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BRINE WARMING IN A SEALED CAVERN: WHAT CAN BE DONE?

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ABSTRACT

For the past several years, concerns have raised about the long-term behavior of brine-filled sealed and abandoned caverns. In many cases, and especially when caverns are large and deep, the absence of thermal equilibrium when a cavern is sealed is a major concern: brine temperature increases, resulting in brine thermal expansion and cavern pressure build-up. In many cases, observing a "waiting period" to let brine temperature increase before sealing a cavern is not a realistic option, because this period may be several decades long. Instead, it is suggested that a small quantity of gas be injected into the cavern to increase cavern compressibility: the pressure increase generated by a given increase in brine temperature then will be much smaller. This solution is simple and robust. It can be proven that a gas leak, or gas dissolution in cavern brine, is beneficial in that it makes pressure build-up even slower. Mathematical equations that describe gas and brine behavior are derived, and examples are provided.

Keywords: Abandonment, Cavern Plugging and Abandonment

INTRODUCTION

Main factors in the behavior of a sealed cavern

The long-term evolution of brine pressure in a sealed and abandoned cavern is governed by five main factors:

(1) brine warming and brine thermal expansion,

(2) cavern creep closure,

(3) brine (micro) permeation through the cavern walls,

(4) (possible) leaks through the plugged and cemented well; and

(5) cavern compressibility. (Phenomena (1-4) result in cavern or brine-volume changes that are related to the cavern pressure change through cavern compressibility.)

Brine warming originates in the temperature difference between rock temperature and cavern brine temperature. In general, brine is colder than rock. Brine warming is more intense when the initial temperature difference, which depends on cavern depth and cavern history, is greater. It is faster in a smaller cavern. However, brine warming ends after a period of time that can be several decades long in a large cavern. Brine warming generates the thermal expansion of the brine and pressure build-up in a closed cavern.

The *cavern creep closure* rate depends on rock-mass mechanical properties, which may vary widely from one site to another (Brouard and Berest, 1998). In a given site, it is faster in a deeper cavern. The cavern volume loss rate is slower when the cavern brine pressure is higher; it vanishes to zero when brine pressure equals geostatic pressure at cavern depth. When a cavern shrinks, less room is left for brine, and the cavern pressure increases.

Brine (micro) permeation through cavern walls generally is slow, as salt permeability is exceedingly small (belonging to the range $K = 10^{-22}$ to 10^{-18} m^2). The relative brine outflow (i.e., the actual brine flow in bbls/year divided by the cavern volume in bbls) is slower in a larger cavern and, in opposition to the cavern-creep closure rate, it is faster when brine pressure is higher. Brine outflow leads to the release of cavern pressure.

Leaks generally are smaller (often much smaller) than, say, 1000 bbls/year in a hydrocarbon storage cavern (Thiel, 1993). It is expected that leaks are smaller still in an abandoned cavern after a cemented plug is set at the bottom of the well. Leaks result in the release of cavern pressure.

Cavern compressibility is the stiffness of the (cavern + fluids stored in the cavern) system. This notion is described in more detail in Appendix I.

Classification of abandoned caverns

The relative importance of the above four factors depends on many parameters: cavern depth and size; rock permeability and rock-mass pore pressure; rock-salt mechanical properties; and cavern history before abandonment. It must be assessed on a case-by-case basis, but three main cases can be considered.

1. Shallow ($H < 3000$ ft, or 1000 m) and Small ($V_c < 100{,}000$ bbls, or 15,000 m^3) Caverns, relatively large permeability ($K > 10^{-20}$ m^2) — In a small cavern, the temperature difference at the end of cavern operation rapidly reduces, and a waiting period of a few years is sufficient to reduce this difference to an acceptable level. Later, the cavern pressure slowly converges to an equilibrium pressure, significantly smaller than geostatic pressure, such that the effects of creep closure exactly balance the effects of brine (micro) permeation, preventing any fracturing. Several *in situ* tests (supported by the SMRI) have confirmed this (Bérest et al., 2001; Brouard et al., 2004; Brouard Consulting et al., 2006).
2. Deep ($H > 3000$ ft) and Large ($V_c > 1{,}000{,}000$ bbls) Caverns, small rock-salt permeability ($K = 10^{-21}$ m^2), no or small initial temperature difference — Here, again, cavern pressure reaches an equilibrium value. However, this value is close to geostatic (as only a small pressure release results from the brine permeation, and the cavern creep closure is fast due to cavern depth). When the cavern is high (say, > 600 ft), brine pressure at the cavern top may be larger than rock pressure at the same depth. (These two pressures are almost equal at the cavern mid-depth). The possibility of fracturing exists (Wallner, 1986; Wallner and Paar, 1997). However, the pioneering work of Fokker (1995), completed by further studies (Ratigan, 2000 —All these studies were supported by the SMRI.) proved that salt permeability becomes significantly greater than its natural initial value when cavern pressure is close to geostatic, allowing faster brine (micro) permeation and effective pressure release. Such a beneficial property was established clearly in the laboratory,

and *in situ* confirmation is expected. In hindsight, this increase in permeability may explain the results of the Etzel test (Rokhar et al., 2000).

3. Large Caverns, large initial temperature difference — This case is more likely to be observed in a deeper cavern (as geothermal temperature is warmer). In a large cavern, observing a waiting period to let the brine temperature increase before cavern sealing is not a realistic option, as the waiting time can be several decades long. An example of this is displayed in Figure 1. As represented in this figure, the cavern volume is 300,000 m^3 (1,800,000 bbls), and its depth is 1300 m (4000 ft). The initial temperature difference is 30 °C (54 °F). After a long period of time (40 years), equilibrium nearly is reached, and cavern pressure is almost equal to equilibrium pressure. However, 1.5 years after the cavern was sealed, and during a "transient period" lasting several decades, cavern brine pressure is significantly larger than geostatic pressure. Rock mass fracturing during this transient period is likely. One possible option is to wait before sealing the cavern. The minimum "waiting period" in this example would be 8.3 years. (When a cavern is sealed after such a "waiting period", cavern pressure increases, but it remains smaller than geostatic pressure.)

This paper is dedicated to Case 3, which is the most difficult.

