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Research Project Report 2005-1

IMPROVEMENTS IN MECHANICAL INTEGRITY TESTS FOR SOLUTION-MINED CAVERNS USED FOR MINERAL PRODUCTION OR LIQUID-PRODUCT STORAGE

prepared by

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EXECUTIVE SUMMARY

E.1 INTRODUCTION

Underground caverns in salt can be used to provide chemical plants with brine (mineral production) or for storage of hydrocarbons (both gaseous and liquid), compressed air, and waste products. For almost all applications, tightness of the cavern and external well components is a fundamental requirement. Tightness ensures that a leak does not cause contamination of drinking water resources or allow the uncontrolled escape of storage products to the surface.

Almost all solution-mining wells and storage caverns in rock salt are tested on a regular basis to prove their mechanical integrity, typically upon commissioning and then again every 5 years. Although technologies for Mechanical Integrity Tests (MITs) for caverns filled with a liquid are reasonably well advanced and established, potential improvements in the MIT technology were investigated by reviewing aspects of MIT methods and protocols, test results interpretation, and formulation of cavern tightness conclusions.

E.2 CURRENT INDUSTRY-STANDARD MECHANICAL INTEGRITY TESTS

Basically, two MIT methods are currently used, the Nitrogen Interface Test (NIT) and the Liquid-Liquid Interface (LLI) tests such as Pressure Observation Tests (POT) or Pressure Difference Observation Tests (PDO), as depicted in Figure 1. In both cases, the cavern is emptied of product before the test (wellhead pressure is removed) and the well is equipped with a central tubing or string.

The Nitrogen Interface Test (NIT) consists of injecting nitrogen to form a gas column in the annular space to below the last cemented casing. The central string remains 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; an upward movement of the interface is deemed to indicate a nitrogen leak. Pressures are measured at ground level, and temperature logs are performed to allow precise calculation of nitrogen leakage.

The Liquid-Liquid Interface (LLI) tests consist of injecting liquid hydrocarbon (instead of nitrogen, as for the NIT) to form a column in the annular space. During the test, the evolution of the brine and hydrocarbon pressures are measured at the wellhead. A significant pressure drop is a clear sign of poor tightness–particularly when the pressure decay is linear with no indication of stabilizing of a slower decay. Changes in the difference in pressure between the annulus and tubing can also be used to monitor movement of the liquid-liquid interface.

