can change a lot.

I.3 - Pressure in the gas column

The simpler hypothesis, and easier to handle, states that the gas density is constant throughout the colum and then : $p(z) = P_g + \rho_g g z$

where P_g is the gas pressure at the well head, $\rho_g . g$ is the "gas gradient". For nitrogen at a temperature of 30°C (86°F) and a pressure of 20 MPa (2900 psi) , then :

$$\rho_g \cdot g = 1.25053 \cdot \left(\frac{20}{0.101325}\right) \cdot \left(\frac{273.15 + 30}{273.15}\right)^{-1} \cdot 9.81 \approx 0.0022\ \text{MPa / m} \approx 0.1\ \text{psi / ft}$$

The previous approximation is a little bit too rough. A better approximation consists in considering nitrogen as an ideal gas whose state equation is

$$p = Z \cdot \rho r T \approx \rho r T$$

where : T is the absolute temperature (in °K)

r is a constant. (r=296.6 Pa.m^3.kg^{-1}°C^{-1})

Z is the compressibility factor , $Z \approx 1$

From the equilibrium condition, dp/dz = $\rho(P,T) \cdot g$ it can be deduced

$$p(z) = P_g \left(\frac{T_0 + Az}{T_0} \right)^{\frac{g}{rA}} = P_g (1 + az)^{\gamma}$$

Where we have set $a = A / T_0$ and $\gamma = g / (rA)$

A still better approximation would be reached by using the state equation of the real gas.($Z \neq 1$) The pressure calculation raises no difficulty, in principle, but a small computer is needed and a fully analytical expression is out of reach.

In fact, the simpler hypothesis (gas density constant throughout the column) appears to be sufficient in many cases. The reason is that both temperature and pressure increase with depth, and have an opposite effect on the density variation :

$$\frac{\rho'_z}{\rho} = \frac{p'_z}{p} - \frac{T'_z}{T} = \frac{g}{rT_o(1+az)} - \frac{A}{T_o + Az}$$

The effects of pressure and temperature compensate one another, if we take into acount a well head temperature To=20°C (68°F) then $\frac{\rho'_z}{\rho}$ vary from 1.5 10^{-4} m^{-1} at the well head to 4.5 10^{-5} m^{-1} at the depth of 2000 metres (6600 ft).

In such a favourable case, gas density can simply be estimated as a function of T_0 and P_g which are the temperature and the pressure at the well head :

$$\boxed{\rho_g = \frac{P_g}{r \cdot T_0}}$$

I.4 - Pressure at the interface

In the following, h will be the interface depth and P will be the pressure which reigns both in the brine and in the gas columns at that depth.

$$P = P_g + \rho_g h g = P_b + \rho_b g h = P_g (1 + h.g/(rT_0))$$

so the interface depth is : $\boxed{h_1 = \frac{P_g - P_b}{(\rho_b - \rho_g) \cdot g}}$ (1) and $\boxed{P = \frac{\rho_b \cdot P_g - \rho_g \cdot P_b}{\rho_b - \rho_g}}$ (2)

If we use the better approximation, then we must solve the equation :

$$P = P_b + \rho_b g h = P_g \cdot (1 + \alpha . z)^{\gamma}$$

which is most conveniently solved by a small computer.

Note that the calculation of h_1 as given in (1) provides a simple method for checking the interface depth. See figure 2 drawn with two test gradients : 0.02 MPa/m and 0.014 MPa/m and with the better approximation for gas pressure evolution. One can notice that the "gas gradient" is quite constant.

I.5 - Mass of injected gas

If m if the total amount of injected gas, then , due to mechanical equilibrium considerations, we get :

$$\boxed{mg = s.(P - P_g)} \quad (3)$$

where s is the annular cross section and g the gravity acceleration.

If we use the simplest approximation then :

$$m.g = s.\rho_g \cdot \frac{P_g - P_b}{\rho_b - \rho_g} = s.\rho_g.g.h \quad (4)$$

Note that this formula must be corrected if there is a neck below the casing shoe.

It must be noticed that (4) gives us an easy way to check the interface calculation, provided that the mass of injected gas is well known. Let $h_3 = m/(s\rho_g)$ be the theorical depth, deduced from the mass of injected nitrogen and h the actual measured depth.

i) if $m/(s\rho_g) > h$, it is reasonable to assume that some gas leak occured during gas injection

ii) if $m/(s\rho_g) < h$, the density estimation is incorrect or the cavity is not stabilized (the pressurization has triggered a transient creep or percolation which is still active).

If we use the more sophisticated approximation, then we get :

$$\boxed{m.g = s.P.\left(1 - (1 + a.h)^{-\gamma}\right)} \quad (5) \qquad \text{(See figure 3)}$$

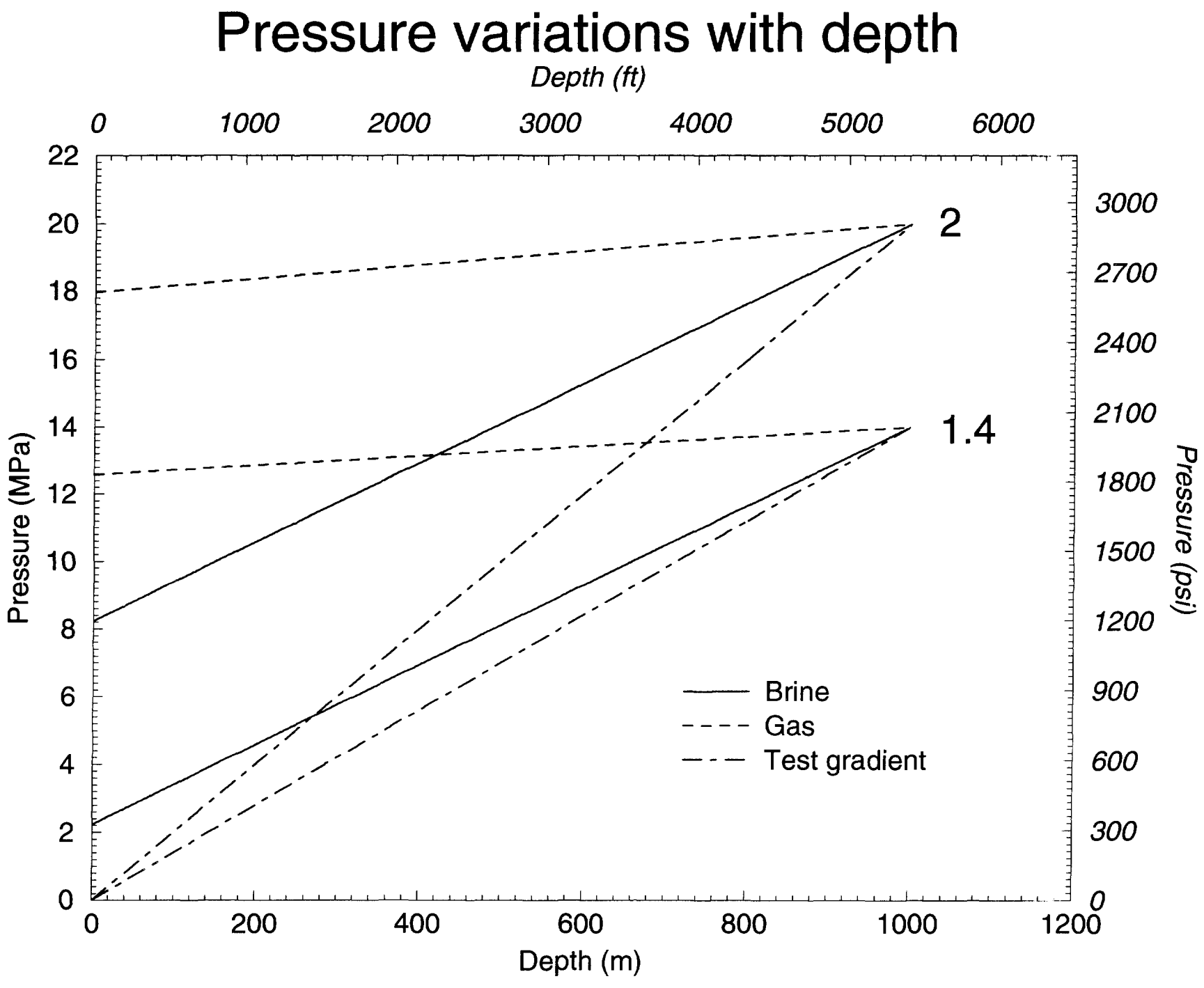
Pressure variations with depth
Depth (ft)
0
1000
2000
3000
4000
5000
6000
Pressure (MPa)
22
20
18
16
14
12
10
8
6
4
2
0
Pressure (psi)
3000
2700
2400
2100
1800
1500
1200
900
600
300
0
2
1.4
Brine
Gas
Test gradient
0
200
400
600
800
1000
1200
Depth (m)

