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The Effect of a Gas Blanket

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PRESSURE BUILD-UP IN A SEALED CAVERN: THE EFFECT OF A GAS BLANKET

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ABSTRACT

In a paper presented during the Rapid City SMRI 2006 Fall Meeting; the authors suggested that, before abandonment, a small quantity of gas be injected in the cavern to increase cavern compressibility and to prevent pressure build-up from being too severe. This solution proved to be robust in that a gas leak can be beneficial, making pressure build-up even slower than when gas remains trapped in the cavern.

Here, a 100,000-m^3 gas storage cavern is studied. The cavern is filled with soft water before being abandoned, and the temperature gap between the rock mass at cavern depth and the cavern brine is large. The amount of gas to be injected in the cavern prior to abandonment and the effect of a possible gas leak are discussed.

Keywords: Abandonment, Cavern Plugging

1 INTRODUCTION

1.1 Main factors in the behaviour 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.)

When brine warming is negligible, an equilibrium pressure is reached when cavern creep closure (which leads to pressure build-up in a closed cavern) exactly equals brine permeation toward the rock mass plus possible leaks. (Both reduce the brine volume contained in the cavern.) This notion has been proven by two SMRI-supported in-situ tests (Bérest et al., 2001; Brouard Consulting et al., 2005).

Brine warming raises the most difficult issues. Brine warming originates from the temperature difference between the rock temperature and the cavern brine temperature that exists before the cavern is sealed. In general, brine is colder than rock. After cavern sealing, heat slowly is transferred from the rock mass to the cavern brine, and the brine gently warms to reach equilibrium with the rock mass. Brine warming is more intense when the initial temperature difference, which is dependent on cavern depth and cavern history, is greater. The brine warming rate is faster in a smaller cavern. Brine warming generates the thermal expansion of the brine and the pressure build-up in a closed cavern. In sharp contrast with the effects of creep closure alone, brine warming plus creep closure can cause the pressure to build up to figures larger than geostatic ("overburden" or "lithostatic") pressure, leading to possible hydro-fracturing and the pollution of shallow water-bearing strata (Figure 1).

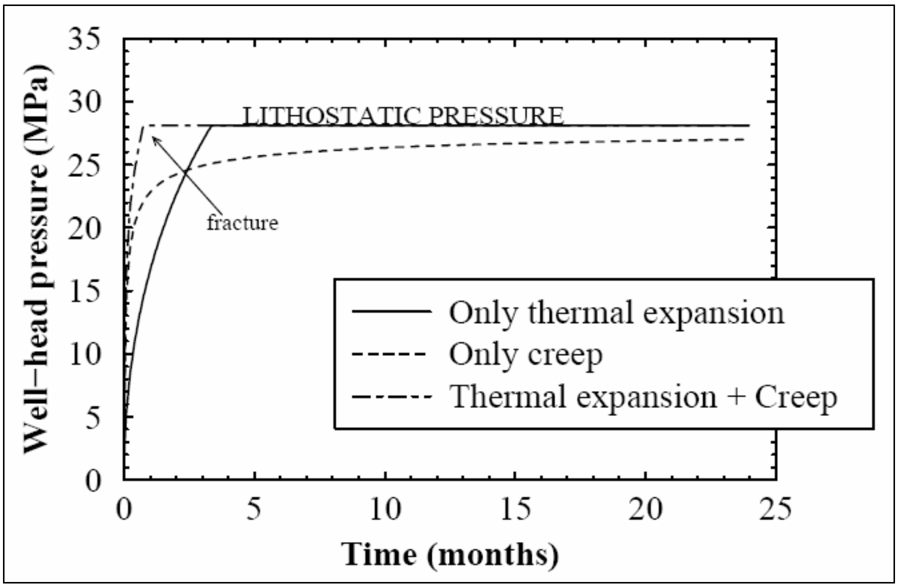

Figure 1 - Computed pressure evolution in a closed cavern. Brine thermal expansion leads to fracture.

1.2 Waiting period

In some cases, such a scenario simply can be alleviated by waiting for some time before sealing the cavern. During the waiting period, a significant part of the temperature difference resorbs, and brine warming effects become sufficiently small to allow safe cavern sealing. Unfortunately, such an option is not realistic when a large and deep cavern is considered. In such a case, the waiting period can be several decades long.