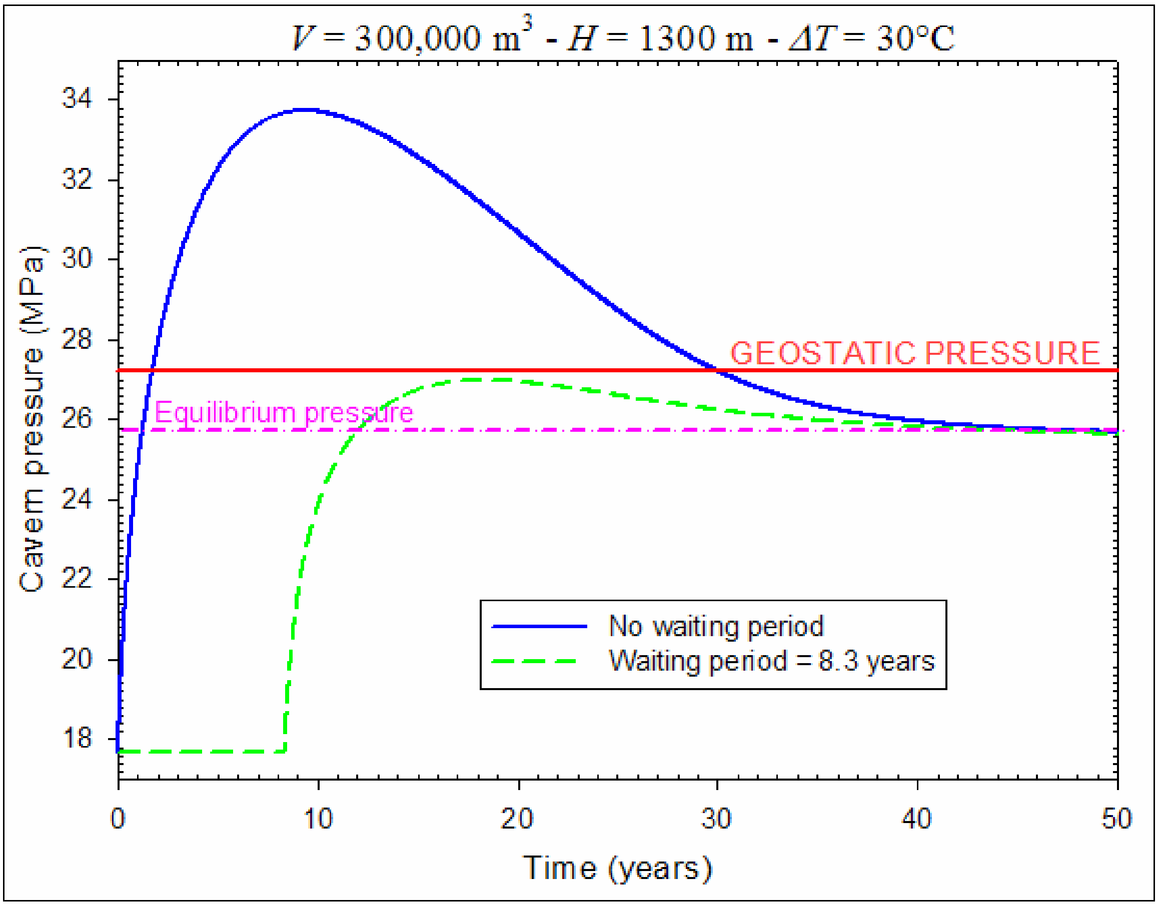

Figure 1 **Cavern brine pressure as a function of time. (Pressure builds above geostatic pressure when no "waiting period" is provided.)**

PRESSURE BUILD-UP IN A CLOSED CAVERN

Brine thermal expansion

In many cases —for example, a gas storage cavern, which must be filled with brine before being abandoned — brine temperature at the end of the operating phase is lower than rock temperature at cavern depth. The temperature difference (ΔT) depends on the cavern history: it is likely to be larger when cavern is deeper and it is smaller when cavern has been kept idle for a long period before the cavern is abandoned.

This temperature difference slowly resorbs with time. Temperature evolution is governed by heat transfer through the rock mass (conduction) and the cavern brine (convection). The temperature difference is divided by a factor of approximately 4 after a "thermal characteristic time", which, in an idealized spherical cavern, equals $t_c \text{ (in years)} = V^{2/3} \text{ (in m}^2) / 4k \text{ (in m}^2\text{/year)}$ and $k \approx 100 \text{ m}^2\text{/year}$, or t_c = 1 year in an 8,000 m^3 (50,000 bbls) cavern and t_c = 16 years in a 512,000 m^3 (3,000,000 bbls) cavern. These figures hold for the case of an idealized spherical cavern; the thermal characteristic time is shorter in a "real life" cavern; it can be computed easily when the cavern shape is known.

Pressure build-up due to thermal expansion

Pressure build-up

Brine warming generates brine expansion — or $\Delta V_b / V_b = \alpha_b \, \Delta T$, where the brine thermal expansion coefficient is $\alpha_b = 4.4 \times 10^{-4}$/°C = 2.45×10^{-4}/°F. In fact, in a closed cavern, brine expansion partly is prevented by cavern stiffness. Let β be the cavern compressibility factor (see Appendix I); then, the increase in cavern pressure generated by the thermal increase in brine in a closed cavern is

$$\Delta P = \frac{\alpha_b}{\beta} \Delta T$$

The cavern compressibility factor may vary from one cavern to another cavern, but $\beta = 4 \textit{ to } 5 \times 10^{-4} \text{/MPa} = 3 \text{ to } 3.5 \cdot 10^{-6} \text{/psi}$ generally is considered as a good starting point. In other words, $\alpha_b/\beta \approx 1$ MPa/°C ≈ 80 psi/°F. (This figure is indicative and must be assessed on a case-by-case basis, but it can be considered as a reasonable assumption; smaller values, for example, can be encountered in a flat cavern.)

In an actual abandoned cavern, the pressure build-up generated by thermal expansion combines with other factors (Pressure build-up due to cavern creep closure must be added; pressure release due to brine migration or leaks must be subtracted.) For simplicity, we consider here the effect of brine thermal expansion *alone*.

Initial pressure difference

The pressure build-up due to brine warming after a cavern is sealed must be added to the cavern brine pressure that existed before sealing (i.e., halmostatic pressure). The sum must be smaller than the geostatic pressure. (Pressures are computed at the cavern top.)

When a cavern is abandoned, its pressure is halmostatic: it equals the weight of a brine column filling the well opened to atmospheric pressure:

$$P_h \text{ (in MPa)} = 0.012H \text{ (in meters) or } P_h \text{ (in psi)} = 0.52H \text{ (in feet)}$$

The geostatic pressure at average cavern depth is approximately

$$P_\infty \text{ (in MPa)} = 0.022H \text{ (in meters) or } P_\infty \text{ (in psi)} = 0.95H \text{ (in feet)}$$

(larger values sometimes are met) and the initial difference between the geostatic pressure (at average cavern depth) and the halmostatic pressure (at cavern depth) is

$$P_\infty - P_h \text{ (in MPa)} = 0.01H \text{ (in meters) or } P_\infty - P_h \text{ (in psi)} = 0.43H \text{ (in feet)}$$

Maximum initial temperature difference

From the definitions given above, it is expected that cavern pressure will reach figures higher than geostatic when the brine pressure increase due to thermal expansion is larger than the difference between geostatic pressure and halmostatic (or initial) pressure:

$$\Delta T \text{ (in °C)} > \frac{\beta(P_\infty - P_h)}{\alpha_b} \approx 0.01\, H \text{ (in meters) or } \Delta T \text{ (in °F)} > 0.0058\, H \text{ (feet)}$$

For instance, when $\Delta T > 10$ °C and $H = 1000$ m (i.e., $\Delta T > 18$ °F and $H = 3100$ ft), a cavern cannot be abandoned safely. In fact, in many cases, brine temperature at the end of cavern operation is even lower, and the immediate plugging of the cavern cannot be considered as a reasonable option.

It must be kept in mind that this estimation [ΔT (in °C) > 0.01 H (in meters)] *is not conservative*, as the effects of cavern closure have been neglected.