Fig. 2

Evolution of the interface depth with the mass of injected gas

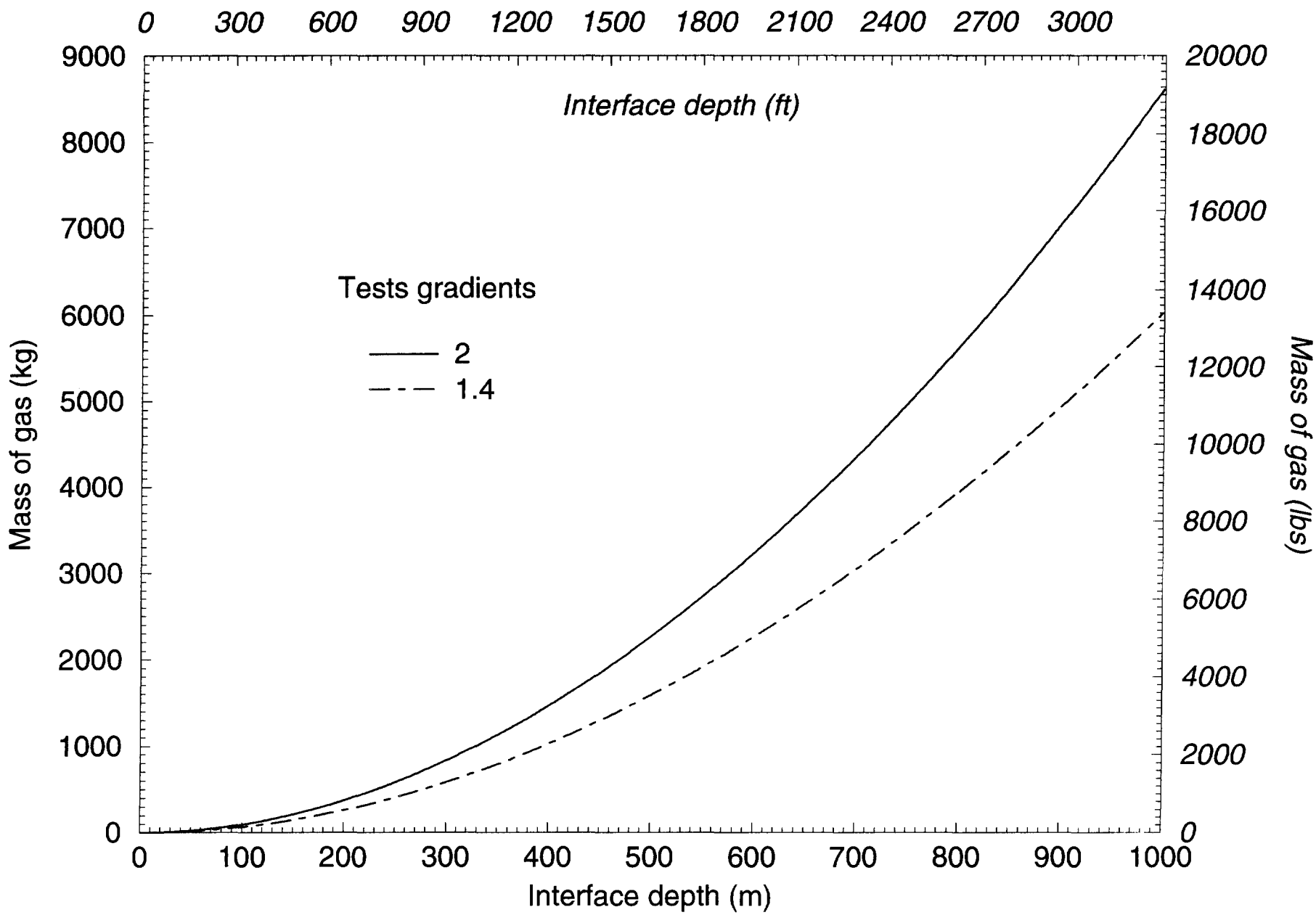

Fig. 3

I.6 - Why is it neccessary to pre-pressurize ?

The aim of the MIT test is to lower the gas/brine interface, down to a certain level h (below the casing shoe) and to reach, in that particular point, a certain pressure P which is calculated according to the maximal pressure which will be applied in that point when the storage will be in operation. A simple way to calculate this pressure is to consider the "test gradient", or $\rho_t g$ such as $P=\rho_t gh$. For instance, in a gas cavern, a typical value for $\rho_t g$ is 0.02 MPa/m or 0.884 psi/ft. When gas is injected, it displaces a volume of brine which is equal to s.h (if there is no neck). If no brine is withdrawn or added during the test, it means that this displaced brine is forced into the cavity and then will increase the brine pressure in the cavern (and in the brine tubing) by an amount which is $(s.h)/(\beta.V)$ where V is the cavern volume and β is the cavern compressibility. The quantity $\beta.V$ can be most simply measured during the pre-pressurization, see for instance Thiel [1993] (see figure 15). A typical value for β , according to Boucly [1982], is : $\beta=4.10^{-10}$ Pa^{-1} ($2.8\ 10^{-6}$ psi^{-1}) which is the sum of brine compressibility $\beta_b=2.7\ 10^{-10}$ Pa^{-1} ($1.9\ 10^{-6}$ psi^{-1}) and cavern compressibility $\beta_c=1.3\ 10^{-10}$ Pa^{-1} ($9.0\ 10^{-7}$ psi^{-1}). The last figure depends upon the cavern shape.

In other words if we want the final pressure to be P at the interface h , or $P-\rho_b gh$ at the well head in the brine tubing, then the cavern must be "pre-pressurized" by forcing some brine in the closed cavern before injecting the gas. The pressure which must be reached is called P_p and must be such as :

$$P_p + (s.h)/(\beta.V) = P - \rho_b gh = (\rho_t-\rho_b).g.h$$

The amount of brine to be injected will be:

$$\boxed{V_p = \beta V P_p = [\beta V g(\rho_t - \rho_b) - s].h} \quad (6)$$

Note that the pre-pressure P_p can be "negative" if $s>\beta Vg(\rho_t-\rho_b)$.

For instance if $\beta=4.10^{-10}$ Pa^{-1} ($2.8\ 10^{-6}$ psi^{-1}) , s=250 cm^2 (38.5 sq inch) , then the condition is V<4000 m^3 (25000 bbls). In such a case, the cavern being relatively small, the fluid system is "stiff" : a small injection of fluid leads to a large increase of pressure. Then it is necessary to withdraw some brine during the gas injection in order to reach the aim of the test.

Thoses remarks allow for a second check of the interface level calculation. If there was no leak during gas injection, then $P = P_b + \rho_b gh = P_p + [\rho_b g + s/(\beta.V)].h$

$$\boxed{h_2 = \beta V.(P_b - P_p)/s} \quad (7)$$

If this value is smaller than the observed depth, a leak during gas injection can be suspected.

I.7 - Effects of a gas leak

In this paragraph we disregard all the phenomena such as cavern creep, thermal expansion, brine percolation, saturation change which can generate a change in the gas/brine interface even in the absence of leak. Those phenomena will be addressed later in the paper.
In this paragraph we discuss the effect of a gas leak, which can be most conveniently expressed as a relative loss of mass rate, i.e. $\dot{m}/m$ where m is the mass of the injected gas.

From a practical point of view, the problem is to link this loss rate to some measurable quantity such as $\dot{h}$, the interface depth rate ; or $\dot{P}_g$ and $\dot{P}_b$, the pressure rates as observed at ground level. A rough estimation of the link between the interface depth rate $\dot{h}$ and the gas loss rate is given for instance in CH2M HILL [1995].

" An interface is observed to move upward 3 feet in 20 days under near equilibrium conditions (i.e. , 0.15 ft/day). The average borehole diameter across this interval is 8 feet (i.e., 50.27 ft^3/ft). Therefore the average nitrogen leak rate is calculated as :

$$Q=AV=(50.27\ ft^2)(0.15\ ft/day)=7.54\ ft^3/day.\ "$$

In other words, the leak is estimated by multiplying the annular cross section by the interface rate. We suggest in the following some corrections which can be easily done in order to get a more precise estimation.

We will now consider movements of the interface ; $\dot{h}$ will be the interface displacement rate (for instance, in metres per day or feet per day).

By eliminating P_g, which is the gas pressure at the wellhead, between the two relations $mg=s(P-P_g)$ and $p = P_g \cdot (1 + a \cdot z)^{\gamma}$, and derivating this relation with respect with time we get :

$$\frac{\dot{m}}{m} = \frac{\dot{P}}{P} + \frac{\rho s \dot{h}}{m} \cdot \frac{P_g}{P} \qquad (8)$$

where ρ is the gas density at the interface depth which, in the simplest approximation, is equal to the constant value ρ_g.

Now a gas leak ($\dot{m}$<0) will provoke an upwards movement of the interface ($\dot{h}$<0) and a gas volume change ($\dot{v} = s\dot{h}$) which in turn will bring a change in the pressure at the interface level $\dot{P}$. As a whole, the pressure inside the cavern will change by $\dot{P} - \rho_b g \dot{h} = \dot{P}_b$ which will result in a $\beta(\dot{P} - \rho_b g \dot{h}).V$ change of brine volume. There comes $\beta\left(\dot{P} - \rho_b g \dot{h}\right) \cdot V = s\dot{h}$ and finally :

$$\frac{\dot{m}}{\rho} = s\dot{h} \cdot \left\{1 + \left(1 - \frac{P_g}{P}\right) \cdot \left[\frac{\rho_b - \rho}{\rho} + \frac{s}{\beta V g \rho}\right]\right\} \qquad (9)$$

In many cases, it is sufficient as a first approximation to consider the gas density (ρ_g) to be constant through the whole tubing and equal to the density of gas at the well head, $\rho.g = \rho_g.g = P_g.g/(rT)$ and then :

$$\boxed{\frac{\dot{m}}{\rho_g} = s\dot{h} \cdot \left\{1 + \left[\rho_b - \rho_g + s / (\beta V g)\right] / \rho_t\right\} = s\dot{h} \cdot C} \qquad (10)$$

The "apparent " leak, as stated before, is $s\dot{h}$ (in volume per day) or $\rho_g s\dot{h}$ (in mass per day) : but the "**real**" leak is larger.

The mistake which is done by assimilating the apparent leak to the real leak is all the larger than :

- the "test gradient" $\rho_t g$ is small
- the ratio "annular cross section divided by cavern volume" or s/V is large
- the depth (then the gas density ρ_g) is small

In the following we call "C" the ratio between the actual leak and the apparent leak.

$$\boxed{C = 1 + \frac{\rho_b - \rho_g}{\rho_t} + \frac{s}{\beta \cdot V \cdot g \cdot \rho_t}}$$

See figure 4 next page.

The parameters are :

$\rho_b.g = 0.012$ MPa/m = 0.530 psi/ft

$$\rho_g \cdot g = 1.25053 \cdot \left(\frac{P}{P_o^{ref}}\right) \cdot \left(\frac{273.15 + T}{273.15}\right)^{-1} \cdot 9.81$$

$\rho_t.g = 0.02$ Mpa/m = 0.884 psi/ft

$s = 4.15\ 10^{-2}\ m^2$ (see Thiel [1993])

