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Technical Paper

In-Situ Salt Permeability Testing

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IN-SITU SALT PERMEABILITY TESTING

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Abstract

Salt permeability is generally considered to be exceedingly small, with typical figures in the range $K = 10^{-21}$ m^2 to $K = 10^{-19}$ m^2. These figures imply minute amounts of fluid loss from a storage cavern operated under standard conditions. However, when very long periods of time (decades and centuries) are considered, the cumulated brine flow from a fluid-filled closed cavern cannot be neglected; it can lead to the release of cavern pressure, which is an important concept in the study of cavern abandonment. For this reason, accurate assessment of salt formation permeability is of major importance.

Laboratory tests provide some insight into the mechanisms of salt permeability, but they underestimate the actual permeability of a salt formation to some extent. In-situ tests on full-sized caverns are scare. Tests performed on wells, conducted prior to any leaching, are much easier to perform and interpret, because phenomena such as salt creep or brine warming play a much smaller role in wells than in full-sized caverns.

This paper describes leak tests performed on a dozen wells at two different sites. During these tests, pressure was built up to a relatively high figure and kept constant for several days or weeks through small fluid injections. The amount of injected fluid was recorded daily. The transient Darcy law was assumed and allowed back-calculation of the in-situ permeability. Test results for each individual site are consistent, but a clear difference can be observed between the two sites discussed here. The permeability values of these sites are in the range $K = 1 - 3 \times 10^{-21}$ m^2 and $K = 0.5 - 2 \times 10^{-20}$ m^2 respectively. Tests performed at different pressure levels in the same cavern prove that rock mass permeability increases when cavern pressure is close to geostatic pressure. This result is confirmed by a re-examination of a year-long test performed at the Etrez site in 1988.

1 Introduction

The permeability of geological rock-salt formations is considered generally to be exceedingly small — so small that the applicability of the Darcy law (Fluid flow is proportional to the head gradient.) can be questioned. The same can be said of pore pressure (i.e., a continuous quantity describing fluid pressure in the interconnected pores and microcracks present at the crystal boundaries). In fact, these notions are of empirical origin: when in pressure builds up in a well or in a cavern, seepage flow is more or less proportional to the difference between the built-up pressure (P_i) and the pressure (P_o) that is deemed (to be the pore pressure of the salt formation. The proportionality ratio between brine flow and pressure difference can be related to salt formation permeability (K) provided that the Darcy law is assumed, but the exact mechanisms allowing brine to permeate through the rock mass are still open to discussion.

1.1 Storage Cavern

When the Darcy law is accepted, values such as $K = 10^{-21}$ m^2 to $K = 10^{-19}$ m^2 can be back-calculated from available test results. The origins of these data will be discussed later. How small these figures are is demonstrated clearly when one considers the case of a 100,000-m^3 cavern leached out from a salt formation at a depth of 1000 m. If the brine pore pressure is assumed to be $P_o = 12$ MPa (approximately 1700 psi), and the brine cavity pressure is assumed to be 22 MPa (approximately 3100 psi), then the steady-state brine seepage rate from the cavern to the rock mass is

$$Q = 4\pi R \frac{K}{\eta} \left(P_i - P_o\right) \tag{1}$$

where $\eta = 1.2 \times 10^{-3}$ Pa.s is the dynamic viscosity of the brine, and $R = 30$ m is the equivalent radius of the cavern (a spherical cavern shape is assumed). A permeability value of $K = 10^{-20}$ m^2 leads to an brine-loss rate of $Q = 1$ m^3/year — a definitely negligible quantity from the perspective of economics. or comparison, it should be kept in mind that Crotogino (1994) [9] recommends a Minimum Detectable Leak Rate (MDLR) during a nitrogen leak test of 250 kg/day. In other words, fluid leakage through the cased and cemented casing is, in most cases, much larger than fluid leakage through the cavity wall.

From the perspective of environmental protection, the fluid seepage rate through the rock mass in the given example would be

$$v = \frac{K}{\eta \phi} \frac{P_i - P_o}{R} \tag{2}$$

where ϕ is rock salt porosity ($\phi = 1\%$ is typical), or $v = 10^{-2}$ m/year. In this example, fluid will have migrated by 10 cm through the rock mass after ten years of operation.

1.2 Long-Term Behavior

The general picture changes when very long-term (decades and centuries) behavior is considered. Salt creep leads to cavern shrinkage and brine pressure build-up in a closed cavern (Wallner 1986 [24]; Cauberg et al. 1986 [7]; Van Sambeek 1990 [23]; Ehgartner and Linn 1984 [12]; Cosenza and Ghoreychi 1996 [8]; Wallner and Paar 1997 [25]; Bérest et al. 2001 [4]). If brine pressure reaches a figure significantly larger than geostatic pressure ($P_\infty = 22$ MPa or 3100 psi at a 1000 m depth), hydrofracturing is likely to occur, and brine will flow upward through fractures to shallow water-bearing strata, leading to water pollution, cavern collapse and subsidence.

This pessimistic scenario can be alleviated by taking into account salt permeability, which, in some cases, can contribute to brine pressure relief via brine seepage through the cavern walls. Bérest et al. (2001 [4]) conducted an in-situ test that proved, for the case of the Etrez salt formation, that equilibrium occurred at a relatively low pressure level, when cavern shrinkage (due to salt creep) exactly balanced brine seepage (due to salt formation permeability). At the present time, many researchers think that a similar phenomenon could take place even in an extremely tight salt formation because of enhanced permeability when cavern pressure is close to geostatic pressure (Ratigan 2001 [19]). In this context, an evaluation of salt formation permeability is important.

