WHY MIT INTERPRETATIONS CAN BE WRONG:
APPARENT AND ACTUAL LEAKS

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ABSTRACT

This paper concerns MITs performed using a test fluid (nitrogen or liquid hydrocarbon). During such tests, the fluid/brine interface location is tracked with a logging tool and/or by recording wellhead pressures at ground level. They can be performed before or immediately after cavern creation and during cavern operation. MIT tests also can be performed in a borehole (before cavern creation). It is proven that too simple an interpretation of MIT tests may be wrong. Basic equations governing cavern behavior during an MIT are discussed, and the limits of the different MIT techniques are assessed.

ACKNOWLEDGEMENT

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INTRODUCTION

Tightness is a fundamental prerequisite for the underground storage of oil and gas. However, the aim of tightness has no absolute nature, but, rather, depends upon the stored products, the specific sensitivity of the environment and the economic context.

The economic context depends basically on the speed of the stock rotation and the nature of the products stored. For example, when storing compressed air to absorb daily excess electric power, a loss of 1% per day can be considered reasonable. When storing oil for strategic reasons (e.g., oil that will be used only during a crisis), a loss of 1% per year is a maximum value. Air or natural gas is not poisonous from the perspective of underground-water protection: the leakage of sufficiently diluted natural gas into underground water has minor consequences for water quality. This would not apply to other products, such as crude oil. From the viewpoint of ground-surface protection, the most significance risk is the accumulation of flammable gas near the surface. In this situation, gases that are heavier than air (propane, ethylene, propylene) are more dangerous than natural gas.

Underground storage is by far the safest way to store large amounts of hydrocarbons (Evans, 2008). However, accidents sometimes do occur (Bérest et al., 2003). Various steps can be taken to prevent such accidents, among which tightness tests. This paper is dedicated to some theoretical aspects of tightness tests in salt caverns.

In the case of salt caverns, the salt formation itself can be considered to be practically impermeable; salt permeability belongs to the range $K = 10^{-22}$ to 10^{-19} m^2. These figures are extremely low. (However, during tightness tests, transient permeation following a rapid pressure build-up in the cavern must be taken into account when precise interpretation of the test is required). In fact, in much the same way as for all pressure vessels, it is the "piping" that is the real problem — i.e., the cemented borehole through which the hydrocarbons flow to and from the cavern.

Cementing in gas and oil wells is a "rough and ready" operation; underground-storage engineers work under a higher standard than is typical in ordinary oil-industry operations (use of admixtures, re-cementing, leak tests). Various logs allow the cement-steel or cement-rock quality bonding to be assessed (ATG Manual, 1985; Jordan, 1987; Kelly and Fleniken, 1999).

The architecture of the well (number and length of steel casings) must include leakage prevention as a major objective. In particular, it is better that the last two cemented casings be anchored in the salt formation or in an overlaying impermeable formation. As Thoms and Kiddoo (1998) state, *"Once in the porous sand formations, the [leaking] gas can readily migrate (…) This has happened in US Gulf Coast wells (…). Thus two casing strings are now "cemented" into the salt"*.

In addition, well testing ("Mechanical Integrity Tests", or MITs) is mandatory in most countries — every five years in Texas and Louisiana.

1. DIFFERENT TYPES OF MITs IN A BRINE-FILLED CAVERN

1.1. MIT Types in Full-Size Caverns

In general, testing a pressure vessel involves increasing the pressure in the vessel above the maximum operating pressure and detecting leaks through records of pressure evolution. A slightly different test procedure is possible in deep salt caverns. The cavern-plus-well system is similar to the ball-plus-tube system used in a standard barometer or thermometer. Compared to a huge cavern, the well appears as a very thin capillary tube, and tracking movements of a fluid-fluid interface in the well allows highly sensitive records of tube fluid-volume changes. Several current types of the MIT are described below (Figure 1).

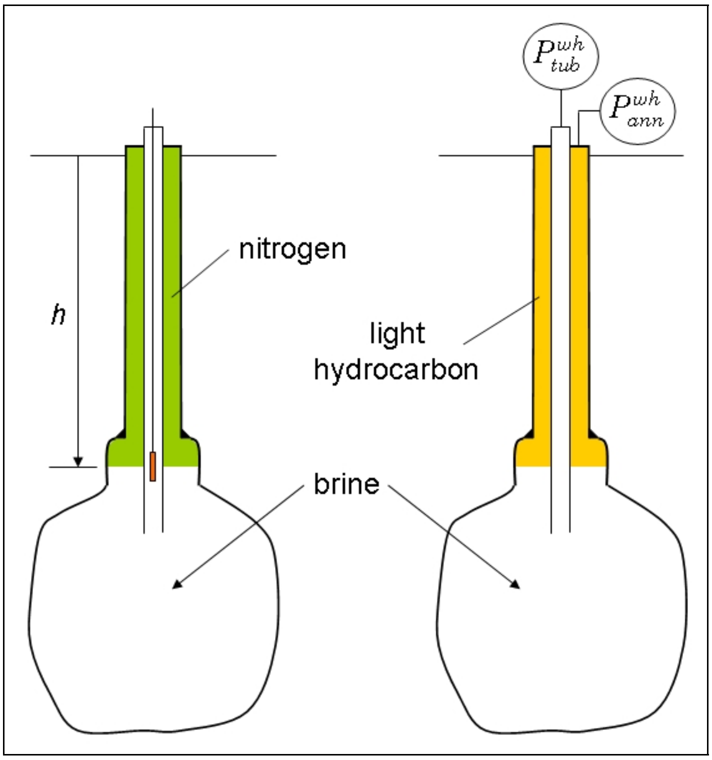


Figure 1. The Nitrogen Leak Test (NLT) and Liquid-Liquid Interface Test (LLI): In the former, the nitrogen/brine interface is tracked through a logging tool. In the latter, tubing (P_{tub}^{wh}) and annular (P_{ann}^{wh}) pressures are recorded continuously at the wellhead during the test.

- ***The Nitrogen Leak Test*** **(*NLT*)** consists of injecting nitrogen into the annular space formed by the last casing and the central string to develop a nitrogen/liquid interface in the cavern neck, below the last cemented casing. The central string and the cavern remain filled with brine, and a logging tool is used to measure the brine/nitrogen interface location. Two or three measurements, generally separated by 24 hours, are performed. Upward movement of the interface is deemed to indicate a nitrogen leak. Pressures are measured at ground level, and temperature logs are recorded to allow precise back-calculation of nitrogen seepage.

- ***The Liquid-Liquid Interface Test (LLI)*** consists of injecting a liquid hydrocarbon (instead of nitrogen, as for the NLT) into the annular space. During the test, attention is paid to the evolution of the brine and hydrocarbon pressures as measured at the wellhead. A severe pressure-drop rate is a clear sign of poor tightness. In addition, the hydrocarbon can be withdrawn at the end of the test and weighed, allowing comparison with the weight of the injected hydrocarbon volume.