1.3 Increasing cavern compressibility

Increasing cavern compressibility is another option. The cavern compressibility is the inverse of the stiffness of the (cavern + fluid stored in the cavern) system. The cavern compressibility is relatively small, because brine is a stiff body (much stiffer than gas), and the cavern compressibility factor generally is in the range 3.5 to 5×10^{-4} /MPa (Bérest et al., 1999) — i.e., approximately 3×10^{-6}/psi (Blair, 1998). This means that a temperature increase of 1°C, which leads to an increase of $\alpha_b = 4.4\times10^{-4}$ /°C in brine volume when the cavern is opened, will lead to brine pressure build-up of (approximately) $\beta/\alpha_b \approx 1$ MPa/°C in a closed cavern. This figure explains why brine warming has a dramatic effect on cavern pressure. However, cavern compressibility can be increased easily by injecting a small amount of gas before sealing the cavern (Figure 2). Nitrogen, which is inert and inexpensive, is a good candidate. Equations that describe pressure evolution in a cavern whose compressibility was lowered were discussed in Bérest et al. (2006), in which several examples were given and in which the following was proved.

1. The existence of a gas "leak" (an actual leak, or dissolution of nitrogen in brine, which acts as a leak) is favourable. A gas leak offers more room for the thermal expansion of brine and prevents fast cavern pressure build-up.

2. The "waiting period" option and the "compressibility increasing" option can be combined conveniently. A 2-3 year waiting period allows a smaller amount of gas to be injected into the cavern than would be were the cavern sealed without a waiting period. The duration of the "waiting period" can be optimized on a case-by-case basis.

Computations were performed in Bérest et al. (2006) in the case of idealized spherical caverns. More realistic computations are presented in this paper. The case of a gas cavern was selected. Natural gas storage caverns in general are especially demanding from the point of view of cavern abandonment because they are large and deep (Kansas is an outstanding exception); prior to abandonment natural gas is withdrawn from the cavern and cold water (or brine) is injected in the cavern, resulting in a high initial temperature difference between cavern brine and rock mass.

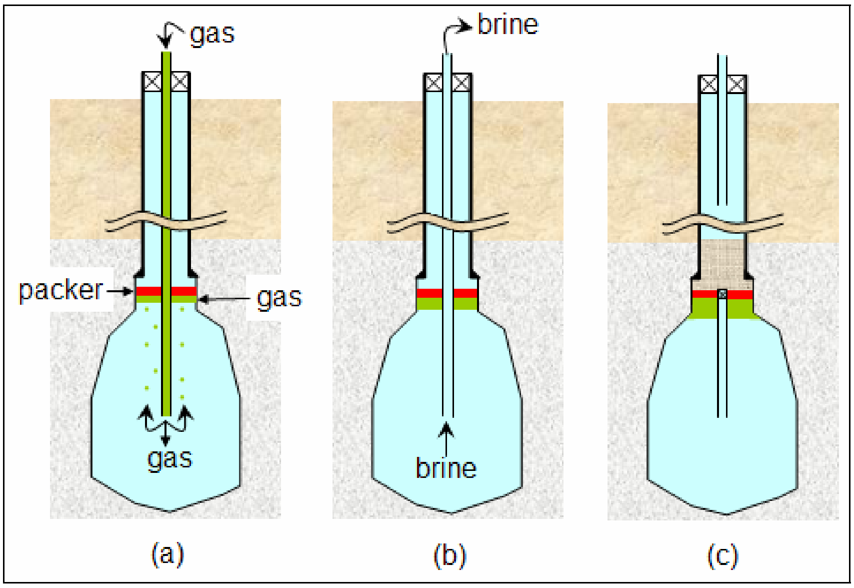

Figure 2 - Increasing cavern compressibility: (a) gas is injected below the packer; (b) brine is withdrawn to release pressure build-up; (c) the central tubing is sealed and cement is poured into the well.

2 CAVERN BEHAVIOR

2.1 Cavern shape and history

A vertical cross-section of the cavern is shown on Figure 3. The casing-shoe depth is 1360 m (4150'), the average depth is 1425 m (4350'), and the cavern volume is 300,000 m^3 (1,900,000 bbls). Before cavern sealing, natural gas is withdrawn, water is injected into the cavern, and a small nitrogen cap is left at cavern top.

For this example, the cavern has been operated as a natural-gas storage cavern for 30 years before being abandoned. During the operation period, cavern pressure is cycled on a yearly basis to be between 7 MPa and 27 MPa. The average pressure is 17 MPa, which also is the halmostatic pressure at cavern mid-depth (i.e., the pressure of the cavern when the cavern and the well are filled with saturated brine). The geostatic pressure at the casing shoe is approximately 30 MPa. At the end of the operating period, the cavern pressure is halmostatic (i.e., 17.1 MPa at a 1425-m depth). Cold brine is injected into the cavern (Figure 4), and the cavern temperature is lowered abruptly from 58 °C (i.e., 136 °F geothermal temperature) to 28 °C (i.e., 82 °F) — in other words, the temperature is lowered by 30 °C or 86 °F. The rock temperature, which was 58 °C at cavern average depth before the cold brine injection, slowly decreases as heat is transferred from the rock mass to the cavern brine, whose temperature slowly increases.