1.3 Permeability Test Results

Laboratory tests allow salt permeability to be analyzed under well-defined conditions, but rock samples can be damaged during sample collection and preparation, leading to an increase of salt permeability by orders of magnitude (Aufricht and Howard 1961 [1]; Baar 1977 [2]; Guessous et al. 1988 [14]; Sutherland and Cave 1980 [22]; Peach 1991 [17]; Stormont and Daemen 1992 [21]; Bérest et al. 2001 [4]). This damage can be partly healed by applying an isotropic stress to the rock samples, but uncertainty on the exact value of natural salt permeability remains.

In-situ tests performed in the vicinity of gallery walls provide direct information on permeability increase in the disturbed zone. For example, Dale and Hurtado (1997) [10] found that the permeability of undisturbed salt was smaller than $K = 10^{-21}$ m^2 during experiments performed at the WIPP site.

Few permeability tests are available in the specific context of solution-mined cavities or wells. Conditions are so different in this context (fairly high saturated brine pressure rather than air at atmospheric pressure) that results should not be transposed heedlessly.

A one-year-long test was performed by Durup (1994) [11] in the 200 m-high unlined part of a 1000 m-deep well. A permeability of $K = 6 \times 10^{-20}$ m^2 was found. This test, supported by the SMRI, will be discussed below. In another SMRI-supported test, Bérest et al. (2001 [4]) back-calculated the permeability in a 7500-m^3 cavern, as $K = 2 \times 10^{-19}$ m^2. In this paper, we present tests performed in a dozen wells at two storage sites.

2 The GDF Testing Method

2.1 Introduction

Fluid seepage from a pressurized cavern can take place (Figure 1):

- (a) through the cemented casing;
- (b) in the vicinity of the casing shoe; and/or
- (c) through the rock formation.

During the Nitrogen Leak Test (Figure 2), both the steel casing and the vicinity of the casing shoe [(a) and (b), above] are tested. A nitrogen column is lowered into the annular space below the shoe of the last cemented casing, and movement of the nitrogen/brine interface is monitored. Upward displacement of the interface is interpreted as a nitrogen leak (Crotogino 1994 [9]; Bérest et al. 2001 [6]).

During the GDF leak test (Figure 3), both the vicinity of the casing shoe and the rock formation [(b) and (c), above] are tested; tightness of the steel casing (a, above) is tested separately. This testing procedure is generally used before any leaching of the salt formation.

2.2 Testing Gradient

Testing pressure is generally defined as the prescribed fluid pressure that reigns at the casing-shoe depth during the test. This pressure equals the fluid pressure measured at the well head plus the pressure of the saturated brine column that runs from the well head to the casing shoe in the central tubing:

$$P_T = P_h + \rho_b g H \tag{3}$$

where P_T is the testing pressure. P_h is the well-head pressure, ρ_b is the saturated-brine density ($\rho_b \approx 1200$ kg/m^3), H is the casing shoe depth, and g is the gravity acceleration ($g \approx 9.81$ m/s^2).

The testing gradient, γ, is defined as

$$\gamma = \frac{P_T}{\rho_w g H} = \frac{P_h + \rho_b g H}{\rho_w g H} \tag{4}$$

where $\rho_w \approx 1000$ kg/m^3 is the density of soft water. The testing gradient is a dimensionless quantity: its value is $\gamma = 1$ when the column is filled with soft water and no pressure is applied at the well head; its value is $\gamma = 1.2$ when the column is filled with saturated brine (a situation often encountered in salt cavern wells) and no pressure is applied at the well head. The testing pressure is always smaller than $\gamma = 2.2$, a figure above which hydrofracturing is to be feared. A testing gradient of $\gamma = 2$ is often selected when natural gas is to be stored in a cavern; gradient values are smaller when liquid or liquefied hydrocarbon storage is considered.

A somewhat different definition of the testing gradient is sometimes used:

$$\gamma' \ \text{(MPa/m)} = P_T \ \text{(MPa)}/H \ \text{(m)} \tag{5}$$

or

$$\gamma' = 10^{-3} g\gamma \tag{6}$$

In other words, γ' is smaller than $\gamma/100$ by approximately 2%. In the following, by “testing gradient”, we mean γ.

2.3 Testing Procedure

The GDF leak test consists of two steps (Figure 3). At least one month after drilling (to allow thermal stabilization of the well to be completed), a central tube is set in the well. The length of the last cemented casing is somewhat smaller than the last cemented casing length. A packer is set in the annular space a few meters above the casing shoe to isolate the annular space from the brine volume encapsulated in the central tubing and the unlined part of the well. Then, a testing gradient of $\gamma = 1.46$ is built up both in the annular space and in the central tubing. Soft water is injected or withdrawn twice a day to keep the testing gradient constant in the two distinct spaces, and the injected volumes are measured carefully. The daily amount of water injected in the annular space is called the “casing seepage rate”, and the daily amount of water injected in the central tubing is called the “rock-formation seepage rate”. Because the testing gradients are identical in the annular space and the central tubing, no seepage takes place between these two spaces. The test is considered to be satisfactory when the casing seepage rate is smaller than $q = 1$ liter per day.

The second step consists of the "casing-shoe+plus-rock-formation" test. The testing gradient in the annular space is $\gamma = 1.46$, as it was during the first step. The testing gradient in the central tubing and in the unlined part of the well ranges from $\gamma = 1.8$ to $\gamma = 2.2$ depending on the site. (For the lifespan of a given site, there is a trend to increase the testing pressure when early test results and existing cavern behavior indicate that the cavern can withstand high storage pressure without any damage.)

Pressure evolution is then monitored in both the annular space and in the central tubing; soft water is withdrawn or injected twice a day to keep the pressures (or gradients) fairly constant during the entire test.