Note that testing a well with no interface between the cavern brine and a fluid provides poor results. (The actual leak cannot be distinguished easily from other factors contributing to wellhead pressure evolution.)

1.2. MIT Types in a Borehole

Various tightness tests can be performed in a borehole (ATG, 1985; Kunstman et al., 2007; Bérest, 2007), including NLT and LLI tests.

2. WHAT CAN BE MEASURED DURING AN MIT

2.1. Quantities To Be Assessed

The aim of any MIT is to assess the actual leak rate — i.e., the amount of nitrogen or liquid hydrocarbon that leaks from the annular space, or Q_{act} (in m^3/day, or bbls/day), see Figure 2. Q_{act} is always positive.

The "other factors" also are of interest. The "other factors" generate a change in brine volume and/or cavern volume. They may lead to an underestimation or an overestimation of the actual leak. In a cavern, the "other factors" include cavern creep closure, brine thermal expansion, brine permeation through the cavern walls, additional dissolution, etc. They are discussed in more details in Section 3.3. In a borehole, the dominant "other factor" is brine permeation through the borehole walls, which is related closely to the permeability of the salt formation. The effect of the other factors is Q (in m^3/day, or bbls/day), see Figure 2. Q is negative when the test-triggered effects are pre-eminent and positive when the pre-existing factors are pre-eminent. In the special case of a borehole, $Q \approx -Q_{perm}$ and Q_{perm} (the brine-flow rate toward the rock mass) is positive.

Also of interest is the "interface" flow rate, or $Q_{\text{int}} = -\Sigma\dot{h}$, (in m^3/day, or bbls/day), see Figure 2; it is the rate of interface rise or drop, or $\dot{h}$, in m/s or ft/s (It is positive when the interface drops.) multiplied by the cross-sectional area of the cavern neck at interface depth, or Σ (in m^2 or ft^2).

2.2. Quantities That Can Be Measured During an MIT

The following three quantities can be measured during an MIT.

- The central-tubing pressure drop rate, or $\dot{P}_{tub}^{wh}$ (in MPa/day, or psi/day) — In most cases, the central tubing is filled with saturated brine.
- The annular-space pressure drop rate, or $\dot{P}_{ann}^{wh}$ (in MPa/day, or psi/day) — In most cases, the annular space is filled with nitrogen (during an NLT) or a light liquid hydrocarbon (during an LLI).

- The brine/nitrogen (in an NLT) or the brine/hydrocarbon (in a LLI) displacement rate, or $\dot{h}$ (in m/day, or ft/day) — $\dot{h}$ is negative when the interface rises.

Note that pressure rates are low in a large cavern, making uncertainties troublesome. It is important to set the brine/fluid interface at such a depth that the cross-sectional area is consistent (i.e., Σ is known and does not vary rapidly with depth).

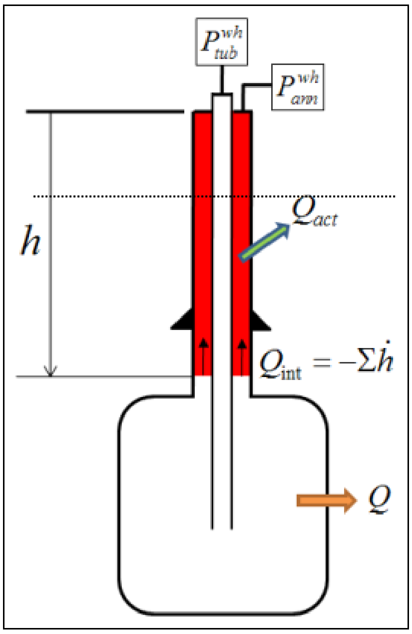


Figure 2. Main quantities to be assessed or measured.

2.3. Quantities That Must Be Measured Before an MIT

2.3.1. Cavern Compressibility Measurement

Cavern compressibility must be measured before an MIT.

When a certain volume of liquid, Δv_{inj}, is injected into (or withdrawn from) a closed cavern, the wellhead pressure increases (or decreases) by ΔP. An example of such a cavern compressibility measurement is given in Figure 3. The slope of the curve (injected brine volume versus wellhead pressure) is called the cavern compressibility (in m^3/MPa or bbls/psi):

$$\Delta v_{inj} / \Delta P = \beta V_c \qquad (1)$$

Cavern compressibility results from the elastic properties of both the stored products and the "box" (i.e., the cavern) in which the products are stored.

2.3.2. Compressibility of a Brine-Filled Cavern

Cavern compressibility, or βV_c, can be expressed as the product of the cavern volume, V_c (which also is the brine volume, $V_c = V_b$, when no hydrocarbon is stored), and a compressibility coefficient, β. This compressibility coefficient does not depend upon the size of the cavern. A typical value is $\beta = 4 - 5 \times 10^{-4}$/MPa, or 3×10^{-6} / psi. In a brine-filled cavern, the compressibility coefficient, $\beta = \beta_c + \beta_b$, is the sum of the compressibility coefficient of brine ($\beta_b = 2.7 \times 10^{-4}$/MPa) and the compressibility coefficient of the cavern alone, or β_c. This cavern compressibility coefficient depends on cavern shape and the elastic properties of the rock mass. A typical value is $\beta_c = 1.3 \times 10^{-4}$/MPa — more in a "flat" cavern.

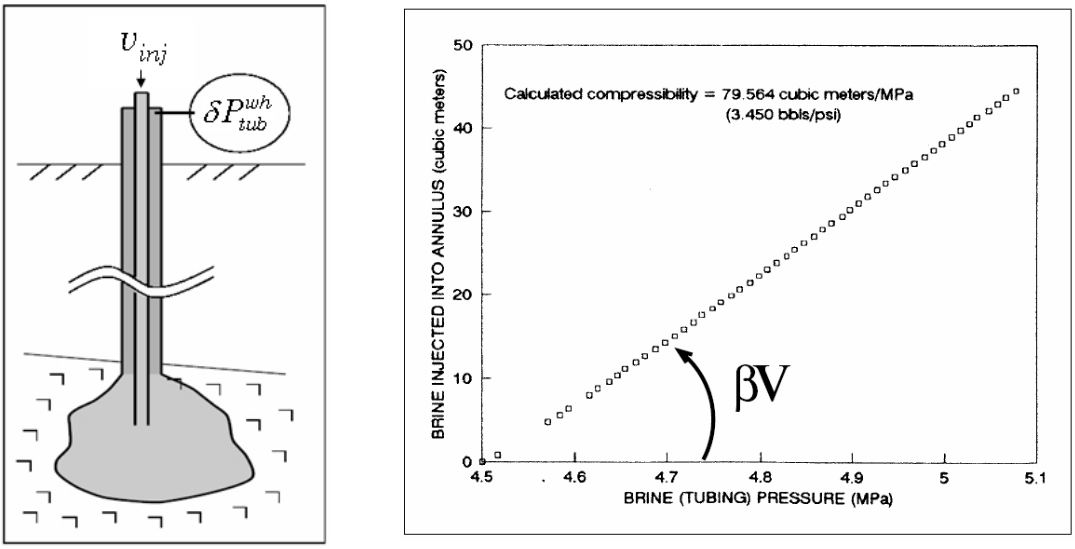


Figure 3. Cavern compressibility is the slope of the curve of the injected liquid-vs-wellhead pressure increase.

