Nummers 477 t/m 491

477

SOLUTION MINING RESEARCH INSTITUTE
105 Apple Valley Circle
Clarks Summit, PA 18411, USA

Telephone: +1 570-585-8092
Fax: +1 570-585-8091
www.solutionmining.org

Technical Conference Paper

A Liquid-Liquid Mechanical Integrity Test Analysis That Implements a Fluid Equation of State

SMRI Fall 2013 Technical Conference
30 September–1 October 2013
Avignon, France

Solution Mining Research Institute Fall 2013 Technical Conference
Avignon, France, 30 September–1 October 2013

A Liquid-Liquid Mechanical Integrity Test Analysis That Implements a Fluid Equation of State

Brandon Schulte, Parsons Brinckerhoff, Houston, Texas USA
Brandon Lampe, Parsons Brinckerhoff, Rapid City, South Dakota USA
Ian Welsh, Keyera Corp., Calgary, Alberta Canada

Abstract

Solution-mined salt storage caverns provide an efficient and cost-effective means of storing liquid hydrocarbons. Caverns are easily mined from salt using freshwater, and the impermeable salt provides an ideal storage medium. A Mechanical Integrity Test (MIT) is regularly conducted on the cavern system to ensure the continuing safety for hydrocarbon storage. The nitrogen-brine interface MIT is the North American industry's preferred method for testing a cavern casing shoe and wellbore. A liquid-liquid interface MIT provides an alternative test method when the nitrogen-brine interface MIT is not feasible. Factors that make a nitrogen-brine test impractical or impossible include limitations in the casing or wellhead pressure rating and the lack of a cavern neck where the interface can be placed for a short duration test.

It is common practice to use a liquefied petroleum gas (LPG) as the test fluid in liquid-liquid MITs (LL MIT). Widely practiced and accepted LL MIT methods assume a constant test fluid density. However, temperature and pressure changes during the test period may cause measureable density changes. A density change can lead to interface movement without an actual loss in test fluid volume. By using the measured surface pressure, down-hole temperature, and test media composition, the test fluid density may be estimated, which allows for a more accurate calculation of the change in test fluid volume during the MIT.

A new liquid-liquid, external well MIT method, based on the nitrogen-brine external well MIT, is proposed in this paper. This method accounts for test fluid density changes and, using a liquid hydrocarbon in place of nitrogen, applies the existing mass balance analysis of a nitrogen-brine MIT. In the mass balance, an algorithm that implements the most current thermodynamic and transport property models is used to calculate the test fluid density. This method provides a more robust analysis of cavern integrity in the well and cavern systems where density changes in the test fluid are significant during the testing period.

Key words: Caverns for Liquid Storage, Mechanical Integrity Testing, Liquid-Liquid MIT

Introduction

Solution-mined salt caverns are a proven, cost-effective method of storing an array of products ranging from liquefied petroleum gases (such as propane and butane) to natural gas, crude oil, hydrogen, and compressed air. North American regulations typically stipulate that a cavern's suitability for storage be proven before engaging in storage service and at regular intervals thereafter. Storage suitability is proven by demonstrating that a cavern system has mechanical integrity or tightness, and this is accomplished via a Mechanical Integrity Test (MIT).

Integrity testing methods for solution-mined salt cavern systems have been well established in several publications (e.g., Crotogino [1995], Van Sambeek et al. [2005], Bérest et al. [2001]). The test method is classified by the test medium. A nitrogen-brine MIT, also known as a Nitrogen Leak Test (NLT) or Nitrogen Interface Test (NIT), is the preferred method of cavern testing in North America. A Liquid-Liquid interface MIT (LL MIT), also known as a Fluid Leak Test (FLT) or Liquid Interface Test (LIT), is more commonly practiced in Europe. LL MIT methods, which include the Pressure Observation Test (POT) and Pressure Difference Observation (PDO) test, are discussed in detail by Van Sambeek et al. [2005].

In both the external well nitrogen-brine MIT and the LL MIT, the test fluid is injected below the last cemented casing (casing shoe) to expose the casing shoe to the test fluid. Test methods using nitrogen as the test fluid are considered to be more sensitive to leaks than tests using liquid test fluids [Heitmann, 1987]; therefore, some regulating agencies mandate that a nitrogen-brine well and casing shoe MIT be performed to quantify a cavern system's integrity. However, caverns developed in relatively deep salt deposits may not be suited for a nitrogen-brine MIT and, therefore, are tested using the LL MIT method.

Background

In many deep caverns, a nitrogen-brine MIT cannot be completed because of wellhead or casing pressure limits. For example, caverns developed in the Lotsberg Salt Formation (east-central Alberta, Canada) range in depth from 1,800 to 1,900 meters (m). With no surface pressure, saturated brine (specific gravity of 1.2) will exert 21,240 kPa on a casing shoe set at 1,800 m:

$$P_{\text{casing shoe}} = 11.8\frac{\text{kPa}}{\text{m}} \times 1{,}800\,\text{m} = 21{,}240\,\text{kPa}\ (3{,}166\,\text{psi}) \tag{1}$$

In many cases, if nitrogen replaces brine or product in the annulus, the production casing burst pressure is exceeded. Furthermore, if a larger casing shoe test pressure is desired, the annular wellhead pressure quickly exceeds commonly used wellhead components rated at 20.7 MPa (3,000 psi).

By performing an MIT with a denser hydrocarbon, the casing shoe can be exposed to the test fluid at the preferred test pressure without exceeding the maximum wellhead and casing pressure ratings. Additionally, stored product can often be used as the test fluid. This approach has the added benefit of readily available test fluid, and test conditions can be achieved at modest cost and time to the cavern operator.

Traditionally, MITs that use a liquid hydrocarbon as the test fluid are analyzed based on simply multiplying the annular wellhead pressure decay rate by the measured cavern compressibility [Thiel and Russell, 2004]; however, several types of phenomena can cause the apparent leak rate to deviate from the actual leak rate when using this method. Van Sambeek et al. [2005] identified these factors as, among others, steady-state salt creep, wellbore warming, steady-state brine micropermeation, and brine thermal expansion. Performing a PDO test can eliminate some of these factors.

The PDO test is an analysis of the pressure difference between the wellhead annular and hanging string pressures. Olesko et al. [2012] presented a "liquid-liquid interface test protocol and analysis algorithm" to use in the case of insufficient wellhead pressure rating and the absence of a small-diameter borehole. In this analysis, the wellhead pressures and borehole diameter at the interface are used to calculate a leak rate. The uncertainty in the leak rate is found through statistical means. Parsons Brinckerhoff Energy Storage Services, Inc. (PB ESS) has implemented this method for testing numerous caverns and has found the method to be reliable and expedient in most situations. However, some difficulty has been encountered when testing caverns developed in relatively deep strata in northern climates.

When testing caverns in east-central Alberta, PB ESS has commonly experienced differential pressures that continuously rose over the planned testing period, which caused the test to be extended for multiple weeks until the differential pressure stabilized. Analyses have shown that the rise in differential pressure can be caused by additional salt dissolution. Before testing the cavern, the down-hole product is displaced with cool brine stored at the surface. Upon warming, the degree of saturation of the down-hole brine decreases and allows for additional salt dissolution. In an effort to shorten the testing duration, PB ESS developed a new external well casing and wellbore MIT method that includes changes in the test fluid density caused by changes in pressure and temperature.

Thermal expansion of the test fluid (product) can occur during an LL MIT with no interface movement, which can mask a leak. By calculating the fluid mass instead of considering only the physical volume of the test fluid, a correction for the density change can provide a quantitative result that agrees with observations made during the test. The method proposed here provides a more robust analysis when (a) wellhead pressures steadily increase or decrease and (b) the well warms or cools throughout the test period.

The test method presented herein implements a mass balance technique similar to a nitrogen-brine MIT; however, the test fluid is a natural gas liquid (NGL) in place of nitrogen. Compared to nitrogen MIT methods, this method shares similar advantages and disadvantages as other liquid-liquid methods, such as the following:

- Lower wellhead pressures
- Lower cost
- Using stored hydrocarbon of the test fluid is operationally less demanding
- Testing with the stored product leads to a more realistic leak assessment
- Less sensitive to leaks than nitrogen because the viscosity of the hydrocarbon is higher
- Less robust when transient pressure and temperature changes are present, because liquid hydrocarbons have higher values of thermal diffusivity.

In addition, the proposed test method can shorten the test duration, because complete thermal and pressure stabilization are not necessary to prove the cavern well and wellbore tightness. This method, through compensation of moderate pressure and temperature changes, is more robust than current liquid-liquid methods. However, when implementing this method, the additional cost of wireline logging is incurred. Furthermore, this external well MIT method gives an indication of mechanical integrity above the interface only (as with other nitrogen-brine or PDO MIT techniques), and further analysis is required to prove the cavern below the interface has integrity.

Test Method Theory

The proposed MIT method implements a mass balance of the test fluid (NGL product) to calculate an apparent leak rate. Surface wellhead pressures, down-hole temperature, and the physical volume of product are used to calculate the product mass at both the start and end of the test period. The change in mass over the test period is used to calculate an apparent leak rate.

Product density at the wellhead is calculated and numerically integrated down to the product-brine interface depth. With knowledge of the cross-sectional area with depth, the mass of product is determined at both the start and end of the test period. This analysis method makes the following assumptions:

- Temperature gradients in the radial direction are negligible compared to temperature changes with depth and time (i.e., the brine temperature in the hanging string represents the test fluid temperature in the annulus).
- Hydrocarbon migration does not occur from within the cavern during the test period (e.g., product does not migrate from traps below the established product interface).
- Test fluid composition is well known (i.e., has minimal impurities), and the behavior is consistent with the implemented equation-of-state model.

Test Fluid Equation of State

For the examples included herein, the GERG-2008 equation of state (EOS) was implemented [Wagner, 2012]. This EOS is valid for natural gasses and other mixtures of natural gas components and is based on a multifluid approximation explicit in the reduced Helmholtz free-energy equation. The uncertainty in the density of pure and multicomponent liquid phase mixtures, at pressures up to 40 MPa and temperatures between 90 K and 450 K calculated from GERG-2008 EOS, is approximately 0.1 to 0.5 percent, which is in agreement with experimental uncertainty [Wagner, 2012]. REFPROP, software developed by the National Institute of Standards and Technology (NIST) [Lemmon et al., 2010], was used to solve the GERG-2008 EOS. Table 1 provides an example of the isobaric density change from a temperature increase in typical hydrocarbons stored in solution-mined salt caverns.

Table 1. The Change in Density with Temperature of Commonly Stored Products at a Constant Pressure of 18 MPa

Hydrocarbon (P = 18 MPa)	Density (T=0°C) (kg/m^3)	Density (T=45°C) (kg/m^3)	Change (%)
Butane	620.9	579.3	–7.2
Ethylene	438.2	353.5	–24.0
Ethane	453.9	386.9	–17.3
Pentane	661.6	624.2	–6.0
Propane	556.3	507.3	–9.7

In the case study presented later in this paper, transient temperature changes in the wellbore have a measureable effect on the apparent leak rate. A large temperature difference between the injected product and in situ temperatures causes long stabilization periods. In Canada, product from surface storage or a pipeline, where ambient temperatures can be as low as –30°C, is injected into the cavern well and wellbore where temperatures may be in excess of 45°C.

Calculating Test Fluid Mass

The test fluid density is a function of temperature, pressure, and composition. Down-hole temperature logs yield discrete temperature measurements in the wellbore, and surface wellhead pressures are recorded, from which down-hole pressure may be determined using Equation 2. For the analyses given herein, approximate numerical solutions have been determined from a discretized form of Equation 2 and are in Equations 3 and 4. A summation over the test domain yields a pressure at each discrete location using a first-order, explicit, backward difference numerical scheme.

$$\frac{\partial P(T)}{\partial z} = \rho(T, P)\, g \tag{2}$$

$$\frac{P_{j+1} - P_j}{\Delta z} = \rho_j(T_j, P_j)\, g \tag{3}$$

$$P_{j+1} = P_j + \Delta z \rho_j\left(T_j, P_j\right) g \tag{4}$$

where:

P = pressure (MPa)

T = temperature (K)

ρ = test fluid density $\left(\frac{\text{kg}}{\text{m}^3}\right)$

z = depth (m)

j = discrete location

g = gravitational acceleration $\left(\frac{\text{m}}{\text{s}^2}\right)$.

At each discrete location, the pressure is calculated using the density at the previous location plus the mass of the fluid over the discrete interval. This value is assumed to be an accurate representation of current density, assuming that sufficiently small depth increments are used and no anomalous, extreme temperature gradients are present.

The mass is calculated using the test fluid density and the wellbore geometry, as shown in Equation 5:

$$m_j = \rho_j\left(P_j, T_j\right) V_j \tag{5}$$

where:

m = mass

V = volume $\left(\text{m}^3\right)$.

As the product-brine interface is placed below the casing shoe, some knowledge of the borehole below the casing shoe is required. At a minimum, the diameter of the borehole at the interface and the volume from the casing shoe to the interface are needed. This information is best estimated with either a sonar survey, or through borehole "strapping," which involves running successive logs while injecting a known volume of product.

Leak Rate and Test Accuracy

The leak rate is calculated as shown in Equation 6.

$$\text{CLR} = \frac{\left(m_1 - m_2\right)}{\rho_{\bar{T},\bar{P}}\left(t_2 - t_1\right)} \tag{6}$$

where:

CLR = calculated leak rate $\left(\frac{\text{m}^3}{\text{day}}\right)$

$\bar{T}$ = average temperature of test domain over test period (K)

$\bar{P}$ = average pressure of test domain over test period (MPa)

t = time (days).

Here, the CLR is calculated using the average wellbore temperature and pressure at both the start and end of the test. A more conservative approach involves selecting the smaller of the two densities. Furthermore, if a nitrogen-brine casing MIT confirmed the tightness of the cased well above the casing shoe, a better approximation would include only the density of the hydrocarbon below the depth of the nitrogen-brine interface during the casing MIT.

The test sensitivity defines the ability of the test measurements to evaluate the mechanical integrity of the well and wellbore. The pass/fail criteria are developed from this test sensitivity. The conventional Minimum Detectable Leak Rate (MDLR) is calculated, as shown in Equation 7.

$$\text{MDLR} = \frac{V \cdot r}{t} \tag{7}$$

where:

MDLR = minimum detectable leak rate $\left(\frac{\text{m}^3}{\text{day}}\right)$
V = unit volume at interface $\left(\frac{\text{m}^3}{\text{m}}\right)$
r = tool resolution (m)
t = test duration (day).

This method provides a reasonable measure of the test accuracy and sensitivity. However, because the proposed test method results require P-V-T calculations, a rigorous analysis of the test accuracy must also include considering pressure, temperature, and a borehole measurement. The MDLR calculation is based on down-hole measurements of the wellbore and test conditions.

Test Method Application

The following steps outline the procedure used to implement this method and are consistent with industry practice and published test procedures:

- Isolate the cavern system.
- Run a wireline log in the brine tubing to record base conditions.
- Place the product-brine interface a few meters below the casing shoe. The product can typically be injected with the facility pumps. Note that the wellbore diameter at the interface depth is an important parameter in the test assessment.
- Pressure the cavern to the chosen test pressure.
- Allow sufficient time for stabilization. The stabilization time required is determined through wellhead pressure trends and knowledge of the testing history. The cavern size, brine saturation, and cavern temperature gradients are contributing factors in the required stabilization time.
- Run a wireline logging tool to locate the product-brine interface and record the well temperature with depth. Note the wellhead pressures at the time of the interface log. The test period starts at the time of the interface log.
- The MDLR will decrease proportionally with the inverse of time. Once the required MDLR has been achieved, run a wireline logging tool to locate the product-brine interface and record well temperatures. Note the wellhead pressures at the time of the interface log. Ending the test at the same time of day as the start time is preferable to minimize ambient temperature effects.