The daily fluid loss is then computed as follows:

Daily injected water volume in the central tubing
\+ Daily injected water volume in the annular space
\- Daily observed casing seepage rate during the first test (q)

= **Apparent daily fluid loss (Q)**

It must be noted that, in the "casing-shoe+rock-formation" permeability, the test procedure eliminates casing seepage, which is considered to be the same during the first and second steps. (This is a reasonable assumption, as the casing is submitted to the same fluid pressure during the two steps).

The observed daily fluid loss will be used later to back-calculate the equivalent permeability of the salt rock formation. It should be noted that these computations overestimate the actual equivalent permeability, because seepage through the casing shoe cannot be distinguished from seepage through the rock mass itself.

The test duration ranges from a few days to a couple of months. Special attention is given to the apparent daily fluid loss that occurs at the end of the test. The typical daily injected flow rate versus time is displayed on Figure 4.

2.4 A Comment on Test Accuracy

Testing the well before any leaching takes place has several advantages, as noted below.

- Leaching out a full-sized cavern is a costly operation; it is reasonable to check for any major flaws in well tightness before beginning such an operation.

- A well is much stiffer than a cavern, and testing in a well is much more accurate than in a cavern. Let v be the brine volume contained in a well (say, $v = 20$ m^3 during a GDF test) and V be the brine volume in a full-sized cavern (say, $V = 50,000$ m^3).

The well or cavern compressibility factor is approximately $\beta = 4 \times 10^{-4}$ MPa^{-1} (Bérest al. 1999 [3]). Thus, a brine loss of $Q = 1$ liter per day will induce a pressure drop in a well of $\dot{P} = Q/(\beta v)$, or 0.125 MPa/day (an easily detectable figure), and a pressure drop in a cavern of $\dot{P} = Q/(\beta V)$, or 5×10^{-5} MPa/day (an undetectable figure, easily hidden by a factor such as the thermal expansion of the brine).

- The pressure build-up in a closed cavern results from the combination of three phenomena: cavern creep, thermal expansion, and brine permeation (Bérest et al. 2001 [4]). Cavern creep and thermal expansion play preeminent roles, in all but old caverns (as thermal expansion may then be negligible) when brine pressure is high (cavern creep is then very slow).

  The diameter of the test well is smaller than the diameter of a cavern by two orders of magnitude. As a consequence, thermal equilibrium is reached within a few hours (instead of after several years, as in the case of a cavern). Moreover, the relative volumetric creep rate does not depend on cavity dimensions — in sharp contrast to permeation, which is proportional to the inverse of the square of the diameter. In other words, pressure evolution in an unlined well is governed mainly by brine seepage. Permeation effects are much easier to measure in a well than in a full-sized cavern.

The major drawback of the testing procedure is that well testing takes place before leaching operations are completed, which means that the effects of leaching on cavern tightness are not taken into account.

3 Test Interpretation

At the beginning of the second step of the test, fluid pressure in the well is rapidly increased to reach testing pressure. The response of the well to this pressure increase includes the following phenomena:

- (a) transient fluid permeation through the salt walls;
- (b) transient salt creep;
- (c) additional salt dissolution following pressure changes; and
- (d) brine thermal evolution (when the fluid temperature has not reached thermal equilibrium by the time the test begins).

The following effects are taken into account in the **LOSEEP** software[1]:

- With the well diameter being relatively small, thermal equilibrium is rapidly met (a few hours).

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[1] The **LOSEEP** software has been developed by Brouard Consulting and LMS/Ecole polytechnique, it allows to evaluate in-situ rock-salt permeability by simulating permeability tests before leaching.

- Transient salt creep and additional salt dissolution are difficult to separate, as they generate similar effects —i.e., a transient pressure decrease following any significant pressure increase (Bérest et al. 1999 [3]). Transient creep is simulated through the Lemaître law, which can be expressed as:

  $$\underline{\underline{\dot{\varepsilon}}}^{fl} = \frac{1}{K_{fl}} \left(\frac{\sqrt{3J_2}}{K_{fl}}\right)^{n-1} \frac{d}{dt}\left[\int_{-\infty}^{t} \frac{d(\underline{\underline{s}})}{d\tau}(t-\tau)^{\alpha} d\tau\right] \tag{7}$$

  where $\underline{\underline{s}}$ is the deviatoric stress tensor, $J_2 = 1/2 s_{ij} s_{ji}$ is the second invariant of the deviatoric stress tensor, and (α, n, K_{fl}) are Lemaître's parameters (Hugout 1984 [16]).

- Transient permeation is described by the Darcy law:

  $$\frac{\partial P}{\partial t} = \frac{K}{\eta\beta\phi}\,\Delta P \tag{8}$$

  where P is the brine pressure in the pores of the salt mass, K is the intrinsic permeability of the salt formation, η is the dynamic viscosity of the brine; β is the pore compressibility factor of the rock salt, and ϕ is the rock porosity.

Cylindrical symmetry of the brine flow is assumed, because the well length is much larger than its diameter. During the tests, a constant pressure difference between well fluid pressure, P_t, and initial pore pressure in the rock mass, P_o, is applied; then, the fluid pressure distribution has the following form:

$$P(r,t) - P_o = (P_t - P_o)\; f\left(\frac{r}{a}, \frac{K\,t}{a^2\eta\beta\phi}\right) \tag{9}$$

where a is the well radius, and t is the time since the pressure increase was applied. The function $f = f(\lambda, \tau)$, where $\lambda = r/a$, and $\tau = Kt/(a^2\eta\beta\phi)$, is such that

$f(1,\tau) = 1$ (Fluid pressure is $P(a,t) = P_t$ at cavern wall.)
$f(\infty,\tau) = 0$ (Fluid pressure is $P(\infty,t) = P_o$ at large distance.)