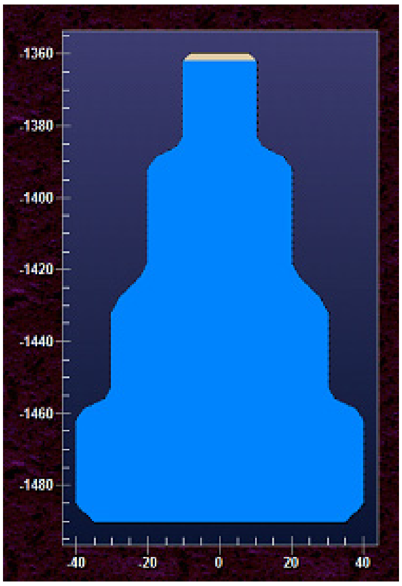

Figure 3 - Cavern shape – Nitrogen cap volume is $V_g = 300\ \mathrm{m}^3$ in this example.

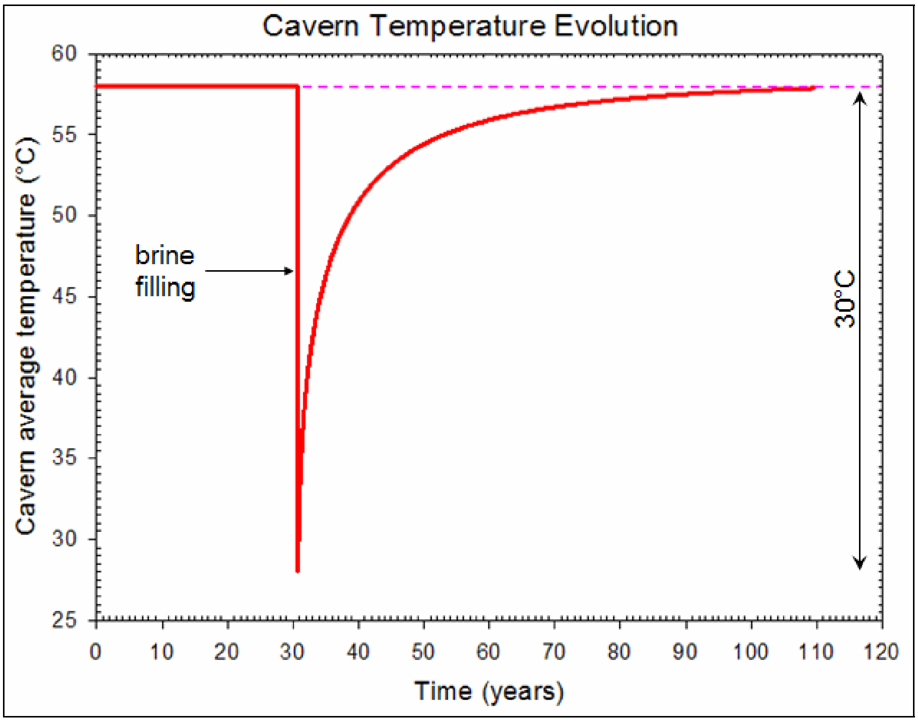

Figure 4 - Cavern temperature evolution.

Later, the brine temperature increases. Brine temperature evolution is governed by heat conduction in the rock mass and heat convection in the cavern. Convection results in an almost uniform temperature in the entire cavern.

Depending on the selected sealing strategy, the cavern is sealed 6 months, 1 year, 5 years or 6 years after cold brine injection. (The objective of the "waiting period" is to allow some of the initial temperature difference to resorb.) When the cavern is sealed, a small volume of nitrogen is injected into the cavern. (The objective of this injection is to increase cavern compressibility and lessen the detrimental effect of the brine temperature increase on cavern pressure.) After cavern sealing, the brine pressure slowly increases under the combined effects of cavern creep closure, brine thermal expansion, brine permeation through the rock mass, and additional dissolution generated by cavern pressure and temperature changes.

The objective of the numerical computations is to select the length of the waiting period and the amount of injected nitrogen in such a way that hydrofracturing does not occur.

2.2 Selection of parameters

2.2.1 Temperature evolution

Rock temperature evolution is governed by thermal conduction. The thermal conductivity of salt is approximately $K_{salt}^{th} = 6$ W/m-K , and the heat capacity of rock is $\rho_{salt} C_{salt} = 2\times10^6$ J/m^3-K, making the thermal diffusivity of salt $k_{salt}^{th} = 3\times10^{-6}$ m^2/s. Brine temperature is uniform in the entire cavern. The heat flux through the cavern walls results in brine warming. The brine heat capacity is $\rho_b C_b = 4.8\times10^6$ J/m^3-K , the thermal expansion coefficient of brine is $\alpha_b = 4.4\times10^{-4}$ /°C , and the cavern compressibility factor (when no nitrogen is injected in the cavern) is $\beta \approx 3.5\times10^{-4}$ /MPa.