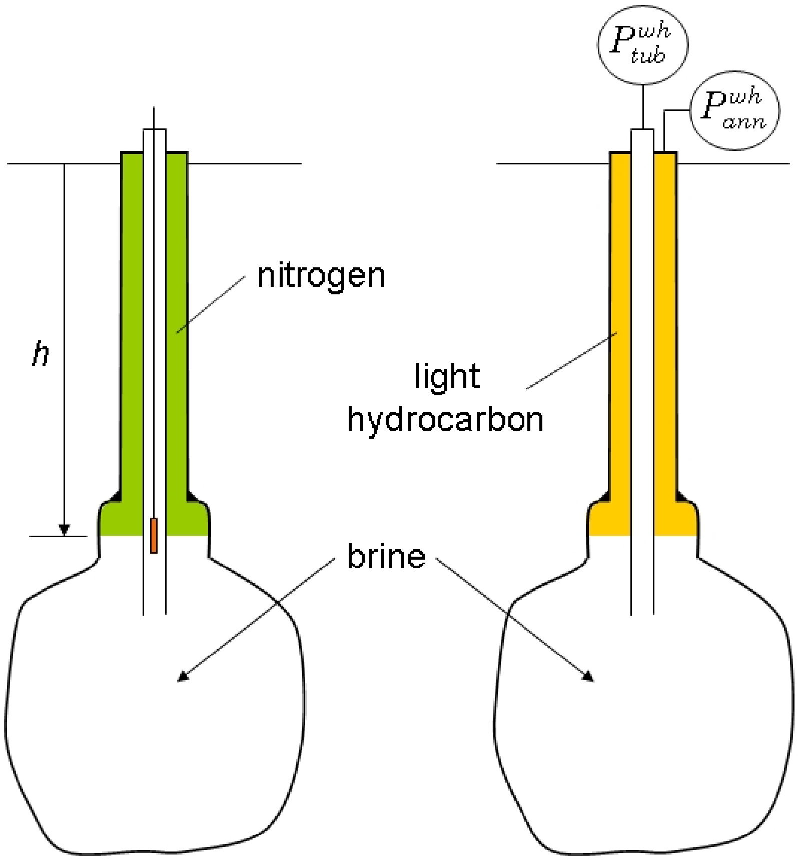

Figure 1. NIT (Left) Versus LLI (Right) Integrity Tests. (In the NIT, the nitrogen/brine interface is tracked through a logging tool. In the LLI, tubing (P^{wh}_{tub}) and annular (P^{wh}_{ann}) pressures are continuously recorded at the wellhead during the test.)

E.3 DEFINITION OF ACTUAL, APPARENT, AND CORRECTED LEAKS

For any method of testing, the presumption is that any unexplained pressure drop in an LLI or measured interface rise in an NIT is caused by or can be attributed to leakage from the cavern or wellbore. The key question thus becomes how to ensure that observed pressure changes in an LLI or interface rises in an NIT are explained properly to avoid suggesting a leak when none exists and also to recognize an actual leak when it might be explained away as something else.

In fact, the pressure drop in an LLI or the measured interface rise in an NIT can be described in terms of:

1. The "**actual leak**," or the true leak.
2. The "**apparent leak**," which is directly deduced from the observed pressure decrease.

3. The “**corrected leak**,” obtained by accounting for quantifiable factors contributing to pressure changes, which, in some cases, can still differ greatly from the true leak (and even the corrected leak).

In a POT, the apparent leak (in barrels (bbls)/day or m^3/day) is simply obtained by multiplying the pressure decay rate (in psi/day or MPa/day) as it is observed at the wellhead by the so-called “cavern compressibility” (in bbls/psi or m^3/MPa). Cavern compressibility, which is proportional to cavern volume, can be readily measured when liquid is injected in the cavern to build up cavern pressure at the beginning of the test.

In an NIT or a PDO, the apparent leak (in bbls/day or liters/day) is simply obtained by multiplying the interface rise rate (in ft/day or m/day) as it is measured through the logging tool (NIT) or reconciled from the pressure difference change (PDO) by the cross-sectional area (in bbls/ft or liters/m) at interface depth. More sophisticated approaches can be adopted. For instance, during an NIT, gas pressure and gas temperature distribution can be measured to compute the changes in gas **mass** (rather than in gas **volume**). However, as leaks generally are small, such corrections in turn generate some uncertainties that often are of the same magnitude as the leaks.

In this research report, a list of the various factors is compiled that contribute to the pressure decay (in a POT) or the interface rise (in an NIT or PDO). The effects of these factors are quantified, which provides a basis for correcting the apparent leak.

E.4 AN EXAMPLE OF WHY THE APPARENT LEAK CAN BE WRONG

An example of a potential misinterpretation of the leak rate is provided in Figure 2. In this small (10,000 m^3 or 60,000 bbls) 700-m (2,300-ft) deep cavern, the cavern pressure is successively built up to several distinct stages. It is clear that pressure decays when cavern pressure is high and the pressure increases when the cavern pressure is low (something commonly observed in most caverns). A blunt interpretation would lead to the (incorrect) conclusion: the cavern is leaky when the cavern pressure is high; a “negative” leak is calculated when cavern pressure is low. In fact, various factors are more or less significant, depending upon cavern pressure, and the resulting pressure evolution depends on the combination of these factors; all contributing factors must be identified to obtain a meaningful “corrected” leak rate. (Incidentally, it was proved in this case that the “actual” casing leak was exceedingly small, although the pressure decays rapidly when cavern pressure is high.)