The exact mathematical expression of f can be obtained easily. Here, we are mainly interested in the fluid flow permeating through the unlined walls:

$$Q(t) = 2\pi h \frac{K}{\eta}\; (P_t - P_o)\; \frac{\partial f}{\partial \lambda}\left(1,\; \frac{K\,t}{a^2\eta\beta\phi}\right) \tag{10}$$

where h is the height of the unlined part of the well ($h \approx$ 200 m).

During the test, the apparent daily fluid loss is measured at a given instant t, or $Q = Q(t)$ (and corrected from the effects of transient creep and additional dissolution by the **LOSEEP** software). Quantities such as h (unlined well height), a (unlined well radius), or η (brine viscosity) can be considered to be well-known, and, while the testing pressure, P_t, is also known, the initial pore pressure, P_o, is difficult to assess. The same can be said of the quantity $\beta\phi = 1/M$.

Natural brine pressure in the interconnected pores or cracks cannot be measured directly. The Durup test (Durup 1994 [11]) proved that a linear relation did exist between the brine seepage rate and the pressure build-up in the tested Etrez well. Extrapolating this relation proves that no flow takes place when cavern pressure is equal to halmostatic pressure, which strongly suggests that natural pore pressure is equal to halmostatic pressure. Even if no clear physical argument can be made, this hypothesis seems to be widely accepted. The distribution of pore pressure in the formation is, then,

$$P_o \text{ (MPa)} = 0.012\ H \text{ (m)} \tag{11}$$

where H is the cavity depth.

However, test performed at the WIPP mine excavated in the Salado formation have provided higher figures ($P_o = 0.014\ H$; see Howarth et al. 1991 [15]). As seen by the halmostatic distribution expressed in (11), no brine flow to or from a cavern takes place when the cavity well is fill with saturated brine and opened to the atmosphere.

Figure 5 displays the daily fluid loss (in liters per day) as a function of rock permeability (in m^2) 60 days after the initial pressure build-up. Several values of $M = 1/(\beta\phi)$ have been considered ($M = 20$ GPa, 250 GPa and 37,000 GPa). During the computations provided below, salt pore compressibility and porosity are assumed to be $\beta = 4 \times 10^{-4}$ MPa^{-1} and $\phi = 1\%$, or $M = 250$ GPa, respectively. In other words, pores are assumed to behave as a cavern from the point of view of their compressibility factor, or β; the proposed salt porosity value, or ϕ, is probably an upper bound.

3.1 Test Results

Two different gas storage sites have been examined, Tersanne (Table 1) and Etrez (Table 2).

Well #	Testing Gradient	Test Duration (days)	Daily Volume Loss (liters/day)	Back-calculated Permeability (m^2)
Te01	1.89	6	0.65	1.6×10^{-21}
Te02	1.77	7	0.65	1.8×10^{-21}
Te03	1.73	305	0.57	3.2×10^{-21}
Te04	1.74	10	0.60	1.9×10^{-21}
Te05	1.73	10	0.58	1.1×10^{-21}
Te06	1.77	4	0.56	8.6×10^{-22}
Te07	1.77	20	0.57	1.4×10^{-21}
Te15	1.77	30	0.89	3.0×10^{-21}

Table 1: Tersanne tests results. (Daily volume loss is measured at the end of the test.)

Well #	**Testing Gradient**	**Test Duration (days)**	**Daily Volume Loss (liters/day)**	**Back-calculated Permeability (m^2)**
Ez11	1.8	5	4.50	1.3×10^{-20}
Ez12	1.8	4	2.08	4.6×10^{-21}
Ez12	2	5	4.66	9.2×10^{-21}
Ez17	2	42	7.8	1.9×10^{-20}
Ez18	2	126	6.24	1.4×10^{-20}
Ez18	2.2	84	9.15	1.6×10^{-20}

Table 2: Etrez tests results. (Daily volume loss is measured at the end of the test.)

The following conclusions can be drawn.

1. The computed permeability figures are consistent for the two series of tests: Tersanne ($K = 8.6{\times}10^{-22}$ m^2–$3.2{\times}10^{-21}$ m^2; and Etrez ($K = 4.6 \times 10^{-21}$ m^2 – 1.9×10^{-20} m^2).
2. When tests are performed on the same well but with two distinct pressure gradients (i.e., $\gamma = 1.8$ and $\gamma = 2$ for Ez12, $\gamma = 2$ and $\gamma = 2.2$ for Ez18, $\gamma = 1.8$ and $\gamma = 2$ for Te10), the apparent permeability is larger when the gradient is larger. This is consistent with observations made after several laboratory tests (Fokker 1995 [13]; Bérest et al. 2001 [5]) during which rock salt permeability increased when fluid pressure (or cavity pressure) was close to confining pressure.
3. Salt permeability at the Tersanne site is significantly smaller (by one order of magnitude) than salt permeability at the Etrez site. Tersanne salt is known to be more creep-prone than Etrez salt, but it is not clear at this time whether this correlation can be considered to be general — i.e., Are creep-prone salts less permeable?.

4 The Ez58 Test

At the present time, Statement 2, above, is of special significance, because the evolution of salt permeability as a function of cavern fluid pressure is an important question from the perspective of cavern abandonment (Ratigan 2000 [18]; Rokahr et al. 2000 [20]). In order to discuss permeability evolution, the test results have been revisited. This SMRI-supported test, performed 10 years ago by Durup, provides interesting field data from this perspective.

The Ez58 test has been performed in the Etrez upper salt formation. The last cemented casing shoe was 870.8-m deep, and the well was 1069-m long, or $h \approx 198$ m. A comprehensive description of the test can be found in Durup (1994 [11]). From October 1988 to December 1989, pressure in the well was built up incrementally. The testing gradient was increased from $\gamma' = 1.43 \times 10^{-2}$ MPa/m ($\gamma = 1.46$) to $\gamma' = 2.35 \times 10^{-2}$ MPa/m ($\gamma = 2.40$). Each step was approximately one month long. Pressure steps were $\delta\gamma = 0.2$ at the beginning of the test and $\delta\gamma = 0.05 \times 10^{-2}$ MPa/m at the end of the test. Table 3 and Figures 5 and 6 provide the main test results. Permeability has been back-calculated at the end of each step; the pressure history, including each of the steps, has been taken into account.