$\beta = 4.10^{-10}\ Pa^{-1} = 2.8\ 10^{-6}\ psi^{-1}$

$g = 9.8\ m.s^{-1}$

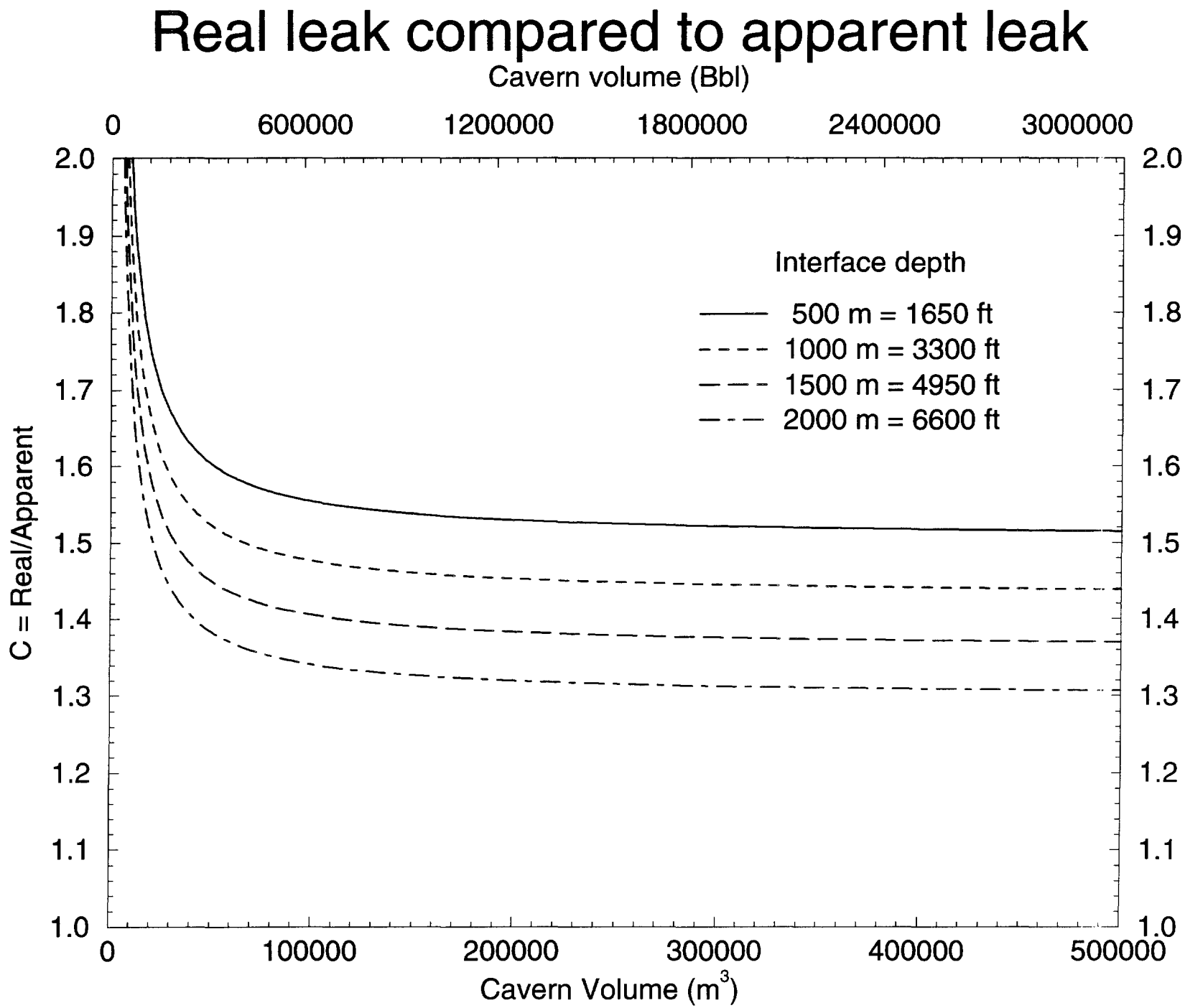
Real leak compared to apparent leak
Cavern volume (Bbl)
0
600000
1200000
1800000
2400000
3000000
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
C = Real/Apparent
Interface depth
500 m = 1650 ft
1000 m = 3300 ft
1500 m = 4950 ft
2000 m = 6600 ft
0
100000
200000
300000
400000
500000
Cavern Volume (m3)

Fig. 4

PART II FACTORS INFLUENCING INTERFACE LEVEL EVOLUTION

II.1 - Introduction

In Part I, we assumed that gas leak was the only phenomenon able to modify the interface depth. In fact, as emphasized for instance in Van Fossan and Whelply [1985], several factors can influence the results of a leak test, leading again to a distinction between "apparent leak" (i.e.,as deduced from the interface measurement) and "real leak" (i.e.,as corrected from the parasite factors).

In the following will be more specifically examined :

- Brine thermal expansion
- Cavern creep
- Brine percolation

Some of those effects did exist before the test (thermal expansion,steady state cavern creep) ; some can be drastically modified by the test (cavern transient creep) ; others appear as a consequence of the test itself (brine saturation,brine percolation).

We will note $\dot{\varepsilon}$ the relative volumetric change rate associated with any one of thoses effects. For instance, $\dot{\varepsilon}_{th} = \alpha\dot{T}$ if $\dot{T}$ is the average temperature change rate in the cavern and α is the brine thermal expansion coefficient ; or $\dot{\varepsilon}_{cr} = -\dot{V}/V$ if $\dot{V}$ is the cavern volume change rate due to creep ($\dot{V} < 0$ if the cavern shrinks) etc...

Now the change in brine volume will be $\beta \cdot \left(\dot{P} - \rho_b g \dot{h}\right) \cdot V - \dot{\varepsilon} V$, and finally instead of (10) we get :

$$\boxed{\frac{\dot{m}}{\rho_g} = s \cdot \left[\dot{h}C + \frac{\dot{\varepsilon}}{\beta g \rho_t} \right]} \quad (11)$$

where $\dot{\varepsilon}$ holds for :

- $\dot{\varepsilon}_{th}$ (>0 in general)
- $\dot{\varepsilon}_{cr}$ (>0 for steady state creep,<0 for transient creep)
- $\dot{\varepsilon}_{perc}$ (<0 in general)

In other words, an interface level change ($\dot{h}$) is the sum of two effects :

- a gas leak $\dot{m}$ (in mass) or $\dot{m}/\rho_g$ (in volume)
- and a change in brine (or cavern) relative volume $\dot{\varepsilon}$

Then in the absence of any leak ($\dot{m}$ =0) a volumetric change rate $\dot{\varepsilon}$ will provoke an interface rate

$$\boxed{\dot{h} = \frac{-\dot{\varepsilon}}{C\beta g \rho_t}} \qquad (12)$$

For a rough estimation, let us take :

* C=1.5 , β=4.10^{-10} Pa^{-1} (2.8 10^{-6} psi^{-1}) , g=10 m.s^{-2} , ρ_t=2000 kg.m^{-3}

$\underline{\dot{h} = -8.3\ 10^4\ \dot{\varepsilon}}$

* C=1.5 , β=4.10^{-10} Pa^{-1} , g=10 m.s^{-2} , ρ_t=1400 kg.m^{-3}

$\underline{\dot{h} = -1.2\ 10^5\ \dot{\varepsilon}}$

In the following, we estimate typical values of $\dot{\varepsilon}$.

It is useful to link the two quantities $\dot{m}$ and $\dot{\varepsilon}$ to the quantities which can be observed at the well head, $\dot{P}_g$ and $\dot{P}_b$:

$$\boxed{\dot{m} = \frac{s\rho_g}{g(\rho_b - \rho_g)} \cdot \left[\dot{P}_g - \dot{P}_b + h\rho_b g \frac{\dot{P}_g}{P_g} \right]} \qquad (13)$$

$$\boxed{\dot{\varepsilon} = \frac{\beta\rho_t}{(\rho_b - \rho_g)} \cdot \left[(1-C)(\dot{P}_g - \dot{P}_b) + h(\rho_b - C\rho_g) g \frac{\dot{P}_g}{P_g} \right]} \qquad (14)$$

or conversely :

$$\boxed{\frac{\dot{P}_g}{P_g} = \dot{m} \cdot \frac{\left(1 - \frac{1}{C}\right)}{sh\rho_g} + \frac{\dot{\varepsilon}}{\beta g h C \rho_t}} \qquad (15)$$

$$\boxed{\dot{P}_b = \dot{m} \cdot \left(\frac{1}{\beta V C \rho_g} \right) + \dot{\varepsilon} \cdot \frac{P_g + \rho_b g h}{\beta g \rho_t C h}} \qquad (16)$$

II.2 - Brine thermal expansion

I.2.1 Introduction

Salt caverns are most often leached out by injecting soft water pumped out from shallow aquifer formations whose water is colder than the deeper salt mass in which the cavern is created. Then, at the end of the leaching process, the temperature of the brine contained in the cavern is significantly smaller than the temperature of the surrounding rock mass. How large is the difference strongly depends upon several factors such as leaching flow rate, leaching duration, cavern depth. The initial gap must be measured (or computed) in each particular case.

For instance, Hugout [1984] gives the following data for the Tersanne and Etrez sites in France :

	Tersanne	Etrez lower	Etrez upper
Approx.depth (m)	1500	1430	930
(ft)	4900	4700	3050
geothermic temperature (°C)	70	55	45
(°F)	158	131	113
Average cavity temperature during leaching (°C)	33-41	35-39	28-33
(°F)	91-106	95-102	82-91

Table 1 - Cavern temperatures (After Hugout,[1984])

If the brine in the cavern is left at rest after leaching, its temperature will slowly increase. The heating rate is governed by thermal conduction in the rock mass ; an equilibrium will be reached when the average brine temperature equals the rock mass temperature at cavern depth.
This increase in temperature will (at least if the cavern remains open) lead to a thermal expansion of the brine in the cavern or, conversely, to a pressure build up if the cavern is kept closed.

II.2.2 The EZ 53 Cavern

A first example is given by the EZ53 cavern. This cavern is located at a depth of 950 m (3100 ft), in the Etrez upper salt, its volume is 8000 m^3 (50000 bbls). The temperature evolution has been carefully measured during the 200 days following the end of leaching (Hugout,1988).