2.3.3. Compressibility of a Cavern Containing Several Liquids

Cavern compressibility is modified when liquids (oil, LPG, etc.) are injected into a cavern. In general, hydrocarbons are much more compressible than brine, and the overall compressibility of a storage cavern is larger than the compressibility of a brine-filled cavern. For example, let V_b and V_o be the brine and oil volumes, respectively; the cavern volume is $V_c = V_o + V_b$, and the oil compressibility coefficient is β_o. The overall compressibility of the cavern is the sum of the compressibility of oil volume, brine volume and cavern:

$$\beta V_c = \beta_c V_c + \beta_b V_b + \beta_o V_o \tag{2}$$

2.3.4. Adiabatic versus Isotropic Gas-Compressibility Coefficient

When the cavern contains gas, the overall compressibility is the sum of the compressibility of gas volume, brine volume and cavern:

$$\beta V_c = \beta_c V_c + \beta_b V_b + \beta_g V_g \tag{3}$$

The gas compressibility coefficient is larger than any liquid compressibility coefficient by several orders of magnitude. In fact, the compressibility coefficient of a gas in a cavern depends on how quickly the gas is injected (or withdrawn). When the pressure change is very rapid, the process is said to be *adiabatic*, as no heat is exchanged between the gas and the rock mass (or the brine beneath the gas). The (adiabatic) gas compressibility coefficient is

$$\beta_g^{ad} = \bar{\gamma}/P \tag{4}$$

where P is the gas pressure, and $\bar{\gamma}$ is a constant that depends on the considered gas. For instance, in the case of nitrogen, $\bar{\gamma}$ = 1.4, and, when the gas pressure is P = 20 MPa, β_g^{ad} = 0.07/MPa.

However, when the pressure change is slow, the process is said to be *isothermal*: heat is allowed sufficient time to be transferred from the rock mass to the gas, and the gas temperature remains approximately constant. In such a case, the gas compressibility coefficient is

$$\beta_g^{iso} = 1/P \tag{5}$$

For example, when P = 20 MPa, β_g^{iso} = 0.05/MPa.

These figures, however, are indicative rather than exact. Exact values for any gas (or gas mixture) can be found in specialized handbooks or calculated.

What "slow" and "rapid" mean exactly depends on the size of the gas body. When the gas is contained in a borehole, whose radius may be a few decimeters, the pressure change is "slow" when its duration is longer than a few dozen minutes. When the gas is contained in a cavern, whose radius may be several dozens of meters, the pressure change is "slow" when its duration is longer than several days or weeks. During standard NLTs, the gas volume in the annular space is relatively small; in the following, the gas compressibility coefficient is the isothermal coefficient $\beta_g = 1/P$.

2.3.5. Compressibility of a Gas-Filled Cavern

The compressibility of a gas-filled cavern is very high. For this reason, it is practically impossible to assess gas-cavern tightness through monitoring of the wellhead pressure. Consider a 160,000-m^3 (1,000,000 bbls) cavern filled with gas of average pressure P = 20 MPa (2800 psi). Assume that the leak rate is $Q_{act} = 1000$ bbls/yr. Because the gas compressibility coefficient is close to $\beta_g = 1/P = 0.05$ /MPa (0.00057/psi), the leak rate, $Q_{leak} = 1000$ bbls/yr (160 m^3/year), generates a pressure drop rate of $\dot{P}_g = Q_{leak}/\beta_g V_c = 0.02$ MPa/yr (2.8 psi/year), which is impossible to detect in field conditions.

2.3.6. *Cavern Compressibility During a Nitrogen Leak Test*

The compressibility of a cavern during a Nitrogen Leak Test is not modified significantly, because the volume of gas injected into the cavern to perform the test is generally small. The cavern compressibility can be written as

$$\beta V_c = \beta_c V_c + \beta_b V_b + \beta_g V_g \tag{6}$$

Consider the case of a cavern with volume $V_c = 100{,}000$ m^3. The volume of injected gas typically is $V_g = 40$ m^3, making $V_b = V_c - V_g$ close to 100,000 m^3. When the testing pressure at well mid-depth is P_t = 20 MPa, $\beta_g = 0.05$ /MPa and $\beta_g V_g = 2$ m^3/MPa. Typically, $\beta_c + \beta_b = 4 \times 10^{-4}$ /MPa, making cavern compressibility, or $\beta_c V_c + \beta_b V_b = 40$ m^3/MPa, much larger than $\beta_g V_g$: gas is much more compressible than brine, but a gas volume of $V_g = 40$ m^3 is much stiffer than a brine volume of $V_b = 100{,}000$ m^3. This has important consequences when interpreting an NLT

3. THE APPARENT LEAK AND WHY IT CAN BE WRONG

3.1. Apparent Leak

Testing the tightness of an underground storage facility involves recording the decrease of well-head pressure and/or tracking a fluid/fluid interface in the well. The pressure decrease rate, or the interface velocity, must be converted into a "fluid leak rate" through appropriate calculations to obtain the "apparent" leak.

3.1.1. Apparent Leak During a Liquid-Liquid Interface (LLI) Test

During a Liquid-Liquid Interface Test, the apparent leak is

$$Q_{app} = -\beta V_c \dot{P}_{tub}^{wh}$$

where $\dot{P}_{tub}^{wh}$ (in most cases, $\dot{P}_{tub}^{wh} < 0$) is the decrease rate of the wellhead pressure as measured in the tubing, and βV_c is the cavern compressibility. In fact, this definition is unclear, as the pressure decrease rates measured in the annular space and in the central tube generally are not identical (see figure 4, Thiel and Russel, 2004).

3.1.2. Apparent Leak During a Nitrogen Leak Test (NLT)

During a Nitrogen Leak Test, the apparent leak rate is

$$Q_{app} = -\Sigma \dot{h} = Q_{\text{int}} \tag{7}$$

where Σ is the cross-sectional area of the annular space (at interface depth), $\dot{h}$ [in m/day, or ft/day] (In most cases , $\dot{h} < 0$, and the interface rises) is the interface displacement rate. For this reason, an NLT only can be performed effectively when the cavern neck is consistent — i.e., when Σ is known clearly.