More precisely: K_{fin} is the permeability value (assumed to be constant from the beginning of the test to the end of the considered step) which provides the same flow rates as the actual flow observed at the end of the step when pressure history is taken into account. K_{av} is the permeability value (assumed to be constant from the beginning of the test to the end of the considered step) which provides the volume observed at the end of the step when pressure history is taken into account.

Step #	1	2	3	4	5	6	7	8	9	10	11	12
Well-head pressure (MPa)	2.2	3.4	5.2	6.8	7.25	7.7	8.1	8.6	9.0	9.4	9.8	10.2
Casing-shoe pressure (MPa)	12.47	13.67	15.38	17.08	17.51	17.94	18.37	18.79	19.22	19.65	20.07	20.50
Gradient (GdF)	1.46	1.60	1.80	2.00	2.05	2.10	2.15	2.20	2.25	2.30	2.35	2.40
Gradient ($\times 10^{-2}$ MPa/m)	1.43	1.57	1.77	1.96	2.01	2.06	2.11	2.16	2.21	2.26	2.30	2.35
Step duration (days)	40	32	32	27	31	33	30.5	28.3	28.5	33.5	29.5	29.5
Flow at the end of step (l/d)	4.32	4.56	5.52	6.96	7.20	7.44	7.68	8.40	8.88	9.12	10.08	17.28
Cumulated volume during step (liters)	234	194	225	231	240	270	250	245	260	315	310	415
Average flow during step (l/d)	5.85	6.06	7.03	8.56	7.74	8.18	8.20	8.66	9.12	9.40	10.51	14.07
Average flow since beginning (l/d)	5.85	5.94	6.28	6.75	6.94	7.15	7.29	7.44	7.61	7.80	8.03	8.51
$K_{\textbf{fin}}$ **($\times 10^{-20}$ m^2)**	11	4.0	2.4	1.8	1.3	1.0	0.82	0.74	0.66	0.58	0.56	0.91
$K_{\textbf{av}}$ **($\times 10^{-20}$ m^2)**	13	7.4	4.7	3.5	2.6	2.0	1.7	1.4	1.2	1.1	1.0	0.90

Table 3: Ez58 test back-calculation results.

5 Conclusions

Even if extremely small, the in-situ permeability of a rock salt formation can be measured through in-situ tests in wells, which can be conveniently performed before the cavity is leached. A good knowledge of the permeability is of importance for various reasons — notably because cavern abandonment strategy is governed largely by the order of magnitude of the permeability of the salt formation.

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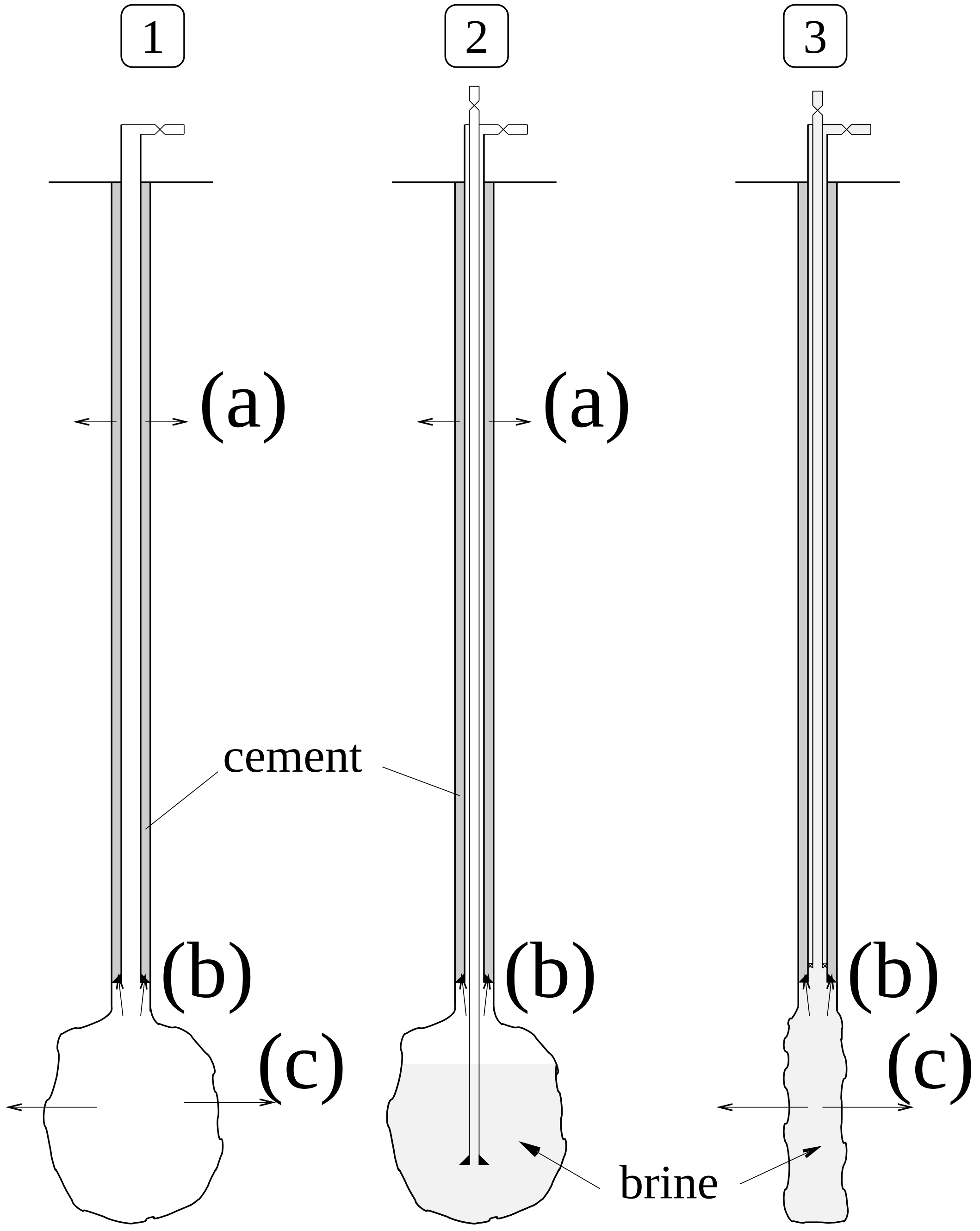