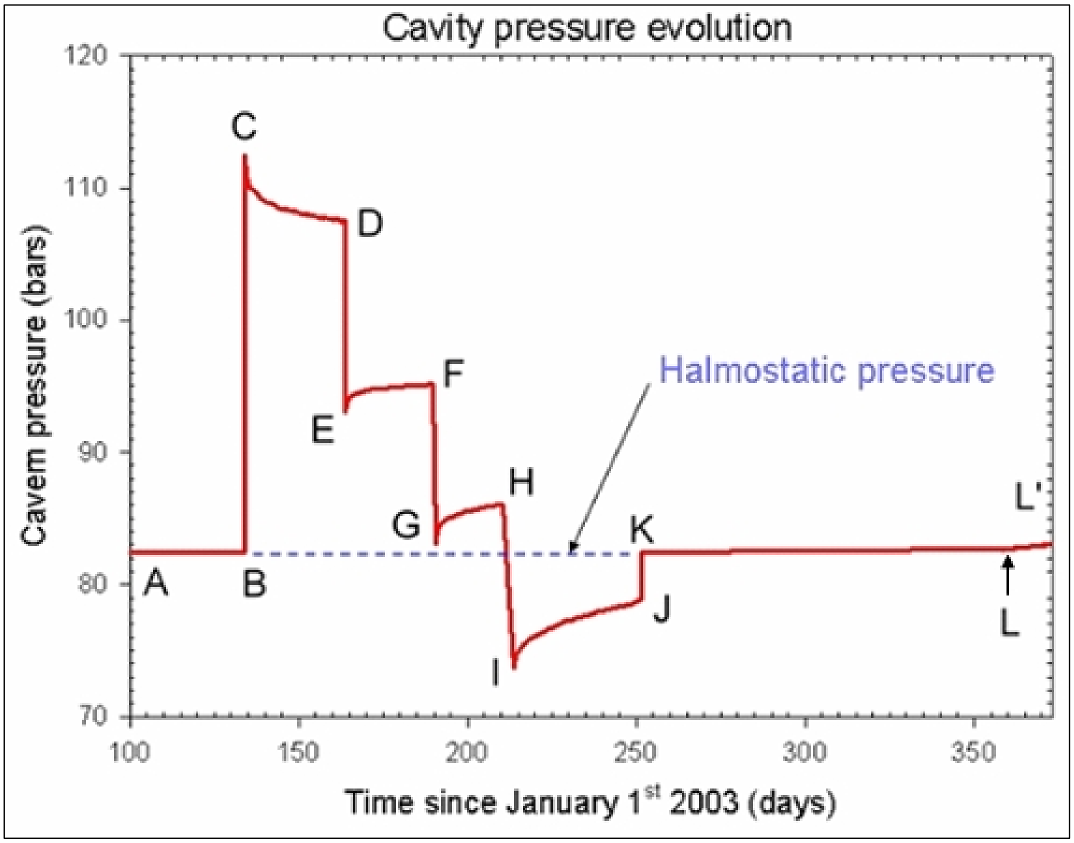

Figure 2. Cavern Pressure Evolution During a 250-Day-Long Test in a Cavern 700 m Deep and Volume 10,000 m^3. The cavern had been kept idle for several years before the test. Wellhead was left open during the A-B and K-L steps. Note that pressure decreases when cavern pressure is more than 2 MPa (20 bars) greater than halmostatic pressure and the cavern pressure increases when the cavern pressure is less than 2 MPa greater than halmostatic pressure.

E.5 IDENTIFICATION OF FACTORS CONTRIBUTING TO AN APPARENT LEAK

Two groups of conditions (other than leak) conveniently categorize phenomena that contribute to pressure decay or interface displacement during an MIT: phenomena preexisting the test and phenomena triggered by the test.

Preexisting phenomena that are potentially active during an MIT are:

- Brine thermal expansion (or contraction).
- Salt creep (cavern closure).
- Well warming (or cooling).

- Steady-state brine permeation into the rock mass.
- Ground and air temperature variations.
- Earth tides, atmospheric pressure variations.

In LLIs, brine thermal expansion, steady-state salt creep, and well warming produce results that appear to "increase" the amount of brine in the closed container–they will mask the amount of leaking fluid. Hence, the apparent leak results are nonconservative with regard to preexisting phenomena. The inverse is true when an NIT is considered. Fluctuations in the interface (in an NIT) measurement, or in the pressure (in an LLI) caused by the effects of ground and air temperature, earth tides and atmospheric pressure are more or less periodic. Brine permeation through the rock mass decreases the amount of brine in the cavern and it increases the apparent leak in an LLI.

The rapid pressure build-up performed at the beginning of an MIT triggers several transient phenomena. Test-triggered phenomena are:

- Transient salt creep.
- Transient brine permeation.
- Adiabatic temperature increase.
- Additional dissolution.