2.2.2 Salt mechanical behaviour

The constitutive law of rock salt is elasto-visco-plastic. The elastic parameters of salt are shown inTable 1.

Table 1 – Salt elastic parameters.

Properties	Unit	Value
Young's modulus	MPa	25000
Poisson's ratio	—	0.25

Long-term salt creep rate is described by a Norton-Hoff relation with the parameters shown in Table 2.

Table 2 – Norton-Hoff law parameters.

$$\dot{\varepsilon}_{ss}^{ij} = A\exp\left(-\frac{Q}{RT}\right)\frac{1}{n+1}\frac{\partial}{\partial\sigma_{ij}}\left[\left(\sqrt{3J_2}\right)^{n+1}\right]$$

Parameter	Unit	Value
A	/MPa^n-year	0.64
n	—	3.1
Q/R	*K*	4100

The selected parameters were suggested by Pouya (1991) to describe Etrez salt and were backfitted against the results of an in-situ test, Bérest et al. (1999).

2.2.3 Micro-permeation

The virgin brine pressure in the salt formation is assumed to be halmostatic. (No brine flow takes place before sealing, when the cavern pressure is halmostatic.) Brine thermal expansion and cavern creep closure result in cavern pressure build-up and brine flow from the cavern to the rock mass. Brine flow is governed by Darcy's law. The intrinsic permeability of salt is $K_{salt}^{perm} = 5\times10^{-20}$ m^2. Brine viscosity is $\mu_b = 1.2\times10^{-3}$ Pa.s, and Biot's modulus is $M = 250$ GPa, making the hydraulic diffusivity of salt $k_{salt}^{hyd} = K_{salt}^{hyd} M / \mu_b = 3.8\times10^{-6}$ m^2/s.

2.2.4 *Additional dissolution*

Brine concentration at saturation is a function of both temperature and pressure. After cavern sealing, the brine temperature and pressure change, resulting in the additional dissolution of salt to restore chemical equilibrium with the changing environment. Salt dissolution offers additional room for cavern brine and results in a (small) pressure decrease. A complete description of this phenomenon can be found in Van Sambeek et al. (2005); it is taken into account in the numerical computations using *LOCAS* software (Brouard et al., 2006).

2.2.5 *Salt failure criterion*

The major objective is to prevent hydrofracturing. To do so, the following criterion was selected. Let $\sigma_M < \sigma_{\text{int}} < \sigma_m$ be the three main stresses (Compressive stresses are negative.), and let P be the cavern brine pressure. No fracturing occurs when $P + \sigma_m < 0$. (This criterion is conservative, as no tensile strength is taken into account.) Numerical computations prove that, when slow pressure evolutions are considered, this criterion is equivalent to the simpler criterion $P < P_\infty$, where P_∞ is the geostatic pressure at cavern wall depth. (The two criteria are not equivalent when the pressure build-up is fast (Karimi-Jafari et al., 2006); brine pressure evolution in a sealed cavern is slow enough to allow stress redistribution inside the rock mass to be (almost) completed at any time.)

2.2.6 *Mesh*

In numerical computations, 8651 elements (4520 nodes) were used (see Figure 5).