Figure 1: Fluid seepage can take place: (a) through the cemented casing, (b) through the casing shoe, (c) through the rock formation.

Figure 2: Nitrogen Leak Test. (The cemented casing (a) and the casing shoe (b) are tested.)

Figure 3: Gaz de France Test. The rock formation (c) and the casing shoe (b) are tested.

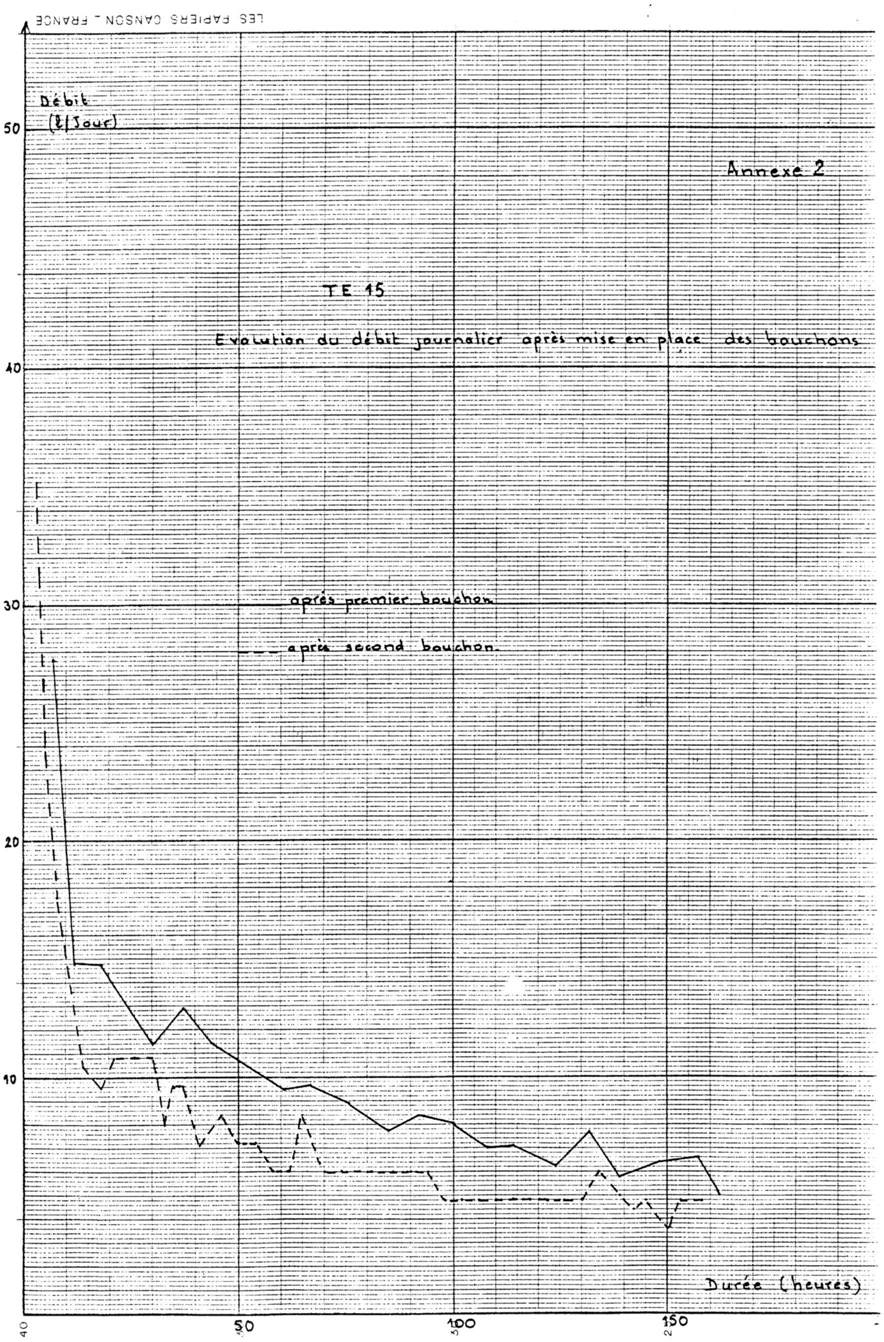

Figure 4: Typical daily injected flow rate (liters/day) versus time (days).