Case Study

To date, an LL MIT has not been performed with the purpose of implementing this test method. Instead, a posttest analysis using test data fitting the parameters of the current test method was completed. The proposed test method is implemented in the following case study.

Background and Test Measurements

The following MIT was performed in Alberta, Canada, on a bedded salt cavern located in the Lotsberg Salt Formation (see Figure 1) using butane as the test fluid. The cavern volume is approximately 1 million barrels (MMbbls), or approximately 150,000 m^3. Approximately 50 m^3 of butane was injected into the cavern before the test. During testing, two wireline logs of the well temperature and product-brine interface were completed. The first log was completed 2 days after product injection and cavern pressurization, and the second log was completed 11 days after the first log was completed. The two wireline logs will be considered at both the start and end of the test. The cavern remained shut-in and monitored after the second wireline log was completed, but this data will not be considered in this paper.

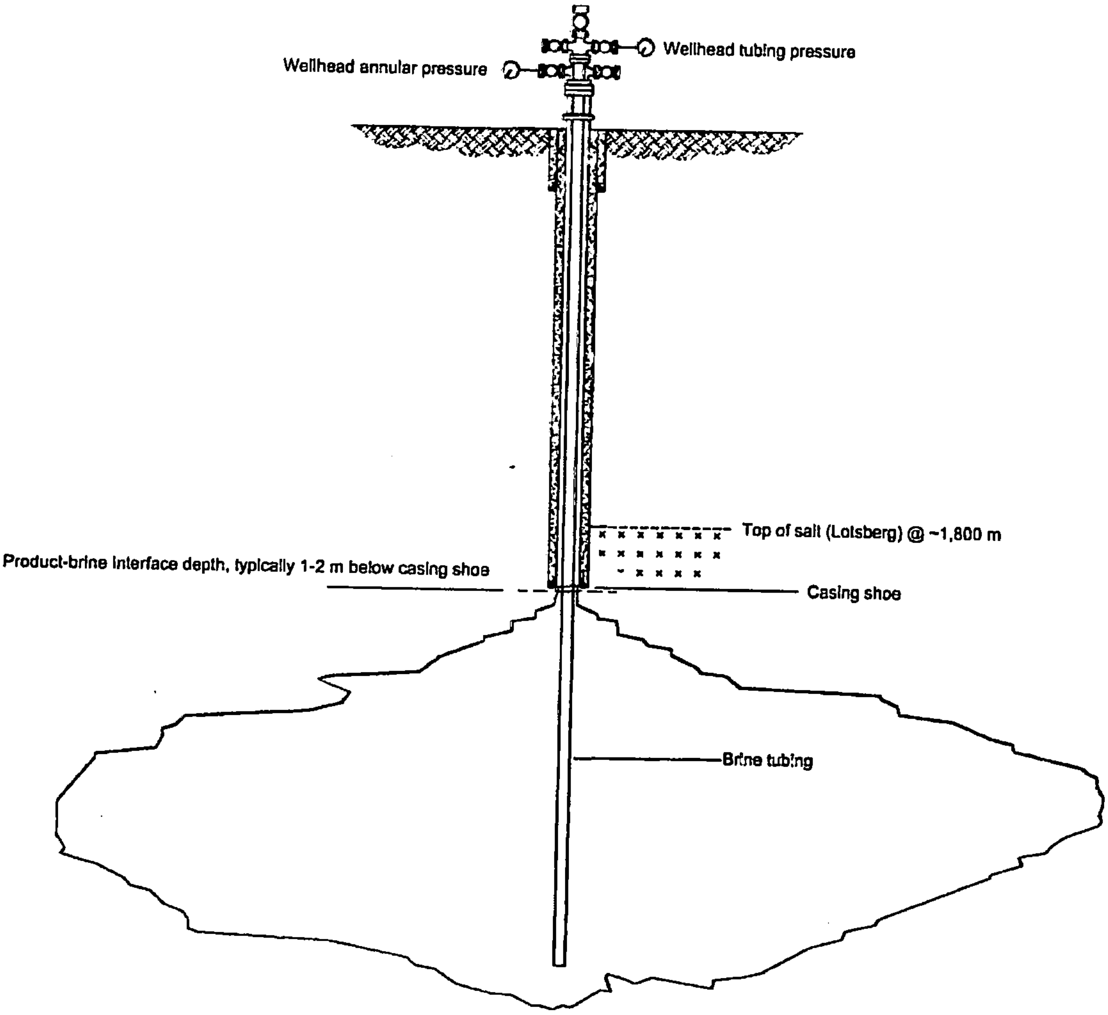


Figure 1. Schematic of Bedded Salt Cavern Mechanical Integrity Test in the Lotsberg Salt Formation.

Several noteworthy observations were recorded during the test. Both the annular (product) pressure and the tubing (brine) pressure steadily increased during the test (see Figure 2). The increasing pressure indicates cavern creep, which can occur at relatively high rates in caverns at this depth. Note that the cavern temperature decreased over the test period, which rules out brine thermal expansion as the underlying phenomena for the increasing pressures (see Figure 3).

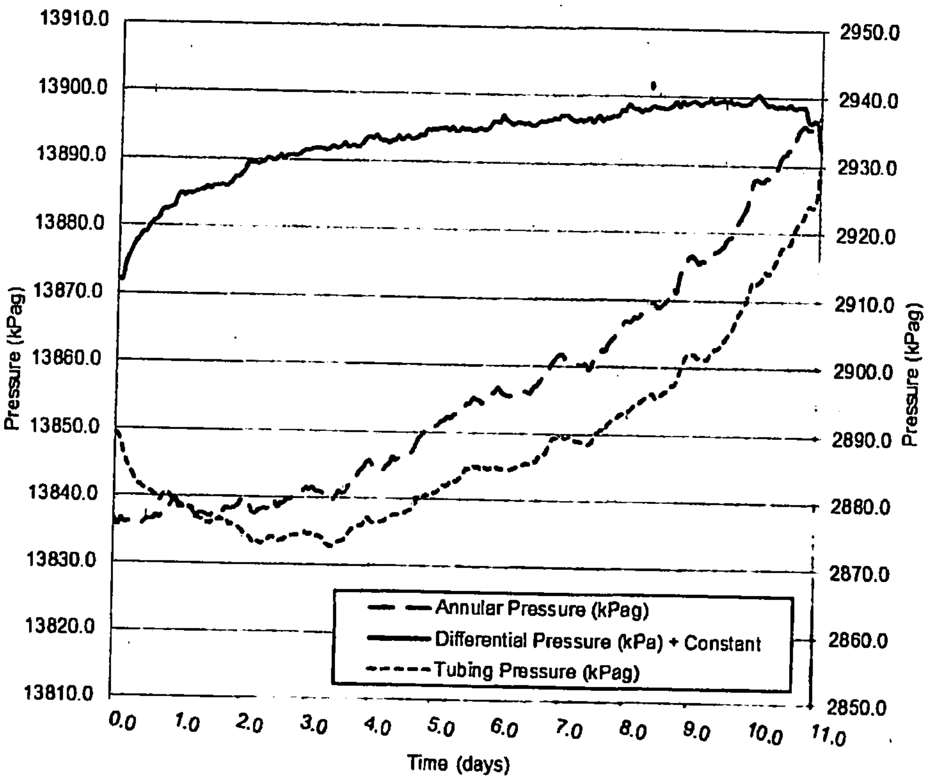


Figure 2. Wellhead Annular and Differential Pressure (Left Axis) and Tubing Pressure (Right Axis).

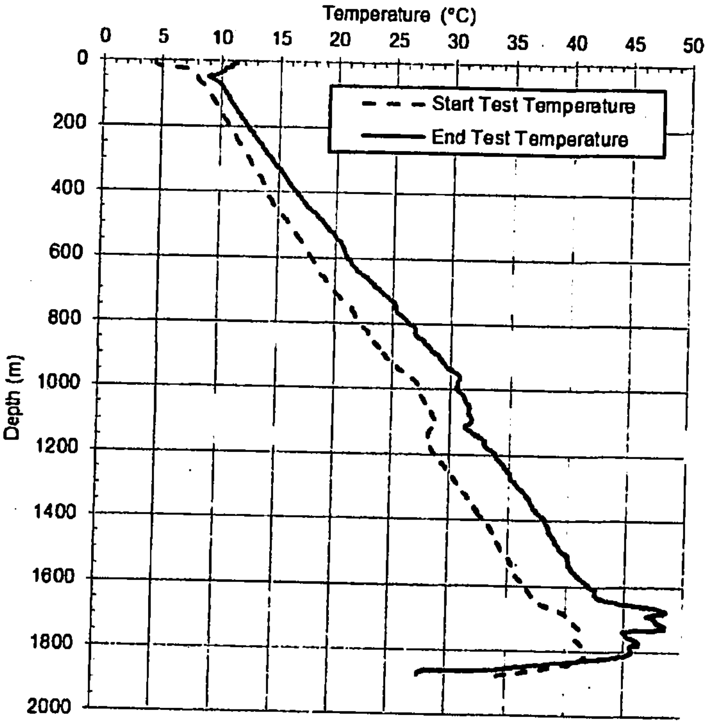


Figure 3. Temperature as a Function of Depth at the Start and End of the Mechanical Integrity Test.

Along with the increasing cavern pressure, the wellbore warmed by an average of 3.6°C over the test period (see Figure 3). This test was performed in December where, as mentioned previously, the product was injected at a much lower temperature than the well temperatures. The measured temperatures and pressures and associated calculated butane density are provided in Table 2.

Table 2. Test Measurements and Calculated Product Density at the Start and End of the Test

	Test Start	Test End	Change
Wellhead Annular Pressure (kPag)	13,837	13,897	60.0
Average Well Temperature (°C)	24.6	28.3	3.6
Average Density (kg/m^3)	600.2	597.0	–3.3

Down-hole movement of the product-brine interface was measured at 0.25 m. The calculated volume increase was 0.86 m^3 (a change of 1.7 percent). The physical volume over the 0.25-m interface movement was 1.2 m^3 (provided by a sonar survey).

Test Results

The results of the test are provided in Table 3. The change in interface depth is at the lower limit of the tool accuracy; it is the smallest incremental movement that can be recorded with reasonable certainty. If the butane is assumed incompressible in this test, the CLR is calculated at the same magnitude as the MDLR. By applying a mass balance and accounting for density changes, the CLR moves within the accuracy limits of the test method. This result provides an illustration of the additional robustness achieved through implementing the present method.

Table 3. Test Results When Assuming the Test Medium Is Incompressible and With Implementing the Current Mechanical Integrity Test Method

	Without Density Calculation	Current Method
Change in Mass (kg)	—	517
Change in Volume (m^3)	1.21	0.86
CLR (bbls/yr)	**–251.1**	**–178.9**
MDLR (bbls/yr)	**±251.1**	**±251.1**

The test is considered successful because the CLR is less than the MDLR, and the differential pressure had stabilized. In many ways, the following conclusions derived from this test are similar to the nitrogen interface test that used a mass balance (the method on which this test method is based):

- Small interface movements, which may appear to be a leak or influx of fluid, can be explained through a mass balance.
- Leaks that are not apparent through direct observations can be calculated.
- A nonzero leak calculation is explained by the limits of the test. Contributing factors include the error of the interface logging tool, and to a lesser extent, pressure and temperature measurement error and the assumptions built into the test method.

Conclusions

An MIT method of testing a cavern well and wellbore integrity using a mass balance of a hydrocarbon test fluid is presented. Using commercially available software allows for the accurate modeling of many common storage products (in this case, butane) when nitrogen cannot be used as a test medium. An MIT analysis of a deep cavern located in Alberta showed that, by accounting for density changes in butane, the integrity of the cavern well and wellbore can be demonstrated.

The work presented here was developed out of a need for more timely and robust testing methods in Alberta. In industry applications, a driving factor for any MIT is to yield acceptable results in a timely manner. In comparison with a POT, PDO, or similar method, the method presented here incurs the additional cost of wireline logs with the trade-off of shorter MIT periods. A shorter MIT duration is achieved by accounting for moderate pressure and temperature changes, which yields a more robust test method. Furthermore, when considering the additional cost of this method, note that it is not uncommon in Alberta to run several logs during an MIT. The logs are often not originally scheduled but are added when (a) wellhead pressures do not stabilize over long periods of time and/or (b) the differential pressure indicates interface movement.

The test method is not limited to deep caverns, but extends the method to caverns in other regions, especially shallow caverns, may not provide any further insight into the cavern integrity. Future work should include a direct comparison with a nitrogen-brine and other LL MIT methods.

Acknowledgements

The authors would like to acknowledge Keyera Corp. for allowing access to cavern testing data, as well as Mr. Nils Skaug and Mr. Paul Nelson of Parsons Brinckerhoff.

References

Bérest, P., B. Brouard, and J. Durup, 2001. "Tightness Tests in Salt-Cavern Wells," *Oil & Gas Science and Technology, 56*, pp. 451–469.

Crotogino, F., 1995. "SMRI Reference for External Well Mechanical Integrity Testing/Performance, Data Evaluation and Assessment," Summary of the Final Project Report, SMRI 95-0001, prepared by KBB Underground Technologies, for Solution Mining Research Insitute, Woodstock, IL.

Heitmann, N. A., 1987. "Experience With Cavern Integrity Testing Using Nitrogen Gas," *Solution Mining Reseach Institute Spring Meeting*, Tulsa, OK, April 27.

Lemmon, E., M. Huber, and M. McLinden, 2010. *NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties - REFPROP*, Version 9.0, Gaithersburg, MD.

Olesko, M., J. Ratigan, and N. Skaug, 2012. "Application of a Liquid-Liquid Interface Mechanical Integrity Test to Bedded Salt Solution-Mined Hydrocarbon Storage Cavern Wells," *Solution Mining Reseach Institute Spring Meeting*, Regina, Saskatchewan, Canada, April 23–24.

Thiel, W. and J. Russell, 2004. "Pressure Observation Testing Solution Mined Underground Storage Caverns in Kansas," *Solution Mining Reseach Institute Spring Meeting*, Witchita, KS, April 18–21.

Van Sambeek, L. L., P. Bérest, and B. Brouard, 2005. *Improvements in Mechanical Integrity Tests for Solution-Mined Caverns Used for Mineral Production or Liquid-Product Storage*, Research Project Report No. 2005-1, prepared by RESPEC, Rapid City, SD, USA; École Polytechnique, Cedex, France; and Brouard Consulting, Paris, France, for the Solution Mining Research Institute, Clarks Summit, PA.

Wagner, O. K., 2012. "The GERG-2008 Wide-Range Equation of State for Natural Gases and Other Mixtures: An Expansion of GERG-2004," *Journal of Chemical and Engineering Data, 57*, pp. 3032–3091.