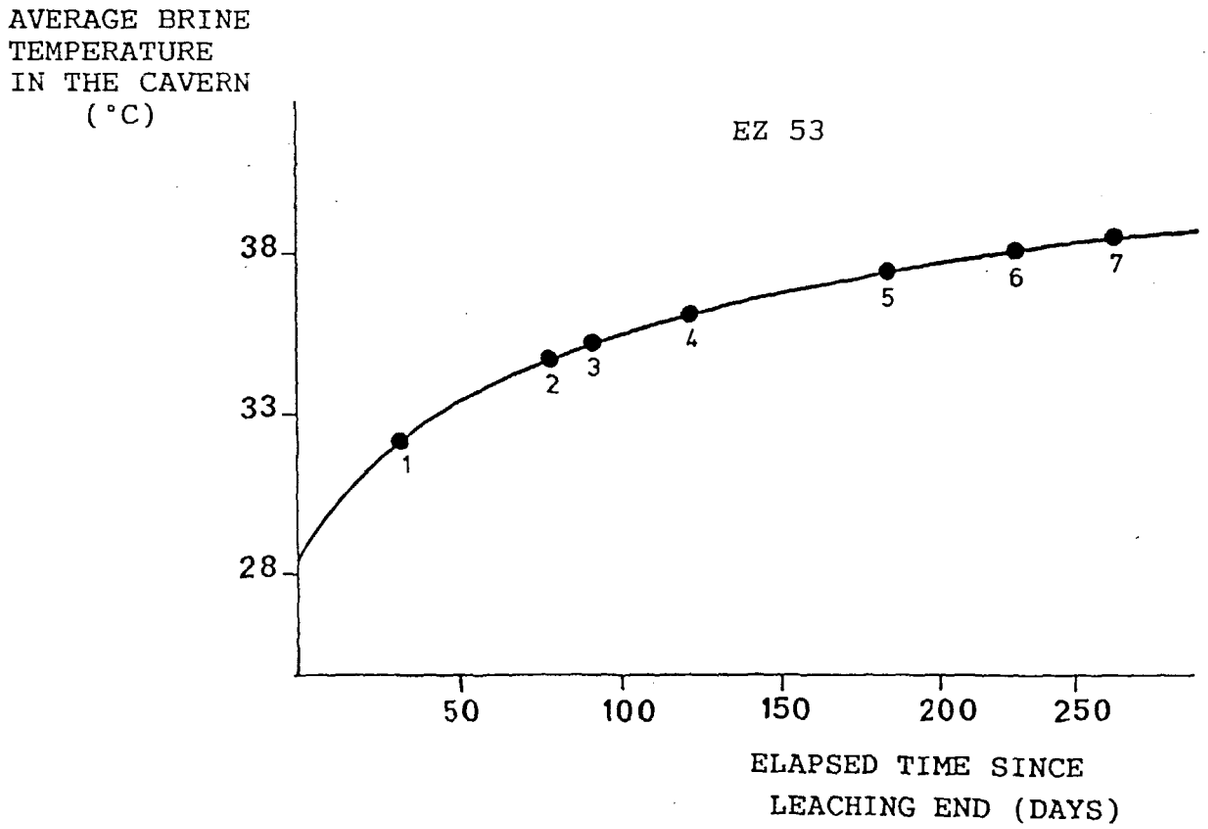

Fig 5 - Temperature evolution (as measured) in the EZ53 cavern

For instance during days 31 to 81 after the end of the leaching, the average temperature rate was 0.057 °C per day (0.123 °F per day), which led to a volumetric thermal expansion rate :

$$\dot{\varepsilon}_{th} = \alpha \cdot \dot{T} = 2.5\ 10^{-5} \text{ per day} \qquad \text{(with } \alpha = 4.4\ 10^{-4}\ °C^{-1} \text{ in the cavern)}$$

One year after the end of leaching, the figure was divided by 4.

II.2.3 The effect of depth and cavern size

It is reasonable to expect that the thermal expansion rate increases with depth, for the initial gap between cavity temperature and rock mass temperature is larger. In fact this is clear in the Tersanne case (Table 1), where the rate would be multiplied by two, when compared to the upper Etrez case, but less convincing in the lower Etrez case (Table 1) where the geothermal temperature is low.

The effect of the cavern size is more important. Brine heating is governed by thermal conduction in the rock mass, which follows the Fourier law : it means that the time scale increases as the square of the space scale. In other words, other things (cavern shape and depth,rock temperature) being kept equal, if the dimensions of the cavern are multiplied by two, the volume is multiplied by eight, but the relative volumetric expansion rate will be divided by four and the absolute brine flow rate will be multiplied by two.

If we take the previous example of the EZ53 cavern and imagine that the cavern dimensions are multiplied by four, then the volume will be 8000 m^3.64 = 512,000 m^3 ; the time scale being multiplied by 16, the average expansion rate due to thermal expansion will be $\dot{\varepsilon}_{th} = 1.56\ 10^{-6}\ day^{-1}$ (instead of 2.5 10^{-5} day^{-1})but during a much longer period (32 months instead of 2).

II.2.4 The EZ14 cavern

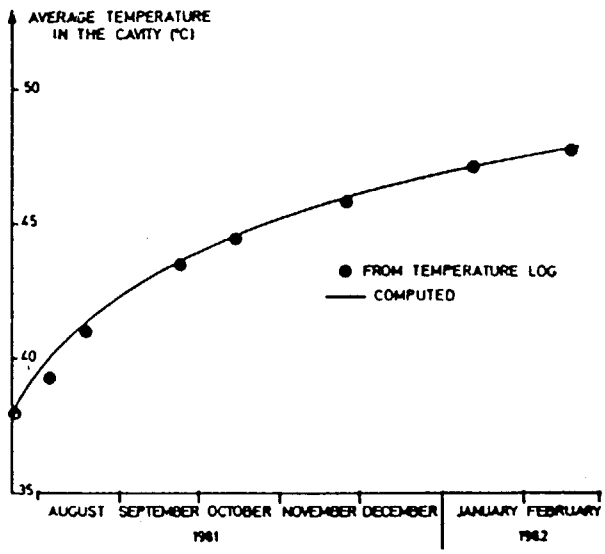

fig.6 - Evolution of cavity's brine temperature (EZ14)

This cavern is located at a depth of 1430 metres in the lower Etrez salt. As can be seen from the figure, the difference between rock temperature (55°C or 131 °F) and initial temperature (38°C or 100 °F) is not very different from the EZ53 case. The volume of the EZ14 cavern was 4700 m^3: the dimensions are approximately 80 % of the EZ 53 geometrical dimensions ; then the time scale is multiplied by 0.64 and the thermal expansion rate is 1.5 times bigger than in the EZ 53 case.

II.2.5 Interface changes due to thermal expansion

We have seen that in the case of the EZ53 cavern the thermal expansion rate was $\dot{\varepsilon}_{th} = 2.5\ 10^{-5}$ per day . If we assume the numerical values selected in paragraph II.1, with ρt=2000 $kg.m^{-3}$, then during the two first months after the leaching end the interface rate would be :

$$\dot{h} = -2.08 \text{ m / day} = -6.8 \text{ ft / day} \qquad \text{(upward movement)}$$

Interface rate due to thermal expansion

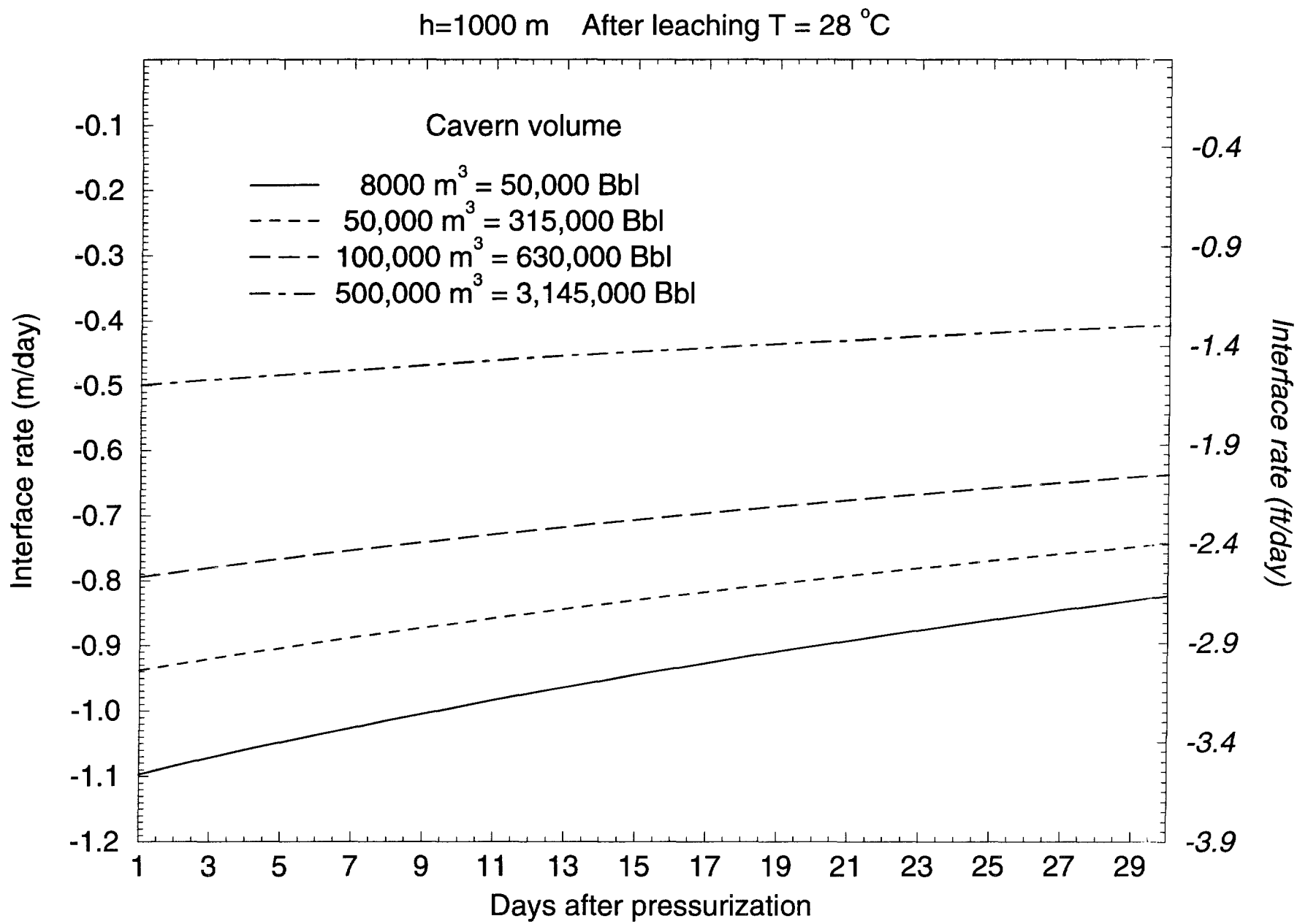

Fig. 7

II.3 - Cavern creep

II.3.1 Introduction

Salt creep rate is a non linear function of the applied stress and is strongly affected by rock salt temperature ; furthermore it is influenced by salt composition, fabrics, texture, amount of insoluble etc... and then can strongly differ from one site to an other.
Most of the caverns are located between the depth of 500 m and 2000 m (approximately 1500 ft and 6000 ft). The average depth of the cavern governs the rate of its loss of volume :

- the deeper the cavern, the higher is the gap between the the geostatic pressure and the fluid pressure inside the cavern. For instance if the cavern is filled with brine and open to atmosphere, both the geostatic pressure P_{geo} and the internal pressure P_c are a linear function of the cavern depth ; the gap between these two pressures, which is the driving force for cavern creep, will be : P_{geo}-P_c = 22 Mpa-12 Mpa = 10 Mpa (1450 psi) at a depth of 1000 m (3000 ft) and 20 Mpa (2900 psi) at a depth of 2000 m (6000 ft).
- the deeper the cavern, the higher is the rock temperature at the cavern level.