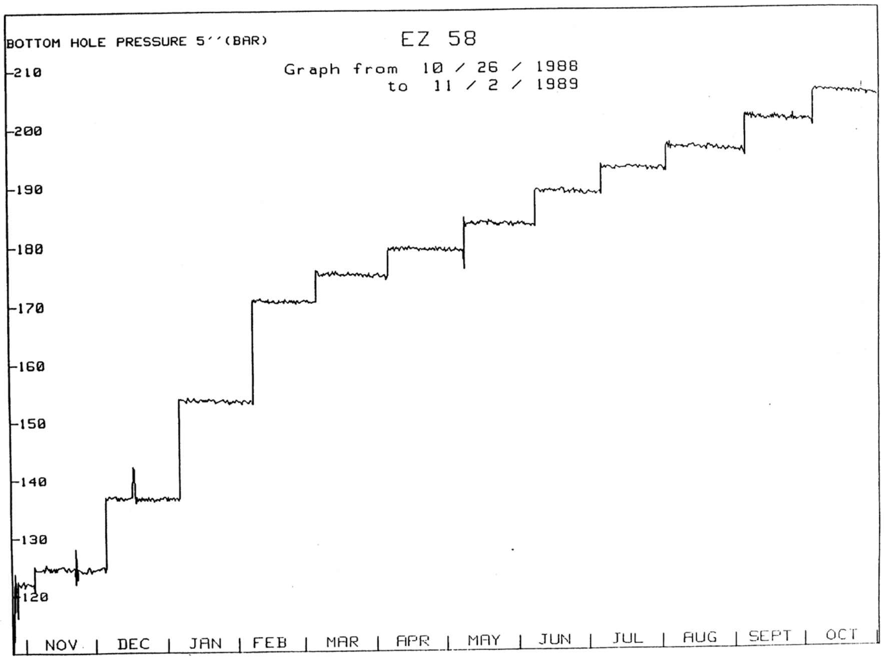

Figure 5: Ez58 test - Bottom hole pressure as a function of time.

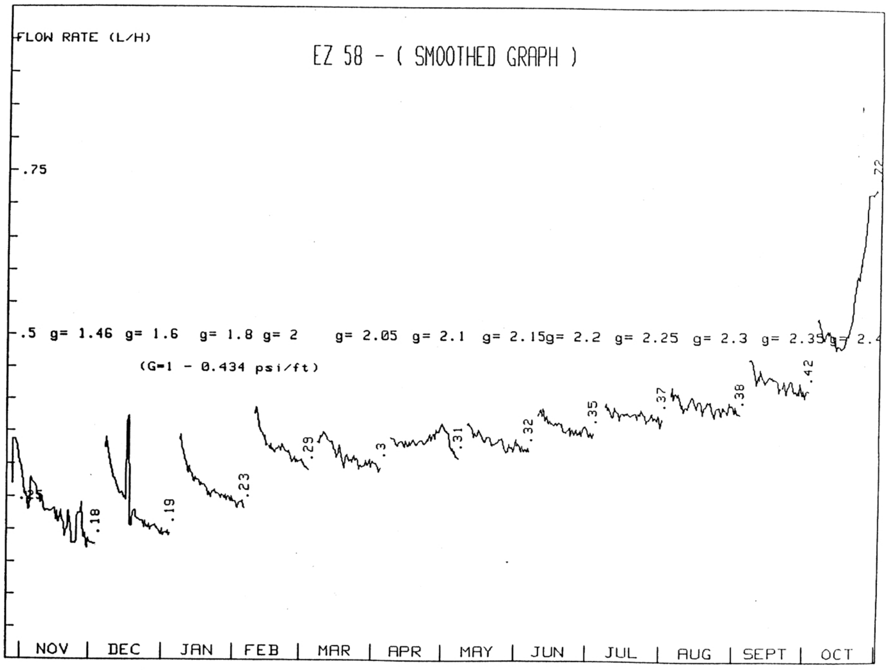

Figure 6: Ez58 test - Expelled flow rate as a function of time.

