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MEETING PAPER

A TENTATIVE EVALUATION OF THE MIT

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Summary

In order to check the validity of the nitrogen-leak MIT, a gas-brine interface was lowered to half-height of a cavern well in order to minimize the risk of (real) gas leak. The cavern, which had been leached out 14 years ago, has stabilized; creep, percolation or thermal effects can be considered negligible. Mock leaks were then provoked by injecting or withdrawing known quantities of nitrogen or brine through the well-head. The test gives clear evidence of the so-called barometric effect; measured and calculated values of the gas-brine interface displacement and leaks were found to be in good agreement.

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Acknowledgements

The authors are deeply indebted to Fritz CROTOGINO and Rod THIEL who spared no time in providing fruitful comments and discussions during the preparation of the test.

The test would not have been possible without dedicated help from Gaz de France Etrez staff (MM. CHARVET, GAYDON and MAZUIR) and from Ecole Polytechnique staff (M. LE BRAS).

INTRODUCTION

The nitrogen-leak test, thereafter called the "MIT" (Mechanical Integrity Test), basically consists of injecting some gas (nitrogen, in many cases, because it is inert and inexpensive) in a closed and pre-pressurized cavern and then forcing the brine/gas interface down to a level slightly lower than the last cemented casing shoe. In general, the gas is contained in an annular space between the casing and a central brine-filled tubing. Once the interface has equilibrated, its movements are monitored: an upward movement indicates a loss of nitrogen through the casing or the casing shoe. The simplest interpretation methodology consists in tracking the gas-brine interface with a wireline logging tool (see Figure 1).

The measured interface upward rate (in ft/day, for instance) is multiplied by the horizontal cross section of the annular space (in ft^2) to obtain a nitrogen leak rate in ft^3/day [see, for example, CH2M Hill, 1995]. A more accurate analysis is provided by taking into account the well temperature and its evolution during the test. A complete overview can be found in Crotogino, 1995; and assessment of precision methods has been discussed by Thiel, 1993.

In a previous paper, presented at the 1995 SMRI Fall Meeting in San Antonio, Texas, Gaz de France and Ecole Polytechnique discussed the nitrogen-leak test and proposed the following conclusions

1. The brine/gas interface rise-rate underestimates the real leak by a factor that can be as large as two. This phenomenon is very similar to the so-called "barometric effect": when brine rises in the annular space and replaces leaked gas, the weight

of the fluid column in the annular space increases, resulting in a small pressure build-up in the cavern that enlarges the cavern volume and mitigates the interface rise.

2. Several phenomena, such as brine thermal expansion, transient and steady-state cavern creep and brine percolation, can modify the interface rate even in the case of no real leak (see, also, Crotogino, 1995, attachment 1).

EVALUATING THE MIT

Although the conclusions cited above seemed to be based on consistent calcultations, in the beginning of 1996, Gaz de France and Ecole Polytechnique decided to perform an in-situ test with the following objectives :

(1) to give clear evidences of the "barometric effect"
(2) to compare theoretical predictions with actual measurements in well-controlled conditions - more precisely, to simulate a gas leak in a nitrogen-filled annular space by withdrawing a known quantity of gas at the well head and checking to determine if this quantity could be back-calculated through the pressure variations measured at the well-head.

The first tasks were to select both a cavern and operating conditions such that :

(1) the (real) gas leak would presumably be extremely small; and
(2) the external factors influencing the interface rise-rate would be negligible or well known.

TEST PREPARATION

For various reasons, which will be noted below, the Ez 53 cavern was selected. A relatively small cavern (7000 to 8000 cubic meters i.e. 44,000 to 50,000 bbls), Ez 53 is seated at moderate depth (3120 ft or 950 meters). Solution-mining operations on this cavern ceased in July 1982; since this period, the cavern has been at rest except for a 91-week pressure build-up period in 1983-1985. Several tests have been performed on this cavern and in this site; much information is available concerning the thermal, mechanical, hydraulic behavior of the cavern.

The first objective of the test was fulfilled as follows : first the gas-brine interface was set at a depth of 400 meters (1310 ft), above the 13 3/8" casing shoe in order to minimize gas leaks through the casing. The gas was separated from the rock mass by a double barrier consisting of two cemented casings (see Figure 2). This settlement necessitated maintaining the gas pressure at a relatively low level in the upper part of the casing. Second, knowing that the annular space (which was to be filled with nitrogen during the test) was filled with fuel oil since 1982, we measured the fuel-oil pressure in the annular space, a few days before the test began. The pressure proved to be slightly higher than it had been 13 years before (3.5 MPa instead of 3.4 MPa i.e. 508 psi instead of 493 psi). The fuel oil was then withdrawn. Although its volume had not been carefully measured, it appeared to be roughly the same as measured more than 10 years before. These two facts gave clear evidence that the annular space had remained tight during a long period, in spite of a relatively severe excess of pressure in the upper part. Accordingly, tubing and casing were expected to prevent any gas leak during the nitrogen-leak test (as a matter of fact, the internal 7" tubing appeared to be slightly leaky.)

MINIMIZING THE EFFECTS OF EXTERNAL FACTORS

The second objective —to minimize the effects of parasite phenomena on the interface level— was met by the very choice of the Ez53 cavern

1. The volume of this cavern is $V = 7000\ m^3$ to $8000\ m^3$ (44,000 to 50,000 bbls) which signifies that the characteristic time after which 75 % of the initial temperature gap between rock-mass and cavern brine was resorbed is $t_c = V^{2/3}/(4\ k) = 1$ year (Berest et al., 1995). In other words, 14 years after leaching, the brine temperature in the cavern stabilized, and the effects of thermal expansion became negligible (See Figure3; the temperature measurements show a fairly homogeneous temperature in the cavern, which gives clear evidence of effective thermal convection stirring up the brine in the cavern.)

2. Brine flow expelled by the Ez 53 cavern has been carefully measured several times since the end of leaching (Hugout, 1984; Berest et al., 1994). It was 200 liters per day (1.26 bbls) under halmostatic pressure a few weeks after the leaching stopped, 50 liters per day (0.31 bbls) one year later, and 5.5 liters per day (0.035 bbls) 8.5 years later. We measured the flow during the Fall of 1995— i.e., 13.5 years after the leaching end; the average flow was 5.05 liters per day (0.032 bbls) under halmostatic pressure (see Figure 4) or, when compared with the cavern volume, $2.5\ 10^{-4}$ per year (approximately). This flow is believed to be generated by cavern creep; it would slow down if the cavern pressure were increased.

3. Brine percolation was measured in a neighboring well (Ez 58) by Durup (1994). He estimated the permeability to be $K = 6\ 10^{-20}\ m^2$. If this figure is accepted, the steady-state brine flow in the Ez 53 cavern percolating from the cavern through the rock-salt increases by 0.64 liters per day (0.004 bbls) when the brine pressure increases by 1 MPa.(145 psi) When the adverse effect of pressure increase on brine outflow, provoked by creep, is considered, it is clear that an equilibrium can be reached when percolation flow exactly balances cavern shrinkage due to creep (see Berest and Brouard, 1995). Calculations suggest that the equilibrium would be met if the pressure in the cavern exceeded the brine column weight (11.4 MPa or 1653 psi) by approximately 3.5 MPa (508 psi). This figure was selected as the test pressure.