II.3.2 Steady state creep

Cavern creep is higher just after the cavern creation and slowly decreases with time and, according to many authors, reaches an asymptotic value if the pressure in the cavern is kept constant (which is the case, for instance, in a brine-filled cavern open to atmosphere).
Such an asymptotic value has been measured in the Etrez site in France ; 8 and 13 years after the end of the cavern leaching, the rate of relative loss of volume was $\dot{\varepsilon}_{cr}$=2.5 10^{-4} year^{-1}. This figure holds for a cavern at a depth of approximately 1000 m (3000 ft) in which the gap between geostatic pressure and internal fluid pressure is 10 Mpa (1450 psi). In this site, salt creep rate follows a so called "power law" in wich the exponent is assumed to be n=3.
If the cavern is closed at ground level and if the pressure in the cavern rises, the cavern creep will be reduced ; for instance in the Etrez site, if an extra pressure of 8 Mpa (1160 psi) is added, the gap is reduced by a factor of 5, then the creep rate is lowered by a factor of 5^3=125, the steady state relative loss of volume during a MIT test would be $\dot{\varepsilon}_{cr}$= 2. 10^{-6} year^{-1} which is a very small figure, even compared to percolation effects, and considered negligible. Such a conclusion holds for a relatively shallow cavern (1000 m or 3000 ft). Let us consider a deep cavern (2000 m or 6000 ft) and suppose that the test pressure at that depth is 16 Mpa (2300 psi) ; the gap between geostatic pressure and cavern pressure is multiplied by two, resulting in a multiplication by eight of the creep rate ; but, due to the additional effect of rock temperature increase, the overall effect of depth will be to increase the cavern creep rate by two orders of magnitude, i.e.

$$\dot{\varepsilon}_{cr} = 2.10^{-4} \text{ year}^{-1} .$$

II.3.3 Transient creep

If we consider the whole story of a cavern, several pressure variations occured which can strongly increase the current creep rate, especially if these changes are recent. Let us take into consideration the typical cavern pressure evolution from the start of leaching to the end of the first MIT test (see below).

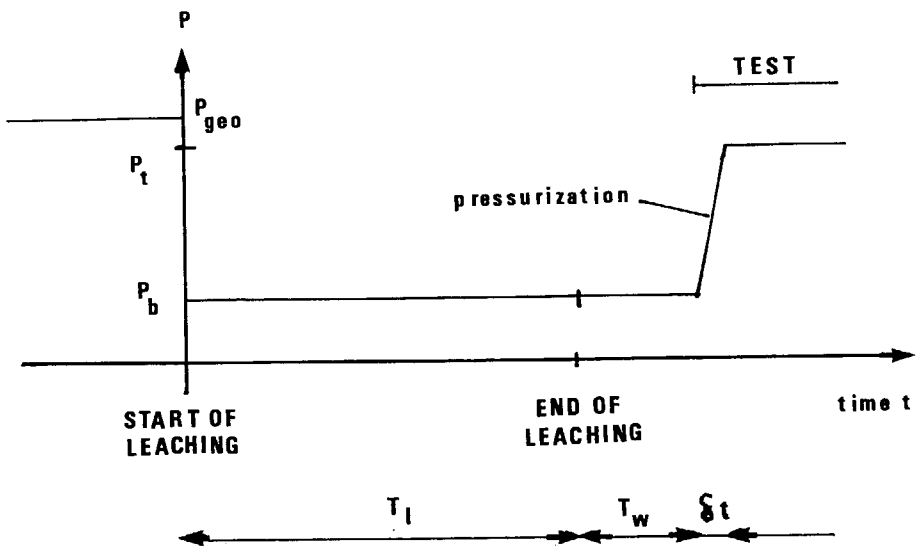

Fig.8 - Typical evolution of the cavern pressure

We call P_{geo} the geostatic pressure at cavern depth, P_b the pressure due to the brine column when the cavern is open to amosphere, P_t the average pressure in the cavern during the MIT test, T_l is the duration of leaching, T_w the waiting time between the end of leaching and the test (important when T_l is short) and δt is the time needed to pressurize the cavern.

According to Gaz de France experience, when the pressure in the cavern is rapidly increased the cavern tends to enlarge during the first days after the pressurization. To take into acount this transient creep, a so called GdF83 law (see Hugout [1984]) has been perfected and it allows to estimate the transient creep during the test period as follows : (17)

$$\boxed{\dot{\varepsilon}_{cr} = \frac{K_{cr}}{\delta t}\cdot\left(P_{geo}-P_t\right)^{n-1}\cdot\left\{\left(P_{geo}-P_b\right)\left[t^m-(t-\delta t)^m\right]+\left(P_t-P_b\right)\left[(t-T_l-T_w-\delta t)^m-(t-T_l-T_w)^m\right]\right\}}$$

where K_{cr},n and m are constants which depend on the salt under consideration.

t is the time since the beginning of leaching.

II.3.4 The EZ53 cavern (see II.2.2)

Several creep measurements have been performed on this cavern ; for instance the cavern have been depressurized from 11.4 MPa (1650 psi) to 8 Mpa (1160 psi), kept at this pressure during several weeks, and then repressurized in one day to 11.4 Mpa ; the cavern volume increased ($\dot{\varepsilon}_{cr}$<0) during the first days after the pressurization as shown in the figure below.

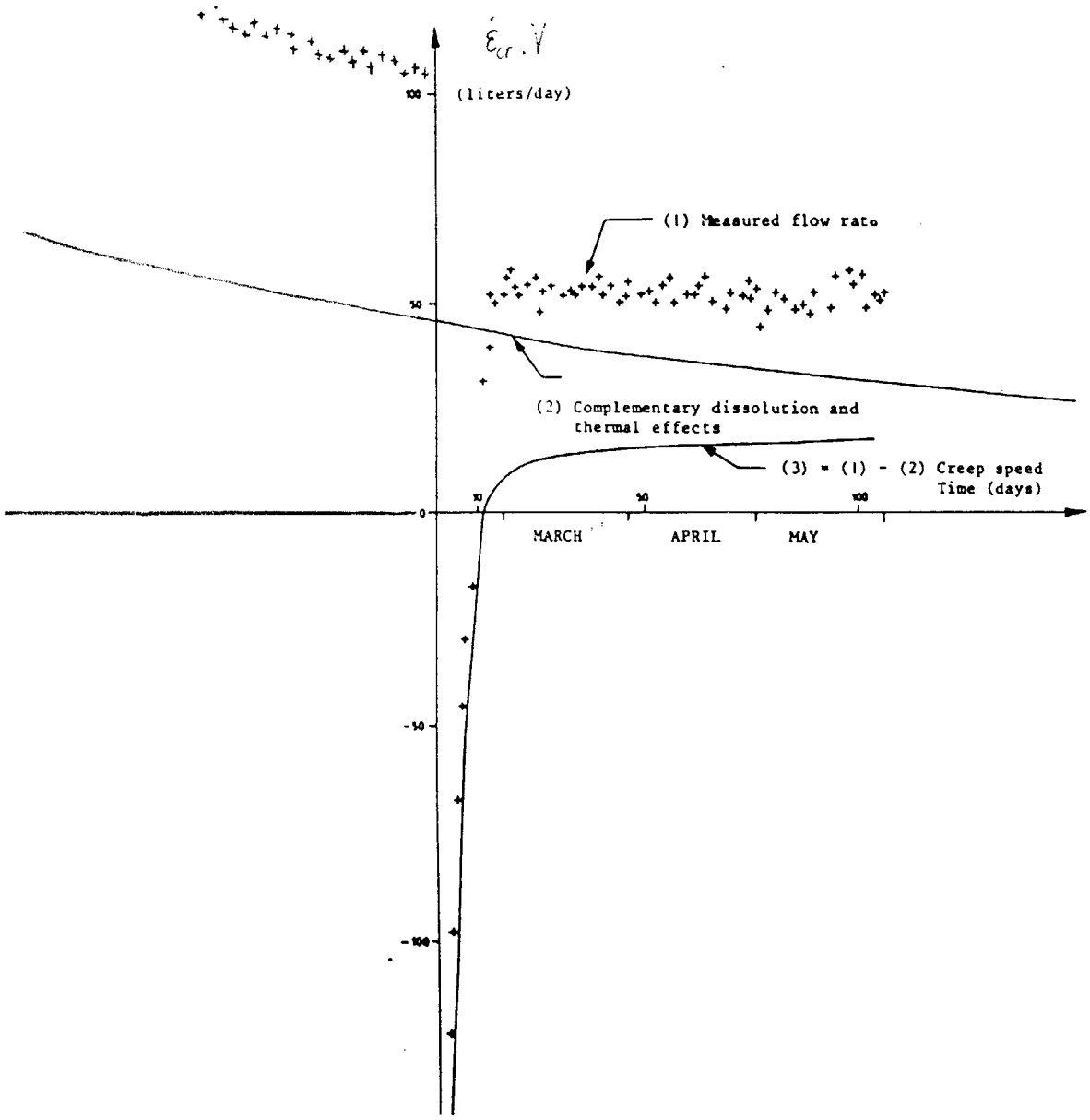

Fig.9 - Creep test on EZ53 (Hugout [1984])

The parameters of the GdF83 law were in that case : $K_{cr}=3.10^{-7}$ $MPa^{-n}.day^{-m+1}$, n=3, m=0.36 (times in days and pressures in MPa).

II.3.5 Interface changes due to creep - general case

As we have seen, the transient creep can be non negligible ; its relative importance depends on the duration factors called T_l (leaching time),T_w (waiting time before the test) and δt (pressurization time). To give an idea of the transient creep rate we could consider that the leaching rate is constant depending on the pump used to draw up brine, for instance Q_{pump}=80 m^3 per hour (500 bbls/hr) ; and for 8 m^3 of brine drawn, 1 m^3 of salt has been leached out, so that the leaching time can be roughly calculated as follows :

$$T_l = 8 .(V/Q_{pump}) \qquad (18)$$

where V is the final cavern volume.
It means that approximately 10 m^3 (63 bbls) of rock salt are leached out per hour.

We have calculated the interface rate $\dot{h}$ due to creep with the parameters :

T_w = 1 day
δt = 1 day
s = 4.15 10^{-2} m^2 (see Thiel [1993])
g = 9.8 $m.s^{-2}$
$\rho_b.g$ = 0.012 MPa/m = 0.530 psi/ft
$\rho_t.g$ = 0.02 Mpa/m = 0.884 psi/ft
$P_{geo} = \rho_{geo}.g$ = 0.022 MPa/m = 0.973 psi/ft
$\beta = 4.10^{-10}$ Pa^{-1} = 2.8 10^{-6} psi^{-1}
$K_{cr} = 3.10^{-7}$ $MPa^{-3}.day^{0.64}$, n = 3 and m=0.36
T_0 = 20 °C (68 °F)

* Fig.10 shows the effect of cavern volume on interface rate due to creep

h = 1000 m (3300 ft) ≈ cavern depth

* Fig.11shows the effect of cavern depth

V = 100,000 m^3 = 630,000 Bbl

These movements take place even if there no leak.