INCREASING CAVERN COMPRESSIBILITY

When the difference between brine temperature and rock geothermal temperature is too high, three options can be considered:

(1) waiting for the cavern temperature to increase to an acceptable level (As explained above, this option is only reasonable when the cavern — and the initial temperature difference —is not too large.);

(2) warming the cavern brine before abandoning the cavern —i.e., injecting heated brine into the cavern (This option may prove to be costly, as well (Crotogino and Kepplinger, 2006.) and

(3) modifying cavern compressibility. This option is discussed below.

Increasing cavern compressibility

Pressure increase due to thermal expansion, ΔP, is related to the initial temperature difference (between rock temperature and brine temperature), ΔT, through the simple relation

$$\Delta P = \frac{\alpha_b}{\beta} \Delta T$$

ΔP must be as small as possible:

- α_b, the brine thermal expansion coefficient, is a physical constant and cannot be modified easily.
- ΔT, the initial temperature difference, can be modified when brine is pre-heated before injection or when a "waiting period" can be observed before plugging the cavern (see above).
- β, the cavern compressibility factor, can be made smaller by injecting a small amount of a compressible fluid (gas) into the cavern before plugging it .

When a small amount of gas (x) is injected into the cavern, cavern compressibility (β) drastically changes. [x is the cavern volume fraction that is occupied by the gas — i.e., if V_c is the cavern volume, the brine volume is $V_b = (1-x)\ V_c$, and the gas volume is $V_g = x\ V_c$; x varies from $x = 0$ (no gas) to 1 (no brine).] Then, the cavern compressibility factor is $\beta(x) = \beta_c + \beta_b + x\ (\beta_g - \beta_b)$. Gas is much more compressible than brine, and, even when x is small, the global compressibility factor, $\beta(x)$, is much larger than it should be when the cavern is filled with brine and no gas, $\beta(0) = \beta_c + \beta_b$. The isothermal compressibility of gas is $\beta_g = 1/P$ when P is the absolute pressure of gas at cavern depth, which is the sum of the initial halmostatic pressure (P_h) plus cavern pressure increase (ΔP; $P = P_h + \Delta P$). Typical values are $P = 20$ MPa and $\beta_g = 0.05$ /MPa: gas compressibility is larger than brine compressibility by two orders of magnitude, $\beta_b << \beta_g$, and even a small fraction of gas is able to increase cavern compressibility drastically. For example, $x = 0.01$ and $\beta(x = 0.01) = \beta_c + (1 - x)\beta_b + x/P = 3.97\times10^{-4} + 0.05\ x = 9\times10^{-4}$ /MPa, to be compared to $\beta(0) = \beta_c + \beta_b = 4\times10^{-4}$ /MPa (no gas in the cavern); see Appendix I for more details.

In other words, the relation between temperature increase and pressure increase is changed:

$$\Delta P = \frac{\alpha_b}{\beta(0) + x \big/ \left(P_h + \Delta P\right)} \Delta T$$

where x is the fraction of gas injected in the cavern, P_h is the initial (halmostatic) pressure, $\beta(0) = \beta_c + \beta_b$ and ΔP is the final pressure increase due to temperature increase by ΔT.

Effect of gas injection

Multiplying β by a factor of 2 (i.e., when $P = 20$ MPa, injecting an $x = 0.8$ % volume of gas in the cavern) has the same effect as dividing the initial temperature difference by 2, a result which, in a large cavern, could be obtained only after a long and costly waiting period.

Any gas can be used, but nitrogen, which is an inert gas (It cannot burn, explode, corrode or combine with other materials.), is a good candidate, as is carbon dioxide.

An example is displayed on Figure 2. Cavern depth and volume are the same as in Figure 1 . The pressure-versus-time curves are drawn (1) when no initial temperature difference exists (Cavern pressure slowly converges to a level ("Equilibrium pressure") lower than geostatic pressure.); (2) when the initial temperature difference is 30 °C (54 °F) (After 1.5 years, the geostatic pressure is exceeded and fracturing is likely.); and (3) when the initial temperature difference is 30 °C (54 °F) *and gas is injected in the cavern before sealing*. (The increase in cavern pressure is significantly smaller.)

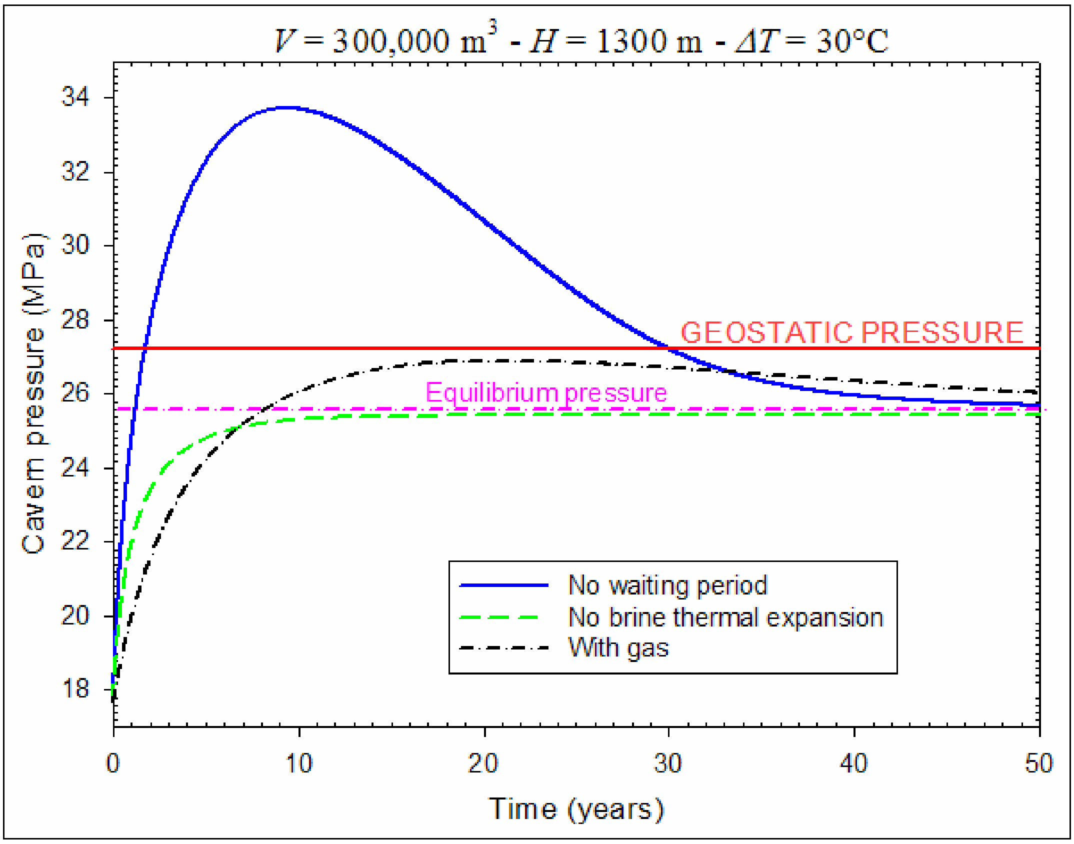

Figure 2 Cavern brine pressure as a function of time. (Injecting gas in the cavern allows the cavern pressure to remain lower than the geostatic pressure.)