Figure 5 shows the idealized pressure-depth curve both in the annular space and in the central tubing. In reality, the distribution of pressure was a bit different due to the various injection-withdrawal phases

The annular space volume is 14.7 liters per meter (0O3bbls/ft) except for the upper part (the 32 first meters i.e. 105 ft) in which the 9 5/8" diameter enlarges into a 13 3/8" diameter, resulting in an additional volume of 1.2 m^3 (7.5 bbls). Before the test, the annular space and the cavern neck were filled with fuel oil; with a total fuel oil volume of approximately 30 m^3 (190 bbls).

At the beginning of the test, the fuel oil was removed by injecting an equivalent volume of not fully saturated brine into the central tubing, whose volume is 20.3 liters per meter (0.42 bbls/ft). After removal, the central tubing and the annular space were both filled with brine, but brine densities were suspected to be different. An additional 9752 liters volume (61.3 bbls) of unsaturated brine was then injected in the closed cavern on February 2, in order to increase its pressure by 3.5 MPa (508 psi).
The cavern compressibility at this stage proved to be $\beta V = 2.77\ m^3/MPa = 0.12$ bbls/psi (see Figure 6), which is a bit smaller than expected (In this site, the cavern compressibility factor has been measured several times and the value $\beta = 4\ 10^{-4}\ MPa^{-1}$ ($2.8\ 10^{-6}\ psi^{-1}$) is commonly accepted. This would lead to a cavern compressibility of $\beta V = 4\ 10^{-4}\ MPa^{-1} \times 8000\ m^3 = 3.2\ m^3/MPa = 0.14$ bbls/psi. The discrepancy proves that the cavern volume is probably overestimated and that the injected brine was unsaturated).

From February 26 to February 29, 633 kg (1400 lbs) of nitrogen were injected in 6 steps; brine was withdrawn from the central tubing after each step so that the pressure in the cavern remained roughly constant. At the end of this phase, the nitrogen/brine interface was lowered to a depth of 399.5 meters (1310 ft) and brine densities in the central tubing were distributed as shown on Figure 8. Then the stabilization phase began. It is important to notice here that

(1) since February 29, the cavern pressure remained roughly constant (the tubing pressure at the well head is about 3.5 MPa i.e. 508 psi); and

(2) in the central tubing, the brine density is not uniform, due to various injection/withdrawal phases. In the upper part ot the tubing the density is as low as 1125 kg/m^3 (394 lbs/bbl) instead of 1200 kg/m^3 (421 lbs/bbl) in the lower part, which is filled with saturated brine. These differences cause some concern for test interpretation.

STABILIZATION PERIOD

As indicated above, the stabilization phase began at the end of the prepressurization period and ended when the tests were performed. During this phase the annular-space pressure decreased from 7.57 MPa=1098 psi (February 29) to 7.30 MPa=1059 psi (March 13) and the tubing pressure increased from 3.42 MPa=496 psi (February 29) to 3.57 MPa=518 psi (March 13); See Figure 7. After a few days, a leak through the 7" tubing separating the gas annular space and the brine tubing was suspected. It was decided to vent the nitrogen in the central tubing. This was done on March 13, resulting in a pressure drop in both the annular space and the tubing. A second venting was performed just before the test on March 18, and several smaller ventings were performed during the test itself. The nitrogen leak from the annular to the tubing was estimated to be small and to have little influence during the tests.

TEMPERATURE MEASUREMENT

Changes in the well temperature during the test must be taken into account when interpreting the nitrogen-leak test, as emphasized by Thiel (1993) and Crotogino (1995). These changes are especially important after a leaching phase, during which cold fluids circulate inside the well. In the particular case of the Ez 53 cavern, the leaching phase was long over when the test was performed ; the temperature logs performed before (February 22) and after the stabilization period (March 18) proved to be merely identical, except perhaps in the lower most part of the tubing (see Figure 9).

TESTS RESULTS

On March 20, 1996, four tests were performed :

(1) brine withdrawal,
(2) brine injection,
(3) nitrogen withdrawal,
(4) nitrogen injection

The volume of injected or withdrawn fluid was measured as carefully as possible, and the evolutions of the brine and nitrogen pressures were recorded.

Interface Measurement

Before and after each test, a wireline tool was used to monitor the nitrogen/brine interface, Figure 10. The interface depth was measured using a gamma-gamma logging tool which provides a density log. The 1" $^{11/16}$ tool is composed of a gamma-ray source (Cs^{137}) and a detector (Thallium crystal, spacing 20") that records back scattered gamma rays. This recorded radiation (Compton scattering) is a function of the electron cloud encountered by the emitted radiation, and the electron density is practically proportionnal to the bulk or fluid density. For each interface measurement, a portion of the well was logged at a 2 m/min speed (6.6 ft/min). Under such conditions, a resolution of ± 0.1 meters (0.3 ft) can be achieved.

Brine injection test

Interface depth before injection	h = 382.3 meters ± 0.1 meters
Brine pressure before injection	P_b = 3.065 MPa ± 0.001 MPa
Nitrogen pressure before injection	P_g = 7.055 MPa ± 0.001 MPa
Amount of injected brine	εV = 200 liters ± 0.5 liters
Interface depth after injection	h' = 379.5 meters ± 0.1 meters
Brine pressure after injection	P'_b= 3.132 MPa ± 0.001 MPa
Nitrogen pressure after injection	P'_g= 7.090 MPa ± 0.001 MPa

Brine withdrawal test

Interface depth before withdrawal	h = 379.5 meters ± 0.1 meters
Brine pressure before withdrawal	P_b = 3.133 MPa ± 0.001 MPa
Nitrogen pressure before withdrawal	P_g = 7.094 MPa ± 0.001 MPa
Amount of withdrawn brine	εV = - 200 liters ± 0.5 liters
Interface depth after withdrawal	h' = 381.9 meters ± 0.1 meters
Brine pressure after withdrawal	P'_b = 3.128 MPa ± 0.001 MPa
Nitrogen pressure after withdrawal	P'_g = 7.090 MPa ± 0.001 MPa

Comment on the brine withdrawal test

During the injection test, brine was pumped into the cavern through a small pump; the total duration of the test was two hours. Withdrawing the same amount (200 liters i.e. 1.26 bbls) of brine was much faster (700 seconds) and did not allow brine temperature in the tubing, creep and brine saturation to equilibrate. This explains why the pressures measured at the end of withdrawal are too high, and not consistent with the values measured before injection, but are far more consistent one hour later when the nitrogen injection test begins.