Strategische gasolieopslag in zoutcavernes opslagvergunning De Marssteden

Inleiding op Techniek en materie

Bijdrage (TNO)

Expertmeeting Enschede

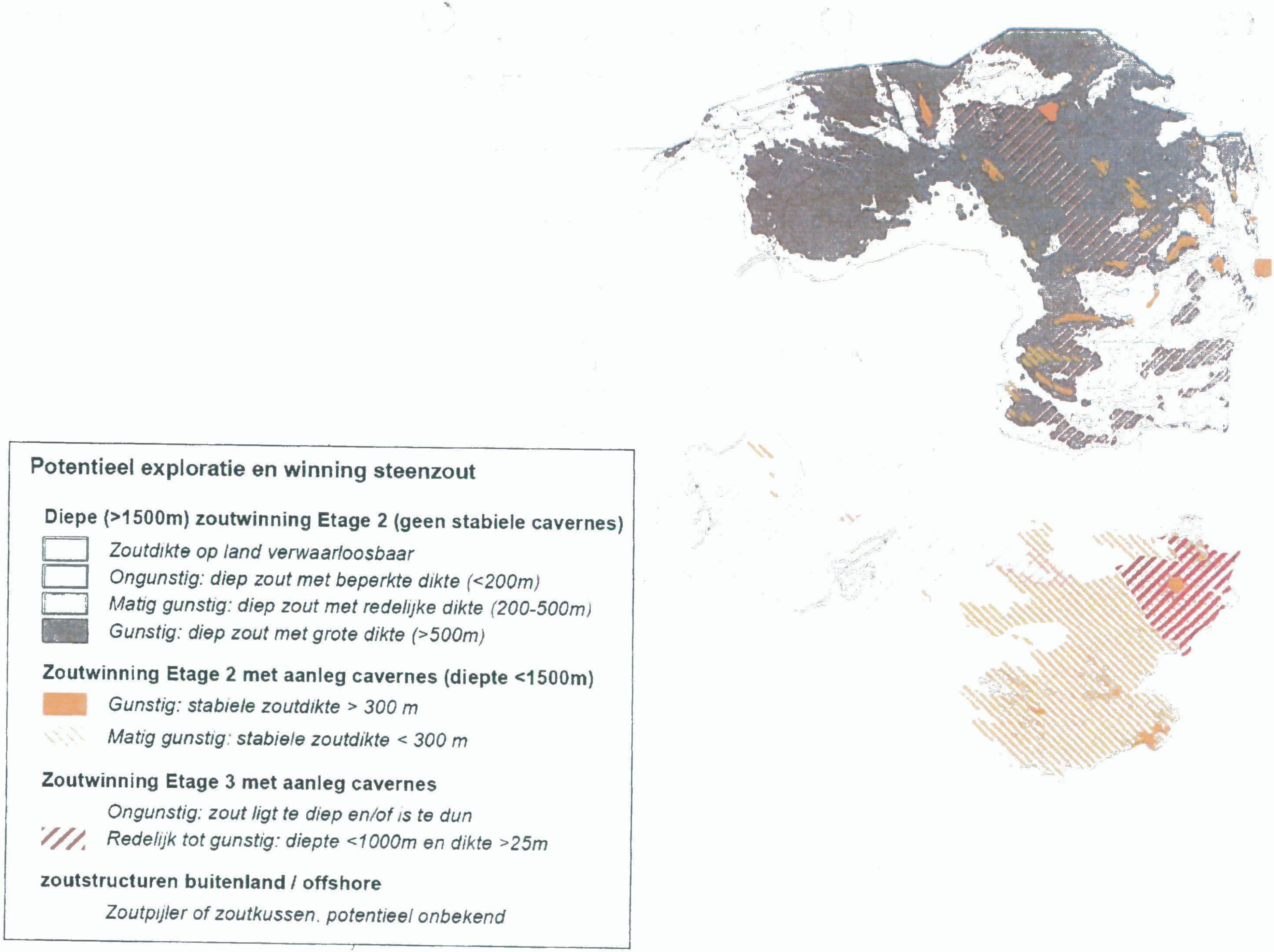
17-12-2014

Inleiding

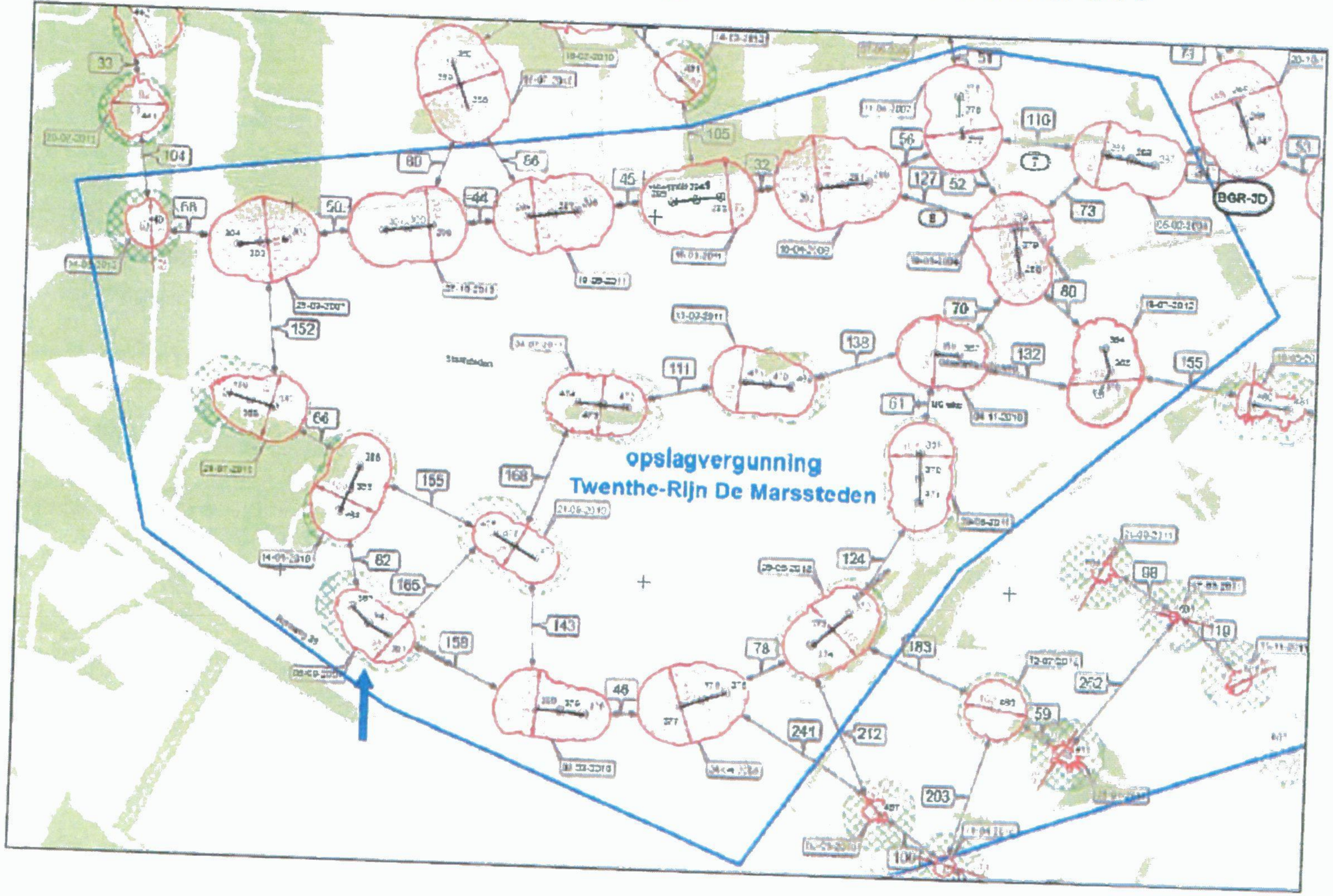
1. Zoutcavernes
    - waar in Nederland?
    - aanleg
    - vormen
    - convergentie (samendrukking)
    - Marssteden vergeleken met Epe (en Barradeel)

2. Materie
    - eigenschappen van steenzout (lekdichtheid)
    - eigenschappen van gasolie i.r.t. steenzout

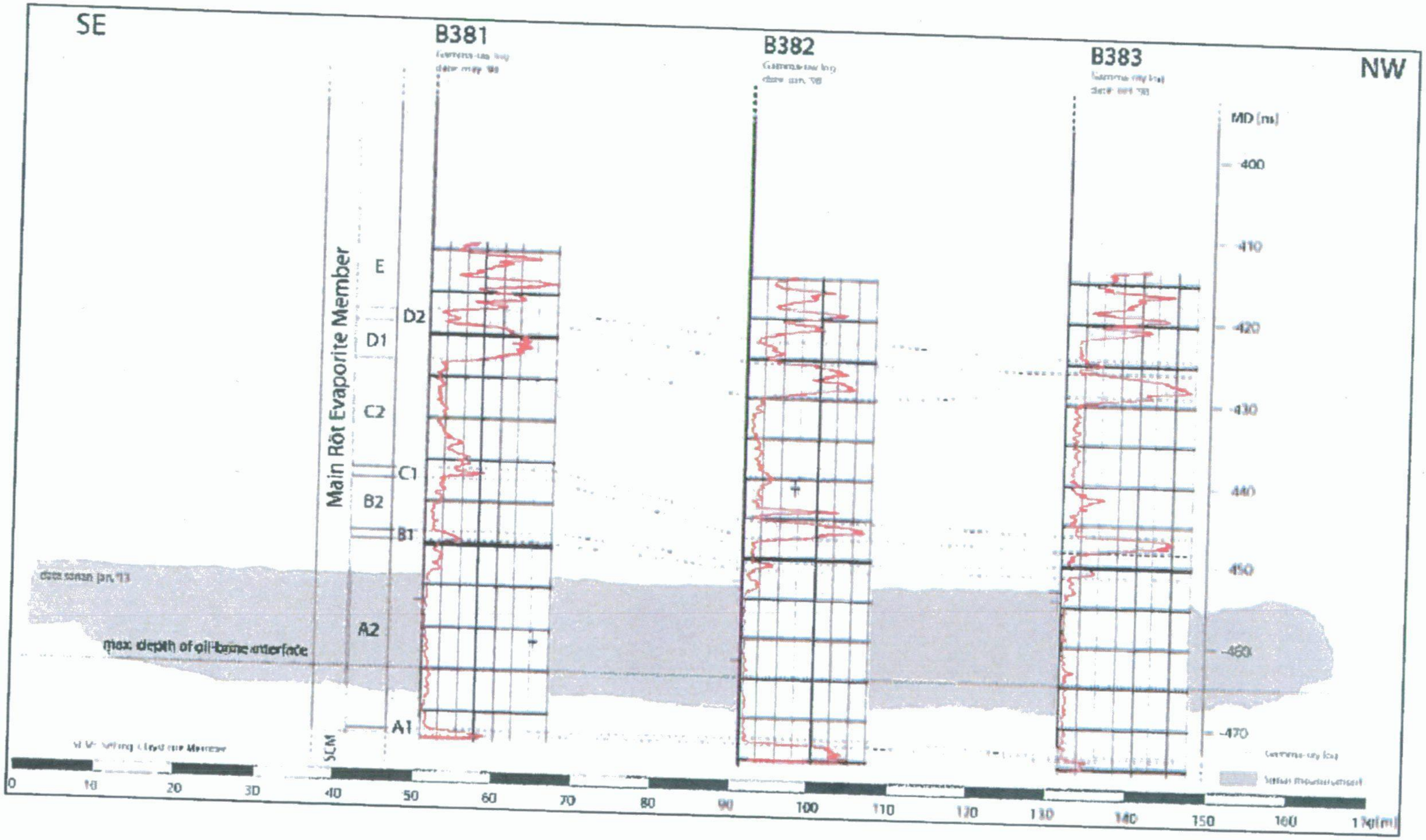
3. Bodembeweging
    - relatie met convergentie
    - computermodel


Potentieel exploratie en winning steenzout
Diepe (>1500m) zoutwinning Etage 2 (geen stabiele cavernes)
☐ Zoutdikte op land verwaarloosbaar
☐ Ongunstig: diep zout met beperkte dikte (<200m)
☐ Matig gunstig: diep zout met redelijke dikte (200-500m)
■ Gunstig: diep zout met grote dikte (>500m)
Zoutwinning Etage 2 met aanleg cavernes (diepte <1500m)
■ Gunstig: stabiele zoutdikte > 300 m
▨ Matig gunstig: stabiele zoutdikte < 300 m
Zoutwinning Etage 3 met aanleg cavernes
Ongunstig: zout ligt te diep en/of is te dun
▨ Redelijk tot gunstig: diepte <1000m en dikte >25m
zoutstructuren buitenland / offshore
Zoutpijler of zoutkussen, potentieel onbekend