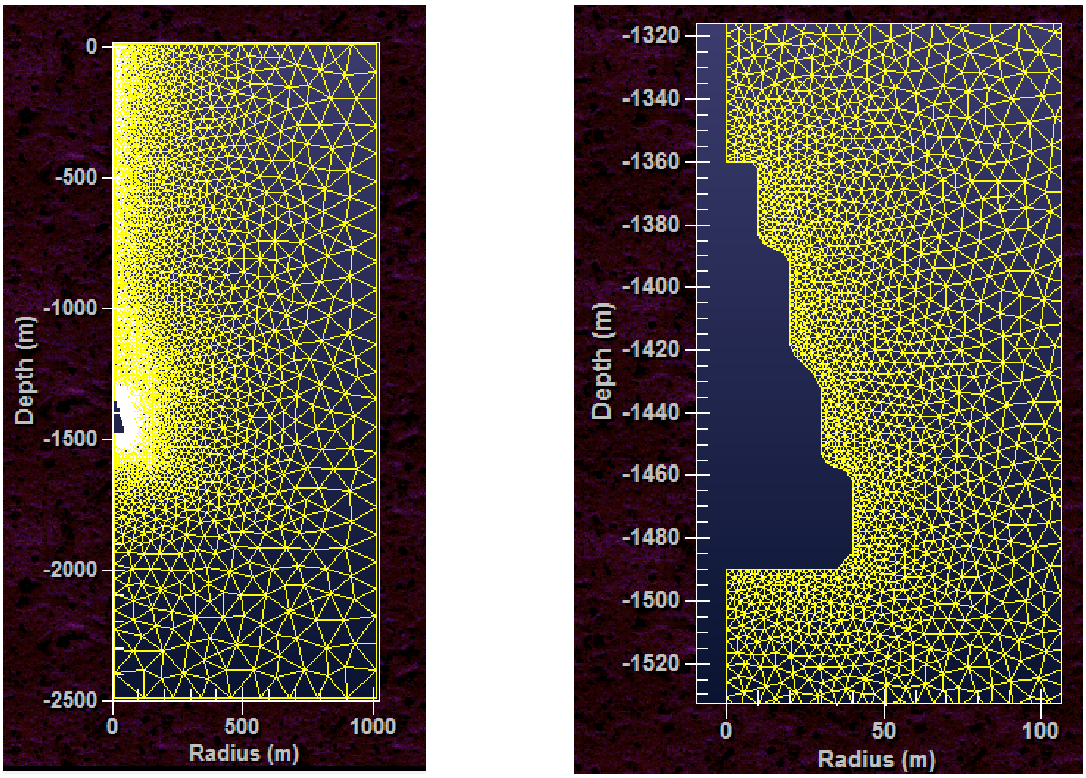

Figure 5 - Rock mass mesh (left) and mesh in the cavern area (right).

3 COMPUTATIONAL RESULTS

Case 1 — 6-month waiting period, no gas

In this case (Figure 6), no gas is injected before closing the cavern, and the cavern is sealed 6 months after cold brine injection is completed. The fracture criterion is reached 1 year after cavern sealing.

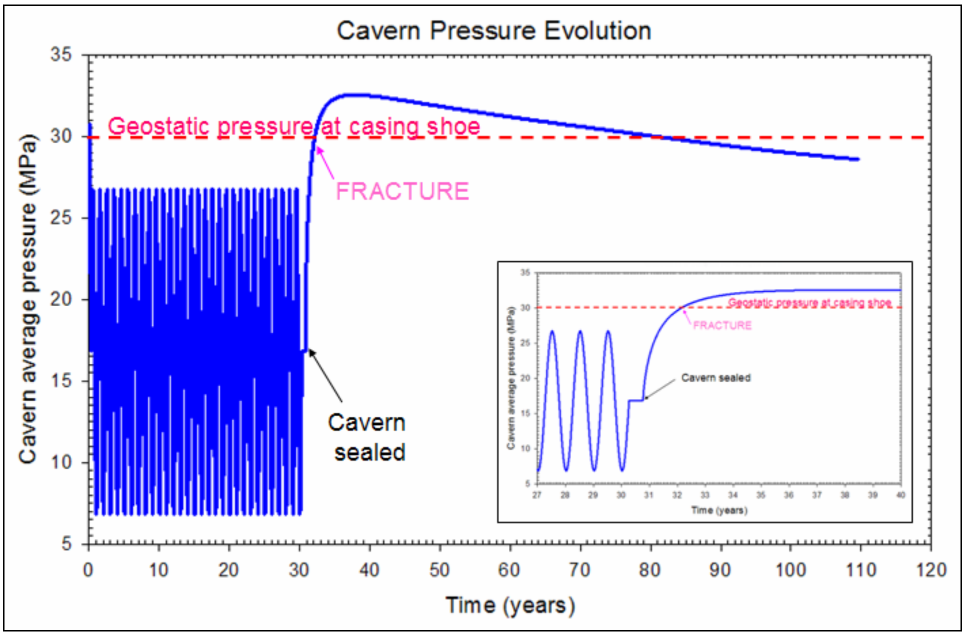

Figure 6 – Cavern pressure evolution, Case 1 — 6-month waiting period, no gas.

Case 2 — 5-year waiting period, no gas

Here, again (Figure 7), no gas is injected in the cavern before cavern sealing. The cavern is sealed 5 years after cold brine injection: no fracture occurs.