Nitrogen injection test

Interface depth before injection	h = 381.9 meters ± 0.1 meters
Brine pressure before injection	P_b = 3.061 MPa ± 0.001 MPa
Nitrogen pressure before injection	P_g = 7.060 MPa ± 0.001 MPa
Amount of injected nitrogen	Δm = + 9.20 kg ± 0.01 kg
Interface depth after injection	h = 385.8 meters ± 0.1 meters
Brine pressure after injection	P'_b= 3.082 MPa ± 0.001 MPa
Nitrogen pressure after injection	P'_g= 7.117 MPa ± 0.001 MPa

Nitrogen withdrawal test

Interface depth before withdrawal	h = 385.8 meters ± 0.1 meters
Brine pressure before withdrawal	P_b = 3.082 MPa ± 0.001 MPa
Nitrogen pressure before withdrawal	P_g = 7.115 MPa ± 0.001 MPa
Amount of withdrawn nitrogen	Δm = - 8.09 kg ± 0.01 kg
Interface depth after withdrawal	h' = 382.1 meters ± 0.1 meters
Brine pressure after withdrawal	P'_b= 3.065 MPa ± 0.001 MPa
Nitrogen pressure after withdrawal	P'_g= 7.065 MPa ± 0.001 MPa

INTERPRETATION

1. The barometric effect

* Nitrogen **withdrawal** is considered a "leak". The following describes the effect of this "leak" on the nitrogen-brine interface

Nitrogen withdrawn Mass	$M = -8.09$ kg = - 17.84 lbs
Nitrogen density	$\rho_g = 86.8$ kg/m^3 = 30.43 lbs/bbl
Volume of withdrawn nitrogen	$M/\rho_g = -9.3\ 10^{-2}$ m^3 = -.0.59 bbl
Annular cross-section	$\Sigma = 14.7$ liters/m = .03 bbls/ft
"Naïve" interface rise	$M/(\Sigma\rho_g) = -6.3$ meters = - 20.8 ft
Measured interface rise	- 3.7 m ± 0.1 m = - 12.1 ft ± 0.3 ft
Measured corrective ratio	$C = 6.3/3.7 = 20.8/12.1 = 1.7$

* Nitrogen **injection** can be considered a "negative leak", which allows for a similar calculation

Nitrogen injected mass	+ 9.20kg = + 20.28 lbs
Nitrogen density	86.1 kg/m^3 = 30.18 lbs/bbl
Nitrogen injected volume	+ 1.07 10^{-1} m^3 = 107 liters = 0.67 bbl
Annular cross section	14.7 liters/m = .03 bbls/ft
"Naïve" interface descent :	107/14.7 = + 7.3 meters = + 23.8 ft
Measured interface descent :	+ 3.8 m ± 0.1 meter = 12.5 ft ± 0.3 ft
Measured corrective ratio	$C = 7.3/3.8 = 23.8/12.5 = 1.9$

These results give clear evidence of the so-called "barometric effect" (see Berest et al., 1995) : the interface rise underestimates the leak by a factor which, in the case of this cavern, is

$$\boxed{C = 1 + \frac{\rho_b - \rho_g}{P} \cdot g \cdot h + \frac{\Sigma \cdot h}{\beta \cdot V \cdot P}}$$

with $\rho_b = 1181$ kg/m^3 = 414 lbs/bbl $\qquad \rho_g = 86.5$ kg/m^3 = 30.3 lbs/bbl,
$P = P_b + \rho_b gh = 7.5$ MPa = 1088 psi,
$\Sigma = 1.47\ 10^{-2}$ m^2 = 0.3 bbl/ft,
$h = 386$ m = 1266 ft,
$\beta V = 2.77\ 10^{-6}$ m^3.Pa^{-1} = 0.12 bbl/psi,
$C = 1.8$

This theoretical prediction of the corrective factor fits the calculated ratios between "naïve" and "measured" interface rise.

2. Prediction of interface movements

The interface movements can be deduced theoretically from the pressure variations measured at ground level. The theoretical calculations are expanded in Berest et al., 1995. For each of the four tests, we input the interface depth before the test and brine pressure and nitrogen pressure (before and after the test). These five values allow for back-calculating the amount of brine (or nitrogen) injected (or withdrawn) and the interface displacement, which can be compared to the measured data.

Note that during a brine injection, for instance, the "measured" displaced nitrogen weight is nil, because no nitrogen is injected (or withdrawn) during this phase.

Brine injection

	calculated	measured
interface displacement (m)	- 2.83	- 2.8
displaced brine (liters)	+ 227	+ 200
displaced nitrogen (kg)	- 0.70	0

Brine withdrawal

	calculated	measured
interface displacement (m)	+3.19	+ 2.4
displaced brine (liters)	-249	- 200
displaced nitrogen (kg)	+1.04	0

* see : discussion of the brine withdrawal test

Nitrogen injection

	calculated	measured
interface displacement (m)	+ 3.49	+ 3.8
displaced brine (liters)	+ 9.5	0
displaced nitrogen (kg)	+ 9.12	+ 9.20

Nitrogen withdrawal

	calculated	measured
interface displacement (m)	- 3.28	-3.7
displaced brine (liters)	+ 1.2	0
displaced nitrogen (kg)	- 8.33	- 8.09

CONCLUSIONS

1. The barometric effect has been clearly proved : when a certain amount of nitrogen is withdrawn (or injected) the brine-nitrogen interface moves but sweeps a much smaller volume than the withdrawn (or injected) gas volume.

2. The pressure variations at the well-head, which follow a nitrogen injection/withdrawal, allow for back-calculating interface displacement and gas injected/withdrawn volume.

3. Based on the results of our investigation, the nitrogen-leak test can be expected to produce precise and confident results.

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X GDF test

February 22	first temperature log
February 22 to 23	cavity pressurization to 3.5 MPa (508 psi)
February 23 to 26	stabilization
February 26 to 27	three nitrogen injections, two brine withdrawals
February 28 to 29	three nitrogen injections, four brine withdrawals
March 1 to 12	stabilization
March 13	gas venting from the tubing second temperature log
March 13 to 17	stabilization
March 18	third temperature log
March 19	gas venting brine withdrawal
March 20	gas venting brine injection test brine withdrawal test gas injection test gas withdrawal test
March 20 and on	stabilization