During an LLI, these test-triggered phenomena tend to restore the preexisting pressure and make the apparent leak larger than the actual leak. As far as the phenomena triggered by the test are concerned, apparent leak results are conservative, because they overestimate the actual leak. The inverse is true for test-triggered phenomena when an NIT is considered.

E.6 RELATIVE SIGNIFICANCE OF VARIOUS FACTORS CONTRIBUTING TO THE APPARENT LEAK

The influence of several of the above-mentioned factors may be small, or they are active only during a short period of time after pressure is increased at the beginning of an MIT. Some rules-of-thumb are useful at this point. The maximum admissible leak rate is often considered acceptable at 1,000 bbls/year or 160 m^3/year (in an LLI) or 270 m^3/year (in an NIT; this figure refers to the nitrogen leak rate). In the case of a POT, this maximum leak rate (1,000 bbls/year or 3 bbls/day) must be converted into a maximum pressure decay rate through the cavern compressibility factor or βV, which can easily be measured before the MIT. Cavern compressibility varies from 0.15 bbl/psi (in a 50,000-bbl cavern) to 6 bbls/psi (in a 2,000,000-bbl cavern). The maximum admissible pressure rate for this cavern compressibility factor range is 20 psi/day (138 kPa/day) to 0.5 psi/day (3.4 kPa/day), respectively. The POT is much more accurate (in terms of volumetric leak rate) when the cavern is smaller.

In the following discussion, a relatively small cavern is considered. Factors which lead to a pressure decay rate smaller than 1 kPa/day can be disregarded; factors which lead to a larger pressure decay rate must be taken into account. In the case of an NIT, factors which contribute to an apparent leak smaller than about 10 bbls/year can be disregarded.

E.6.1 Factors for a Liquid-Liquid Interface Test

The factors preexisting Liquid-Liquid Interface tests (POT or PDO) are divided into two groups. The first group are those factors that are normally insignificant; the second group are those factors that are significant and must be considered in calculating the correct leak. The groups are listed below.

- **Steady-state salt creep** generally is a slow phenomenon except when the cavern is very deep (deeper than 5,000 ft). At a 1,000-m (3,000-ft) depth, a typical open-cavern closure rate is $3 \cdot 10^{-4}$/year or 0.03 percent per year (cavern will be completely closed after more than 30 centuries). Because the cavern compressibility factor generally is $4 \cdot 10^{-4}$/MPa (or $3 \cdot 10^{-6}$/psi), the pressure build-up rate in a closed cavern will be 0.75 MPa/year (2 kPa/day or 0.3 psi/day). These figures will be smaller during an MIT because the pressure is significantly larger than in an open cavern, making the pressure build-up rate exceedingly small. The main concern is with the transient creep triggered by the test, a problem which will be discussed later.

- **Wellbore warming** is very fast (in sharp contrast with cavern brine warming which is addressed later): thermal equilibrium in the wellbore is reached after a few hours, except when the well has been active for a long period before the MIT begins.

- **Steady-state brine micropermeation** into the rock mass is small, and in most cases, from an engineering perspective, the salt surrounding a cavern can be considered to be nearly perfectly tight. From a scientific perspective, however, some brine seepage from the cavern and into the salt must occur, albeit usually at very slow rates. Brine permeation is often larger in bedded salt caverns than in domal salt caverns because bedded salt formations generally contain insoluble interbedded layers whose permeability is larger than the permeability of salt. A typical value of the pressure decay rate caused by brine permeation measured during a test (described in the report) performed on a 8,000-m^3 cavern (leached out in a bedded-salt formation) was 0.87 kPa/day. The pressure decay rate would be even smaller in larger caverns.

- **Earth tides and atmospheric pressure variations** generate very small pressure effects, which can be recorded only when a high resolution measurement system is used (typically, earth tides generate relative cavern volume changes as small as 10^{-7}; i.e., 0.1 bbl in a 1,000,000-bbl cavern; the resulting pressure fluctuations (amplitude) is 0.25 kPa). Atmospheric pressure variations are more erratic but somewhat larger.

Two factors have significant effects: ground and air temperature variations and brine thermal expansion.