Holruimtekaart
opslagvergunning De Marssteden



Dwarsdoorsnede caverne 381



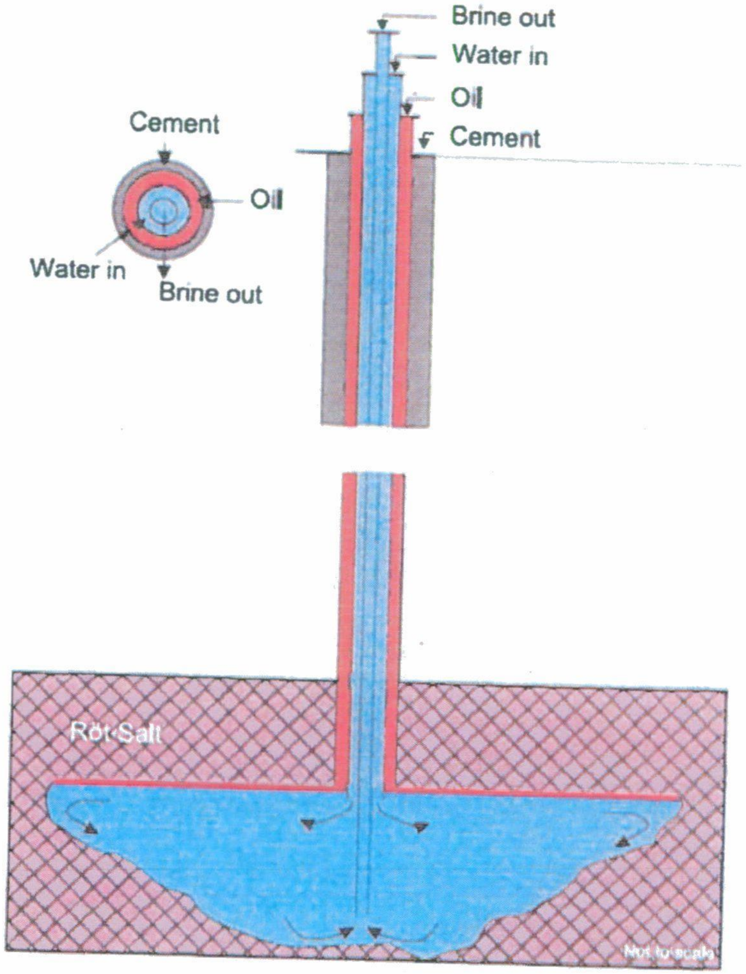
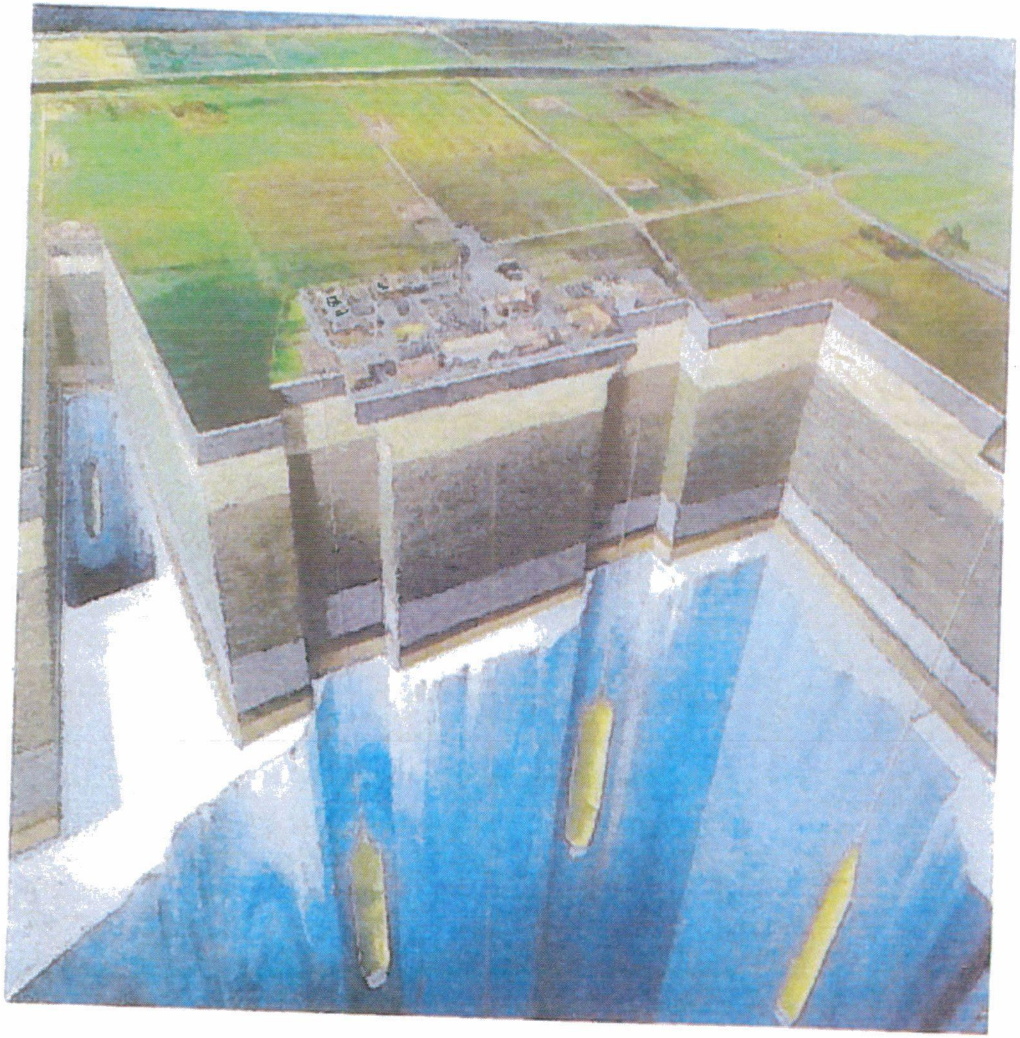
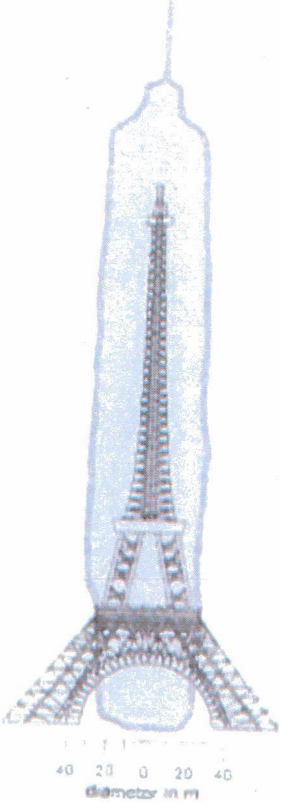


Fig. 9. Cross section of a cavern at a depth of ca. 300 m in the bedded Triassic Röt Salt in the Twenthe-Rijn concession. The flat top of the cavern results from the application of a blanket fluid, and maintains the stability of the roof of the cavern (after Wassmann & Brouwer, 1987).

Oplosmijnbouw (vgl. situatie Barradeel)

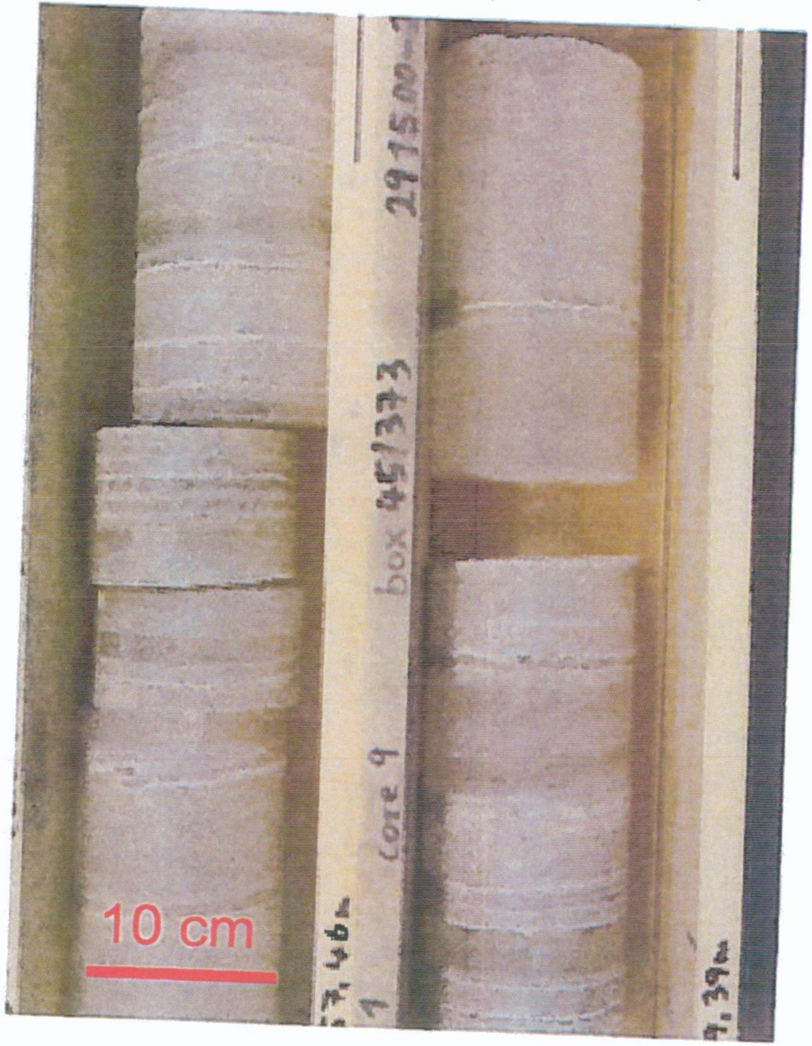


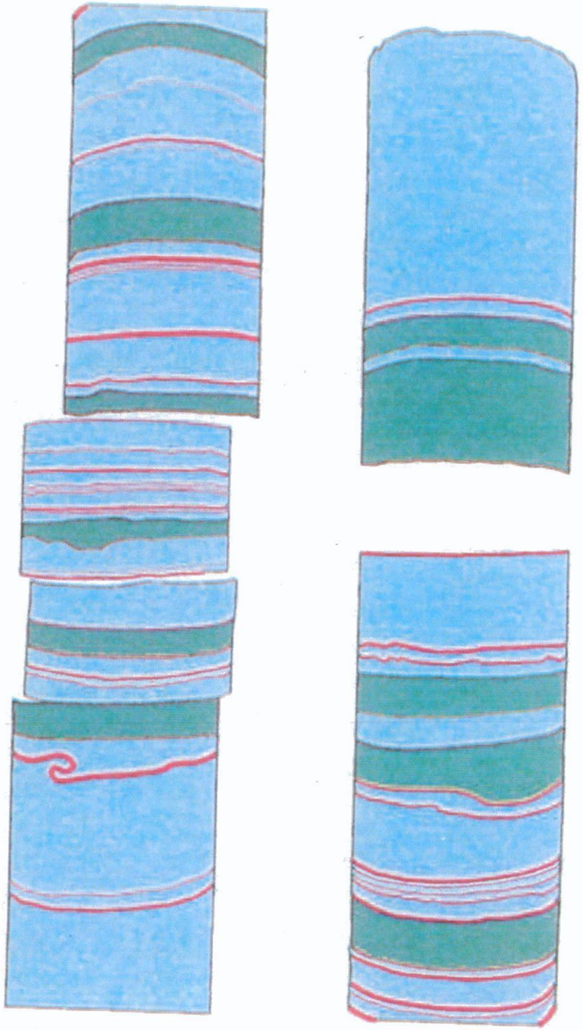


Kenmerken zoutcavernes
Marssteden, Epe en Barradeel

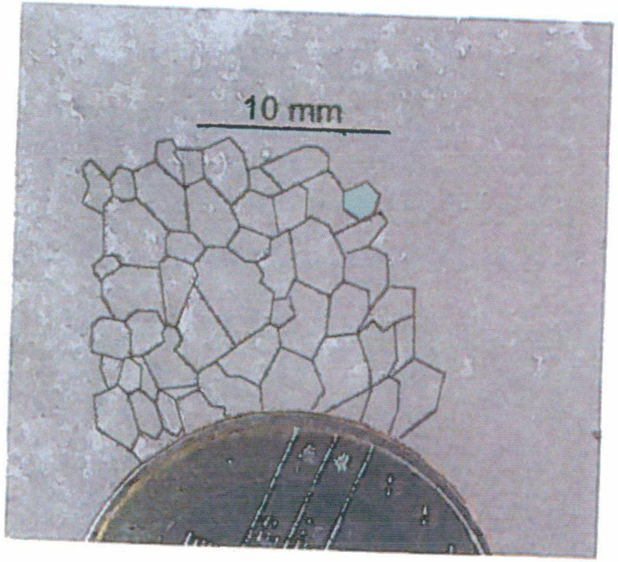
		Marssteden	**Epe**	**Barradeel**
zoutformatie		Roet evap.(Trias)	Zechstein	Zechstein
dieptebereik [m NAP]		400-450	1100-1250	2600-2900
aantal cavernes		2	3	
opgeslagen volume	[mln m³]	0,25	1,4	
opslagvloeistof		gasolie	ruwe olie?	
vorm cavernes		platte ellips	cylinder	smalle cylinder
volume per caverne	[mln m³]	0,125	0,45	0,25
hoogte	[m]	30	145	300
diameter	[m]	150-200	85	50
temperatuur opslag	[C]	22	45	100
gesteentedruk	[bar]	90	220	620
vloeistofdruk	[bar]	60		350
convergentie	[%/jaar]	< 0,1	0,5	50

Steenzout (Barradeel kern)

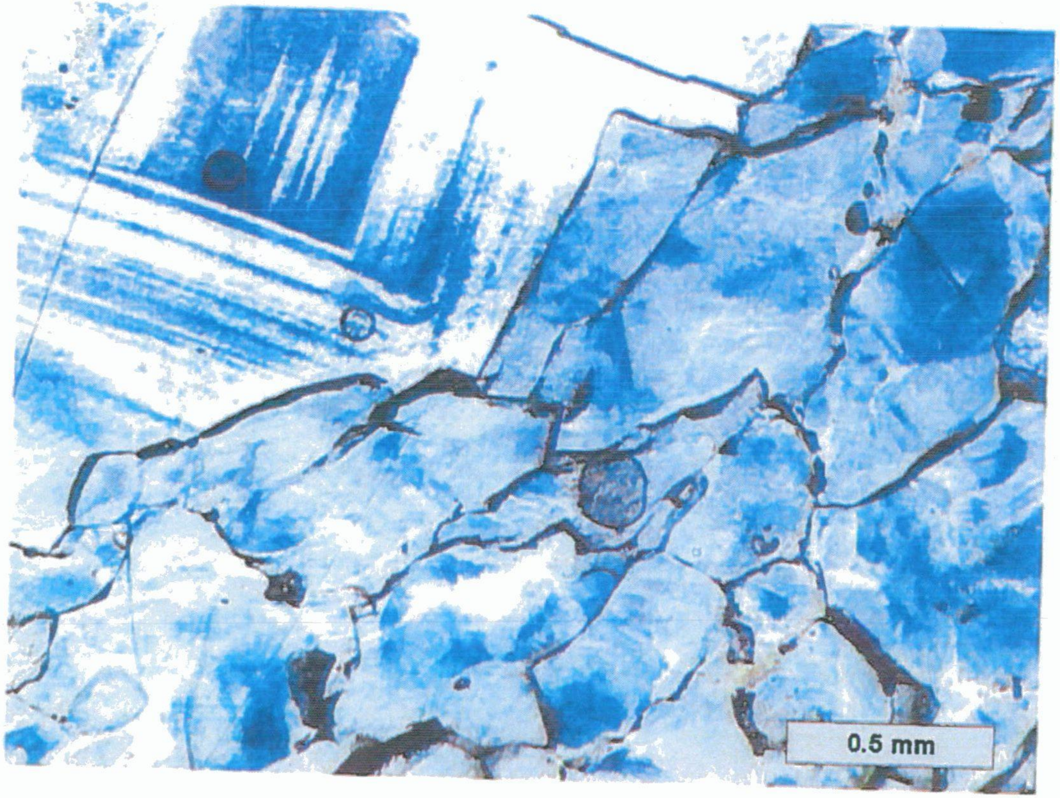




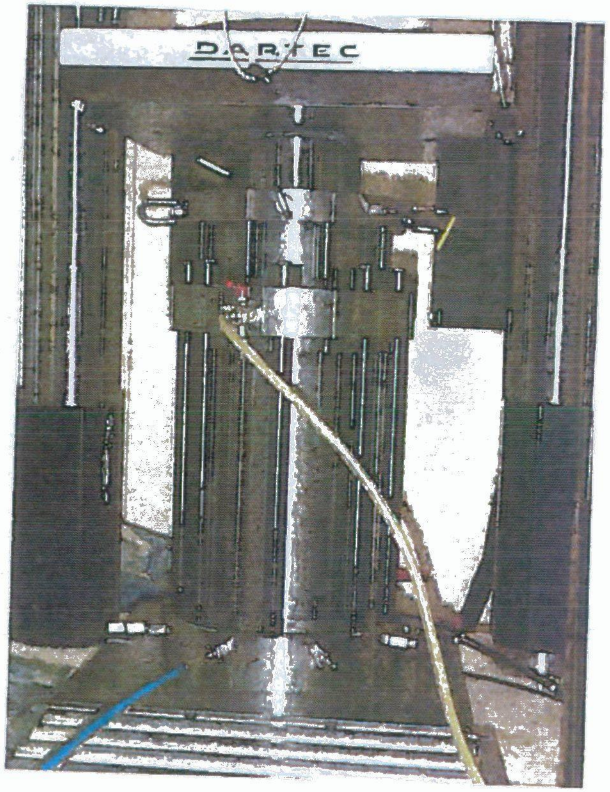
Korrelgrootte (variatie)