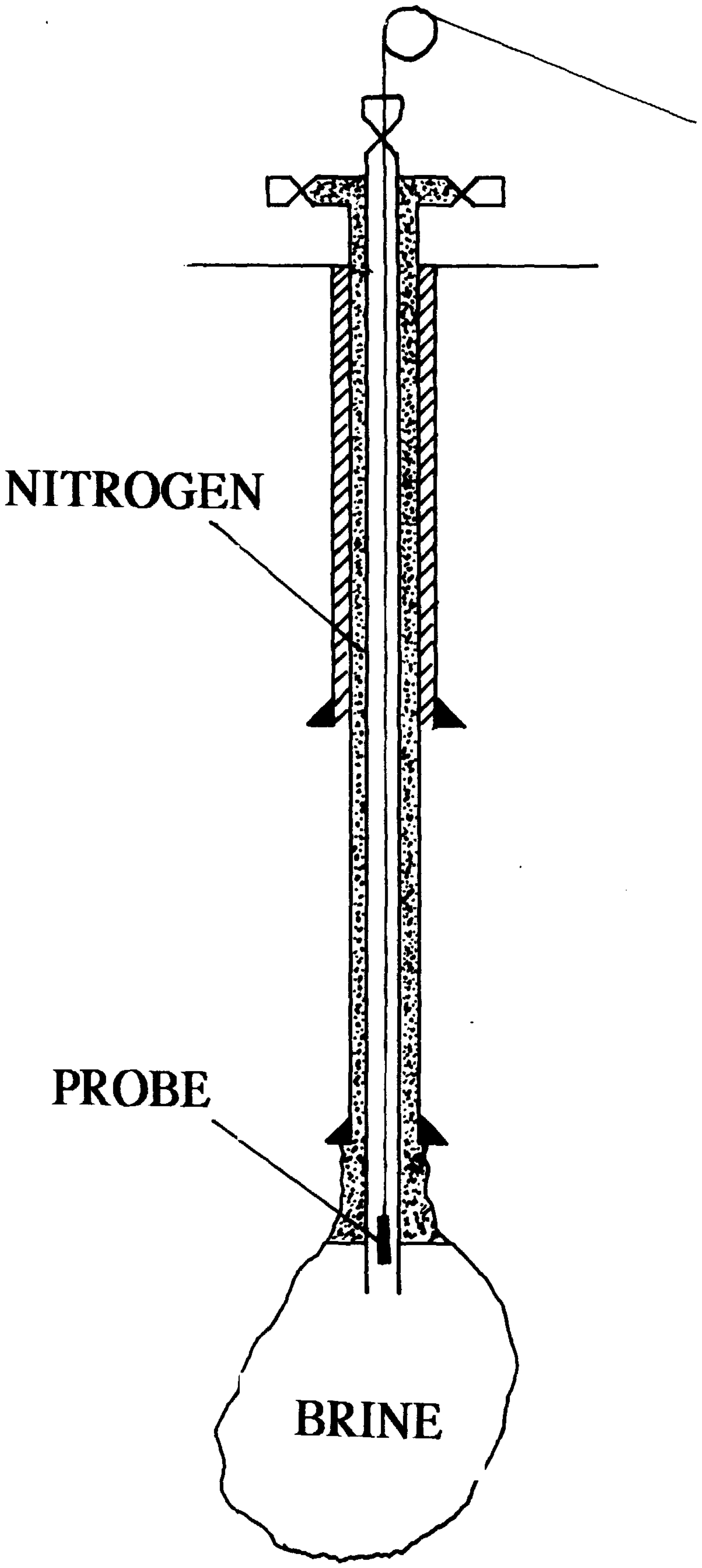
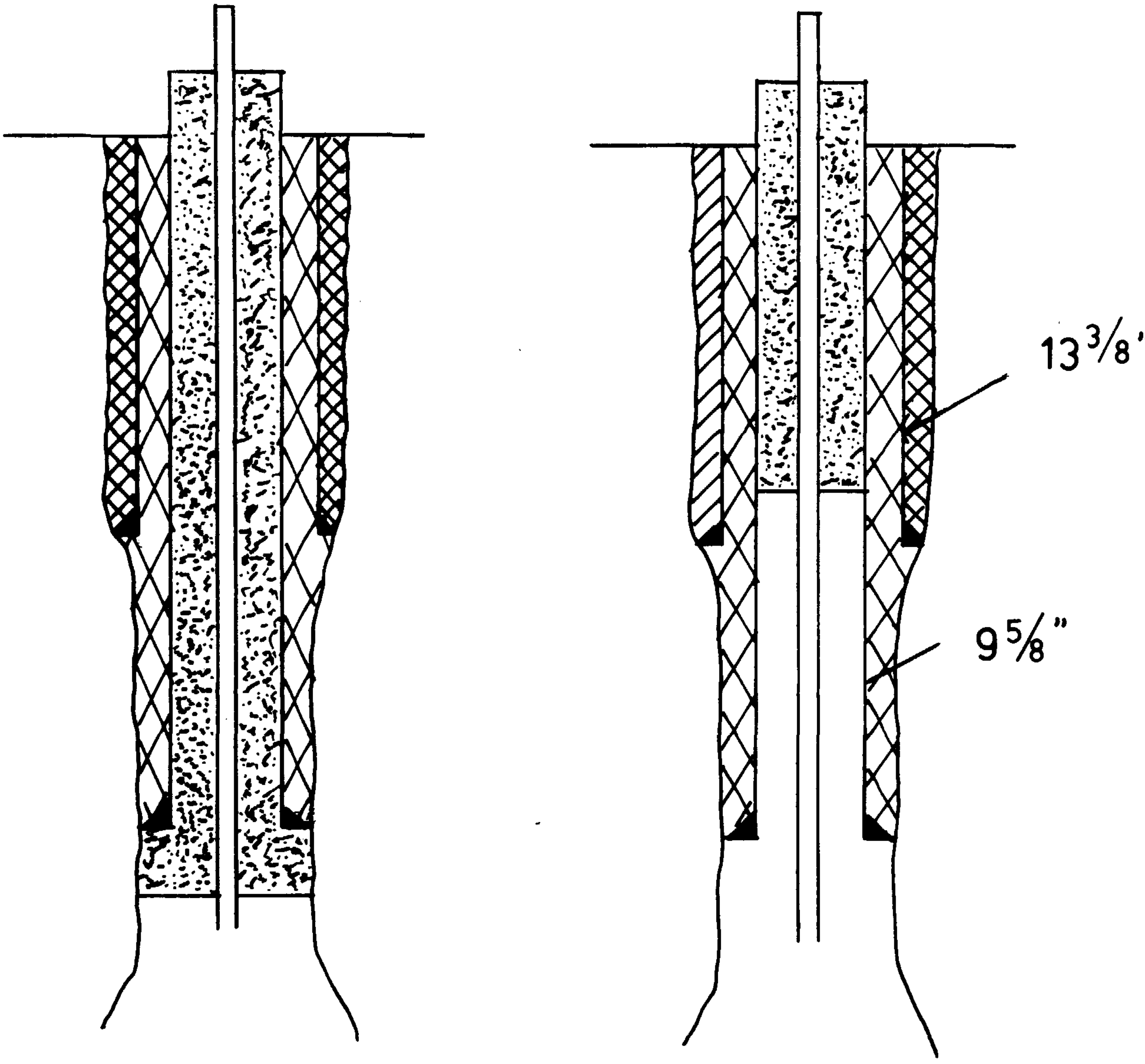