Amount of gas to be injected

When computing the amount of gas to be injected, one must consider the complete set of equations that describe the evolution of the cavern, see Appendix II . One simple criterion is that at no instant can cavern pressure be larger than geostatic pressure. (In an actual cavern, a safety factor must be considered: for instance, the cavern pressure at the casing shoe must remain lower than, say, 90% of the geostatic pressure, see below). In Figure 3 an example is provided of a 300,000 m^3 cavern into which is injected a 1000 m^3 (approximately 140,000 m^3 STP) volume of nitrogen (i.e., 0.3% of the cavern volume) before sealing the cavern to prevent the cavern pressure from reaching geostatic pressure.

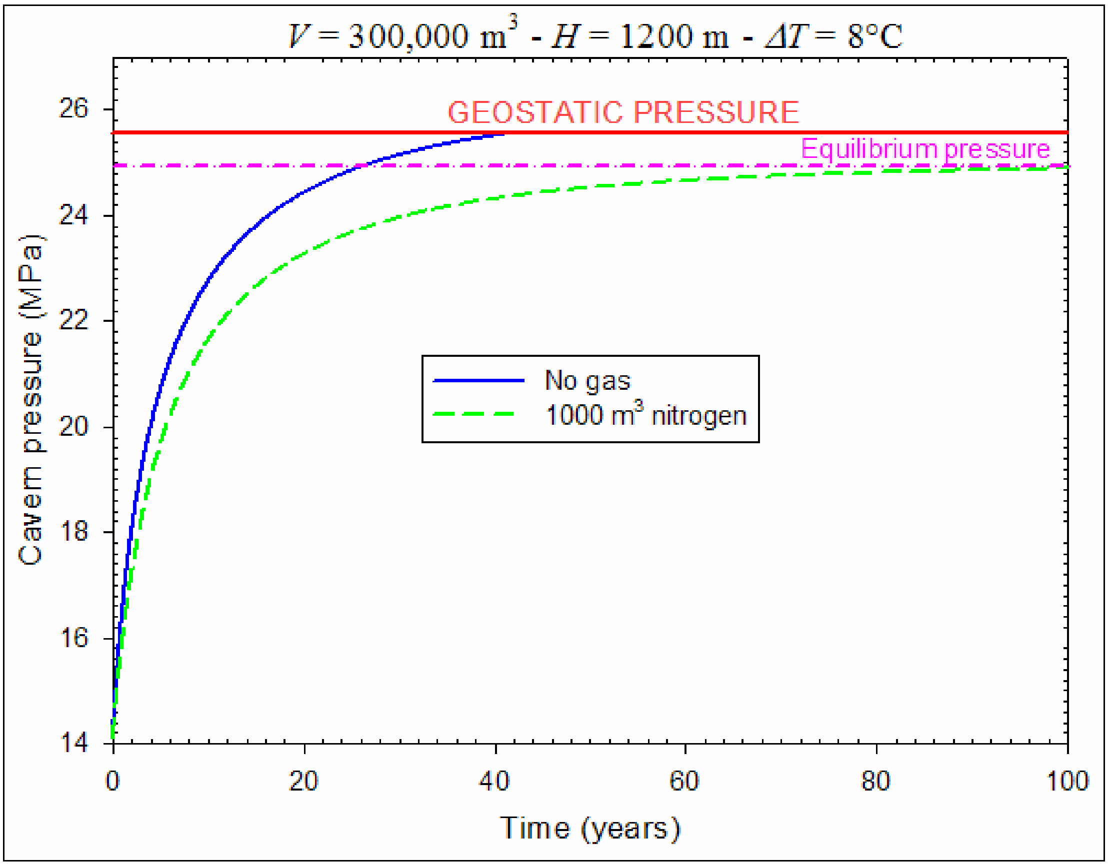

Figure 3 **Cavern brine pressure as a function of time. (Injecting 1,000 m^3 of gas prevents cavern pressure from reaching the geostatic level.)**

Waiting period versus amount of gas to be injected

In many cases, it is feasible (and reasonable) to wait a couple of years ("waiting period") before injecting the gas. The longer the waiting period, the smaller the amount of gas to be injected. The optimum solution can be found in each actual case; it depends on economical and technical aspects. In Figure 4, the length of the waiting period (before gas is injected) is plotted as a function of the volume of nitrogen injected before sealing the cavern. Various criteria are considered: the maximum admissible cavern pressure is geostatic (A pressure of 0.95 psi/ft is typical; larger values, up to 1.15 psi/ft, sometimes are encountered.), or for example, due to site-specific regulations, the maximum admissible pressure may be smaller than geostatic pressure (0.86 psi/ft or 0.77 psi/ft, respectively). When the most severe criterion is considered (0.77 psi/ft), the waiting period is 12 years long when no gas is injected; injecting 1000 m^3 of gas (140,000 m^3 STP) before sealing the cavern would make the waiting period much shorter (6 years).

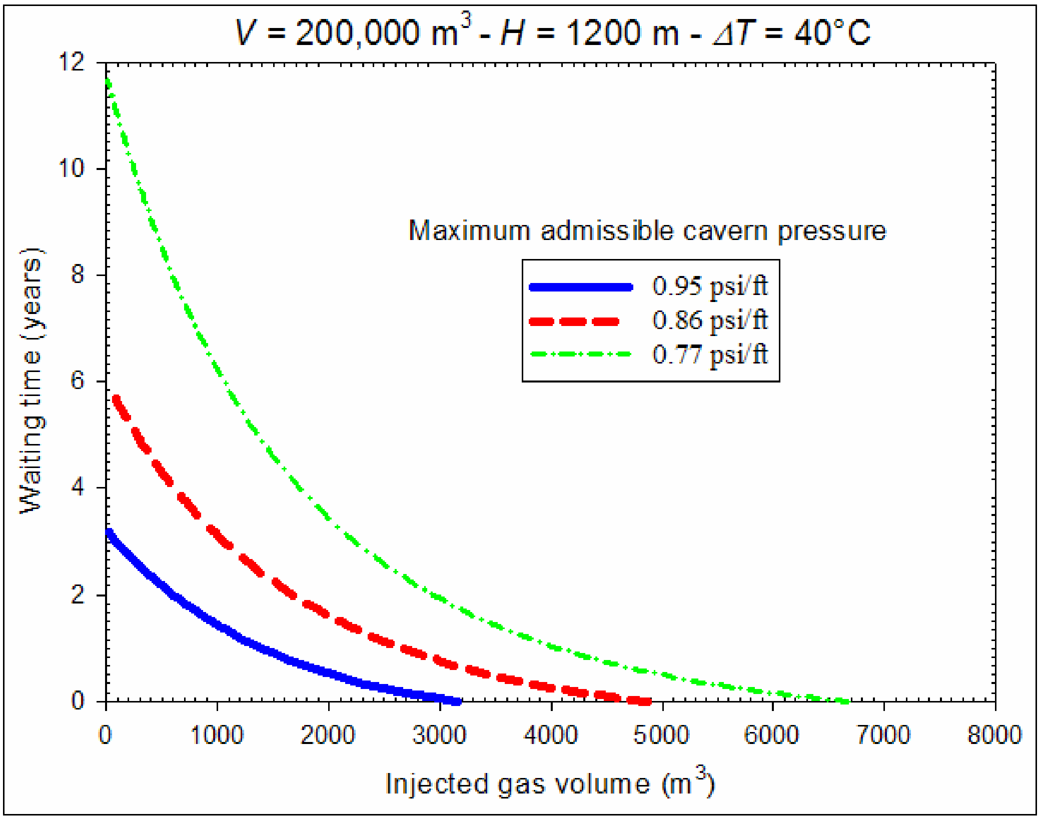

Figure 4 **Nitrogen volume to be injected as a function of "waiting period" length for different values of the "maximum admissible pressure in the cavern". When the pressure criterion is more severe, more gas must be injected (and/or the "waiting period" is longer before injecting gas.)**