Transient creep after pressurization

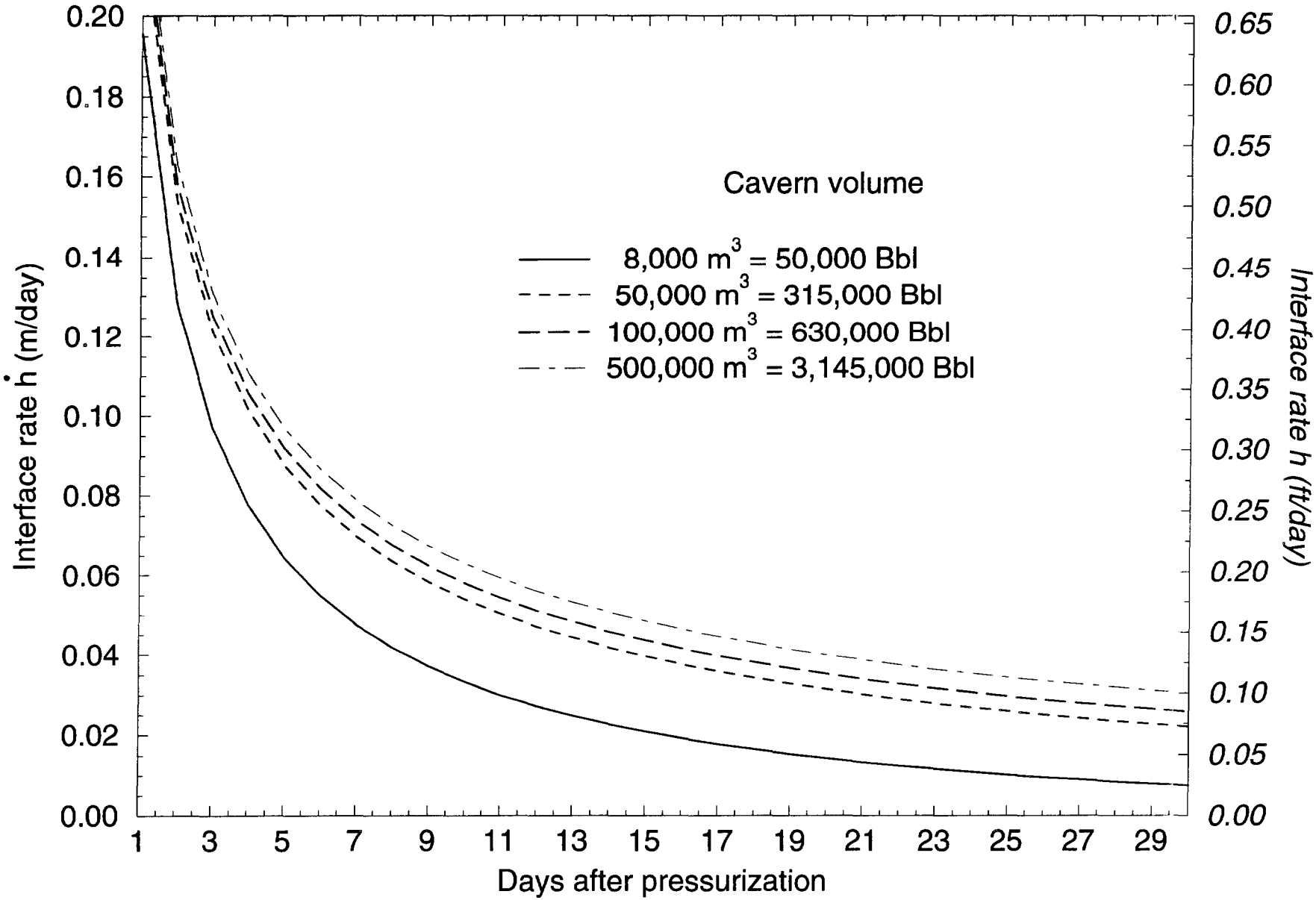

Fig. 10

Transient creep after pressurization

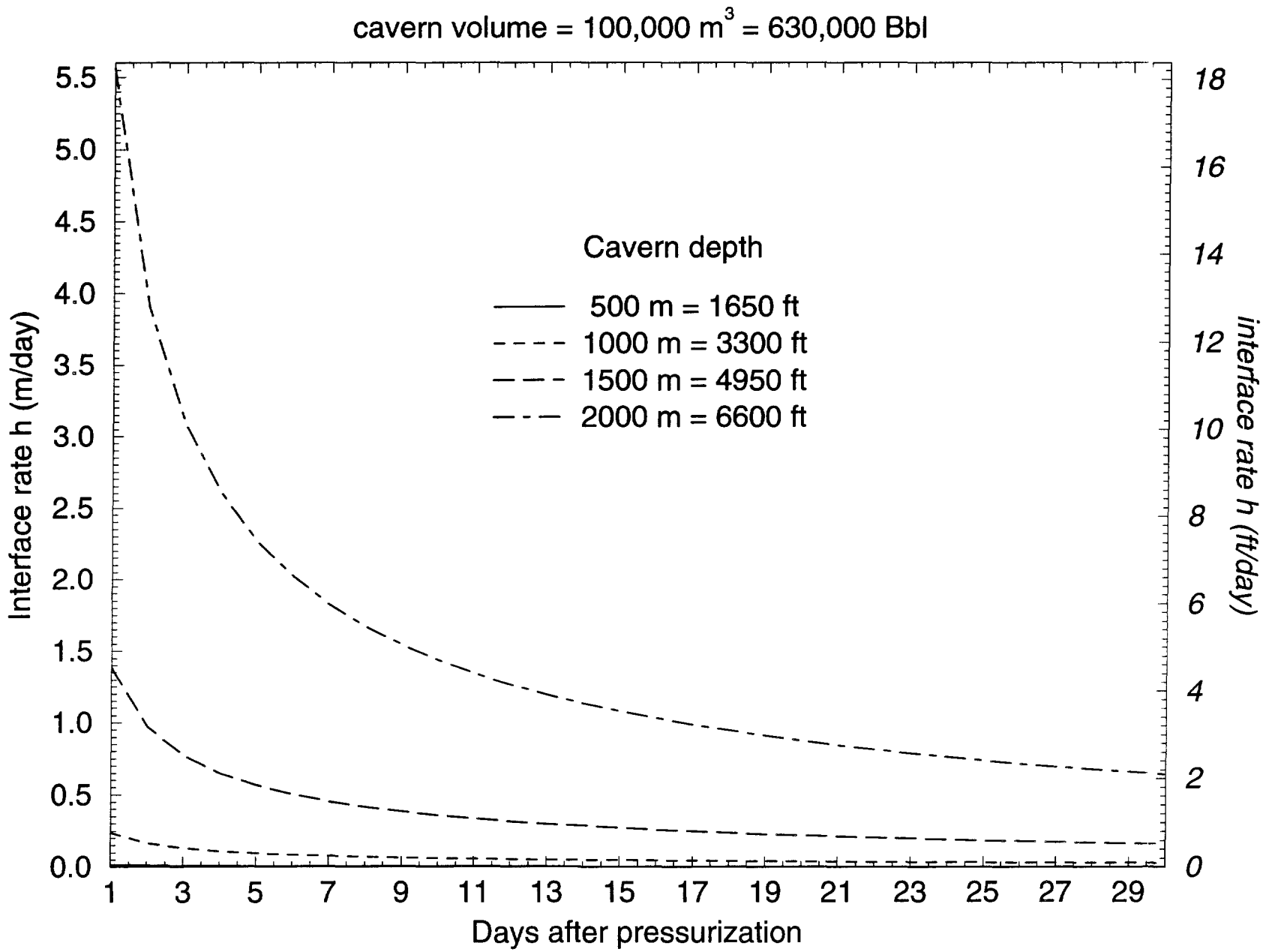

Fig. 11

II.4 Brine percolation

II.4.1 Introduction

According to Darcy's law, the flow of brine crossing the cavern walls is a function of the rock salt permeability and of the difference between brine pore pressure in the rock mass and brine pressure in the cavern. Rock salt is generally considered as an "impermeable" rock.
As a matter of fact, its permeability is very small or extremely small ; $K=10^{-22}$ m^2 (10^{-7} mdarcy) to $K=10^{-19}$ m^2 (10^{-4} mdarcy) is a typical range for intrinsic permeability values as measured in situ. On the other hand, the natural brine pore pressure seems to be quite often very close to the pressure of a brine column, $P_{pore}=\rho_b gh$ where $\rho_b g=0.012$ MPa per m (0.53 psi/ft). One must notice that others figures are sometimes reported (the WIPP site seems to be a good example). The cavern pressure is equal to $\rho_b gh$ too, when opened at ground level : then no brine flows from the cavern to the salt rock mass. During a MIT test, some extra pressure is added at the wellhead, P_b, and then in the cavern, resulting in a flow of brine from the cavern towards the rockmass.
A reasonable test pressure in the case of a gas cavern is $P_t=\rho_t gz$ where $\rho_t g=0.02$ MPa per m (0.884 psi/ft) and then $P_b=(\rho_t-\rho_b)gh$.

II.4.2 Steady-state percolation

In order to estimate the steady-state brine percolation during a MIT test, we will assume that the cavern behaves as a spherical cavity of radius R, such as $V=4\pi R^3/3$ (V is the actual volume of the cavern). This is a gross assumption, which allows for simple calculation and comparison. In the steady-state regime, the relative loss of brine in such a cavern would be :

$$\boxed{\dot{\varepsilon}_{perc}=\left(\frac{Q}{V}\right)_{steady}=\frac{-3K\left(P_t-P_{pore}\right)}{\eta R^2}} \qquad (19)$$

η is the brine kinematic viscosity, whose value at 45°C (113 °F) is 1.2 10^{-3} Pa.s. Viscosity is decreasing with temperature or, in other words, with depth. The variations of viscosity with depth can be roughly approximated as follows :

$$\eta(z)=1.69\ 10^{-3}\ -\ 4.44\ 10^{-7}\cdot z \qquad (20)$$

(z in metre and η in Pa.s)

Let us consider the case of a $V=8000$ m^3 (R=12.5 m or 41 ft) cavern at a depth of 1000 m (like EZ53 mentioned before). If we take into acount a permeability of $K=6.10^{-20}$ m^2 as measured in a near hole called EZ58 (see DURUP [1994]), the brine outflow due to percolation during a MIT test will be :

$$\dot{\varepsilon}_{perc}=9.6\ 10^{-12}\ s^{-1}=8.3\ 10^{-7}\ day^{-1}$$

This is a small value, which would be lower still in a bigger cavern (in a 500,000 m^3 or 3 million bbls cavern the figure would be divised by 16) but would be multiplied by 4 at a depth of 2000 m (6000 ft), which does not significantly alter the previous statement.