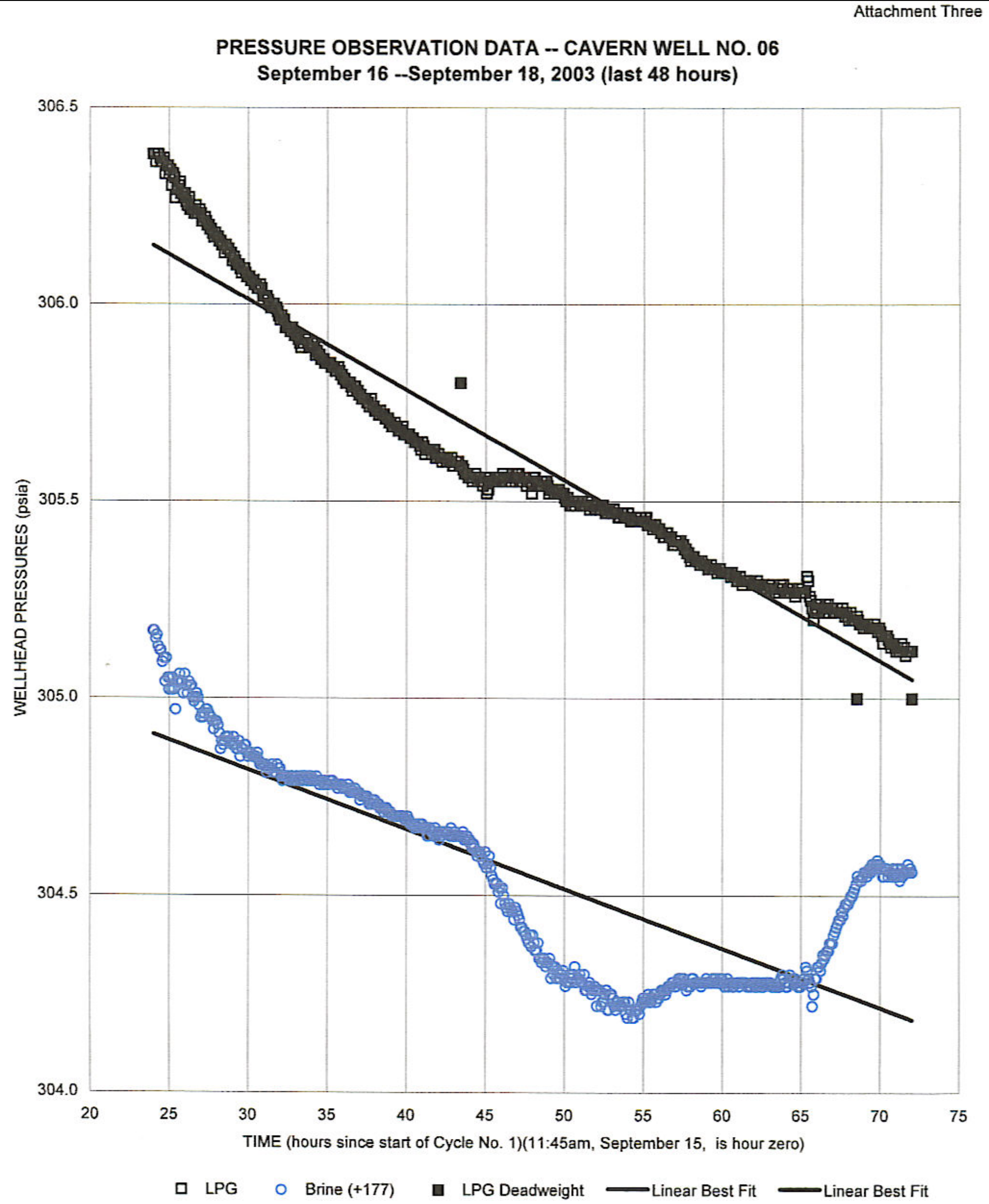
This leak is said to be "apparent" because the actual leak is

$$Q_{act} = Q_{\text{int}} - \beta_g V_g \dot{P}_{ann}^{wh} \tag{8}$$

3.2. Why an Apparent Leak Rate can be (Quite) different from the Actual Leak Rate?

An example of why an apparent leak rate can under- or over-estimate the actual leak rate is provided in Figures 5 and 6. An SMRI-supported test was performed on the SPR2 cavern, which is located at the Carresse storage site operated by Total in southeastern France (Brouard et al., 2006). The central string and the annular space are filled with brine; cavern compressibility is $\beta V_c = 3.97 \ \text{m}^3/\text{MPa}$. There is no interface, and $\dot{P}_{tub}^{wh} = \dot{P}_{ann}^{wh} = \beta V_c \left(Q - Q_{act}\right)$. On September 15, 2005, pressure was increased rapidly by 6.5 MPa. From September16, 0h00, to September 18, 12h00, the average pressure-drop rate was $\dot{P}^{wh} = -19 \ \text{kPa/day}$. (See the straight line on Figure 5.) An apparent leak rate of $Q_{app} = -\beta V_c \dot{P}^{wh} = 0.075 \ \text{m}^3/\text{day}$ could be inferred from the measurements.

In fact, two months later, it was observed (Figure 6) that the cavern pressure increased again (due to the effect of cavern brine warming), proving that (a) the initial pressure-drop rate was transient; and (b) no, or only minute, leaks existed in this cavern. The 0.075-m^3/day apparent leak was caused mainly by transient effects other than the actual leak.



NOTES:

1. Using a linear curve fitting program to analyze the product pressure for the last 48 hours, $\Delta P/\Delta T$ = -.02294 psi/hour; R^2=.9383.
For $\Delta V/\Delta P$ = 1.29 bbls./psi (see Attachment One), $\Delta V/\Delta T$ = -260 bbls./year.

2. Based on brine pressure, $\Delta V/\Delta T$ = -170 bbls./year.

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Figure 4. Wellhead pressure evolution (annular space: LPG; central tubing: brine) during an LLI (Thiel and Russel, 2004).

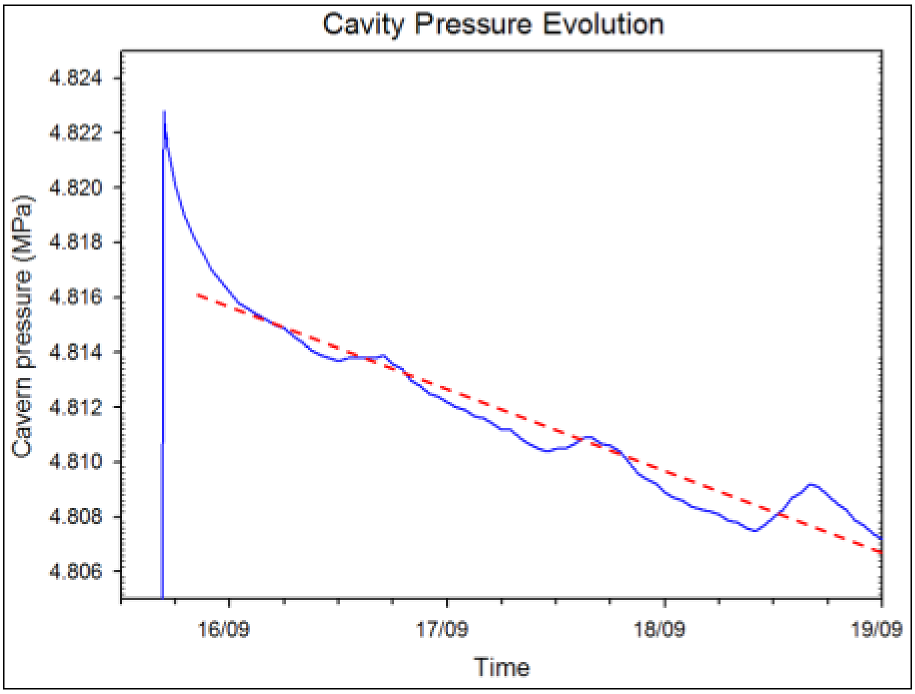

Figure 5. Wellhead pressure as a function of time. (The test lasted 3 days. The red line represents the average pressure evolution from September 16, 0h00, to September 18, 12h00.)