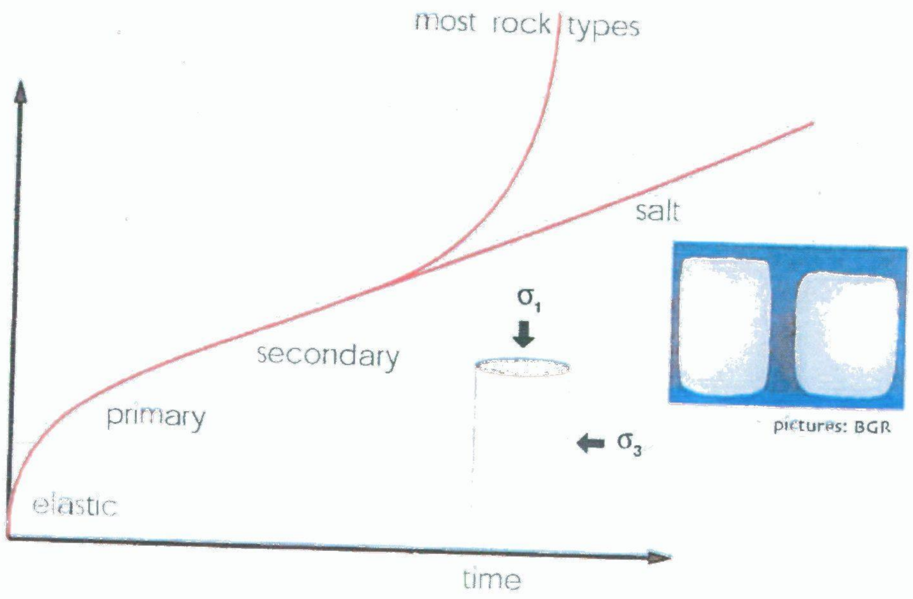
Korrelstructuur (micro)



Onder druk



Ductile deformation of salt

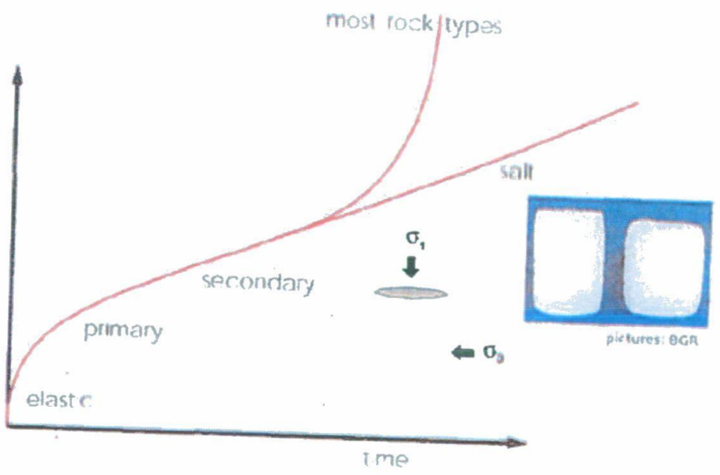


pictures: BGR

Eigenschappen van steenzout

Kleine schaal (lab)

- zeer lage porositeit (0,2 tot 1%)
- zeer lage doorlatendheid
- plastisch gedrag



Grote schaal (ondergrond)

- gasdicht
- breuken kunnen zich niet uitbreiden
- goede asfsluitende laag gebleken voor gasvelden
- wereldwijd toegepast als ‘container’ voor gasopslag en gasolieopslag

Eigenschappen van gasolie

Algemeen

- Gasolie: verzamelnaam voor dieselolie, huisbrandolie en brandstof voor scheepvaart
- In Marssteden: dieselolie

In relatie tot steenzout

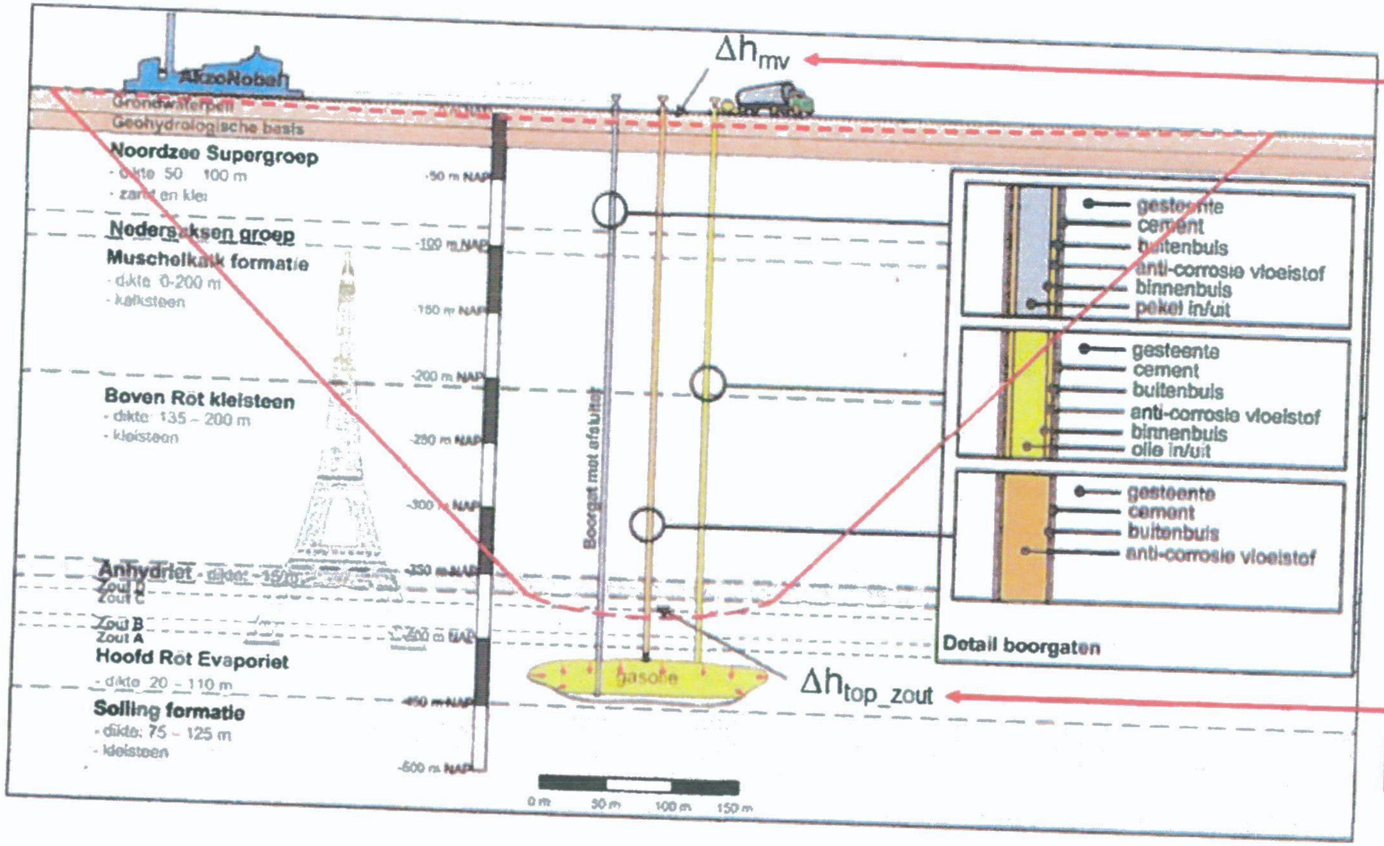
- steenzout is chemisch inert voor koolwaterstoffen
- steenzout is niet oplosbaar in dieselolie
- dichtheid : 820-860 kg/m^3 , vgl. pekel (1025 kg/m^3)

In relatie tot staal (putten, ..)

zwavelgehalte lager dan in ruwe olie

Deformatie ondergrond

(figuur: bron Akzo)

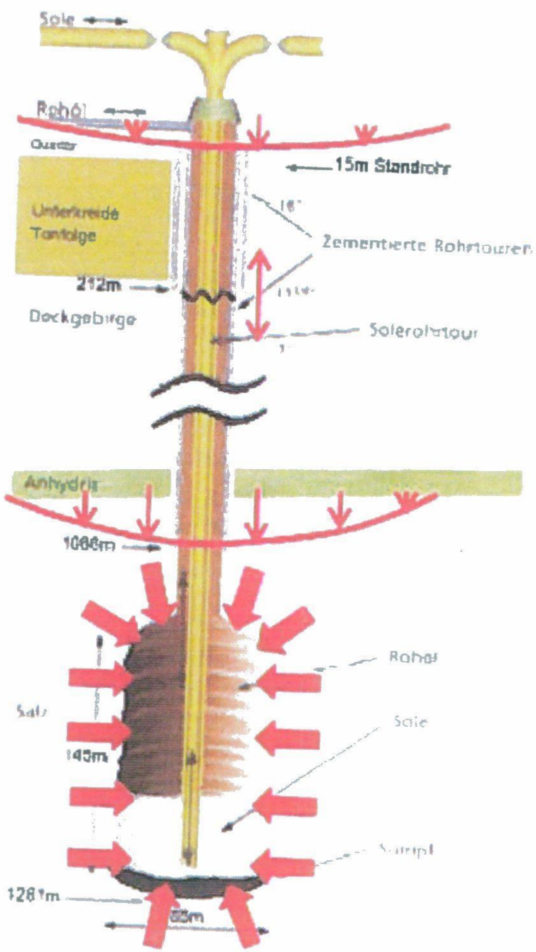


Ordegrootte: enkele centimeters per 100 jaar

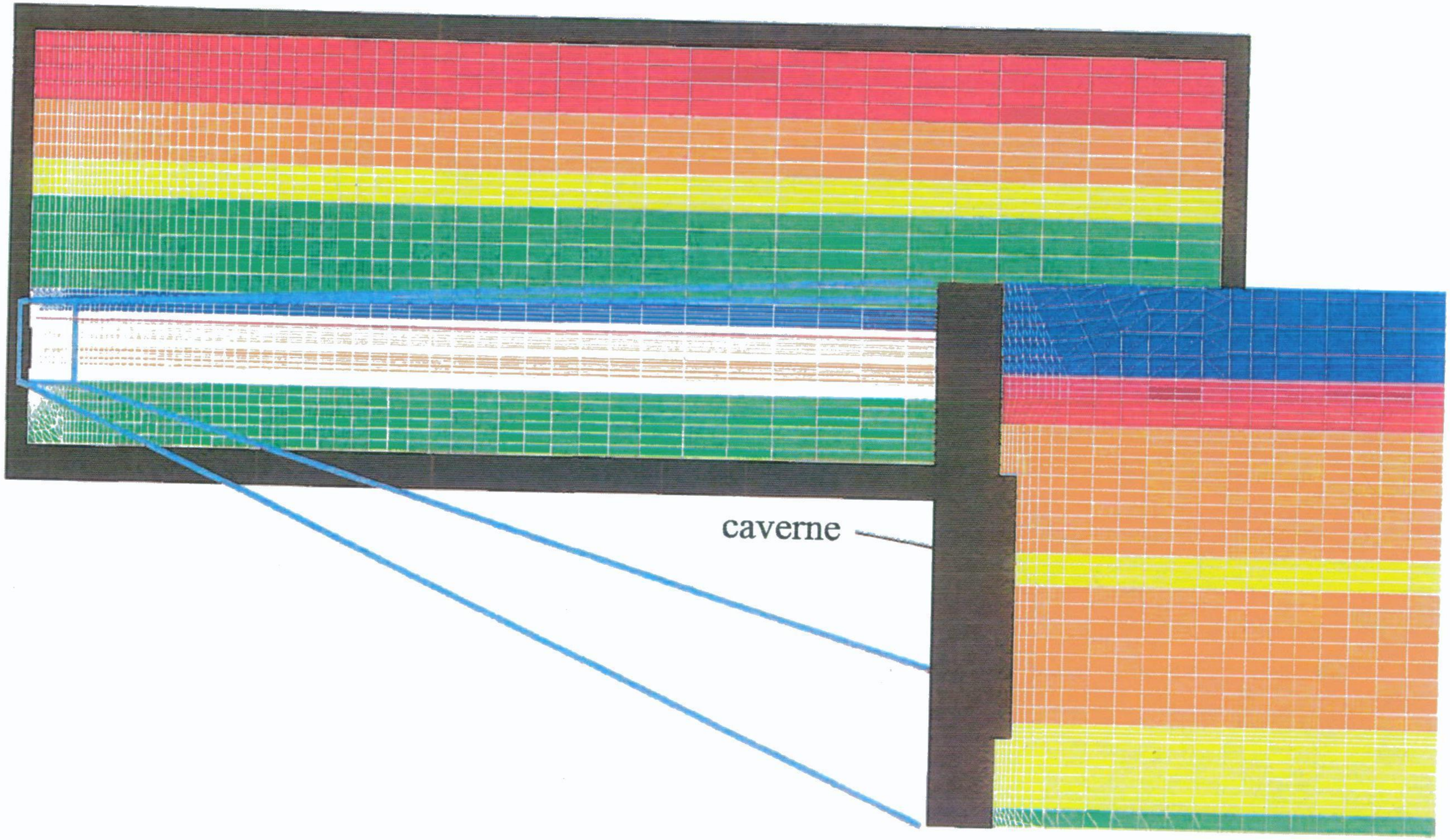
Ordegrootte: enkele decimeters per 100 jaar

Deformatie rond put

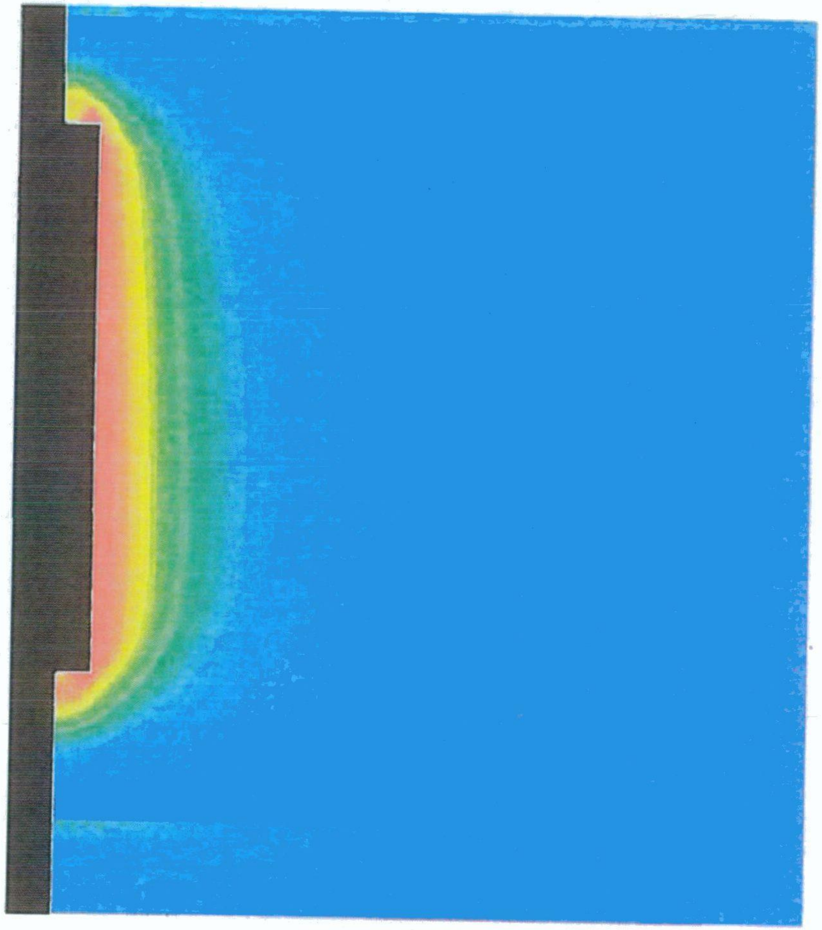
(bron: Akzo)