Figure 1 : Nitrogen leak test

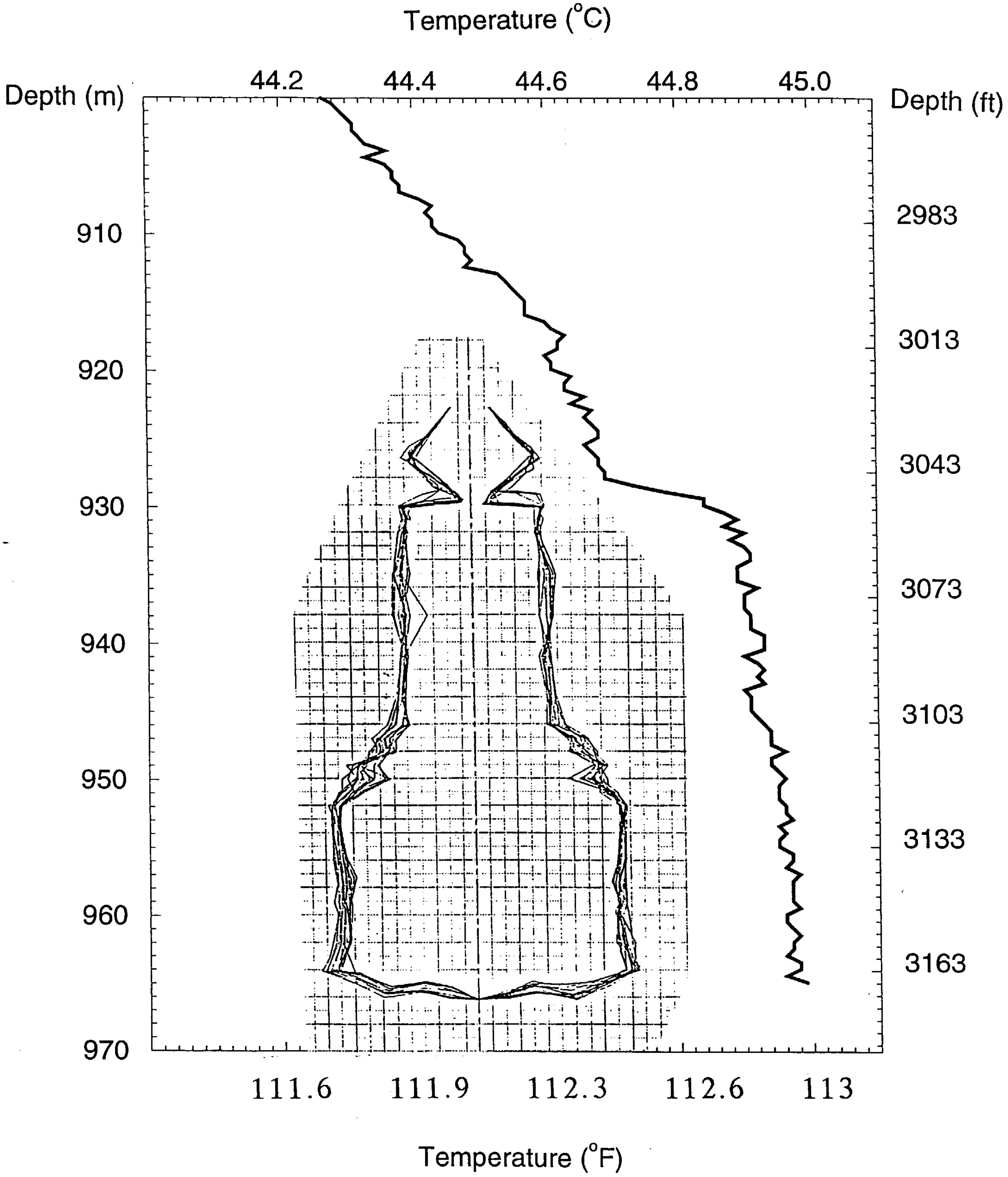


MIT test **X-GDF test**

During a MIT test, the brine-gas interface is lowered down to the cavern neck. During our test, the interface was lowered above the second cemented casing to prevent nitrogen leaks.