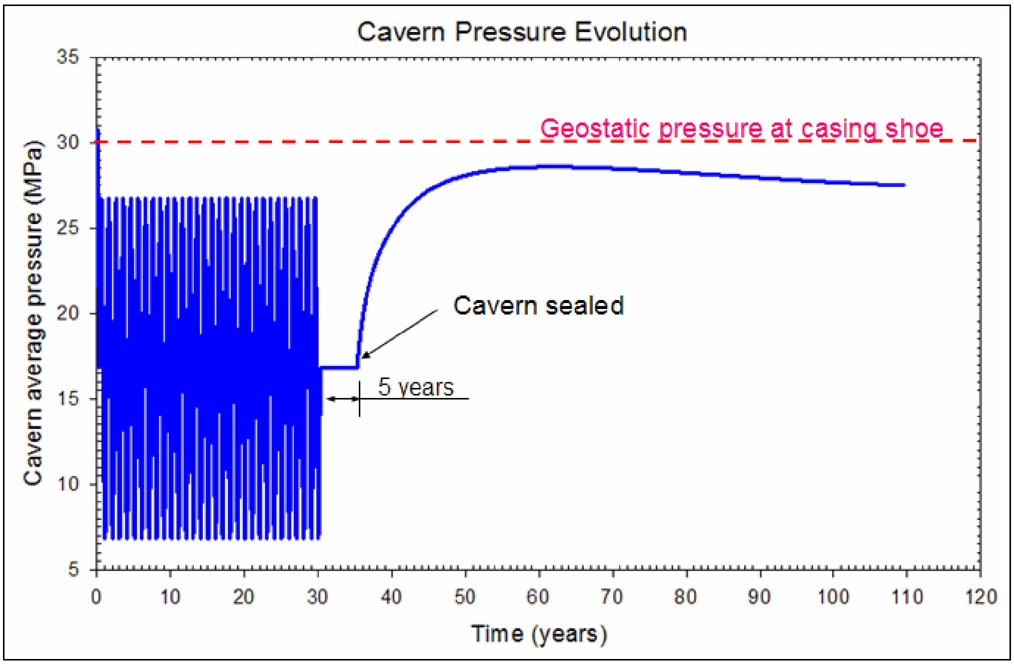

Figure 7 - Cavern pressure evolution, Case 2 — 5-year waiting period, no gas.

Case 3 — 6-month waiting period, $V_g = 900\ m^3$ (0.3% of cavern volume)

In this case (Figure 8), $900\ m^3$ of nitrogen are injected before cavern sealing, 6 months after cold brine injection. Cavern pressure reaches the maximum allowable pressure, but no fracturing occurs.

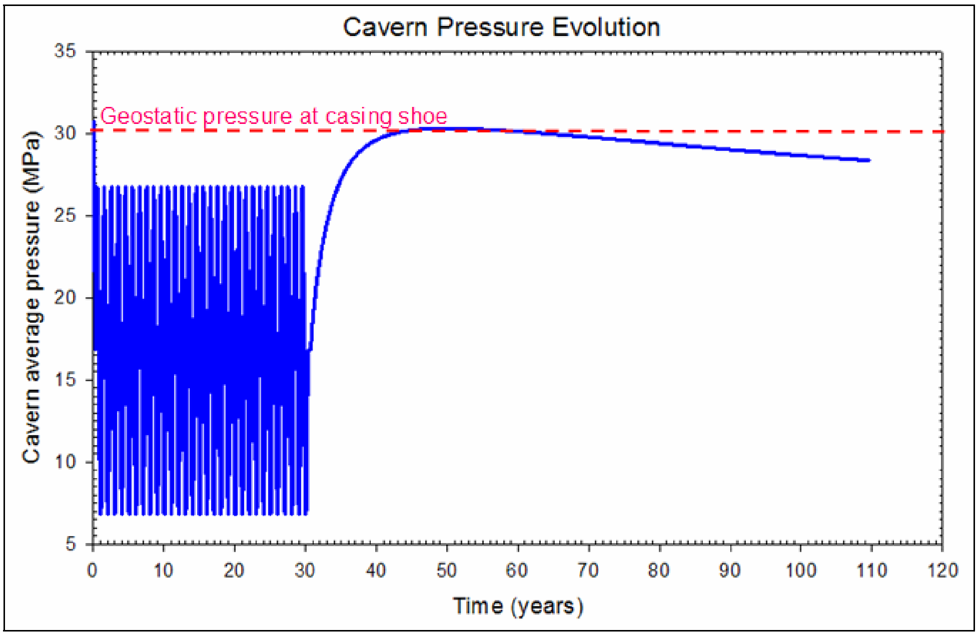

Figure 8 - Cavern pressure evolution, Case 3 — 6-month waiting period, $V_g = 900\ m^3$.

Case 4 — 1-year waiting period, $V_g = 300\ m^3$ (0.1% of cavern volume)

In this case (Figure 9), $300\ m^3$ of nitrogen are injected before cavern sealing, and the cavern is sealed one year after cold brine injection. Cavern pressure reaches the maximum allowable pressure, but no fracturing occurs.