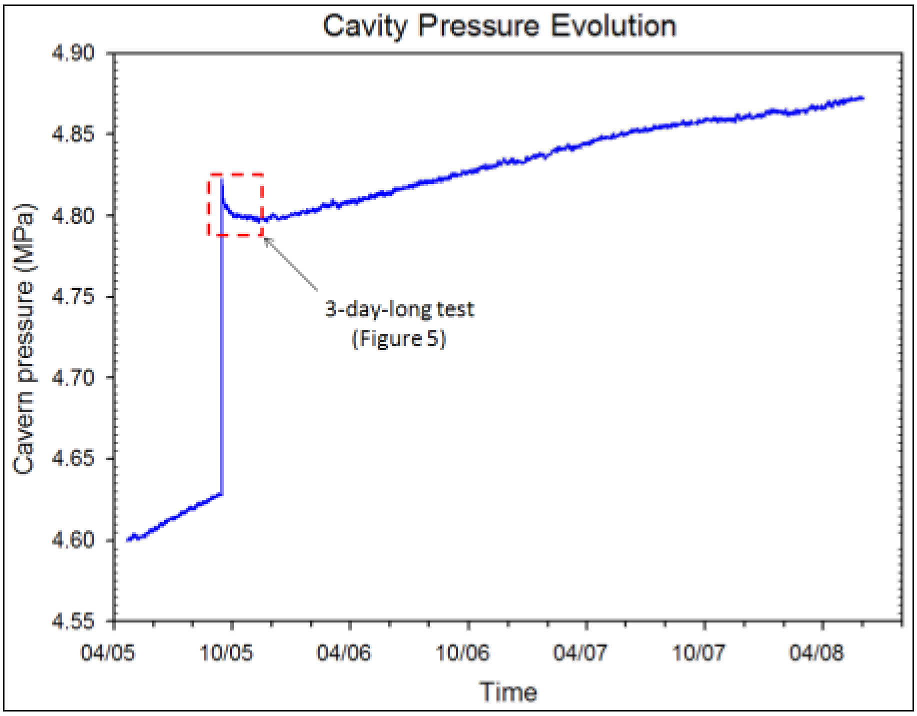

Figure 6. Same test as in Figure 5 but with pressure evolution recorded during more than one year after the test began.

3.3. Actual and Apparent Leaks

During an MIT, two types of factors may influence cavern pressure evolution or interface displacement: : (1) the actual leak rate; and (2) what we call, here, “other factors”.

- The actual leak rate, or Q_{act} (in m^3/day, or bbl/day) — The actual leak is through the last cemented casing or through the casing shoe; it is of primary interest when interpreting an MIT.

- Other factors — The other factors are those that affect cavern brine volume and/or cavern volume during the test. Some of these factors pre-exist the test; they include cavern creep closure and brine thermal expansion. In general, these pre-existing factors make the apparent leak smaller than the actual leak. (The apparent leak underestimates the actual leak.) Conversely, some of these factors are triggered by the test itself — i.e., the pressure increase applied at the beginning of the test to reach the testing pressure. These factors include additional dissolution, transient brine permeation through the rock mass, adiabatic brine heating at the beginning of the test, and transient creep. [A detailed description of these effects is given in an SMRI-sponsored report by Van Sambeek et al. (2005.)] In general, these factors make the apparent leak larger than the actual leak. (The apparent leak overestimates the actual leak.) The sum of the effects of all these factors is Q (in m^3/day). Q is negative when the test-triggered effects are pre-eminent and positive when the pre-existing factors are pre-eminent. Q may be quite large. Consider, for instance, a freshly washed out cavern. Its volume is $V_c = 100{,}000 \text{ m}^3$; due to the difference between rock temperature and brine temperature, the cavern brines warms at a rate of 3°C/year. The “pre-existing” effect is

  $$Q = \alpha_c V_c \dot{T} = 4.4 \times 10^{-4} \text{ /°C} \times 100{,}000 \text{ m}^3 \times 3\text{°C/yr} = 132 \text{ m}^3/\text{yr}.$$

  “Reverse” creep ($Q < 0$) triggered by the pressure increase applied to reach the testing pressure also may be fast, especially in a large and old cavern (Karimi-Jafari et al., 2005).

Consider the Carresse Test mentioned above (Section 3.2). During the first days after the initial pressure build-up, test-triggered effects clearly are dominant ($Q < 0$), and the pressure drop rate is negative. The actual rate (Q_{act}) is smaller than the apparent leak. After a couple of months, the transient effects have had enough time to dissipate, and the pre-existing effects (cavern brine warming) are dominant ($Q > 0$): the wellhead pressure increases, and the apparent leak is negative!

It is impossible to separate the other effects from the actual leak (hence, to assess the actual leak alone) when the two columns in the well have the same density.

3.4. The Size of Apparent Leaks

Fail/pass criteria for standard Nitrogen MITs (in a full-size cavern) have been proposed by several authors. Thiel (1993) suggests 1000 bbls/year (440 liters/day), whereas Crotogino (1996), who performed a study sponsored by the SMRI, suggests 270 m^3/year (750 liters/day) as the Maximum Admissible Leak Rate during a Nitrogen MIT. (Crotogino also suggests that test resolution, or the Minimum Detectable Leak Rate, is one-third of the actual leak). These figures are relatively high, and the actual leak often is smaller. (To account for such figures, the permeability of the cemented annular space between the rock mass and the last steel casing must be assumed to be (unrealistically) high.)

In fact, as suggested by the example provided above (Section 4.2), it may be better to specify, for example, that the apparent leak is 1000 bbls/year *at the end a 3-day-long test*. In most cases, the as-observed leak rate decreases with time (see Figure 4, 5 and 11), proving that the initial "apparent" figures are transient and that they overestimate the actual leak. (Outstanding exceptions are deep caverns, where creep closure is fast, and freshly washed-out caverns, where brine warming is active. In such caverns, the apparent leak rate may underestimate the actual leak rate.) In most other cases, the actual leak is likely to be much smaller than the apparent leak.

4. A THEORETICAL ANALYSIS OF MITs

During an MIT test, the cavern behaves as an elastic system. The actual leak rate, the interface rate and the rate of the "other factors" are linked to wellhead pressure rates by the "stiffness" of the cavern, of the annular space and of the interface, which are defined below.