Effect of gas loss

It has been noted that cavern walls (and/or plugged and cemented wells) sometimes are not perfectly tight, as is proved by the results of Nitrogen Leak Tests. Gas also may dissolve in brine. In other words, the gas loss must be considered: when the amount of gas (x) is lessened, the cavern compressibility factor (β) decreases, and the beneficial effect of larger compressibility apparently vanishes. *However, gas loss in most cases is beneficial* in that a loss of cavern gas provides more room for brine expansion. This is especially true when the gas loss is fast enough to allow most of the gas to escape from the cavern before brine warming is completed, or $Q_{loss}/V_g > 1/t_c$. The amount of gas injected in the cavern, V_g, is a small fraction of the cavern volume, $V_g = x\ V_c$, and the condition also writes $Q_{loss} > 4k \times V_c^{1/3}$, a condition that often is fulfilled: k = 100 m^2/year, $x \approx 5\times10^{-3}$, $V^{1/3} \approx 60m$ (or $V_c = 216{,}000$ m^3 or 1,300,000 bbls) are typical, leading to $4k \times V_c^{1/3} = 30$ m^3/year (180 bbls/year), a relatively small loss rate.

Loss of all the injected gas can accommodate a temperature increase of x/α with no increase in cavern pressure. For example, when $x = 4.4 \times 10^{-3}$, a temperature increase of $\Delta T = 10$ °C (18 °F) will generate no pressure build-up after the entire amount of injected gas has escaped from the cavern. Generally, after all the gas (x) has escaped from the cavern, the pressure build-up (ΔP) generated by an initial temperature difference ΔT is

$$\Delta P = \frac{\alpha_b \Delta T - x}{\beta}$$

Note that the increase in cavern brine pressure after the loss of gas is completed is always less than the pressure increase when no gas leak takes place — gas loss is beneficial.

The gas injected in the cavern may also dissolve in cavern brine. The solubility of nitrogen or carbon dioxide in brine is a decreasing function of temperature and brine concentration, and an increasing function of pressure (Sun et al., 2001). The dissolution process is slow (but much faster when carbon dioxide is used). However, because dissolution takes place with no, or very small, change in liquid volume, gas dissolution acts exactly as a gas loss — i.e., its effects are beneficial from the perspective of lessening pressure build-up in a sealed cavern.

The favorable effect of gas loss is shown clearly in Figure 5 In this relatively small cavern, a gas injection of 1000 m^3, or 120,000 m^3 STP (and *no gas loss*) allows the cavern pressure to remain lower than the geostatic pressure. Various gas-loss rates are considered. (The indicated loss rate is computed when cavern pressure equals equilibrium pressure.) These rates are relatively slow (slower than the generally accepted Maximum Admissible Leak Rate during a Nitrogen Leak Test, or 1000 bbls/year). Note that the slope of the curve drastically changes at the instant that all the gas is lost ("no more gas"). Even a relatively small gas-loss rate has a very favorable effect on the maximum pressure level reached after cavern sealing.

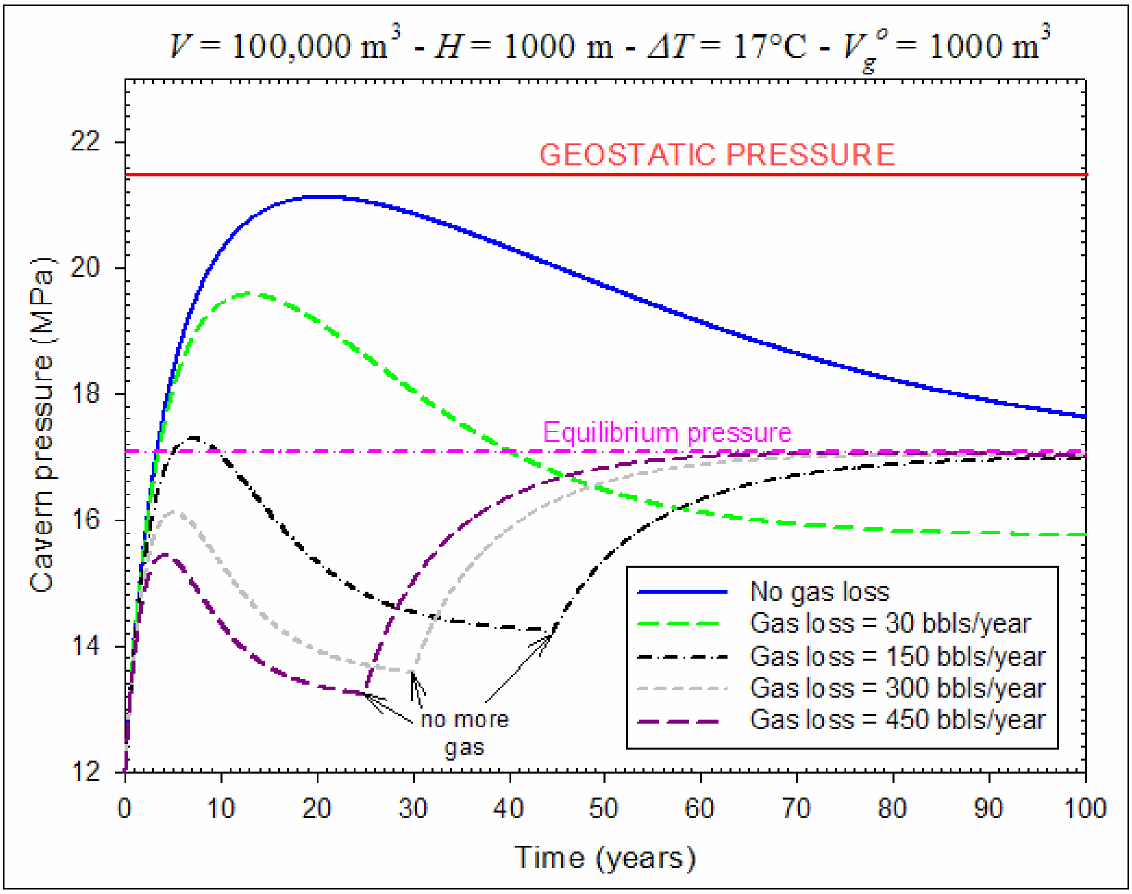

Figure 5 Cavern brine pressure as a function of time when various gas-loss rates are considered.