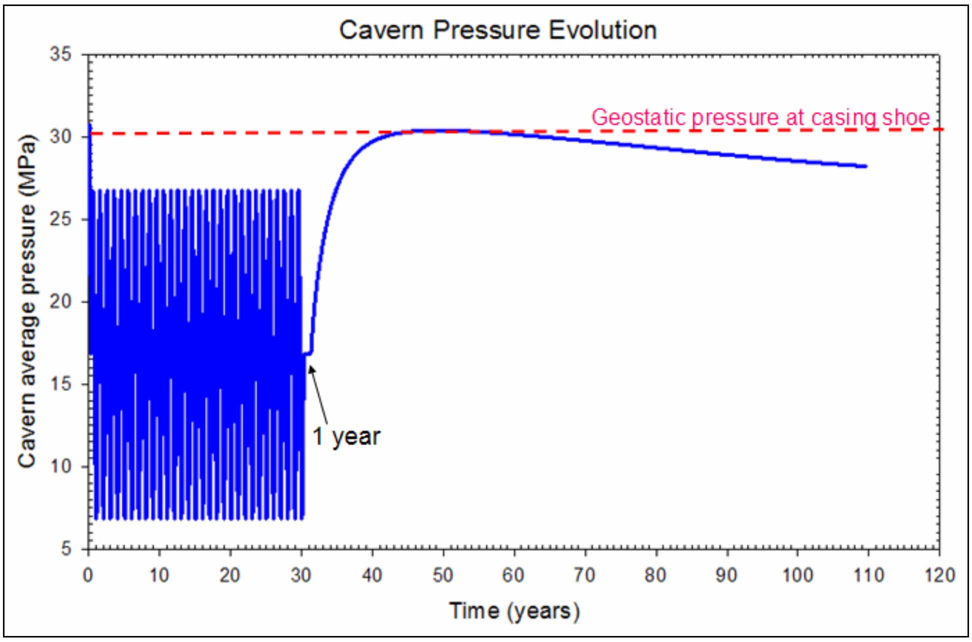

Figure 9 - Cavern pressure evolution, Case 4 — 1-year waiting period, $V_g = 900\ m^3$.

Case 5 — 6-month waiting period, V_g = 300 m^3, small gas leak

In this case (Figure 10), 300 m^3 of nitrogen are injected before sealing and cavern is sealed, only 6 months after cold brine injection. A gas leak of $\chi = 5$ m^3/MPa/year (i.e., a 250 bbls/year leak during an MIT when testing gradient is 0.78 psi/ft) is permitted. Cavern pressure reaches the maximum allowable pressure, but no fracturing occurs.

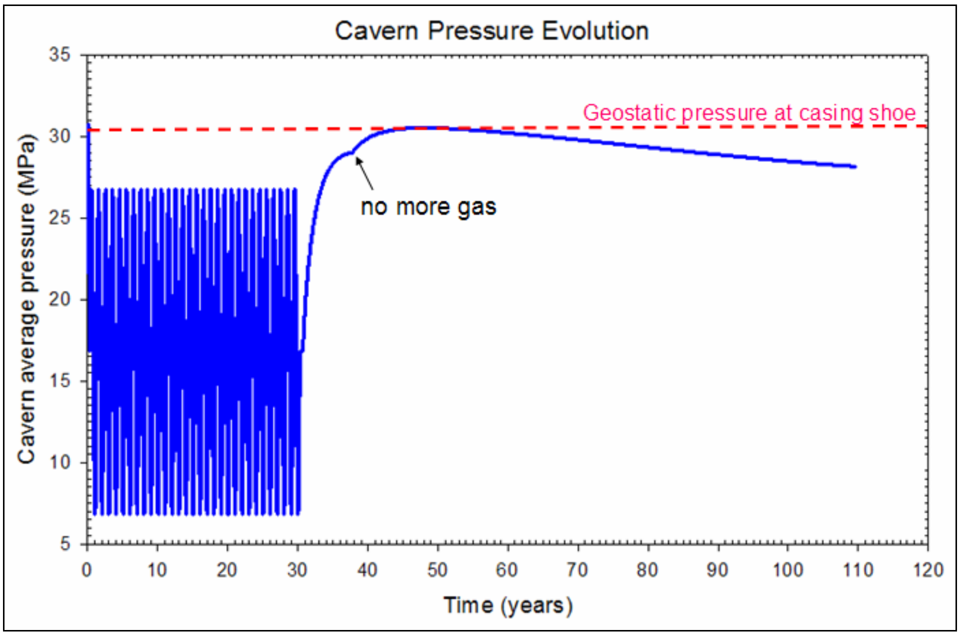

Figure 10 – Cavern pressure evolution, Case 5 — 6-month waiting period, V_g = 300 m^3, small leak.

Case 6 — 6-year waiting period, no gas, $K_{salt}^{perm} = 10^{-21}$ m^2

In this case (Figure 11), a lower value of salt permeability, $K_{salt}^{perm} = 10^{-21}$ m^2, is considered. No gas is injected, but, to avoid fracturing, there is a 6-year waiting period after cold brine injection.