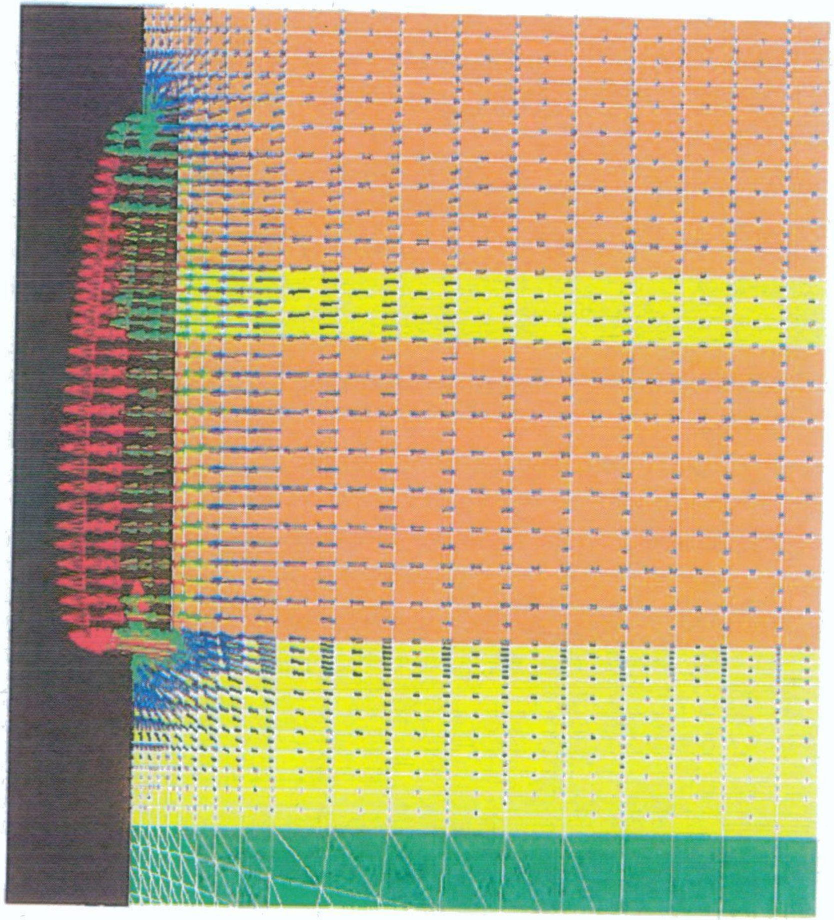
Computermodel zoutcaverne



Computermodel caverne convergentie



Spanningen



Verplaatsingen

Referentie naar artikel

Bow-tie risk assessment combining causes and effects applied to gas oil storage in an abandoned salt cavern

Engineering Geology 168 (2014) 149-166 [Elsevier]

479

Van: @vu.nl>
Verzonden: woensdag 17 december 2014 11:58
Aan: @itc.nl'; @eia.nl'; 'gvanderveen@akd.nl'
Onderwerp: Re: expertmeeting
Bijlagen: presentatie_vHuissteden.pptx

Allen,

Ik zie nu dat ik een oude versie van mijn presentatie had opgestuurd. Hier is de goede

Met vriendelijke groet

Vrije Universiteit, Faculty of Earth and Life Sciences
Department of Earth Sciences, Earth and Climate Cluster
De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands
tel. 31-20- ax 31-2
e-mail @vu.nl

From: < @enschede.nl>
Date: Wednesday, December 17, 2014 11:33 AM
To: "\ @overijssel.nl>. @vu.nl>, < @tno.nl>, ' @itc.nl"' . @itc.nl>, "' minez.nl>, ' @eia.nl"' @eia.nl>, "' @akd.nl"' < @akd.nl>
Subject: RE: expertmeeting

n hierbij alle presentaties.....en een lijst met aanmeldingen van "derden"

Van: @overijssel.nl]
Verzonden: woensdag 17 december 2014 11:30
Aan:
(@itc.nl'; @eia.nl'; @akd.nl'
Onderwerp: expertmeeting

Geachte inleiders, ter voorbereiding op de expertmeeting hedenmiddag ontvangt u via deze mail de door ons ontvangen presentaties. Gelieve hier kennis van te nemen. Tweede punt is dat de dagvoorzitter graag een klein moment voor aanvang van de expertmeeting met u wil kennis maken cq de laatste aandachtspunten / ordetechnische aangelegenheden wil bespreken. Ik zal u op dat moment even bij elkaar roepen. Derde en laatste aandachtspunt is dat richting staten en raad de navolgende tekst is verzonden.

Raad- en Statenleden (zitten achter tafels met microfoons) krijgen per onderwerp als eerste de mogelijkheid vragen te stellen aan de deskundigen en wij verzoeken u rekening te houden met maximaal 2 vragen per woordvoerder (als alle woordvoerders vragen hebben). De gespreksleider zal per "blok" vragen welke woordvoerders het woord willen en kan dan eventueel rekening houden met dit maximum aantal te stellen vragen.Na de vragenronde van Raad en Laten zijn de belangstellenden via een interruptiemicrofoon in de zaal in de gelegenheid om vragen te stellen.

Mijn privé-nummer: 06-

NB: vanuit actualiteitsoogpunt wijs ik u op het bericht van AKOZ NOBEL wat vandaag door RTV OOST op de website is geplaatst. http://www.rtvoost.mobi/nieuws/nieuwsItem.aspx?nid=206291&cat=1&mcats=0

|Statenadviseur Provinciale Staten Overijssel |
provincie Overijssel | Postbus 10078 | 8000 GB Zwolle | Linkedin | Facebook
telefoon 038 | www.overijssel.nl

Van: @tno.nl>
Verzonden: woensdag 17 december 2014 9:39
Aan:
CC: @utwente.nl'; @enschede.nl'
Onderwerp: RE: Programma expertmeeting 17-12-2014

Prima zo wat betreft de slides 6 en 9.

Tot vanmiddag,

-----Original Message-----
From: @vu.nl]
Sent: dinsdag 16 december 2014 21:43
To:
Cc @utwente.nl; r@enschede.nl
Subject: Re: Programma expertmeeting 17-12-2014

Allen,

Wat sheet 6 en 9 betreft: die had ik al wat versimpeld en ik verwijs naar de verdere uitleg van en

Maar om de geologische verschillen tussen Enschede en Epe uit te leggen (wat me expliciet gevraagd is) is het toch handig als ik vast iets over de vorm van die cavernes en het gevolg van de grotere diepte in Epe kan zeggen. Ik zal ze verder wat aanpassen.

Wat de laatste sheet betreft: dit zijn vragen die bij mij gerezen zijn bij het lezen van de rapporten. Ik ben vanuit mijn werk wel gewend om literatuur over modellen kritisch door te lezen en wil de opmerkingen daarover niet achterhouden, ook niet als ze misschien een iets ander licht op de veiligheid van olieopslag werpen. Daarvoor ben ik gevraagd om naar de hoorzitting te komen.

Het staat vrij om op mijn vragen te antwoorden of ze te weerleggen in de sessie die daarop volgt.

Met vriendelijke groet

--

Vrije Universiteit, Faculty of Earth and Life Sciences Department of Earth Sciences, Earth and Climate Cluster De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands tel. 31- ; fax 31- 0 e-mail @vu.nl

On 12/16/14 7:32 PM, "
@minez.nl> wrote:

>Allen,
>
>Ik heb zorgen ten aanzien van de laatste sheet van
>
>
>
>
>
>
>
>
>
>
>
>P.S.
>
>
>Verstuurd vanaf mijn iPad
>
>> Op 16 dec. 2014 om 19:17 heeft "
>> @tno.nl> het volgende geschreven:
>>
>> Allen,
>>
>> Ik heb zojuist de gelegenheid gehad om de presentatie van
>> te bekijken.
>> Geeft een mooie introductie op de algemene en regionale geologie van
>>het gebied.
>>
>>
>>
>>
>>
>>
>>
>> Is dat akkoord?
>>
>> Verder denk ik dat afstemming met gewenst is over
>>die slides, die raken aan risico-analyse en -beheersing.
>> Uiteraard laat ik dat verder aan haar en over,
>>
>> Met vriendelijke groet,
>>
>>
>>
>>
>> -----Original Message-----

>> From: @vu.nl]
>> Sent: dinsdag 16 december 2014 12:29
>> To
>> @utwente.nl
>> Cc:
>>(A @minez.nl)'; '@enschede.nl'
>> Subject: Re: Programma expertmeeting 17-12-2014
>>
>> Allen,
>>
>> Hierbij een link naar mijn concept presentatie:
>>
>>
>>
>>=
>>
>> Met vriendelijke groet
>>
>> --
>>
>> Vrije Universiteit, Faculty of Earth and Life Sciences Department of
>>Earth Sciences, Earth and Climate Cluster De Boelelaan 1085, 1081 HV
>>Amsterdam, The Netherlands tel. 31-20- fax 31-
>> @vu.nl
>>
>>
>>
>>
>>
>>
>>
>>> On 12/15/14 9:04 AM, ' @tno.nl>
>>>wrote:
>>>
>>> Allen,
>>>
>>> Hierbij de draft van mijn inleidende presentatie.
>>> Ik wil nog iets toevoegen over de relatie tussen convergentie en
>>> bodembeweging.
>>> Graag jullie feedback, of dit aansluit bij jullie inleidingen.
>>>
>>> Het is mij nog niet duidelijk, of er 10/15 minuten per inleiding, of
>>>per inleider is.
>>>
>>>
>>> Verder mis ik in het programma nog:
>>> - een kort inleidend verhaal over het project (vgl. Akzo
>>> presentatie)
>>> - de monitoring (of zit dat in jouw verhaal Annemarie?)
>>> - de lange termijn stabiliteit, resp. optie voor opvullen.
>>>
>>> Groet,
>>>
>>>
>>> -----Original Message-----
>>> From: ;@overijssel.nl]

Van: @enschede.nl>
Verzonden: woensdag 17 december 2014 11:36
Aan:
Onderwerp: FW: expertmeeting
Bijlagen: Aanmeldingen via raadsgriffie.doc; 1. blok Geologie 1 1.pptx; 5. blok Juridisch.pptx; 2. blok Geologie 2 Smal.ppt

Onderstaande mail mogen jullie niet ontvangen ivm overschrijding max mb........hierbij nog de aanvulling voor jullie

Van:

|Statenadviseur Provinciale Staten Overijssel |
provincie Overijssel|Postbus 10078 | 8000 GB Zwolle | Linkedin | Facebook
telefoon 038 | www.overijssel.nl

483

Ministerie van Economische Zaken

> Retouradres Postbus 20401 2500 EK Den Haag

Akzo Nobel Industrial Chemicals B.V.
t.a.v. (
Postbus 247
3811 MH AMERSFOORT

Staatstoezicht op de Mijnen
Nr.
18 DEC 2014

CL3/Veld/opsl.verg/onsh/Twenthe-Rijn
Men Heh Rst Won Mun JHP

Directoraat-generaal Energie, Telecom & Mededinging
Directie Energiemarkt

Bezoekadres
Bezuidenhoutseweg 73
2594 AC Den Haag

Postadres
Postbus 20401
2500 EK Den Haag

Factuuradres
Postbus 16180
2500 BD Den Haag

Overheidsidentificatienr
00000001003214369000

T 070 algemeen)
www.rijksoverheid.nl/ez

Behandeld door

Ons kenmerk
DGETM-EM / 14184056

Bijlage(n)
1

Datum 17 DEC 2014
Betreft Gasolieopslag Twenthe-Rijn De Marssteden

Krd

Geachte

Uw brief van 1 oktober 2014 heb ik ontvangen. U geeft in uw brief aan voornemens te zijn om vanaf het einde van het derde kwartaal van 2015 gasolie op te slaan in de daarvoor bestemde zoutcavernes. U stelt dat afdoende is aangetoond dat een olielekkage, zoals die zich heeft voorgedaan in Epe (Duitsland), zich niet voor kan doen bij de gasolieopslag in zoutcavernes in Enschede. U gaat ervan uit dat Staatstoezicht op de Mijnen (SodM) dit onderschrijft. In deze brief ga ik in op bovenstaande.

De benodigde besluiten voor het project gasolieopslag in zoutcavernes, regio Twente zijn reeds genomen. Op 2 april 2014 zijn zowel het inpassingsplan als de omgevingsvergunning als het instemmingbesluit met het opslagplan onherroepelijk geworden. De onderwerpen integriteit van de gasolieopslag en de wijze waarop u uw opslagactiviteiten zal verrichten, zijn bij de beoordeling van deze besluiten aan de orde geweest.

Naar aanleiding van de situatie in Duitsland is door u in juni 2014 nogmaals naar de risicoanalyse voor de gasolieopslag gekeken. Daarnaast is er overleg geweest tussen u, het ministerie van Economische Zaken, SodM, het Duitse Bergamt Arnsberg en de Stichting Centraal Orgaan Voorraadvorming Aardolieproducten (COVA). Hieruit is naar voren gekomen dat er één extra monitoringsmaatregel door u genomen zal worden. De annulaire vloeistof en de vloeistof in de ingesloten put zal constant gemonitord worden in plaats van periodiek. Dit heeft u ook mee genomen in het op 16 oktober ingediende monitoringsplan.

Naar aanleiding van uw brief van 1 oktober heb ik SodM om advies gevraagd. In de bijlage treft u de brief van SodM aan. SodM geeft aan geen opmerkingen of vragen te hebben. Ik concludeer dat afdoende is aangetoond dat een lekkage als zich in Epe heeft voorgedaan, zich in Enschede niet kan voordoen en dat u uw (voorbereidende) werkzaamheden kan continueren en kan starten met de opslag van gasolie.

Ik hoop u hiermee voldoende te hebben geïnformeerd. Mocht u nog nader overleg nodig achten dan hoor ik dat graag.

De minister van Economische Zaken,
namens deze:

Drs. J. van Bergenhenegouwen
Waarnemend mt-lid directie Energiemarkt

cc.
Argos Energies
College van Burgemeester en Wethouders Enschede
COVA
Staatstoezicht op de Mijnen
Veiligheidsregio Twente

Van: @enschede.nl>
Verzonden: vrijdag 19 december 2014 10:09
Aan: @itc.nl'; @eia.nl'; @akd.nl'
Onderwerp: FW: 3 links 17 december

Goedemorgen,
Bijgaand de links naar voor het bekijken van jullie optreden!
Nogmaals dank voor jullie bijdrage

Groet,

Van: @tvenschedefm.nl]
Verzonden: vrijdag 19 december 2014 8:55
Aan:
Onderwerp: FW: 3 links 17 december

Hallo

Hieronder de links naar de verschillende onderdelen van woensdag.
Verder alles nar wens verlopen?
Hartelijke groeten,

Stationsmanager | TV Enschede FM
www.tvenschedefm.nl | 06-

Directeur Radio Hengelo TV
Adviseur RTV Sternet
Initiatiefnemer en hoofdadviseur RMC Twente

Beste nieuws- en actualiteitenprogramma 2014
Beste lokale omroep van Nederland 2012 en 2011
Nominatie beste lokale omroep van Nederland 2013 en 2014
Beste lokale crossmediale project van Nederland 2012 en 2010
Beste lokale radioprogramma van Nederland 2011
Lokale omroepvrijwilliger van Nederland 2011
Onderdeel van de canon van de Lokale Omroep

Frequenties TV Enschede FM
***TV Enschede:** kanaal 40 (Ziggo digitaal in Twente), kanaal 6, 182.25 Mhz (Ziggo analoog), kanaal 2023 (alle Glashart Media), kanaal 50 op KPN Glasnet en kanaal 553 bij KPN IP*
***Enschede FM:** 105.1 FM in de ether, 104.1 FM (Ziggo analoog), kanaal 780 (Ziggo digitaal), kanaal 3026 (alle Glashart Media), 94.3 FM op Glasnet en kanaal 953 bij KPN IPTV*

Deel 1: https://www.youtube.com/watch?v=jD7h9UI1I_o

Gemeente Enschede Expertmeeting Strategische Gasolieopslag Zoutcavernes deel 1 - YouTube

Nu bekijken...