Carbon dioxide injection

It is current practice during the so-called "Nitrogen Leak Tests" (NLT) to inject several dozen cubic meters (several thousand cubic feet) of pressurized nitrogen into a cavern. Injecting several hundred cubic meters of nitrogen does not raise specific problems (It sometimes is necessary to inject nitrogen in a cavern before abandonment to vent off trapped hydrocarbons, see de Laguerie et al. (2004). A significant difference between an NLT and a gas injection (before cavern sealing) is the fact that, after injection, the gas pressure must not be greater than the halmostatic pressure (12 MPa at a 1000-m depth, or 1500 psi at a 3000-ft depth). When only one tube is available for injection, a tight packer must be set in the annular space, and gas is injected through the central tube (Figure 6a). It is convenient to inject the gas in several steps: after each injection step, the cavern is vented and brine is allowed to flow out of the cavern until there is total release of the pressure build-up that resulted from gas injection (Figure 6b). When gas injection has been completed, the central tubing is sealed, and cement is poured into the well above the packer (Figure 6c).

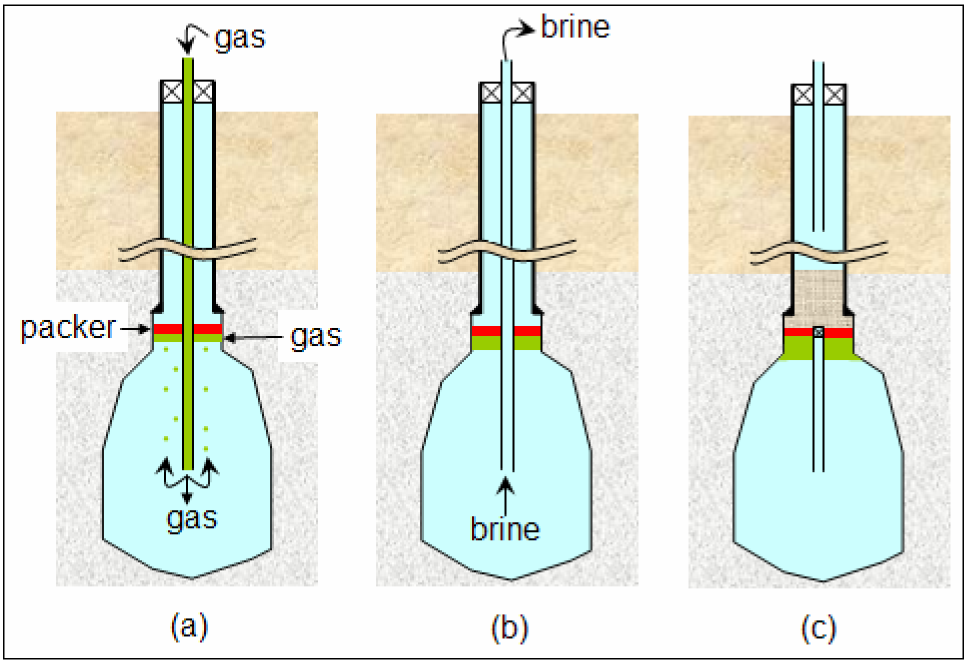

Figure 6 **Gas is injected below the packer (a); brine is withdrawn to release pressure build-up (b); the central tubing is sealed and cement is poured into the well (c).**

Carbon dioxide, CO_2, could be injected instead of nitrogen. Large amounts of carbon dioxide can be dissolved in brine. Gas dissolution in saturated brine acts as a “gas loss”. It was noted that “gas loss” is an advantage (Cavern compressibility increases, but additional room is provided for brine thermal expansion; see Figure 5). Although additional research is needed, injecting a small amount of carbon dioxide before sealing a cavern seems to be an attractive option.

Final equilibrium

When brine thermal expansion is completed, cavern pressure reaches an equilibrium value that is independent of gas injection. (It is the same whatever the amount of gas injected and whether gas leaks occurred or not.) The advantage of gas injection is not that it changes the final equilibrium pressure but, rather, that it avoids the risks generated by the transient phase during which thermal equilibrium has not been achieved.

ACKNOWLEDGEMENTS

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APPENDIX I

CAVERN COMPRESSIBILITY

Introduction

When a certain amount of liquid, v_{inj}, is injected into a closed cavern, the wellhead pressure increases by δP^{wh}, which, at first approximation, is also the cavern pressure increase, δP_c. The relation between these two quantities (v_{inj} and δP^{wh}) generally is linear during a rapid test (see Bérest et al., 1999).

An example of such a test is described in Thiel (1993); see Figure I.1. The slope of the curve (injected brine volume versus brine pressure), or $\beta V_c = v_{inj} / \delta P^{wh}$, is called the cavern compressibility (in m^3/MPa or bbls/psi).

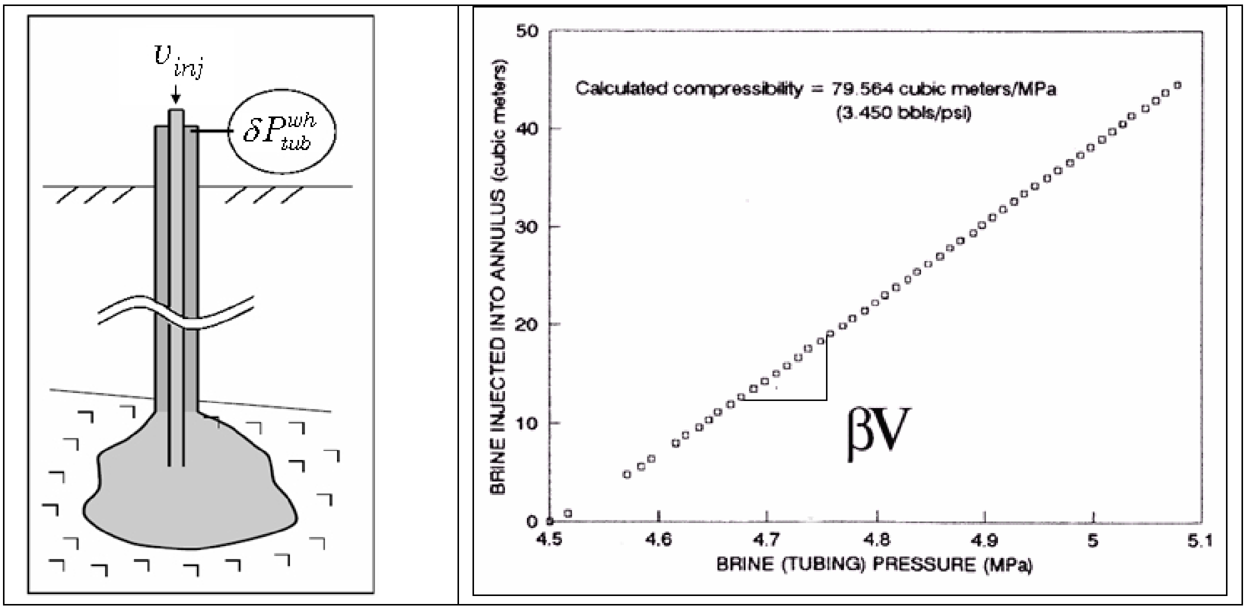

Figure I-1 Measurement of cavern compressibility [after Thiel, 1993].