4.1. Fluid/Brine Interface (Interface Stiffness)

A brine/fluid interface was developed in the annular space (Figure 8). The fluid (gas, or liquid hydrocarbon) is less dense than brine. Fluid and brine pressure gradient are γ_f and γ_b, respectively (pressure gradient, in MPa/m or psi/ft, equals fluid density (in kg/m^3) multiplied by gravity acceleration ($g = 9.8\ \mathrm{m}^2/\mathrm{s}$); $\gamma_b = 0.012\mathrm{MPa/m}$. Let A and B be two fixed points above and below the interface, respectively. Pressures are such that $P_B - P_A = \gamma_f h_A + \gamma_B h_B$. When the interface drops down by Δh, $P_B' - P_A' = \gamma_f\left(h_A + \Delta h\right) + \gamma_b\left(h_B - \Delta h\right) = P_B + P_A - \Delta h\left(\gamma_b - \gamma_f\right)$ or $\Delta P_B - \Delta P_A = \left(\gamma_b - \gamma_f\right)\Delta h$. It is convenient to consider the volume swept by the interface: $\dot{P}_B - \dot{P}_A = -\left(\gamma_b - \gamma_f\right)\dot{h} = \left(\gamma_b - \gamma_f\right)Q_{\mathrm{int}}/\Sigma$ where $Q_{\mathrm{int}} = -\Sigma\dot{h}$ is the "interface volumetric rate" and $\Sigma/\left(\gamma_b - \gamma_f\right)$ is the "interface compressibility".

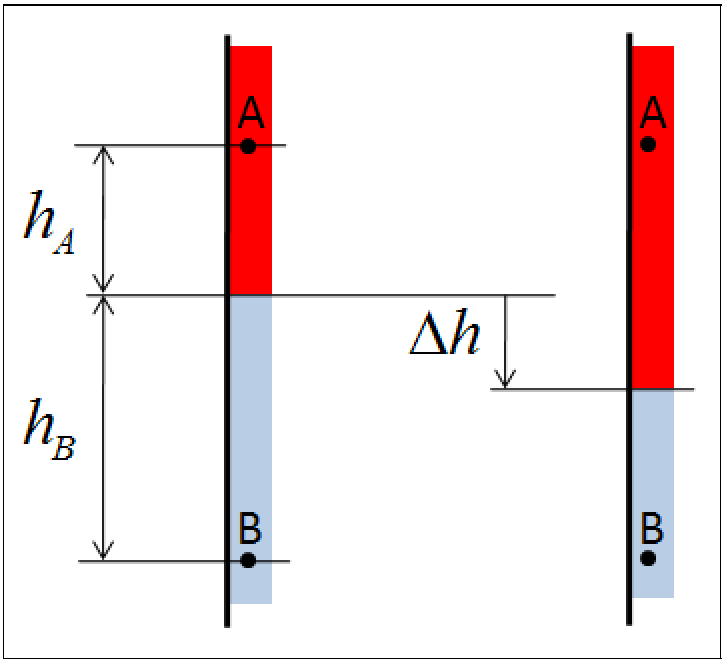

Figure 8. Effect of Interface Displacement on Pressures.

Consider, now, the changes in wellhead pressures (Figure 8). Let P_{ann}^{wh} and P_{tub}^{wh} be the fluid and brine wellhead pressures, respectively. At interface depth, fluid pressure and brine pressure are equal: $P_{ann}^{wh} + \gamma_f h = P_{tub}^{wh} + \gamma_b h$ (Brine below the interface is assumed to be homogeneous.) and $\dot{P}_{ann}^{wh} + \gamma_f \dot{h} + \dot{\gamma}_f h = \dot{P}_{tub}^{wh} + \gamma_b \dot{h}$.

When the "fluid" is very compressible (gas, $f = g$), changes in pressure gradient must be taken into account, $\dot{\gamma}_g = -\gamma_g \beta_g \dot{P}^{wh}_{ann}$, where β_g is the gas compressibility coefficient at mid-depth or

$$\left(1-\delta\right)\dot{P}^{wh}_{ann} = \dot{P}^{wh}_{tub} + \left(\gamma_b - \gamma_g\right)\dot{h} \tag{9}$$

where $\delta = \beta_g \gamma_g h$.

When the "fluid" is stiff (liquid hydrocarbon, $f = l$), it can be assumed that $\dot{\gamma}_l \approx 0$ (Liquid density changes are negligible in this context.), and the same formula holds; however, $\delta = 0$.

$$\dot{P}^{wh}_{ann} = \dot{P}^{wh}_{tub} + \left(\gamma_b - \gamma_l\right)\dot{h} \tag{10}$$

4.2 Cavern Stiffness

Consider, for instance, a cavern in which a fluid (lighter than brine) was injected in the annular space, developing a fluid/brine interface at depth h (see Figure 9; for simplicity, the annular space was not drawn). The annular cross-sectional area at interface depth is Σ. An interface displacement by Δh generates a cavern brine pressure increase of: $\Sigma \Delta h = -Q_{\text{int}} \Delta t = \beta V_c \Delta P$. If, in addition to interface displacement, brine thermal expansion ($Q > 0$), brine permeation ($Q < 0$) or, more generally, an "other factor" (see Section 3.3) takes place at a rate Q, the cavern pressure change rate is such that

$$-Q_{\text{int}} + Q = \beta V_c \dot{P}^{wh}_{tub} \tag{11}$$

where $\dot{P}^{wh}_{tub}$ is the cavern pressure increase (or decrease) rate, as measured at the wellhead in the central tube (not shown on Figure 9.)

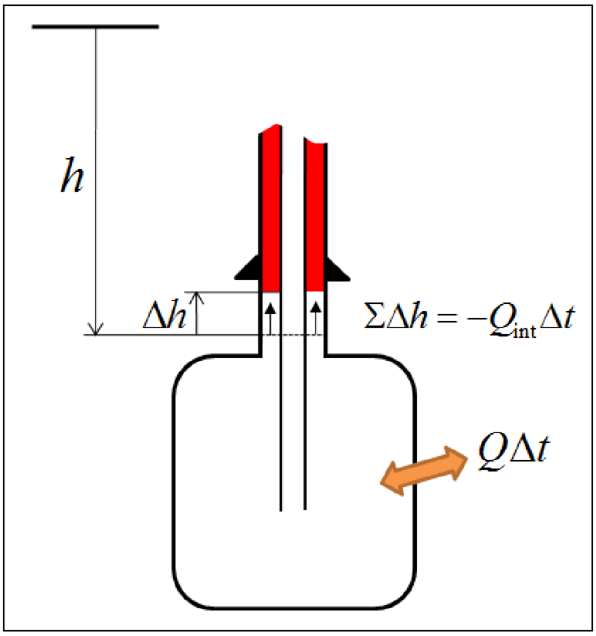

Figure 9. Effect of an interface drop and brine warming.