Figure 2 : Standard Nitrogen leak test and X-GDF test

Figure 3 : Brine temperature in the cavern

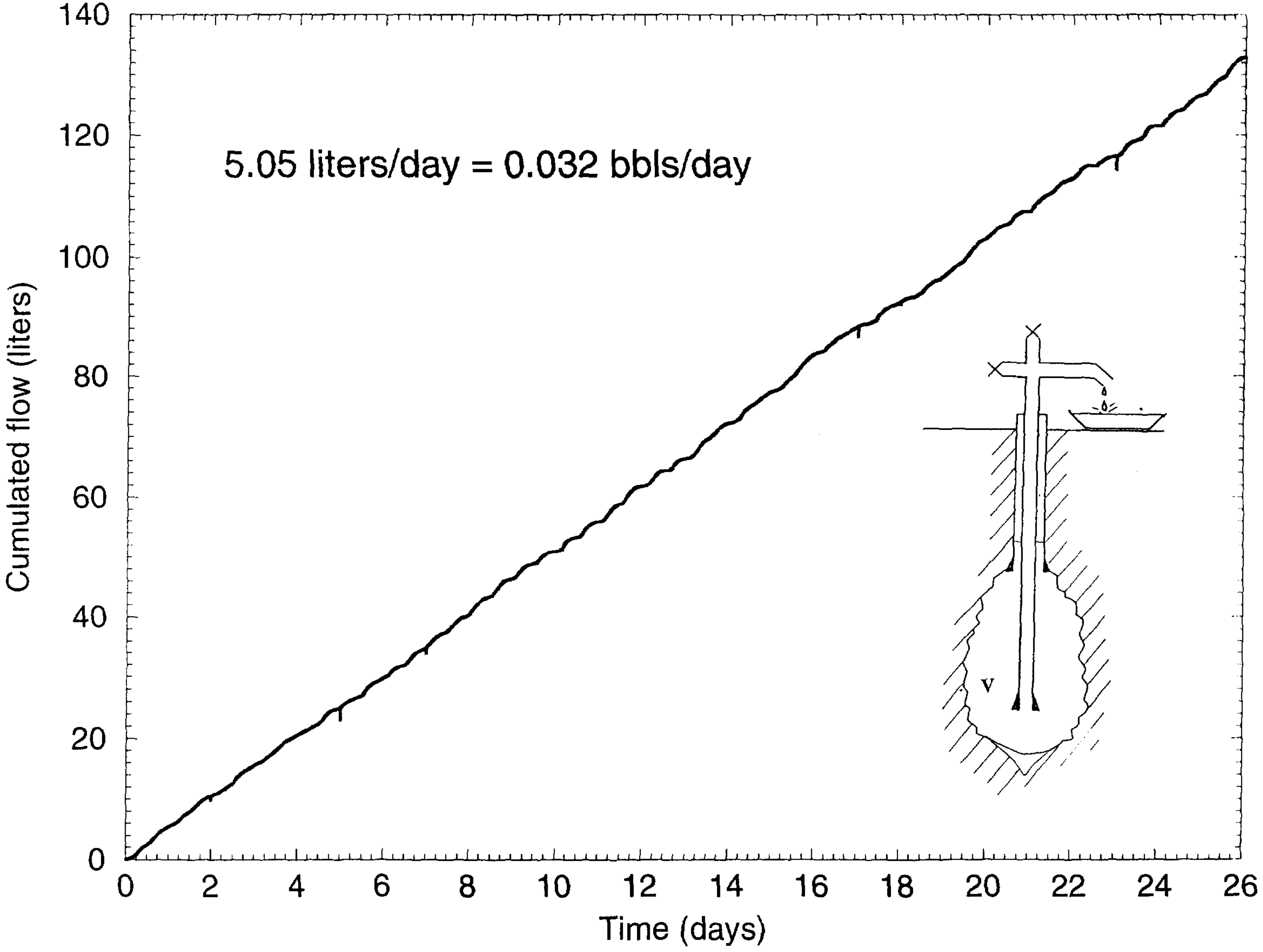


Ez53

Sonar: July 2, 1982 Temperature log: Feb 22,1996

Figure 4 - Evolution of the cumulated flow

Ez53 from October 13 to November 7, 1995



5.05 liters/day = 0.032 bbls/day

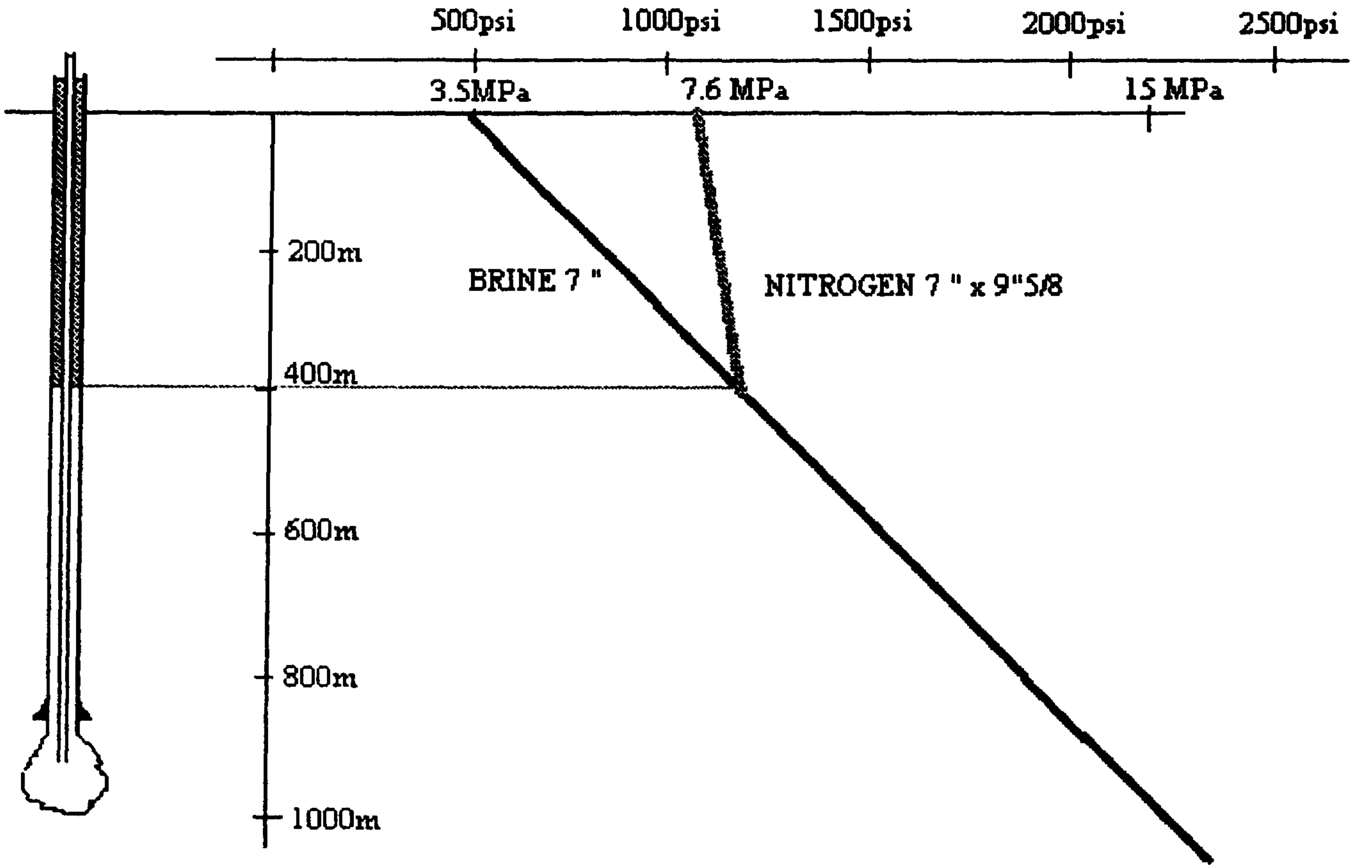


Figure 5 - Idealized Pressure Distributions in the 7" tubing and 7"x9"5/8 annular space