Cavern compressibility, βV_c, can be expressed as the product of the cavern volume, V_c, and a compressibility factor, β. As in most cases, the cavern volume is known before the test, the compressibility factor can be roughly estimated, and the cavern compressibility value can be predicted before the compressibility test.

The compressibility factor, β, is the sum of the fluid compressibility factor, β_f, and the cavern compressibility factor, β_c. During an injection, pressure in a cavern increases by δP_c, the cavern fluid volume decreases by: $-\beta_f V_c \delta P_c$, and the cavern volume increases by: $\beta_c V_c \delta P_c$. In other words, additional room, or $(\beta_f + \beta_c) V_c \delta P_c$, is created to accommodate the injected volume of fluid, $v_{inj} = (\beta_f + \beta_c) V_c \delta P_c$ and $\beta = \beta_f + \beta_c$. In most cases, the cavern compressibility factor, β_c, is smaller than the fluid compressibility factor, β_f.

Cavern Compressibility Factor

The cavern compressibility factor, β_c, depends upon both cavern shape and rock-salt elastic properties. Boucly (1984) suggests $\beta_c = 1.3\times10^{-4}$/MPa ($9\times10^{-7}$/psi) for the Etrez gas-storage caverns operated by Gaz de France. Larger values can be obtained when the cavern is "flat".

Fluid Compressibility Factor

When a cavity is filled with brine, $\beta_f = \beta_b = 2.7\times10^{-4}$/MPa ($1.9\text{x}10^{-7}$/psi) . When two fluids are contained in the cavern (say, brine and gas), the global fluid compressibility is a combination of the compressibility of the two fluids. Let x be the cavern volume fraction that is occupied by a fluid other than brine — i.e., if V_c is the cavern volume, the brine volume is $(1-x)\ V_c$ and the gas volume is $x\ V_c$; x varies from $x = 0$ (no gas) to 1 (no brine). (In fact, x is much smaller than 1). Then, the global fluid compressibility factor is $\beta(x) = \beta_c + x\ \beta_g + (1-x)\ \beta_b$. Gas is much more compressible than brine; even when x is small, the global compressibility factor, $\beta(x)$, is much larger than it should be when the cavern is filled with brine, $\beta(0) = \beta_c + \beta_b$. The isothermal compressibility of gas is $\beta_g = 1/P$ when P is absolute pressure of gas at cavern depth. Typical values are $P = 20$ MPa (2800 psi) and $\beta_g = 0.05$ /MPa ($3.5\text{x}10^{-5}$/psi): gas compressibility is larger than brine compressibility by two orders of magnitude, and even a small fraction of gas is able to increase cavern compressibility drastically. For example, compare $x = 0.01$ and $\beta(x=0.01) = \beta_c + x\ \beta_g + (1-x)\ \beta_b = 9\times10^{-4}$ /MPa ($63\text{x}10^{-7}$/psi) to $\beta(0) = \beta_c + \beta_b = 4\times10^{-4}$ /MPa or 28 x 10^{-7}/psi (no gas in the cavern).

APPENDIX II

PRESSURE EVOLUTION IN A CLOSED CAVERN

INTRODUCTION

In the following, we consider the simple case of an idealized spherical cavern with radius R and volume $V_c = 4/3\,\pi\,R^3$. Gas pressure at cavern depth, P_g, and brine pressure at cavern depth, P_b, are assumed to be equal: $P_g = P_b = P$. (When the cavern has a height of several hundred meters, more precise definitions are required.)

When a small amount of gas is injected before sealing an abandoned cavern, the long-term evolution of brine pressure is governed by four main factors:

(1) brine warming and brine thermal expansion (Q_{therm});

(2) cavern creep closure (Q_{creep});

(3) brine permeation through the cavern walls (Q_{perm}); and

(4) gas leaks through the plugged and cemented well, or gas dissolution (Q_{loss}).

Each of these four factors is described more precisely in the following.

The cavern-volume change rate is the sum of the brine-volume change rate and the gas-volume change rate. These quantities can be expressed as follows:

$$\dot{V}_c = \dot{V}_b + \dot{V}_g \tag{1}$$

$$\dot{V}_c = V_c\left[-\alpha_c\dot{T} + \beta_c\dot{P}\right] - Q_{creep} \tag{2}$$

$$\dot{V}_b = V_b\left[\alpha_b\dot{T} - \beta_b\dot{P}\right] - Q_{perm} \tag{3}$$

$$\dot{V}_g = V_g\left[\dot{T}/T - \dot{P}/P\right] - Q_{loss} \tag{4}$$

P and T are cavern pressure and temperature, respectively. "Q" is always a positive quantity (e.g., $Q_{creep} > 0$). Brine temperature evolution, or $T = T(t)$, is known. Unknown quantities are P (cavern pressure), and the volumes of the cavern, gas and brine (V_c, V_g, V_b ,respectively).

ASSESSMENT OF THE VARIOUS FACTORS

Brine thermal expansion (Q_{therm})

Brine thermal expansion, or $\alpha_b V_b \dot{T} = Q_{therm}$, can be expressed as follows:

$$Q_{therm} = \alpha_b V_b \frac{\Delta T}{t_c}\varphi'\left(t/t_c\right) \tag{5}$$

where $t_c = V_b^{2/3}/4k$ is the thermal characteristic time,

ΔT is the initial temperature difference between the (geothermal) temperature of the rock, T_∞, and the temperature of the cavern brine, T_i^0,

$\alpha_b \approx 4.4\times10^{-4}$/°C $\approx 2.45\times10^{-4}$/°F
is the brine thermal-expansion coefficient, and

φ(u) is a mathematical function (Van Sambeek et al., 2005) that does not depend on cavern size.

Cavern creep closure (Q_{creep})

$$Q_{creep} \approx A\exp\left(-\frac{Q}{RT_\infty}\right)V_c\left(P_\infty - P\right)^n = A^*\left(T_\infty\right)V_c\left(P_\infty - P\right)^n \tag{6}$$

is the (steady-state) creep closure rate, P is the cavern brine (and gas) pressure, and P_∞ is the geostatic pressure (at cavern depth). This very simple expression correctly captures the effects of brine pressure change. For numerical computations the so-called "Etrez 53" parameters were selected — i.e., $A = 0.64$ /MPa$^{3.1}$-year, $n = 3.1$, and Q/R = 4100 K (Brouard and Berest, 1998); T_∞ in K. When more precise predictions are needed, transient creep closure must be taken into account.

Brine permeation through the cavern wall (Q_{perm})

$$Q_{perm} = \frac{4\pi K}{\mu_b}R\left(P - P_o\right) \tag{7}$$

is the (steady-state) brine outflow rate from the cavern rock mass through the cavern wall. It is proportional to the difference $\left(P - P_o\right)$ between brine pressure and brine pore pressure in the rock mass. It often is assumed that pore pressure, P_o, equals halmostatic pressure at cavern depth: P_h (MPa) = 0.012 H (m), or P_h (psi) = 0.52 H (ft). (Larger values of pore pressure sometimes are found; see, for instance, Howarth et al., 1991). The brine outflow rate also is proportional to K/μ_b, where μ_b is the dynamic viscosity of brine (typically, $\mu_b = 1.2$ to 1.4×10^{-3} Pa.s), and K is the intrinsic permeability of salt. (K generally belongs to the range $K = 10^{-22}$ to 10^{-19} m^2; see, for example, Durup, 1994). However, many authors believe that K drastically increases when the cavern pressure is close to the geostatic pressure (i.e., when $P \approx P_\infty$). For numerical computations, the following parameter values were selected: $K = 6\times10^{-20}$ m^2, $\mu_b = 1.2\times10^{-3}$ Pa.s.