- **Ground and air temperature variations** are mainly important in LLIs because test interpretation relies on wellhead pressure measurement. Fluids in the wellhead are heated during the day and cooled during the night, which causes density to vary accordingly, resulting in pressure fluctuations. This heating-cooling process is complex, with time lags between the air temperature changes and annular and central-tubing pressure changes. An example is provided in Figure 3. Pressure fluctuations seem to be larger (0.1 bar or 1 psi) when the annular space is filled with nitrogen or LPG (rather than oil and brine). The effects of ground and air temperature can be at least partially neutralized by analyzing 24-hour-long increments of the MIT.

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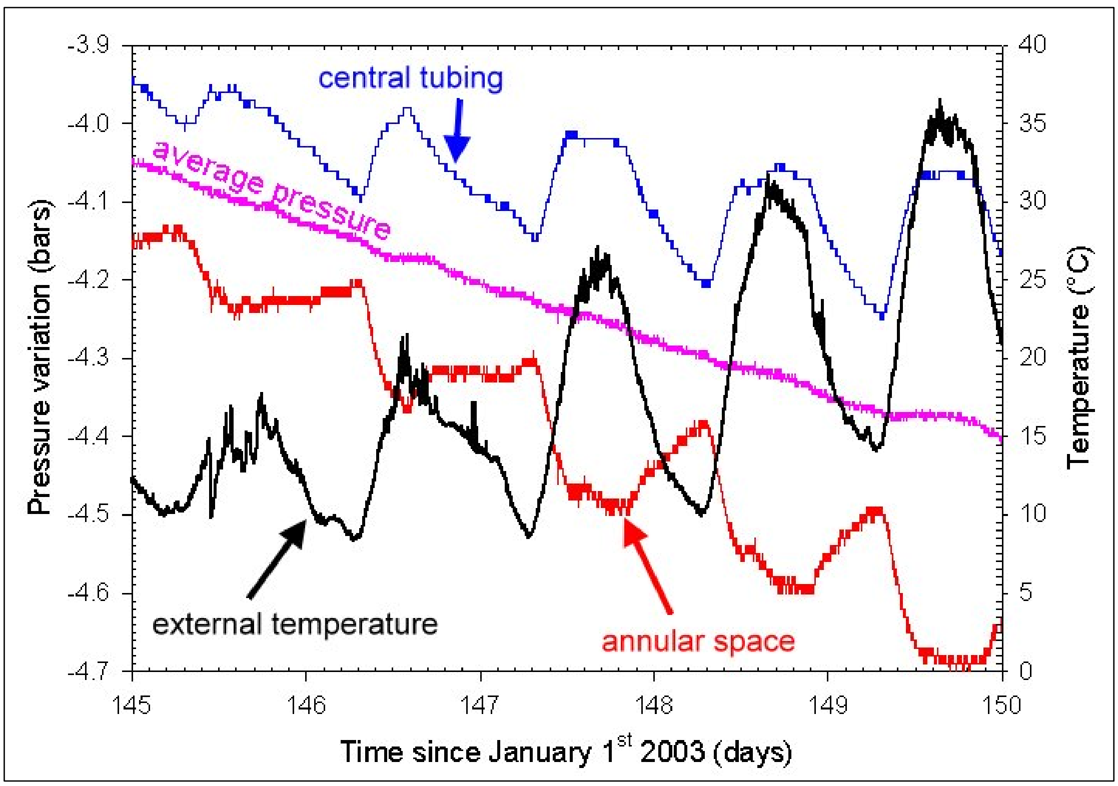


Figure 3. This 700-m Deep, 10,000-m^3 Cavern Was Brine Filled Except for the Annular Space Which Was Oil Filled. The figure displays variations of the central-tubing pressure, the annular space pressure, the average pressure, together with the external temperature. A correlation between external (i.e., air) temperature and oil-filled central-tubing pressure is clearly visible. An inverse correlation is observed when temperature and annular space pressure are compared to the air temperature.