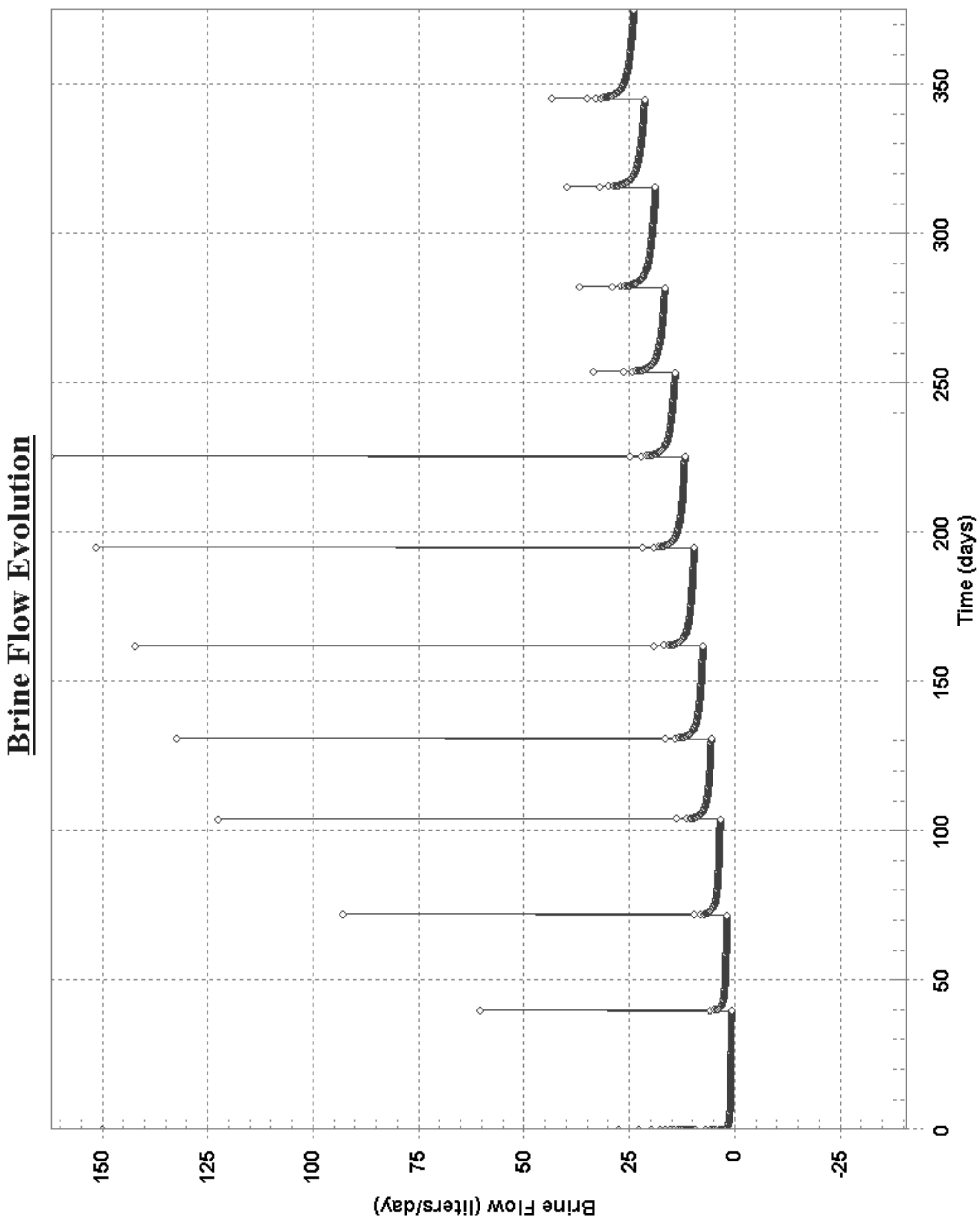

Figure 7: Example of computation using **LOSEEP** for Ez58 test. The considered constant permeability is $K = 10^{-20}$ m^2.

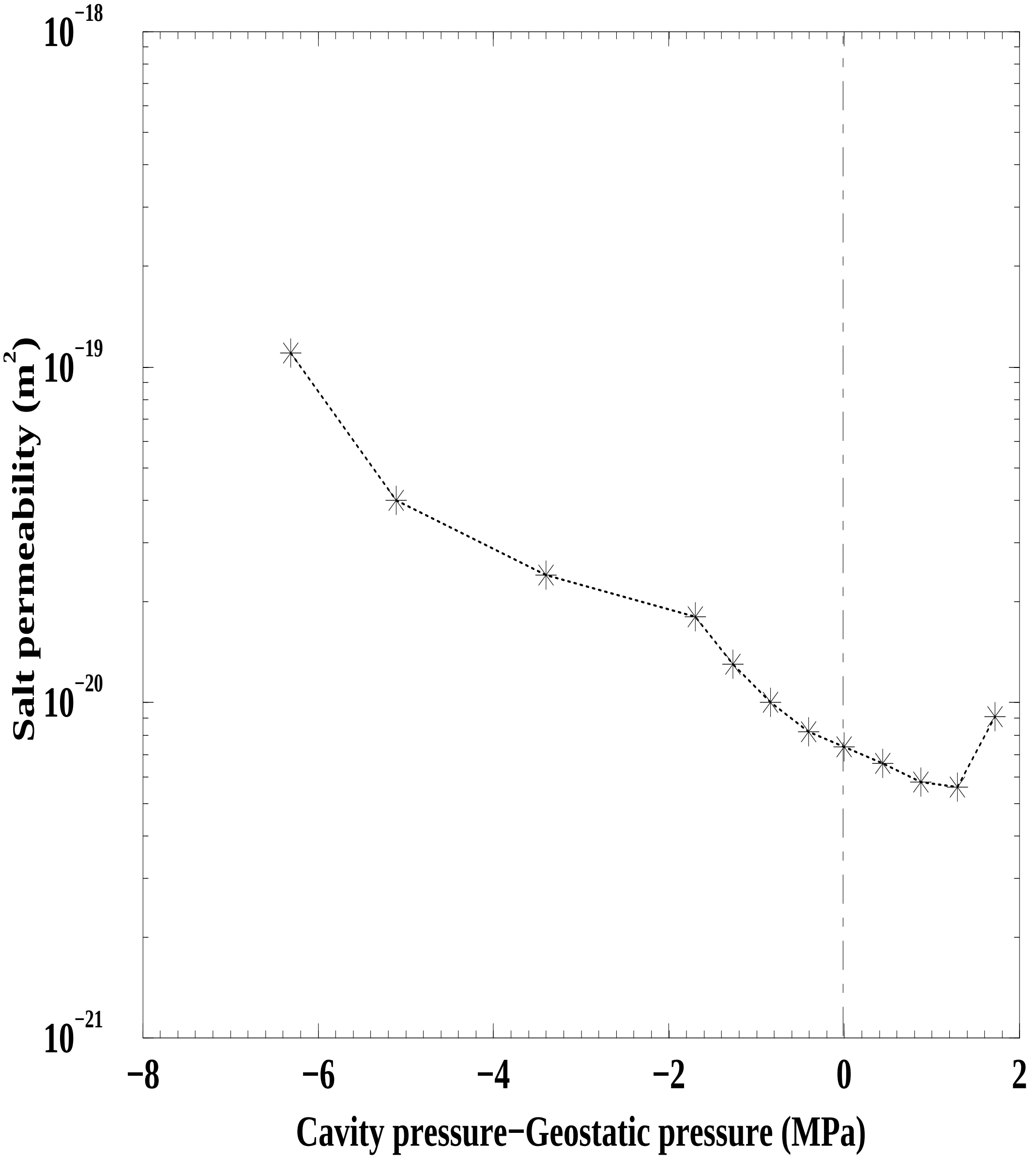

Figure 8: Calculated permeability (K_{fin}) as a function of the difference between cavity pressure and geostatic pressure ($P_i - P_\infty$).