Gas leaks through the well

$$Q_{loss} = \chi\left(P - P_o\right) \tag{8}$$

Gas leaks through the well are assumed to be proportional to the difference between gas pressure and pore pressure in the cement and rock mass. During a Nitrogen Leak Test, the difference $P - P_o$ generally is in the range 5-10 MPa, and the maximum admissible leak rate (MALR) is

1000 bbls/year, or 160 m^3/year (Thiel, 1993). [Crotogino (1994) suggests 270 m^3/year.] In an actual cavern, χ typically ranges from 0 to 15 m^3/MPa-year (0-0.65 bbls/psi-year). One significant difference between gas leaks and brine permeation is the fact that gas leaks (in m^3/year, or bbls/year) are not assumed to depend on cavern size (i.e., cavern radius, R).

When gas losses due to gas dissolution in cavern brine are considered, an additional term must be taken into account.

Thermo-elastic properties of cavern, brine and gas

Typical values of compressibility factors are $\beta_c = 1.3\times10^{-4}$ /MPa , $\beta_b = 2.7\times10^{-4}$ /MPa, $\beta = \beta_c + \beta_b = 4\times10^{-4}$ /MPa (2.8×10^{-6}/psi), and $\beta_g = 1/P$. Typical values of the thermal expansion coefficients are $\alpha_g = 1/T$ (T in Kelvin) and $\alpha_b = 4.4\times10^{-4}$ /°C. α_c is more difficult to assess; in fact, cavern volume changes resulting from cavern temperature changes depend on the entire history of the rock temperature in the rock mass (not upon the cavern temperature alone). However, in the case of an (idealized) perfectly spherical or cylindrical cavern, $\alpha_c = 0$.

ORDERS OF MAGNITUDE

In order to get a simpler set of equations, it is important to discuss the relative orders of magnitude of the volume changes.

Cavern volume

We are interested here in the behavior of a closed cavern about one century after it was sealed. If we restrict ourselves to the case of caverns with depths smaller than, say, $H = 1200$ m (3600 ft), the following can be assumed.

- When cavern depth is smaller than, say, $H = 800$ m (2500 ft), the creep closure rate often is slower than $\dot{V}_c/V_c = 10^{-4}$/year (when cavern pressure is halmostatic). After one century, the overall cavern volume change is smaller than 1% and $V_c \approx V_c^0$; V_c^0 is the initial cavern volume.
- When cavern depth is in the range $H = 800-1200$ m (2500-3500 ft), the creep closure rate is expected to be significantly faster (typically, $\dot{V}_c/V_c = 10^{-4}-10^{-3}$/year). However, when such a cavern is sealed, fast initial pressure build-up rates are likely to develop (Pressure build-up rates due to creep closure alone typically are $\dot{V}_c/\beta V_c = 2.5$ MPa/year .), which results in a rapidly decreasing difference between geostatic pressure and brine pressure and, thus, rapidly decreasing creep closure rates: here again, $V_c \approx V_c^0$.

It can be concluded that in such contexts, Equation (2) can be replaced by:

$$\dot{V}_c/V_c^o = \beta_c\dot{P} - A\exp\left(-\frac{Q}{RT_\infty}\right)\left(P_\infty - P\right)^n \tag{2'}$$

However, the above-mentioned figures are indicative, and it is known that in some salt formations, creep closure rates are faster than indicated above. Analysis must be performed on a case-by-case analysis. In such cases, or when the cavern is deeper than $H = 1200$ m (3500 ft), Equation (2), which is more accurate, must be used.

Brine volume

The same can be said of brine volume: when (2') is accepted, and keeping in mind that gas volume is much smaller than brine volume, Equation (3') can be accepted:

$$\dot{V}_b / V_c^o = (1-x)\left(\alpha_b \dot{T} - \beta_b \dot{P}\right) - \frac{3K}{\mu_b R^2}(P - P_o) \qquad (3')$$

Gas volume

Gas volume changes cannot be neglected as, when a gas loss exists, the volume of gas varies from V_g^o (initial gas volume) to zero (when all the gas has escaped from the cavern). If we set $x = V_g / V_c$ (i.e., $x \approx V_g / V_c^o$), Equation (4) can be re-written as:

$$\dot{x} = x\left[\dot{T}/T - \dot{P}/P\right] - \chi(P - P_o)/V_c^o \qquad (4')$$

Simplified set of equations

When the above-mentioned set of equations is accepted, Equations (1'), (2'), (3'), (4') can be combined to achieve a simpler system:

$$\left[\beta + x(1/P - \beta_b)\right]\dot{P} = \left[(1-x)\alpha_b + x/T\right]\dot{T} + A^*(T_\infty)(P_\infty - P)^n - \left(\frac{3K}{\mu_b R^2} + \frac{\chi}{V_c^o}\right)(P - P_o) \qquad (1')$$

$$\dot{x} = x\left[\dot{T}/T - \dot{P}/P\right] - \chi(P - P_o)/V_c^o \qquad (4')$$

Pressure evolution in a closed cavern

No gas loss

In the absence of a gas leak, the following simplified equations can be adopted:

$$\left[\beta + x(1/P - \beta_b)\right]\dot{P} = \left[(1-x)\alpha_b + x/T\right]\dot{T} + A^*(T_\infty)(P_\infty - P)^n - \left(\frac{3K}{\mu_b R^2}\right)(P - P_o) \qquad (7)$$

$$\dot{x} = x\left[\dot{T}/T - \dot{P}/P\right] \qquad (8)$$

Existence of a gas leak

When gas leaks, the amount of gas in the cavern is a function of time. Two cases must be distinguished:

When $x(t) > 0$ (There is still some gas in the cavern.),

$$\left[\beta + x\left(1/P - \beta_b\right)\right]\dot{P} = \left[(1-x)\alpha_b + x/T\right]\dot{T} + A^*\left(T_\infty\right)\left(P_\infty - P\right)^n - \left(\frac{3K}{\mu_b R^2} + \frac{\chi}{V_c^o}\right)\left(P - P_o\right) \qquad (1')$$

$$\dot{x} = x\left[\dot{T}/T - \dot{P}/P\right] - \chi\left(P - P_o\right)/V_c^o \qquad (4')$$

When $x = 0$ (There is no more gas in the cavern.),

$$\beta\dot{P} = \alpha_b\dot{T} + A^*\left(T_\infty\right)\left(P_\infty - P\right)^n - \left(\frac{3K}{\mu_b R^2} + \frac{\chi'}{V_c^o}\right)\left(P - P_o\right) \qquad (1'')$$

where χ' is a parameter that describes possible brine leaks (instead of gas leaks) through the cemented well.

These equations were used to draw Figures 1 to 5.

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