Figure 6 - MIT on Ez53 - PRESSURIZATION

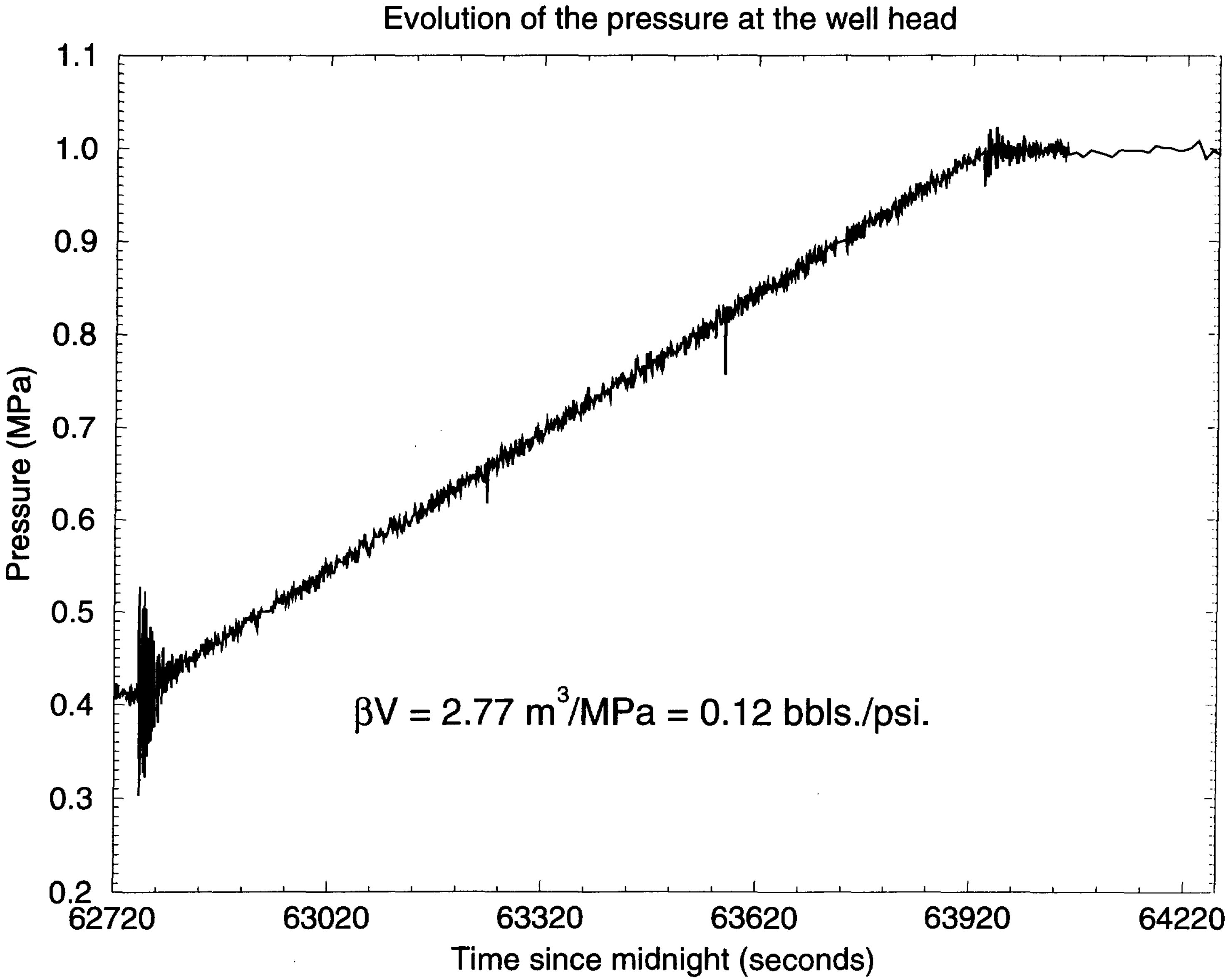
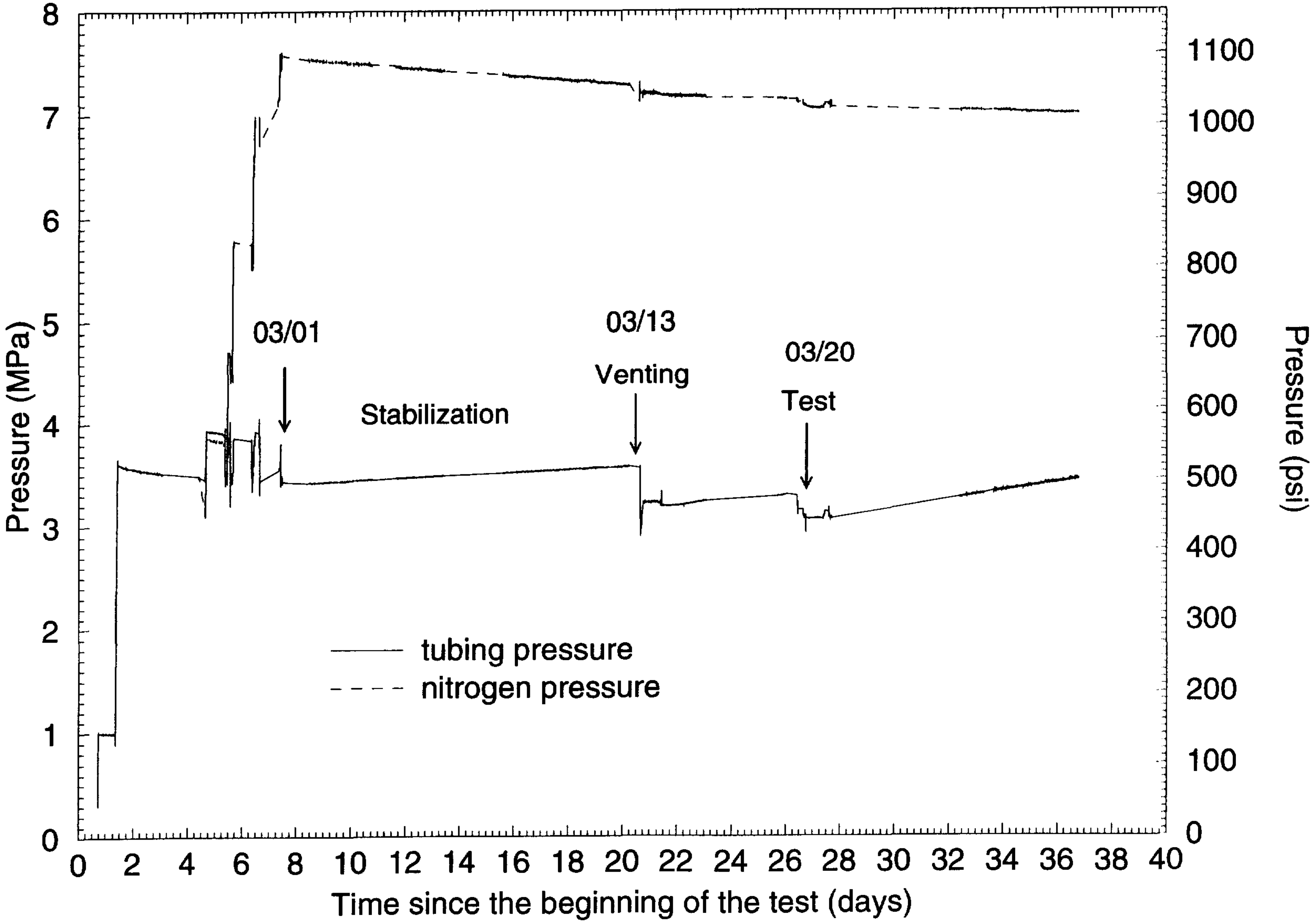
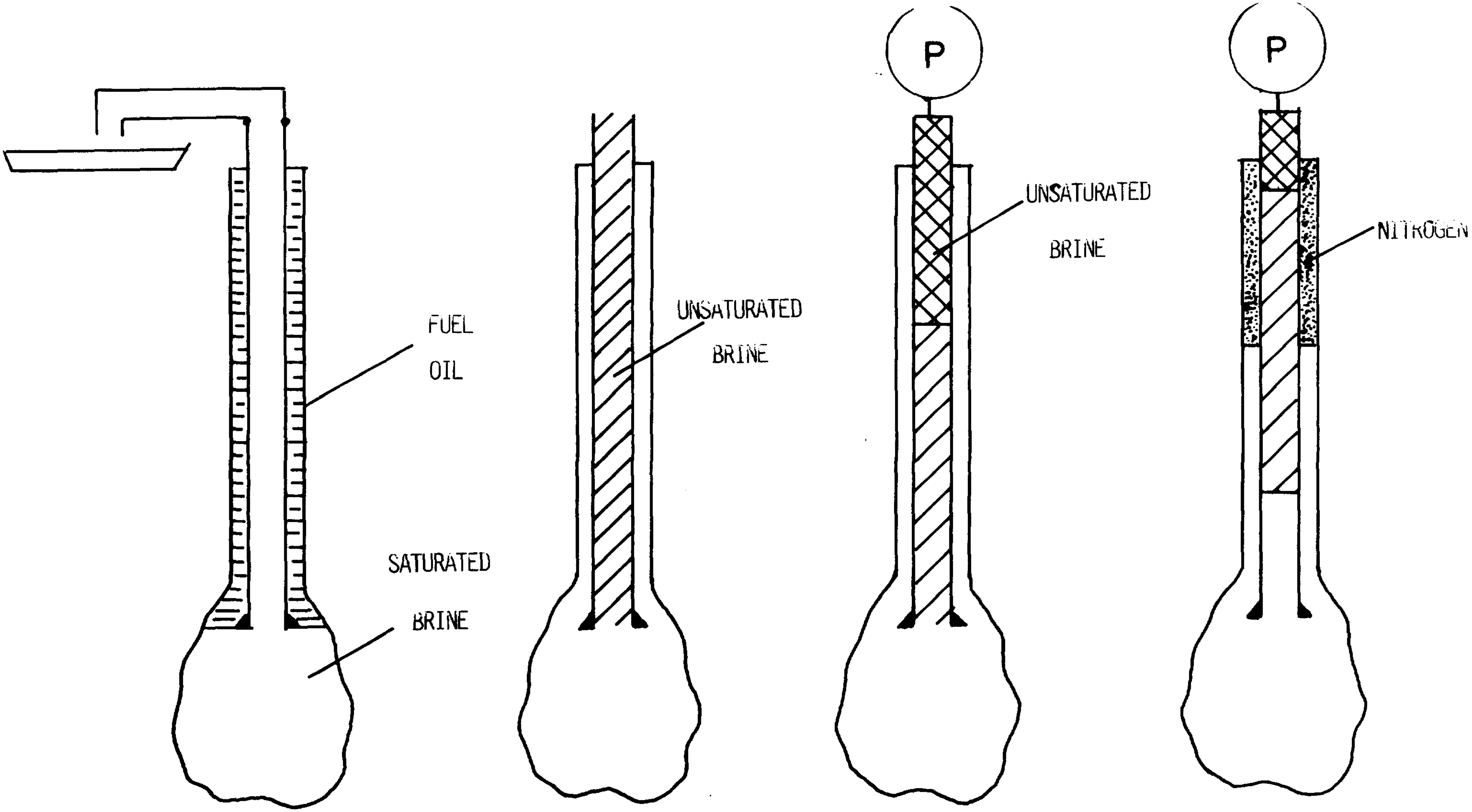