Deel 2: https://www.youtube.com/watch?v=lxh05qgiLKg

Gemeente Enschede Expertmeeting Strategische Gasolieopslag Zoutcavernes 2 - YouTube

Nu bekijken...

Deel 3: https://www.youtube.com/watch?v=TOYRI2lyf14

Gemeente Enschede Expertmeeting Strategische Gasolieopslag Zoutcavernes 3 - YouTube

Nu bekijken...

Van:
Verzonden: dinsdag 30 december 2014 15:05
Aan:
CC:
Onderwerp: FW: ambtelijk overleg op 6 januari 2015
Bijlagen: Offerte zoutkoepels.pdf

Veiligheidsregio Twente heeft opdracht gegeven om uit te zoeken welke incidenten er zijn opgetreden in zoutcavernes met olie-opslag.

Op dinsdag 6 januari a.s. gaat in Enschede de resultaten presenteren aan de Veiligheidsregio Twente

---

Van: @vrtwente.nl]
Verzonden: vrijdag 12 december 2014 11:37
Aan:
CC:
Onderwerp: ambtelijk overleg op 6 januari 2015

Dag

Op 6 januari a.s. komt het en collega's) naar Enschede om een presentatie te geven over het onderzoek, dat het op dit moment verricht in opdracht van de Veiligheidsregio Twente.
Voor deze bijeenkomst is ook het ministerie van EZ van harte uitgenodigd.
Van heb ik begrepen dat jij binnen het ministerie de contactpersoon bent om deze uitnodiging intern af te stemmen.

Mag ik jou langs deze weg vragen, aan mij door te geven wie van het ministerie deze bijeenkomst op dinsdag 6 januari 2015 zal bijwonen?

De bijeenkomst begint om 11.00 uur en zal ongeveer duren tot 13.00 uur.
Adres :

Met vriendelijke groet,

Senior beleidsmedewerker Vb
Telefoon 088
Telefoon 06 - !
E-mail @vrtwente.nl

VEILIGHEIDSREGIO
TWENTE
Nijverheidstraat 30 Enschede
Postbus 1400, 7500 BK Enschede
vrtwente.nl

DISCLAIMER:
De informatie verzonden met dit e-mailbericht is uitsluitend bestemd voor de geadresseerde. Gebruik van deze informatie door anderen dan de geadresseerde is verboden. Openbaarmaking, vermenigvuldiging, verspreiding en/of verstrekking van deze informatie aan derden is niet toegestaan. Aan persoonlijke opvattingen van medewerkers kunnen geen rechten worden ontleend. Veiligheidsregio Twente aanvaardt voor haar medewerkers geen enkele aansprakelijkheid voor eventueel onjuist, onrechtmatig of ontoelaatbaar geacht gebruik van e-mail (inclusief bijlagen).

Van:
Verzonden: dinsdag 30 december 2014 16:42
Aan:
CC:
Onderwerp: FW: ambtelijk overleg op 6 januari 2015
Bijlagen: Offerte zoutkoepels.pdf

Dag

Groet, Jan

Met vriendelijke groet,

drs. '

Senior beleidsmedewerker Vb
Telefoon 088
Telefoon 06 -
E-mail @vrtwente.nl

VEILIGHEIDSREGIO
TWENTE
Nijverheidstraat 30 Enschede
Postbus 1400, 7500 BK Enschede
vrtwente.nl

Van:
Verzonden: maandag 5 januari 2015 9:18
Aan:
Onderwerp: RE: ambtelijk overleg op 6 januari 2015

Goedemorgen en

Van:
Verzonden: vrijdag 2 januari 2015 10:43
Aan:
Onderwerp: RE: ambtelijk overleg op 6 januari 2015

Van:
Verzonden: dinsdag 6 januari 2015 20:10
Aan:
Onderwerp: RE: Presentatie RivM

Dank voor je terugkoppeling

-----Oorspronkelijk bericht-----
Van:
Verzonden: dinsdag 6 januari 2015 13:42
Aan.
Onderwerp: Presentatie RivM

Hierbij mijn aantekeningen van zojuist.

Presentatie

Verstuurd vanaf mijn iPad

Van:
Verzonden: donderdag 15 januari 2015 15:49
Aan: SodM Boren; SodM algemeen
CC:

Onderwerp: FW: Verzoek n.a.v. Akzo presentatie "MIT caverne - Procedure, planning en criteria"
Bijlagen: VanSambeek_2005_Improvement_of_MIT.pdf; Somit_KBB_2013.pdf

Van: @akzonobel.com]
Verzonden: maandag 12 januari 2015 12:08
Aan:
Onderwerp: RE: Verzoek n.a.v. Akzo presentatie "MIT caverne - Procedure, planning en criteria"

Dag

De betreffende waarden komen concreet uit 1 artikel dat een aantal andere artikelen samenvat:

- Van Sambeek, 2005 → zie met name hoofdstuk 4.3

Van recentere datum is het artikel van Socon / KBB (SMRI, 2013). Ook dat heb ik bijgevoegd.

Wat betreft Strategic storage in France (Géosel) is deze waarde afkomstig uit persoonlijke communicatie met Geostock.

Groeten

From: @minez.nl]
Sent: maandag 12 januari 2015 11:36
To
Cc:

Subject: Verzoek n.a.v. Akzo presentatie "MIT caverne - Procedure, planning en criteria"

Dag

In genoemde presentatie is gerefereerd aan de volgende literatuur betreffende lek criteria voor hydraulische MIT's :

- U.S. Strategic Petroleum Reserve (SPR)
- Remizov et al. [2000]
- Branka et al. [2002]
- Thiel (1993)
- Socon / KBB (SMRI, 2013)
- Strategic storage in France (Géosel)

Alvast dank,

SodM

SOLUTION MINING
RESEARCH INSTITUTE
105 Apple Valley Circle
Clarks Summit, PA 18411
USA
Country Code: 1 ◆ Voice: 570-585-8092 ◆ Fax: 570-585-8091
E-mail: smri@solutionmining.org ◆ www.solutionmining.org

Research Project
Report
2005-1

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

prepared by

RESPEC
P.O. Box 725
Rapid City, South Dakota 57709-0725

École Polytechnique
Post 2252
91128 Palaiseau Cedex, FRANCE

Brouard Consulting
101 rue de Temple
75003 Paris, FRANCE

May 2005

NOTICE

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

Topical Report RSI-1799

by

Leo L. Van Sambeek

RESPEC
P.O. Box 725
Rapid City, South Dakota 57709 USA

Pierre Bérest

École Polytechnique
Post 2252
91128 Palaiseau Cedex, FRANCE

and

Benoit Brouard

Brouard Consulting
101 rue du Temple
75003 Paris, FRANCE

prepared for

Solution Mining Research Institute
105 Apple Valley Circle
Clarks Summit, Pennsylvania 18411 USA

May 2005

FOREWORD

This research project was a cofunded initiative between the Solution Mining Research Institute and the Gas Technology Institute. Both organizations benefit from advances made to the state-of-the-art of Mechanical Integrity Test (MIT) technology. The authors acknowledge the respective Research Committees for their support and thank them for the opportunity to contribute to the understanding of MITs and their use.

EXECUTIVE SUMMARY

E.1 INTRODUCTION

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

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

E.2 CURRENT INDUSTRY-STANDARD MECHANICAL INTEGRITY TESTS

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

The Nitrogen Interface Test (NIT) consists of injecting nitrogen to form a gas column in the annular space to below the last cemented casing. The central string remains filled with brine, and a logging tool is used to measure the brine/nitrogen interface location. Two or three measurements, generally separated by 24 hours, are performed; an upward movement of the interface is deemed to indicate a nitrogen leak. Pressures are measured at ground level, and temperature logs are performed to allow precise calculation of nitrogen leakage.

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

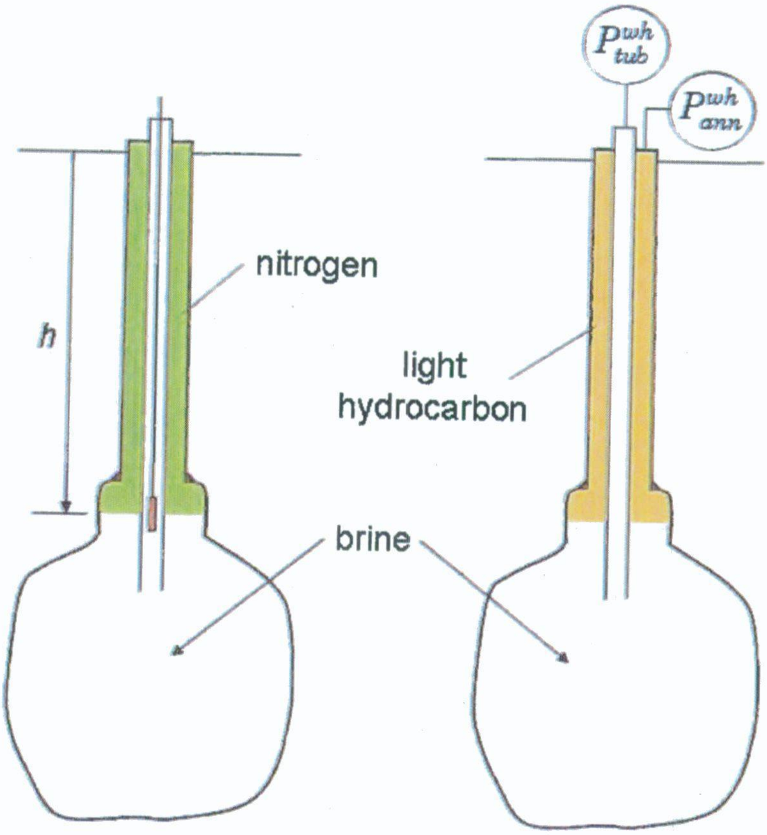


Figure 1. NIT (Left) Versus LLI (Right) Integrity Tests. (In the NIT, the nitrogen/brine interface is tracked through a logging tool. In the LLI, tubing (P_{tub}^{wh}) and annular (P_{ann}^{wh}) pressures are continuously recorded at the wellhead during the test.)

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

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

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

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

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

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

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

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

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

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

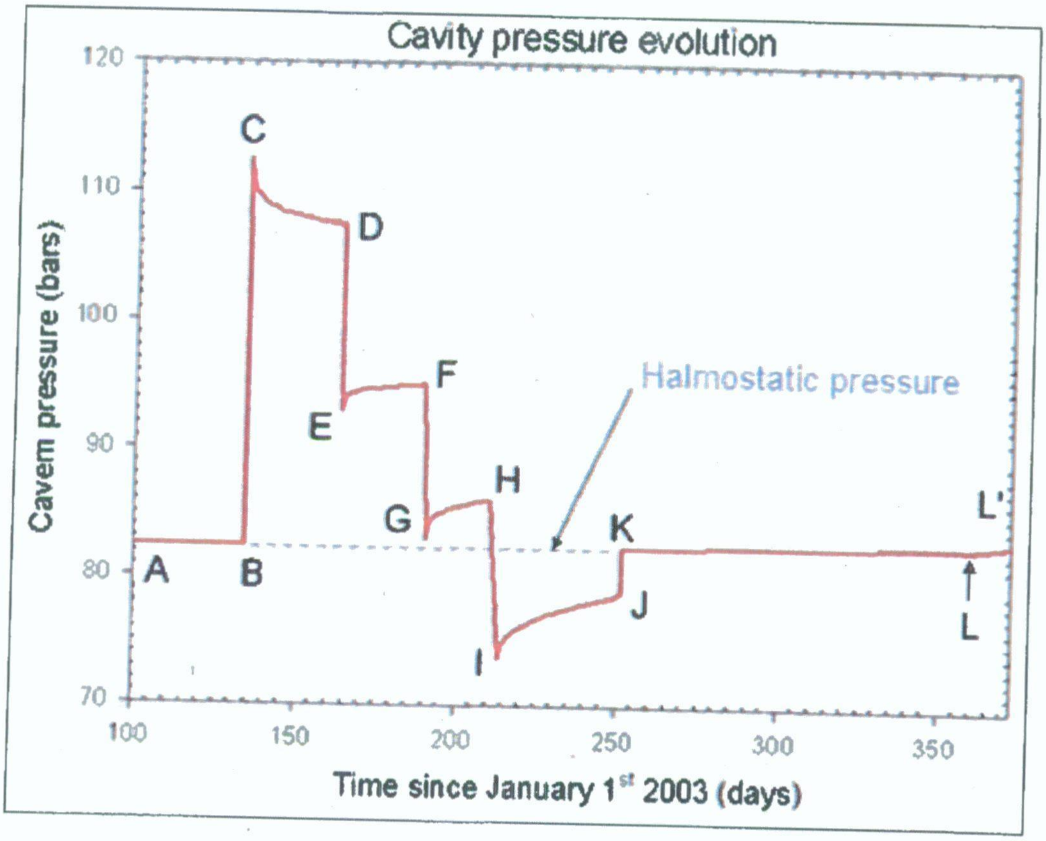


Figure 2. Cavern Pressure Evolution During a 250-Day-Long Test in a Cavern 700 m Deep and Volume 10,000 m^3. The cavern had been kept idle for several years before the test. Wellhead was left open during the A-B and K-L steps. Note that pressure decreases when cavern pressure is more than 2 MPa (20 bars)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

E.5 IDENTIFICATION OF FACTORS CONTRIBUTING TO AN APPARENT LEAK

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

Preexisting phenomena that are potentially active during an MIT are:

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

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

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

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

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

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

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

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

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

E.6.1 Factors for a Liquid-Liquid Interface Test

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

- **Steady-state salt creep** generally is a slow phenomenon except when the cavern is very deep (deeper than 5,000 ft). At a 1,000-m (3,000-ft) depth, a typical open-cavern closure rate is $3\cdot10^{-4}$/year or 0.03 percent per year (cavern will be completely closed after more than 30 centuries). Because the cavern compressibility factor generally is $4\cdot10^{-4}$/MPa (or $3\cdot10^{-6}$/psi), the pressure build-up rate in a closed cavern will be 0.75 MPa/year (2 kPa/day or 0.3 psi/day). These figures will be smaller during an MIT because the pressure is significantly larger than in an open cavern, making the pressure build-up rate exceedingly small. The main concern is with the transient creep triggered by the test, a problem which will be discussed later.
- **Wellbore warming** is very fast (in sharp contrast with cavern brine warming which is addressed later): thermal equilibrium in the wellbore is reached after a few hours, except when the well has been active for a long period before the MIT begins.
- **Steady-state brine micropermeation** into the rock mass is small, and in most cases, from an engineering perspective, the salt surrounding a cavern can be considered to be nearly perfectly tight. From a scientific perspective, however, some brine seepage from the cavern and into the salt must occur, albeit usually at very slow rates. Brine permeation is often larger in bedded salt caverns than in domal salt caverns because bedded salt formations generally contain insoluble interbedded layers whose permeability is larger than the permeability of salt. A typical value of the pressure decay rate caused by brine permeation measured during a test (described in the report) performed on a 8,000-m^3 cavern (leached out in a bedded-salt formation) was 0.87 kPa/day. The pressure decay rate would be even smaller in larger caverns.
- **Earth tides and atmospheric pressure variations** generate very small pressure effects, which can be recorded only when a high resolution measurement system is used (typically, earth tides generate relative cavern volume changes as small as 10^{-7}; i.e., 0.1 bbl in a 1,000,000-bbl cavern; the resulting pressure fluctuations (amplitude) is 0.25 kPa). Atmospheric pressure variations are more erratic but somewhat larger.