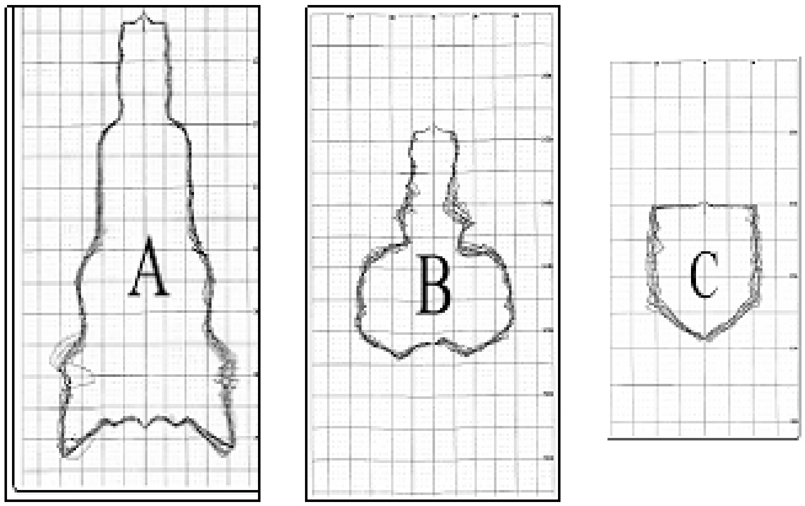
- **Brine thermal expansion**

  In most new caverns or caverns being enlarged by dissolution with fresh water, the cavern brine is not in thermal equilibrium with the surrounding salt mass (cavern brine is cooler than the salt rock, because the soft water came from surface storage or shallow aquifer layers). Brine in the cavern slowly warms up but this warming process may take months in a small cavern and years or decades in a big cavern. The temperature increase rate is fastest in a recently washed-out cavern or in a cavern recently refilled with cold brine or water. Brine warming is also faster when the initial temperature difference is larger (as it generally is for deeper caverns) or when the cavern is small. Brine warming leads to brine thermal expansion and pressure increases or interface rise. Brine cooling can lead to the opposite effect in a mature cavern in a shallow (relatively cool) salt formation in a warm climate (for example, Kansas, USA, in the summer) where cavern brine may be warmer than the salt mass. Theoretical concepts for brine thermal expansion are fully discussed in the report. Figure 4 illustrates the effects of thermal expansion through an actual example. The three caverns (A, B, and C) were leached out at the same time in the same salt formation and are at comparable depths. For technical reasons, leaching was stopped for a couple of weeks, and shut-in pressure tests were performed during this period. As observed, pressure build-up rates were 4 MPa/year (11 kPa/day or 1.5 psi/day), 5.9 MPa/year (16 kPa/day or 2.3 psi/day), and 10 MPa/year (28 kPa/day or 4 psi/day) on the 346,000-m^3, 147,000-m^3, and 48,600-m^3 caverns, respectively. These differences in the rates of pressure increase are consistent with what is known from the laws of thermal conduction in a rock mass: when the cavern is larger, the rate of pressure increase is slower.

  Such a pressure increase would be active during an LLI (brine warming is not modified when cavern pressure changes). This pressure increase could partly hide the actual leak. For example, the apparent leak rate in a POT can be assessed by multiplying the pressure rate by the compressibility βV . With β of the order $\beta = 4\cdot 10^{-4}$/MPa ($3\cdot 10^{-6}$/psi), in the above-mentioned pressure rates, the “negative” leak caused by brine warming should be 560 m^3/year (3,360 bbls/year), 360 m^3/year (2,160 bbls/year), and 300 m^3/year (1,800 bbls/year), respectively (keep in mind that a typical POT objective might be to prove the leak rate is smaller than 1,000 bbls/year). When interpreting a POT, this “negative” leak should be added to the apparent leak to provide a better assessment of the actual leak–which, in this case, is larger than the apparent leak. When brine is warmer than the surrounding rock mass (shallow caverns in a warm climate), the apparent leak is larger than the actual leak.

E.6.2 Test-Triggered Factors for a Liquid-Liquid Interface Tests

The cavern pressure increase at the beginning of an MIT triggers several factors that cause later cavern pressure changes. These later pressure changes in LLI tests are proportional to