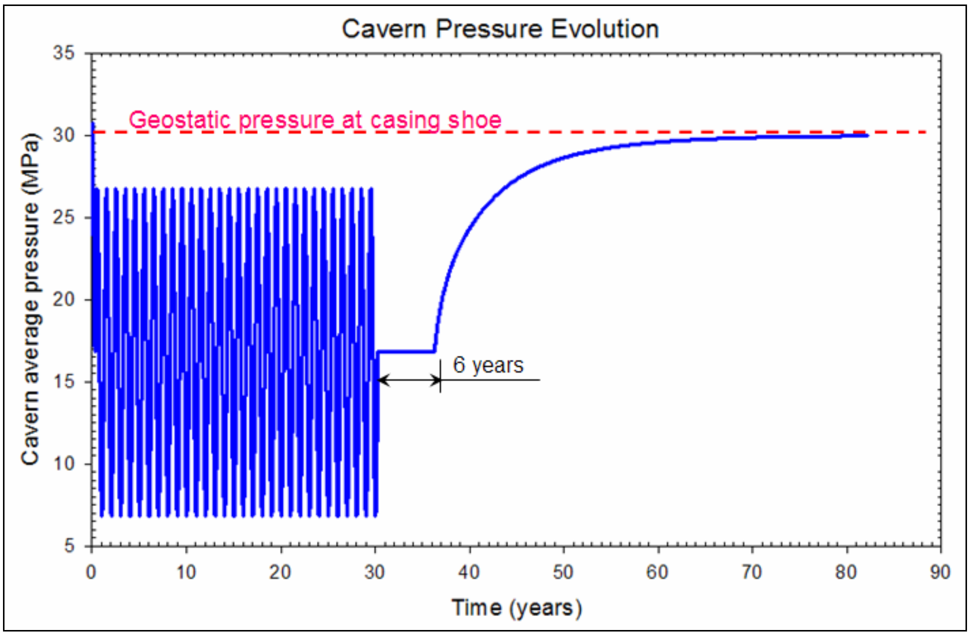

Figure 11 – Cavern pressure evolution, Case 6 — 6-year waiting period, no gas, $K_{salt}^{perm} = 10^{-21}$ m^2.

Case 7 — 2-year waiting period, $V_g = 900\ m^3$, $K_{salt}^{perm} = 10^{-21}$ m^2

In this case (Figure 12), a $K_{salt}^{perm} = 10^{-21}$ m^2 permeability is considered; 900 m^3 of nitrogen are injected before cavern sealing, and the cavern is sealed 2 years after cold brine injection. Cavern pressure reaches the maximum allowable pressure after 50 years, no fracturing occurs. As salt permeability is very small, the final pressure is very close to geostatic pressure.

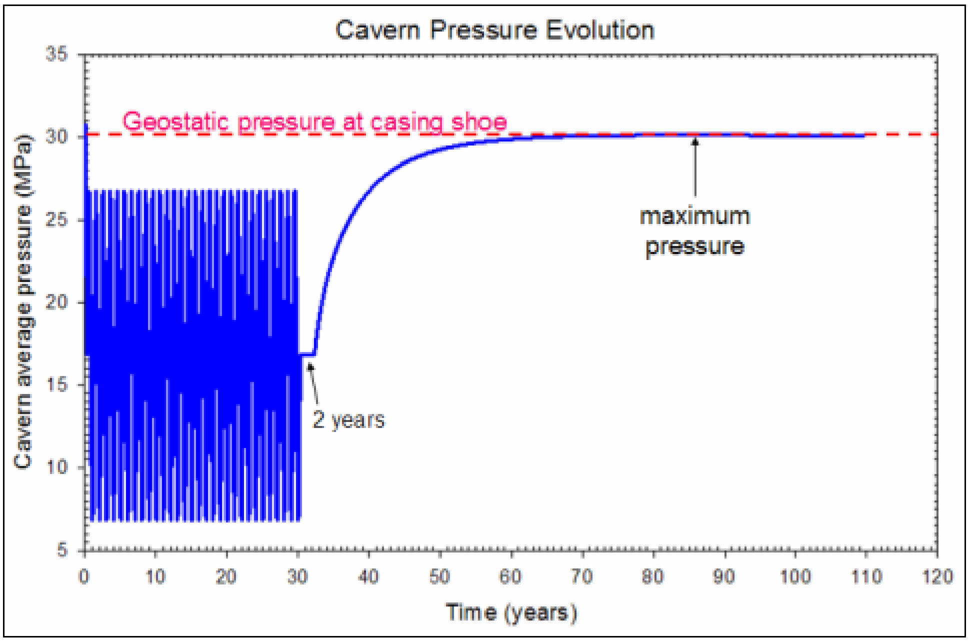

Figure 12 – Cavern pressure evolution, Case 6 — 2-year waiting period, $V_g = 900\,\mathrm{m}^3$, $K_{salt}^{perm} = 10^{-21}$ m^2.

CONCLUSIONS

It has been shown that in deep and large storage caverns, sealing the cavern immediately after hydrocarbon removal leads to cavern fracturing. Fracturing can be prevented when a waiting period is observed before sealing the cavern. The waiting period may be long. Injecting nitrogen before sealing the cavern increases cavern compressibility and prevents too large a pressure build up. Injecting nitrogen after a relatively short waiting period allows a significant reduction in the volume of nitrogen to be injected. Combining nitrogen injection and a waiting period is the best solution, which is optimized best on a case-by-case basis.

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