Figure 7 - MIT on Ez53 - Pressure evolution





Before Test

After Fuel Oil Withdrawal

After Prepressurization

After Nitrogen Injection and Brine Withdrawal

Figure 8 : Different steps in brine injection

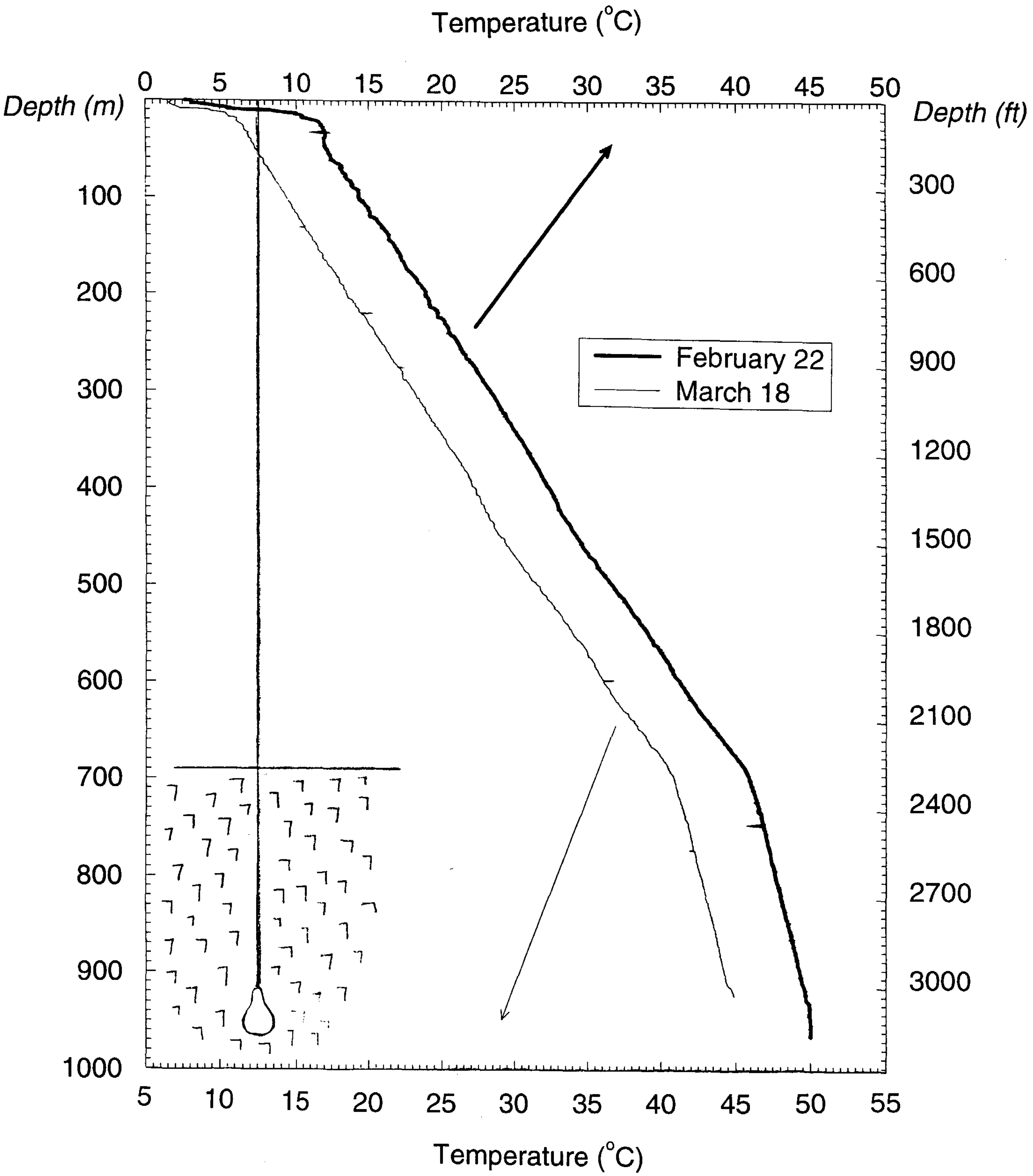


Figure 9 : Two thermographies on Ez 53
(Not the same temperature origin !)

Figure 10 - Nitrogen/Brine Interface

as measured before and after nitrogen injection