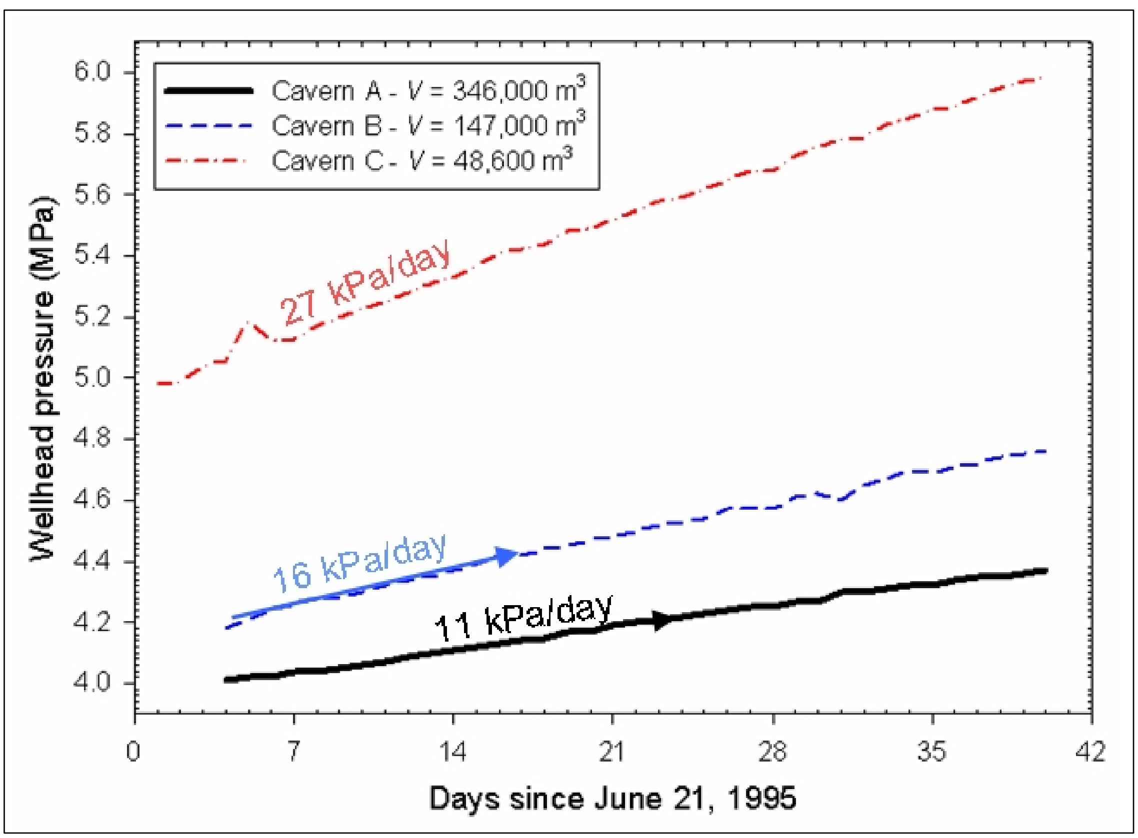


Figure 4. Pressure Increase Caused by Thermal Expansion From Brine Warming in Three Different-Sized Caverns. These caverns were each being actively leached just before shut in for these tests. Thus the temperature gradient between the salt mass and the cavern brine was likely much greater than would be the case in a mature cavern that has not been recently leached.

the amplitude of the initial testing pressure, or p_i^1 (however, the relation is nonlinear in the case of transient creep). These factors have different periods of time for the pressure decay before reaching its final value, or δp_i^∞. The pressure decay rate is fastest immediately after the pressure build-up (i.e., at the beginning of the test). It is convenient to compute the final relative pressure decay, or $\delta p_i^\infty / p_i^1$, that will be reached when the transient process is completed; however, the relative pressure decay reached after 1 day, or $\delta p_i(1 \text{ day})/p_i^1$, is also important.

- **Additional dissolution**

  Any change in cavern pressure leads to a change in brine saturation: following a rapid pressure build-up, salt is dissolved, more room is offered to cavern brine, and cavern pressure drops accordingly. When the additional dissolution process is completed, the final pressure drop is $\delta p_i^\infty / p_i^1 = 43 \cdot 10^{-3}$ (or $\delta p_i^\infty = 215$ kPa when the initial pressure build-up was $p_i^1 = 5$ MPa), and it is independent of cavern size. Equilibrium is almost reached after 10 days in a 10,000 m^3 cavern; the pressure decay rate is faster during the first 2–3 days, making the initial pressure decay rate several tens of kPa/day (several psi/day) during this initial period.