II.4.3 Transient percolation

Things are a little bit different if we consider now the transient percolation which follows a rapid change in cavern pressure (such a change takes place at the beginning of a MIT test). For the sake of simplicity, we will assume that the cavity is of spherical shape ; after a (P_t-P_{pore}) change of pressure, the brine flow can be written as a function of time :

$$\boxed{\dot{\varepsilon}_{perc} = \frac{Q}{V} = \left(\frac{Q}{V}\right)_{steady} \cdot \left(1 + \frac{R}{\sqrt{k\pi t}}\right)} \qquad (21)$$

where $k = \frac{K}{\phi\beta\eta}$; ϕ is the rock salt porosity (ϕ=1% is a typical value), β is the sum of rock salt and brine compressibilities (β= 4 10^{-10} Pa^{-1} is typical), η = 1.2 10^{-3} Pa.s (at 1000 m or 3000 ft); then k=1.25 10^{-5} m^2s^{-1} and :

$$\dot{\varepsilon}_{perc} = \frac{Q}{V} = \left(\frac{Q}{V}\right)_{steady} \cdot \left(1 + \frac{R}{\sqrt{3.4j}}\right) \qquad (22)$$

where j is the elapsed time since the pressure build up, in days (R in metres).
For instance in a 270,000 m^3 cavern (R=40m), the transient flow will be 5 times bigger than the steady state flow 30 days after the beginning of the test, and 12 times bigger 4 days after the beginning of the test (periods shorter than one day do not make sense, because a pressure build up is never instantaneous).

For instance if we decide to wait 3 days after the pre-pressurization before monitoring the interface level and pressures at the well head, then the variations of the interface level due to percolation could be as drawn on figure 11. The parameters for this calculation are :

K = 10^{-22} m^2
ϕ = 1%
β = 4.10^{-10} Pa^{-1} = 2.8 10^{-6} psi^{-1}
$\eta(z) = 1.69\ 10^{-3} - 4.44\ 10^{-7} \cdot z$ with z the cavern depth
ρ_t.g = 0.02 Mpa/m = 0.884 psi/ft
s = 4.15 10^{-2} m^2 (see Thiel [1993])

Relative brine loss due to percolation

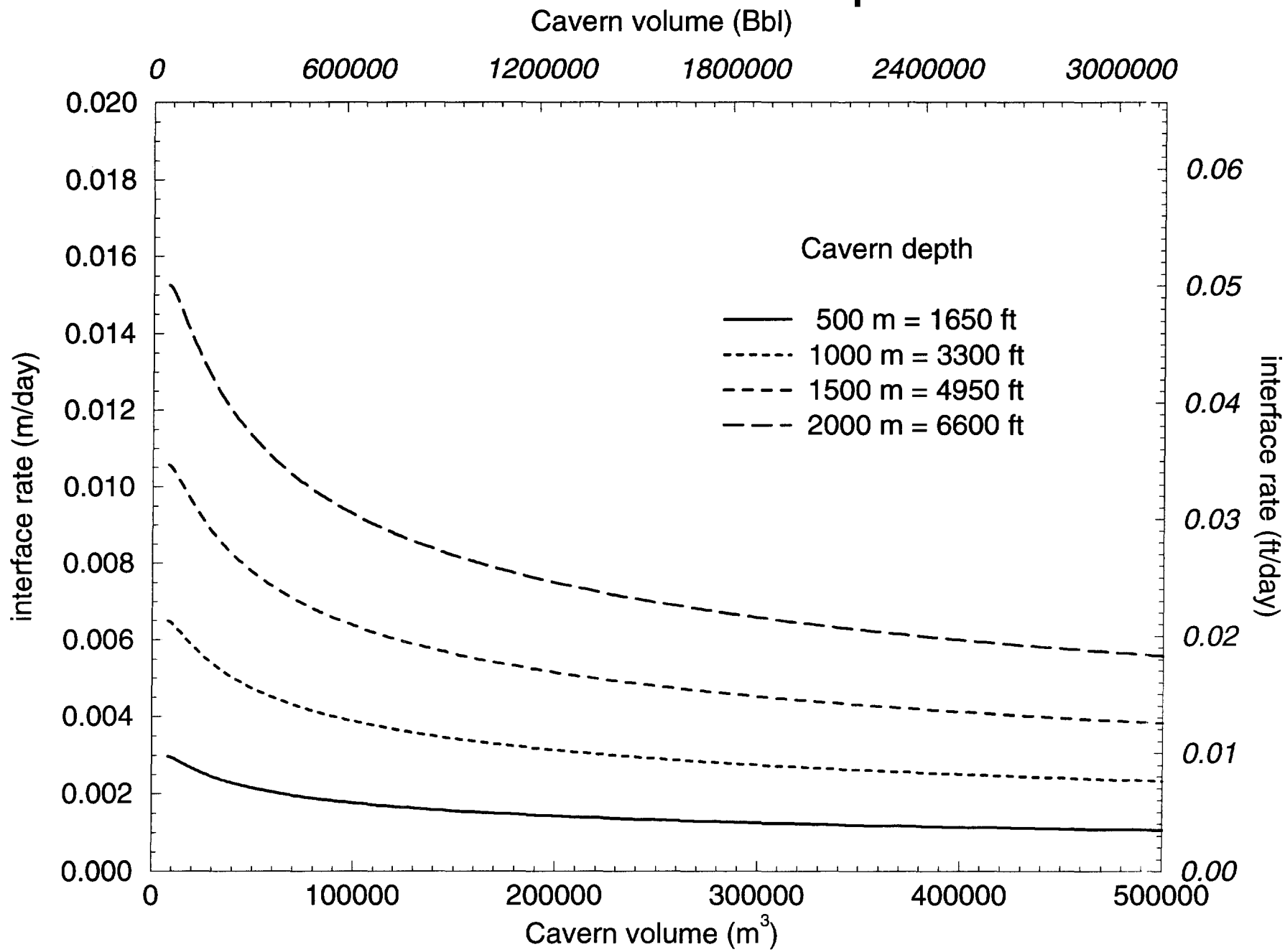

Fig. 12

PART III EXAMPLES OF INTERFACE MOVEMENTS WITHOUT ANY LEAK

The figures 12 and 13 give examples of brine movements without any leak of gas ($\dot{m}$=0).
We take into acount for these calculations the EZ53 cavern configuration (fig.12) and the case of a big and shallow cavern (500,000 m^3 or 3 million bbls, fig.13).
These graphs represent the interface movements when there is <u>no leak</u>.; these movement are issue of both : thermal expansion, transient creep and transient percolation.
The parameters are :

Q_{pump}=80 m^3 per hour (500 bbls/hr)
$T_l = 8 .(V/Q_{pump})$
Tw = 60 days
δt = 1 day
s = 4.15 10^{-2} m^2 (see Thiel [1993])
g = 9.8 $m.s^{-2}$
$\rho_b.g$ = 0.012 MPa/m = 0.530 psi/ft
$\rho_t.g$ = 0.02 Mpa/m = 0.884 psi/ft
$P_{geo} = \rho_{geo}.g$ = 0.022 MPa/m = 0.973 psi/ft
$\beta = 4.10^{-10}$ Pa^{-1} = 2.8 10^{-6} psi^{-1}
$K_{cr} = 3.10^{-7}$ $MPa^{-3}.day^{0.64}$, n = 3 and m=0.36
T_o=20 °C (68 °F)
K = 10^{-22} m^2
ϕ = 1%
$\beta = 4.10^{-10}$ Pa^{-1} = 2.8 10^{-6} psi^{-1}
$\eta(z) = 1.69\ 10^{-3} - 4.44\ 10^{-7} \cdot z$ with z the cavern depth
s = 4.15 10^{-2} m^2 (see Thiel [1993])

For the small cavern (8000 m3=50,000 Bbl) one supposes that the brine temperature in the cavern after leaching is 28 °C (82°F) and 20°C (68°F) for the big and shallow cavern. In the first case the rock mass temperature at 1000 m (3300 ft) deep is about 35°C (95°F) and it is about 45°C (113°F) at 500 m (1150 ft) deep. In the first case, the "gas gradient" is 0.0023 MPa/m and it is 0.001 MPa/m in the second case.