4.3. Annular Space Stiffness

Consider, first, a gas-filled annular space (Figure 10). The gas volume is V_g, and the gas/brine interface depth is h. The annular cross-sectional area at interface depth is Σ. A change in the interface depth by

Δh generates a $\Sigma\Delta h = -Q_{\text{int}}$ change in gas volume and a $\Delta P_g = -\Sigma\Delta h / \beta_g V_g = Q_{\text{int}} / \beta_g V_g$ change in gas pressure. However, neither gas pressure, P_g, nor the gas compressibility coefficient, $\beta_g = 1/P_g^{av}$, is constant along the well. A step-by-step computation must be made. However, as a first approximation, gas pressure at the centre of gravity of the gas body — or at cavern mid-depth — can be selected, $\beta_g = 1/P_g^{av}$. Note that if, in addition to the interface displacement, some gas leak occurs at a rate of Q_{act}, the pressure change rate will be such that

$$\beta_f V_f \dot{P}_{ann}^{wh} = -Q_{act} + Q_{\text{int}} \tag{12}$$

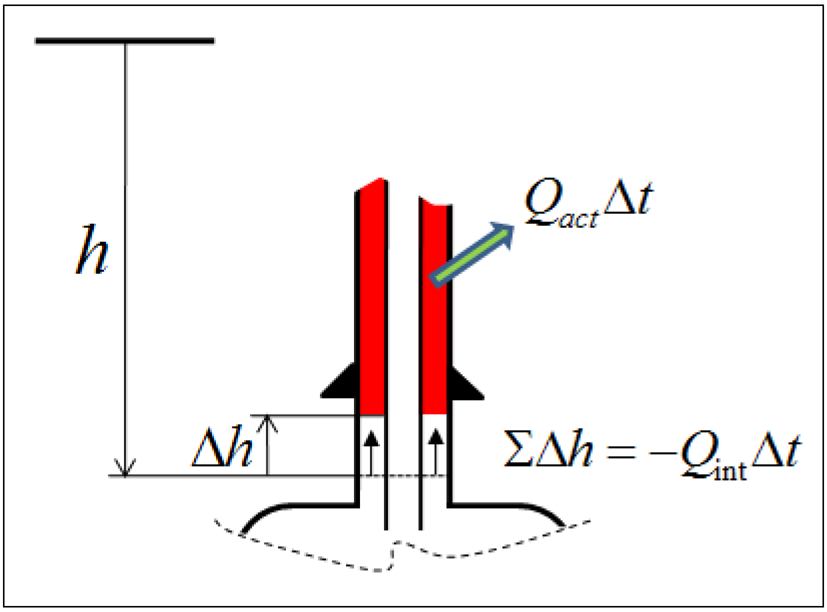

Figure 10 Compressibility of a Gas-Filled Annular Space.

When the annular space is filled with a liquid hydrocarbon, the liquid compressibility coefficient, β_l, can be considered as constant, and

$$\beta_f V_f \dot{P}_{ann}^{wh} = -Q_{act} + Q_{\text{int}} \tag{13}$$

5. COMPARISON BETWEEN NLT AND LLI IN FULL-SIZE CAVERNS AND BOREHOLES

5.1. Behavior of a Cavern during an MIT

The behavior of a cavern (or a borehole) during an MIT is governed by three equations, as proved in Section 4:

$$\begin{cases} (1-\delta)\dot{P}_{ann}^{wh} = \dot{P}_{tub}^{wh} - (\gamma_b - \gamma_f) Q_{\text{int}} / \Sigma \\ -Q_{\text{int}} + Q = \beta V_c \dot{P}_{tub}^{wh} \\ \beta_f V_f \dot{P}_{ann}^{wh} = -Q_{act} + Q_{\text{int}} \end{cases} \tag{14}$$

When the test fluid is a gas, $\delta = \gamma_g \beta_g h$. When the test fluid is a liquid hydrocarbon, $\delta = 0$. The “interface compressibility”, or $\Sigma / (\gamma_b - \gamma_f)$, varies from 0.01 m^3/MPa (small cavern neck) to 1 m^3/MPa (large cavern neck). The “brine volume” compressibility, or βV_c, varies from 0.01 m^3/MPa (borehole, no cavern) to 400 m^3/MPa (very large cavern). The value of the compressibility of the gas volume, or $\beta_g V_g = \beta_f V_f$, is several m^3/MPa; the value of the compressibility of the liquid volume, or $\beta_l V_l = \beta_f V_f$, is several hundredths of m^3/MPa. In other words, the relative significance of the various terms strongly depends on test conditions.

The actual leak rate (Q_{act}) in an NLT must be smaller than 1000 bbls/yr (160 m^3/yr) — in fact, it often is much smaller. The actual leak in an LLI is much smaller still, as hydrocarbon liquids are more viscous than gas by two orders of magnitudes. The "other factors" may generate large flow rates (Q) — for instance, in a large and freshly washed-out cavern, it is several m^3/day.

From these figures, it easily is inferred that pressure rates and interface rise rates differ widely from one test to another.

5.2. Interpretation of an NLT in a Cavern

The following three methods of interpretation can be adopted.

1. The equation inferred from gas mass conservation, or

$$Q_{act} = Q_{\text{int}} - \beta_g V_g \dot{P}_{ann}^{wh} \qquad Q_{\text{int}} = -\Sigma \dot{h} \tag{15}$$

provides a robust and exact basis for gas-leak rate assessment. This method is described by Crotogino (2007): interface displacement, Δh, and gas pressure change, ΔP_g, during a Δt period of time are measured accurately through various logging tools (Temperature logs also are performed to check that temperature remained constant during the test.), allowing computation of $\dot{P}_{ann}^{wh} = \Delta P_g / \Delta t$ and $\dot{h} = \Delta h / \Delta t$.

However, resolution (or the Minimum Detectable Leak Rate, Crotogino 1996) often is not excellent: $\delta h = 6$ inches, or 15 cm, is a typical logging tool accuracy, and the minimum detectable leak rate observed in a test lasting 2 days, ($T = 2$), is $2\Sigma\, \delta h / T = 150$ liters/day when $\Sigma = 1$ m^2.

2. A simplified formulation often is adopted:

$$Q_{act} \approx Q_{\text{int}} \qquad Q_{\text{int}} = -\Sigma \dot{h} \tag{16}$$

This approximation is correct (i.e., $\beta_g V_g \dot{P}_{ann}^{wh}$ can be disregarded) only when the cavern is large (say, $V_c > 50{,}000$ m^3), the cross-sectional area at interface depth is large (say, $\Sigma > 1$ m^2) and the other factors (brine warming, creep closure etc.) are of the same order of magnitude as the actual leak. The reason is that the cavern and the interface are very compressible when compared to the gas volume: the gas/brine interface location is very sensitive to gas leaks. When both the cavern and the cavern neck are large, the "standard" interpretation of the NLT is correct: the gas leak rate approximately equals the cavern cross-sectional area, or Σ, multiplied by the interface rise rate, **or** $\dot{h}$**.** This is a considerable asset of the Nitrogen Leak Test (in a large cavern): even relatively large "other factors" are not able to change test results significantly.