- **Adiabatic pressure build-up (brine-filled cavern)**

  A rapid increase in pressure results in a (small) increase in brine (or fluid) temperature that is followed by a slow brine cooling process. The final pressure drop caused by cooling is $\delta p_i^\infty / p_i^1 = 29 \cdot 10^{-3}$ (or 145 kPa when the initial pressure increase was 5 MPa); however, the cooling process is slow. Cooling is fast in a small cavern; for instance, in a V = 8,000 m^3 cavern, the pressure decay after 1 day is $\delta p_i(1 \text{ day})/p_i^1$ = 2.10^{-3} or 10 kPa (1.5 psi) when $p_i^1 = 5$ MPa.

- **Transient brine permeation**

  Any tentative quantification of transient brine permeation is open to discussion because, in general, rock salt hydraulic properties (permeability, porosity, Biot's coefficient) for the salt at the cavern surface are not well known. In the extreme case of a small (V = 8,000 m^3) cavern in a micropermeable salt formation (porosity = 1 percent, permeability = 10^{-19} m^2), the pressure decay after 1 day is $\delta p_i(1 \text{ day})/p_i^1 = 2.7 \cdot 10^{-3}$. Therefore, this factor is likely to be negligible in a less permeable formation. However, the effect can be large in a small cavern and very large in a wellbore before the cavern is leached out.

- **Transient creep**

  Transient creep is important when a cavern is kept idle for a long time before the LLI and when the testing pressure suddenly increases. The pressure increase at the beginning of a test generates an "instantaneous" elastic response, typically followed by transient cavern expansion and pressure decay. This effect is probably the most significant "triggered-by-the test" effect; however, any precise generalization is difficult. Although the transient behavior of salt caverns following a pressure increase has not been widely investigated, case histories tend to show that this effect is significant during at least a 10-day period. Additional testing and modeling is needed to fully resolve this test-triggered effect.

E.6.3 Effects Triggered by a Nitrogen Interface Test (NIT)

All of the above-mentioned phenomena for the LLI are also active in an NIT. However, their influences are exactly opposite. Thus a factor that leads to leak underestimation in an LLI leads to leak overestimation in an NIT, and vice versa.

The phenomena affecting test results are more difficult to assess in an NIT because of the mechanical coupling between the gas and the brine. The gas/brine interface displacement is small because the gas column is stiff. The gas column is stiff because even though the gas compressibility factor is larger than the brine compressibility by a factor of 100, the nitrogen volume is smaller than the brine volume by a factor which ranges from 100 (in a very small cavern) to 10,000 (in a large cavern). Typically in a large cavern, the nitrogen component is much stiffer than the brine component. The interface displacements caused by phenomena such as brine thermal expansion, additional dissolution, and cavern creep are much smaller than what they would be if gas pressure above the interface was low. In a large cavern, the actual leak is much closer to the apparent leak than what it would be in a small cavern or in an LLI.

E.7 CONCLUSIONS

E.7.1 Conclusions for Liquid-Liquid Interface Test-Type Mechanical Integrity Tests

1. Liquid-Liquid Interface tests are more accurate in small caverns than in large caverns (and might not even be suitable for large caverns).
2. Between a few days and up to a 1-week stabilization period (after an increase in pressure) provides sufficient time for triggered-by-the-test phenomena effects to become negligible.
3. Ground temperature variations can be effectively neutralized by analyzing 24-hour periods.
4. Brine warming usually is the most significant effect, except maybe in shallow caverns (where the salt mass may be sufficiently cool to cause brine cooling rather than brine warming). Brine warming leads to potentially severe underestimation of the actual leak. This effect can be easily assessed by performing a short shut-in pressure test before the actual pressure monitoring phase.
5. When the cavern neck is narrow and its diameter is consistent, LLI test results are comparable to the gas-liquid interface method (Pressure Difference Observation test, or PDO): analysis of the evolution of the difference between the annular pressure and the tubing pressure (as recorded at wellhead) provides a precise estimate of the actual leak.

E.7.1 Conclusions for Nitrogen Interface Test-Type Mechanical Integrity Tests

1. An accurate NIT requires that the cavern neck is narrow and its diameter is consistent.
2. Most of the above-mentioned conclusions for LLI tests are also valid for an NIT; however, when the apparent leak overestimates the actual leak in one method, it underestimates the actual leak in the other method (and vice versa).
3. The impact of these phenomena on the apparent leak is smaller in a larger cavern and smaller than in LLI tests; therefore, the NIT is the more accurate method for a large cavern with a suitable neck.