Interface rate

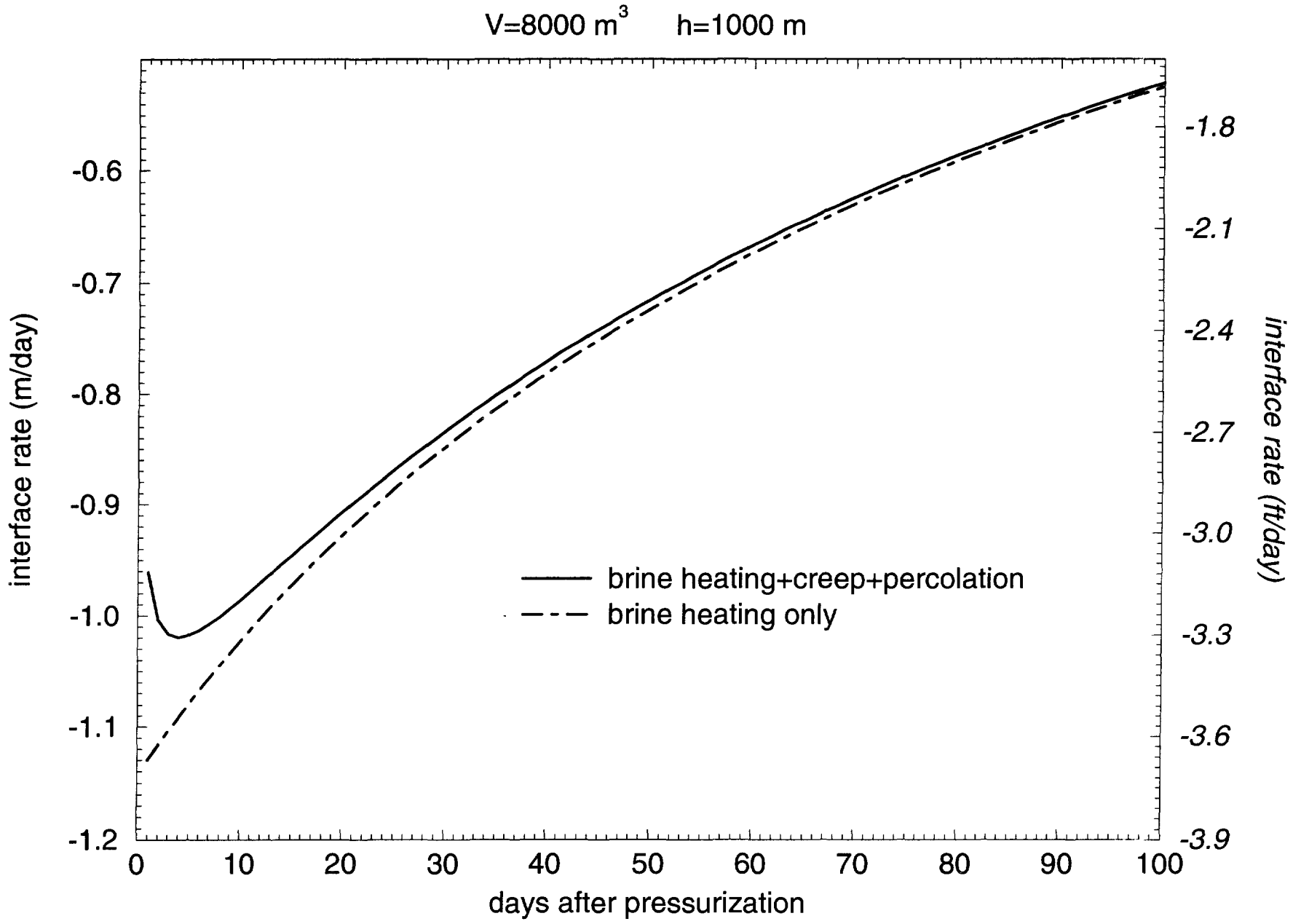

Fig. 13

Interface rate

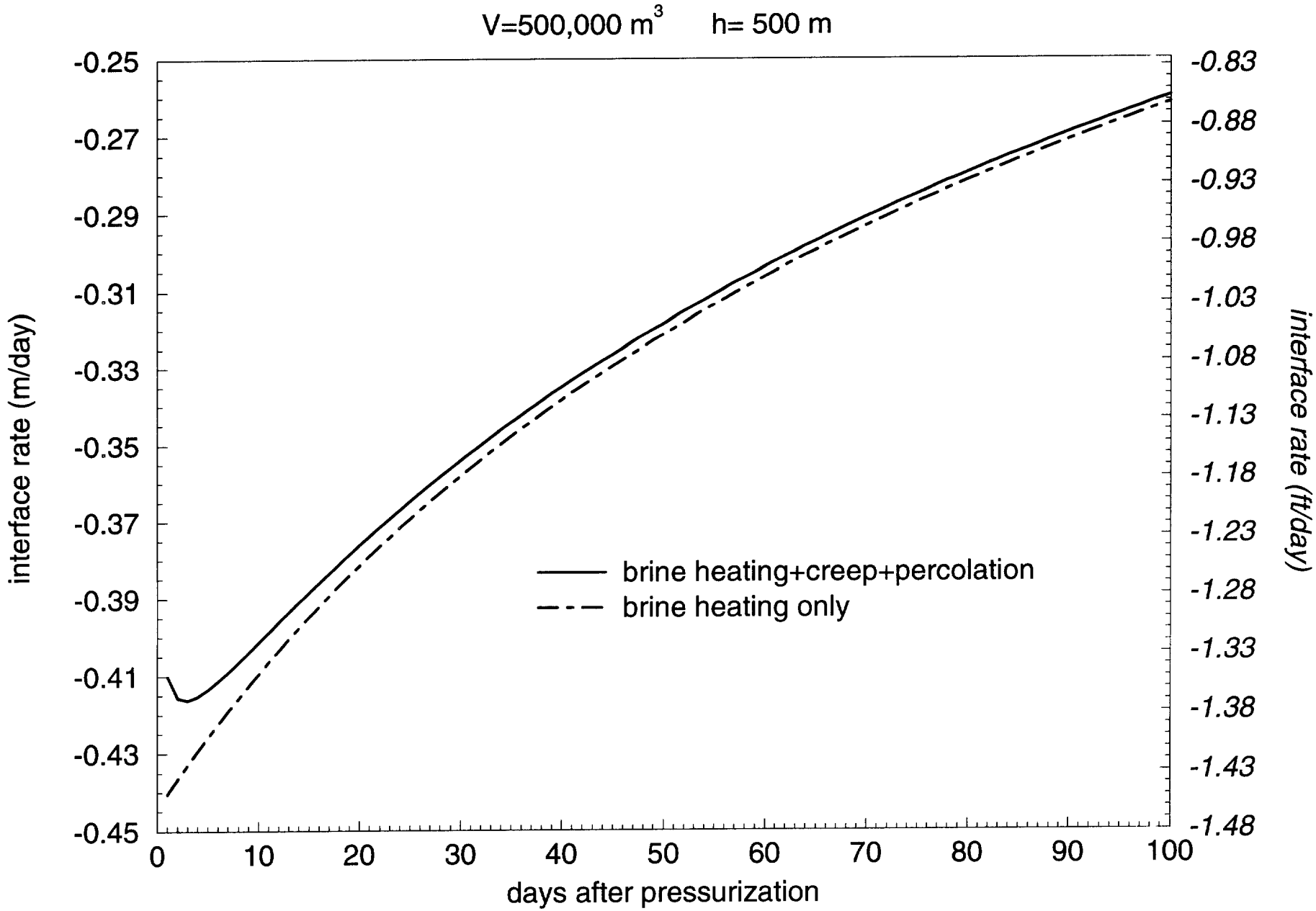

Fig. 14

PART IV SOME RECOMMANDATIONS FOR A BETTER INTERPRETATION OF A NITROGEN LEAK TESTING

IV.1 - Evaluate the thermal expansion rate

Even after stopping soft water injection, the dissolution of salt continues until the cavern brine reaches saturation. This complementary dissolution brings brine level to fall down inside the tubing. This phase lasts a few days (see below, from Hugout [1984]) and is followed by a brine outflow which is mainly due to thermal expansion. It is suggested to wait till the brine flow expelled from the cavern becomes roughly constant and then measure accurately the daily flow rate Q (litres per day). Except if the cavern is very deep (6000' or 2000 metres) this flow is mainly due to thermal expansion ; the expansion rate will be obtained by comparing this flow rate to the cavern volume :

$$\dot{\varepsilon}_{th} = \frac{Q}{V} \qquad (23)$$

IV.2 - Evaluate the cavern compressiblity during the pre-pressurization

The importance of such an evaluation has been clearly pointed out by Thiel [1993] (see below) : during the pressure build up before the gas injection, the injected brine volume is metered and correlated to tubing pressure. The ratio between the two quantities, or βV, is called the cavern (global) compressibility :

$$\Delta V = \beta V \Delta P \qquad (24)$$

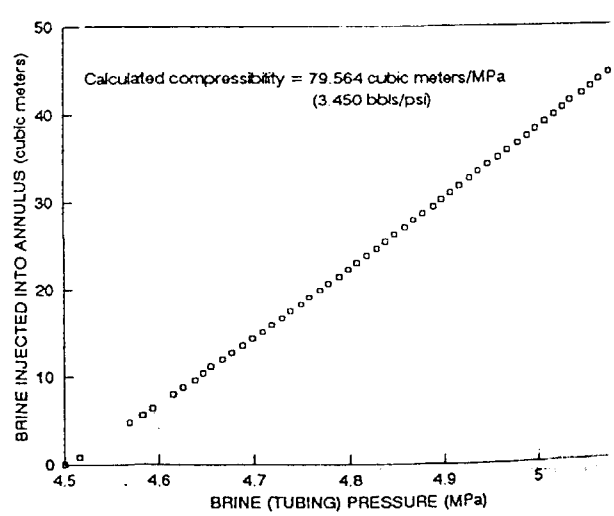

fig.15 - Prepressure data from a domal cavern test (modified from Thiel,1991)

IV.3 - <u>During the nitrogen injection, meter the mass of gas injected into the annular</u>

IV.4 -

When the interface is monitored with a logging equipment, measure the gas pressure (P_g) and brine pressure (P_b) at the interface and :

i- Check that the observed interface depth is not very different from the quantity "h_1" such as :

$$P_b + \rho_b . g \cdot h_1 = P_g \cdot (1 + \alpha \cdot h_1)^{\gamma} \qquad (25)$$

or, more roughly :

$$\boxed{h_1 = \frac{P_g - P_b}{(\rho_b - \rho_g) \cdot g}} \qquad (26) \qquad \text{where } \rho_g = P_g / (rT_0) \qquad (27)$$

ii- Check that if s is the annular cross section, the observed interface depth is not very different from "h_2" such as :

$$\boxed{h_2 = (\beta V) \cdot (P_b - P_p) / s} \qquad (28)$$

where Pp is the pre-pressure.

iii- Check that the observed interface depth is not very different from "h_3" such as

$$\boxed{h_3 = \frac{mg + (P_b - P_g)s}{g\rho_b}} \qquad (29)$$

IV.5 -

When some interface movement has been detected by a logging measurement, for instance Δh (an upward movement is negative), the volume of lost gas can be estimated to be equal to :

$$\boxed{\frac{\Delta m}{\rho} = -s \cdot C \cdot \Delta h} \qquad (30)$$

as indicated in part I.6 : ρ is the gas density at the interface level (not very different from ρ_g), C is a constant and Δm is mass of lost gas as measured. This estimation disregards any factor influencing the interface level except leak.

IV.6 -

If other factors -notably thermal expansion- presumably affect the interface level, then a thoroughfully measure of the brine pressure and gas pressure variations at the well head $\Delta P_b, \Delta P_g$ allow to estimate the "real" loss of gas :

$$\boxed{\Delta m = \frac{s\rho_g}{g(\rho_b - \rho_g)} \cdot \left[\Delta P_g - \Delta P_b + \frac{h\rho_b g \Delta P_g}{P_g} \right]} \qquad (31)$$

In order to check this result, in the case when thermal expansion appears to be the main parasite factor, then the quantity

$$\boxed{\Delta\varepsilon = \frac{\beta\rho_t}{(\rho_b - \rho_g)} \cdot \left[(1 - C) \cdot (\Delta P_g - \Delta P_b) + \frac{h(\rho_b - C\rho_g) g \Delta P_g}{P_g} \right]} \qquad (32)$$

must be equal to $\alpha.\Delta T$, where ΔT is the average temperature change in the cavern during the test, as extrapolated from the measurements above in IV1.

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