However , this may be incorrect. The exact relation between the actual leak, the interface rise rate and the "other factors" can be written as

$$\frac{Q}{\beta V_c} + \frac{(1-\delta)Q_{act}}{\beta_f V_f} = Q_{\text{int}}\left(\frac{1}{\beta V_c} + \frac{1-\delta}{\beta_f V_f} + \frac{\gamma_b - \gamma_f}{\Sigma}\right) \tag{17}$$

In addition, when the "other factors" have a dramatic effect (say, when cavern creep or brine thermal expansion are extremely fast), they can hide the actual leak.

3. The actual leak and the effect of the other factors also can be inferred from the comparison of the decrease rates in the gas and brine pressures measured at ground level:

$$Q_{act}\left(\gamma_b - \gamma_f\right)/\Sigma = \dot{P}_{tub}^{wh} - \left[1 - \delta + \left(\gamma_b - \gamma_f\right)\beta_f V_f/\Sigma\right]\dot{P}_{ann}^{wh} \tag{18}$$

However, in a very large cavern, those pressure rates often are low. Wellhead pressures can be measured accurately; however, during any MIT, daily fluctuations in the wellhead pressure-vs-time curve are observed (see Figure 11), whatever the fluids contained in the well are (gas, brine, LPG, oil). The amplitude of these fluctuations typically is from 1 to 10 kPa (0.015 to 0.15 psi). They make accurate assessment of the pressure-drop rates difficult. These fluctuations result from changes in ground-level temperatures (and, to a smaller extent, Earth tides and atmospheric pressure variations).

Note that this method (based on wellhead pressure evolutions) can be applied *in addition* to the first method; it provides a second, independent assessment of the actual leak.

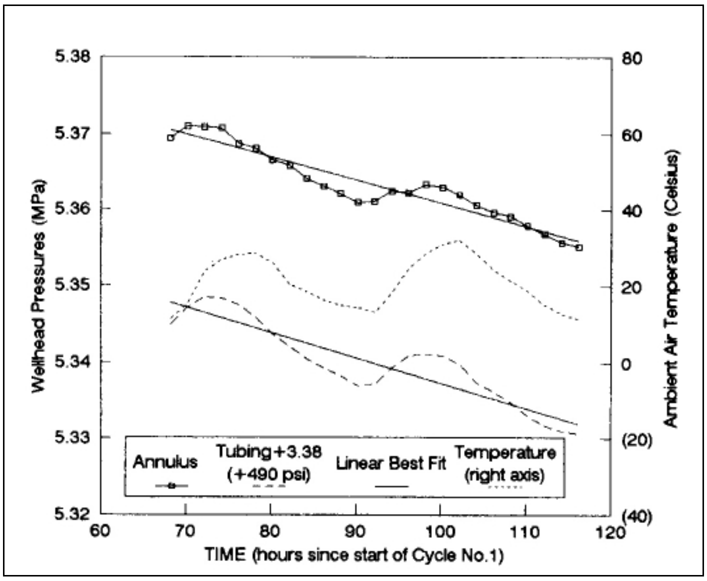

Figure 11 – The annulus is filled with nitrogen; the tubing is filled with brine. Daily pressure variations clearly are correlated with temperature variations (after Thiel, 1993).

5.3. Interpretation of an NLT in a Borehole

Consider, now, the case of an NLT in a borehole (with no cavern). The relative significance of the various terms changes drastically. In a borehole, the brine volume stiffness, or $1/\beta V_c$, is much larger than the gas volume stiffness, or $1/\beta_g V_g$, (because brine volume is small), and interface stiffness, or $\left(\gamma_b - \gamma_g\right)/\Sigma$, also is much larger than in a full-size cavern (because the cross-sectional area at interface depth is smaller). A gas leak generates no, or small, interface displacement. The nitrogen/brine interface displacement rate is almost exactly proportional to the effect of the other effects (typically, brine micropermeation through the open-hole part of the borehole); **measuring the interface displacement provides no, or little, information on the actual (gas) leak.**

Comparison between the evolution rates of the tubing pressure and the annular space allows the actual leak to be computed:

$$Q_{act}\left(\gamma_b-\gamma_f\right)/\Sigma=\dot{P}_{tub}^{wh}-\left[1-\delta+\beta_f V_f\left(\gamma_b-\gamma_f\right)/\Sigma\right]\dot{P}_{ann}^{wh} \tag{19}$$

$$\frac{\left(\gamma_b-\gamma_f\right)}{\Sigma}Q=\left(1+\frac{\gamma_b-\gamma_f}{\Sigma}\beta V_c\right)\dot{P}_{tub}^{wh}-\left(1-\delta\right)\dot{P}_{ann}^{wh} \tag{20}$$

However, both pressure rates are small (when compared to an LLI in a borehole, as gas is much less stiff than liquid hydrocarbon):

$$Q\left(\frac{1-\delta}{\beta_f V_f}+\frac{\gamma_b-\gamma_f}{\Sigma}\right)-Q_{act}\left(\frac{1-\delta}{\beta_f V_f}\right)=\beta V_c\dot{P}_{tub}^{wh}\left(\frac{1}{\beta V_c}+\frac{1-\delta}{\beta_f V_f}+\frac{\gamma_b-\gamma_f}{\Sigma}\right) \tag{21}$$

$$Q-\left(1+\frac{\gamma_b-\gamma_f}{\Sigma}\beta V_c\right)Q_{act}=\beta_f V_f\dot{P}_{ann}^{wh}\left(1+\left(1-\delta\right)\frac{\beta V_c}{\beta_f V_f}+\frac{\left(\gamma_b-\gamma_f\right)\beta V_c}{\Sigma}\right) \tag{22}$$

5.4. Interpretation of an LLI in a Cavern

In the case of an LLI, in principle, measuring interface displacement should give good results; however, a liquid hydrocarbon is more viscous than nitrogen, and liquid leaks are smaller than gas leaks, resulting in slow interface displacement.

Even if small, leaks generate relatively large pressure changes — at least in a small cavern, whose compressibility is low; the actual leak can be inferred from wellhead measurements, provided that the cross-sectional area of the cavern neck is consistent and well known. This method often is used when the wellhead is not able to withstand the relatively high gas pressure implied by an NLT.

5.5. Interpretation of an LLI in a Borehole

In a borehole, brine volume compressibility and hydrocarbon volume compressibility have the same order of magnitude, and the interface cross-sectional area is small. The hydrocarbon/brine interface is influenced both by the actual leak and the "other factors". However, interface displacements are exceedingly small, especially when the effects of the brine permeation partly neutralize the effects of the hydrocarbon leak. In such a case, wellhead brine pressure and wellhead hydrocarbon pressure follow almost parallel evolutions, and it is difficult to infer the value of the actual leak from their comparison (uncertainties are too high). However, when the well is tight (The pressure evolution rates in the annular space and in the tubing then are exactly parallel.), the LLI allows accurate assessment of the "other factors" — i.e., salt permeability.

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