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

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

RSI-1476-05-003

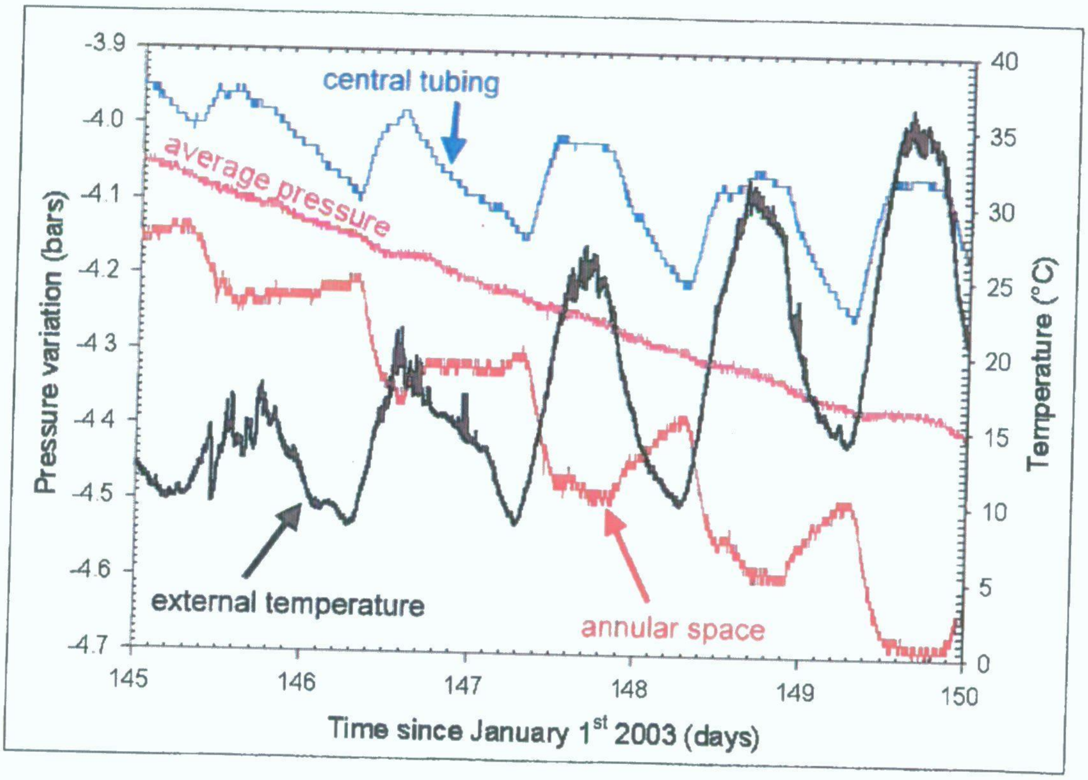


Figure 3. This 700-m Deep, 10,000-m^3 Cavern Was Brine Filled Except for the Annular Space Which Was Oil Filled. The figure displays variations of the central-tubing pressure, the annular space pressure, the average pressure, together with the external temperature. A correlation between external (i.e.,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

- **Brine thermal expansion**

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

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

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

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

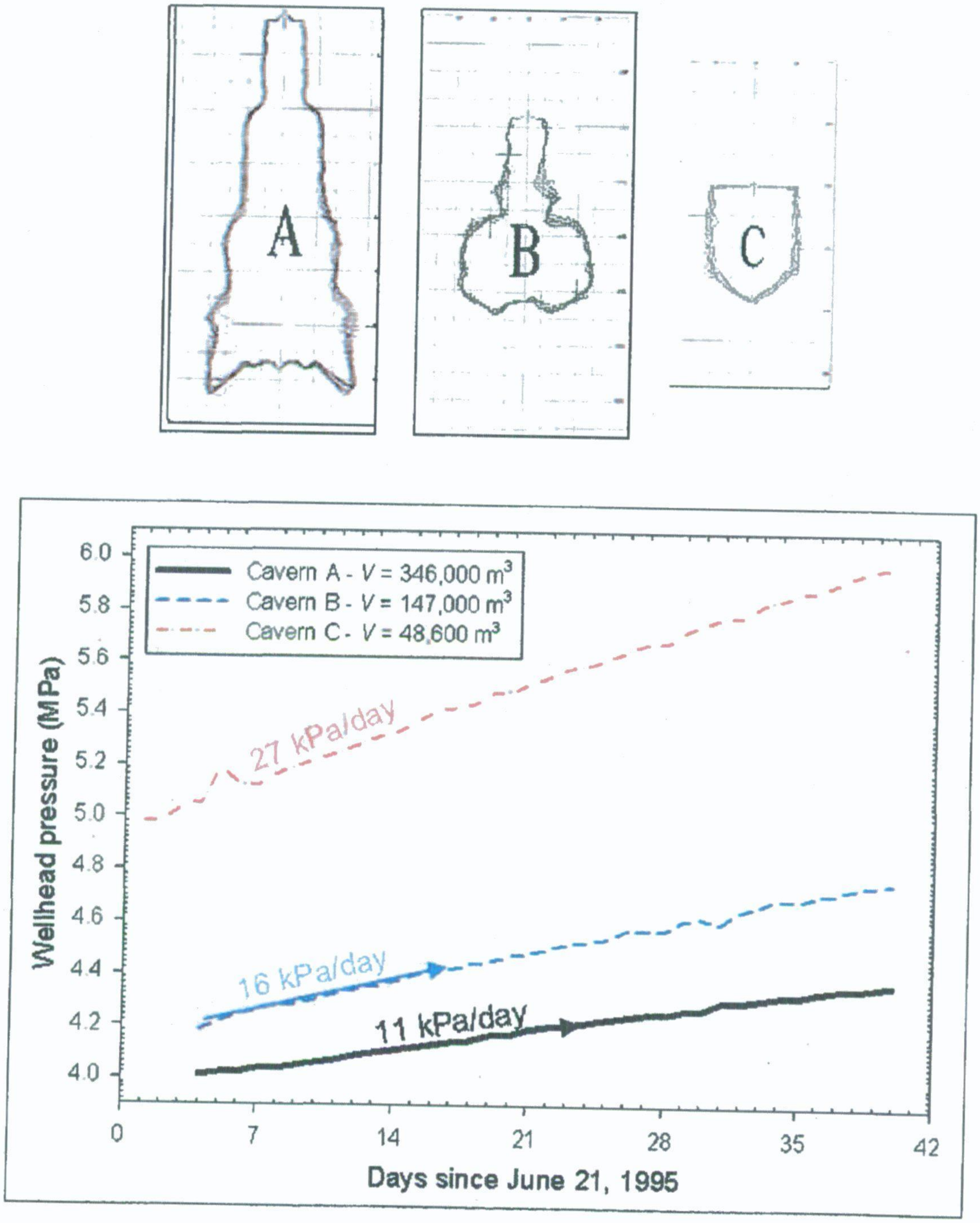


Figure 4. Pressure Increase Caused by Thermal Expansion From Brine Warming in Three Different-Sized Caverns. These caverns were each being actively leached just before shut in for these tests. Thus the temperature gradient between the salt mass and the cavern brine was likely much greater than would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

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

- **Additional dissolution**

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

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

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

- **Transient brine permeation**

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

- **Transient creep**

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

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

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

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

E.7 CONCLUSIONS

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

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

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

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

TABLE OF CONTENTS

1.0 INTRODUCTION 1

2.0 BACKGROUND 2

3.0 MAIN FACTORS CONTRIBUTING TO WELL TIGHTNESS 4
- 3.1 PRESSURE DISTRIBUTION 4
- 3.2 GEOLOGICAL FORMATION 5
- 3.3 CEMENTING WORKMANSHIP AND WELL ARCHITECTURE 5

4.0 THEORETICAL ASPECTS OF MECHANICAL INTEGRITY TESTING 8
- 4.1 INTRODUCTION 8
- 4.2 TIGHTNESS TESTS IN SALT CAVERNS 9
- 4.3 BIBLIOGRAPHY 10
- 4.4 APPARENT, CORRECTED, AND ACTUAL LEAKS 14
- 4.5 PREEXISTING AND TEST-TRIGGERED PHENOMENA 15
  - 4.5.1 Preexisting Test Phenomena 15
  - 4.5.2 Phenomena Triggered by the Test 16
  - 4.5.3 Effect of all the Phenomena 17
- 4.6 COMPARISON BETWEEN THE NITROGEN AND LIQUID-LIQUID TESTS 17

5.0 CAVERN COMPRESSIBILITY 19
- 5.1 COMPRESSIBILITY MEASUREMENT 19
- 5.2 COMPRESSIBILITY ANALYSIS 20
  - 5.2.1 The Cavern Compressibility Factor 21
  - 5.2.2 The Fluid Compressibility Factor 24
  - 5.2.3 Phenomena Influencing the Measurement of Cavern Compressibility 28

6.0 THERMAL EFFECTS 31
- 6.1 WELL TEMPERATURE 31
- 6.2 WELLHEAD TEMPERTURE CHANGES 32
  - 6.2.1 Temperature Change 32
  - 6.2.2 Effects of Temperature Change 34
- 6.3 BRINE WARMING 36
  - 6.3.1 Initial Temperature Difference 36
  - 6.3.2 Temperature History 38
  - 6.3.3 Characteristic Time 39
  - 6.3.4 A Case History 40
  - 6.3.5 Temperature Increase Rate 41

TABLE OF CONTENTS
(Continued)

6.3.6 Brine Thermal Expansion 41
6.3.7 Brine Thermal Expansion During an MIT 42
6.3.8 What Can Be Done During an LLI 44
6.3.9 Simplified Equations for Pressure Change From Brine Temperature Change 45
6.3.10 Brine Thermal Expansion Effects During an NIT 46
6.4 ADIABATIC PRESSURE INCREASE IN A CAVERN 46
6.4.1 Temperature Increase 46
6.4.2 Adiabatic Temperature Increase in a Field Test 48
6.4.3 Temperature Evolution 48
6.4.4 Pressure Decrease During an LLI in a Spherical Cavern 51
6.4.5 Brine Volume Decrease During an NIT 52
6.5 ATMOSPHERIC PRESSURE, EARTH TIDES 52

7.0 FLUID PERMEATION 54
7.1 EFFECTS OF STEADY-STATE AND TRANSIENT FLUID MICRO-PERMEATION INTO THE SALT 54
7.1.1 Boundary Conditions 55
7.1.2 Steady-State Flow 56
7.1.3 Boundary Condition During an MIT Test 56
7.2 THE CASE OF A SPHERICAL CAVERN 56
7.2.1 Steady-State Flow in a Spherical Cavern 57
7.2.2 Characteristic Time in a Spherical Cavern 57
7.3 CAVERN PRESSURE DROP CAUSED BY BRINE MICROPERMEATION 58
7.3.1 The Case of an LLI 58
7.3.2 The Case of an NIT 58
7.4 THE CASE OF A CYLINDRICAL CAVERN 59
7.5 THE CASE OF A WELLBORE 59
7.6 THE CASE OF A PERMEABLE LAYER 59

8.0 ADDITIONAL DISSOLUTION 60
8.1 EXAMPLE OF ADDITIONAL DISSOLUTION EFFECTS 60
8.2 ESTIMATION OF ADDITIONAL DISSOLUTION EFFECTS 60
8.3 DISSOLUTION CHARACTERISTIC TIME 65

TABLE OF CONTENTS
(Continued)

9.0 CREEP 67
9.1 CASE STUDIES 67
9.2 ROCK MECHANICAL TESTING 68
9.3 STEADY-STATE CREEP 69
9.4 TRANSIENT CREEP 70
9.5 CAVERN BEHAVIOR PREDICTION 71
9.5.1 Overburden Pressure, Cavern Pressure, Rock Temperature 72
9.5.2 Steady-State and Transient Creep for Simple Shapes 73
9.6 TRANSIENT BEHAVIOR 73

10.0 LIQUID-LIQUID INTERFACE TESTS: ANALYSIS OF PRESSURE OBSERVATION AND PRESSURE DIFFERENCE OBSERVATION TESTS 78
10.1 ADVANTAGES OF THE TWO PRESSURE TEST METHODS 78
10.2 A TYPICAL POT 79
10.3 A TYPICAL PDO TEST 80
10.4 CROSS-SECTIONAL AREA AT THE INTERFACE DEPTH 82
10.5 TEST SEQUENCE 83
10.6 ACCURACY OF THE PDO TEST 84

11.0 THEORETICAL ANALYSIS OF THE NITROGEN INTERFACE TEST (NIT) 86
11.1 MATHEMATICAL BASIS 86
11.1.1 Gas Equation of State 86
11.1.2 Pressure Equilibrium 87
11.1.3 Gas Mass 87
11.1.4 Other Factors 88
11.1.5 Interface Rise Rate 88
11.2 PRACTICAL APPLICATION 88

12.0 INTERPRETATION OF CASE HISTORIES 90
12.1 INTRODUCTION 90
12.2 THE ETREZ TRANSIENT CREEP TEST (AFTER HUGOUT [1984]) 91
12.2.1 Introduction 91
12.2.2 Cavern Behavior Before the Test 92
12.2.3 Effects of Cavern Pressure Drop 92
12.2.4 Effects of Cavern Pressure Increases 94

TABLE OF CONTENTS
(Continued)

12.3 CARRESSE SPR3 TEST 95
12.4 TRANSIENT EFFECT DURING MIT (AFTER REMIZOV ET AL. [2000]) 97
12.5 ETREZ EZ58 TEST [DURUP, 1994] 98
12.6 LOOP CAVERN MECHANICAL INTEGRITY TEST ANALYSIS 99
12.7 LEAK DETECTION (PDO) AT THE WELLHEAD 104
12.8 PDO TEST IN EZ53 CAVERN 106
12.9 KANSAS MECHANICAL INTEGRITY TESTS 107
  12.9.1 Introduction 108
  12.9.2 Discussion of the Tests 117
  12.9.3 Interface Tests 118
  12.9.4 Interface Location 119
  12.9.5 Casing Leaks 119

13.0 CONCLUSIONS 122
13.1 PREEXISTING TEST PHENOMENA 122
13.2 PHENOMENA TRIGGERED BY THE TESTS 123
13.3 BRINE WARMING CONCLUSIONS 124
  13.3.1 Conclusions for an LLI 124
  13.3.2 Conclusions for an NIT 124
13.4 USEFUL RELATIONS 124
  13.4.1 Estimations of Cavern Volume Change Rates 124
  13.4.2 Brine or Cavern Volume Changes 127
  13.4.3 Relation Between Tubing Pressure Variation and Apparent Leak in an LLI Test 128
  13.4.4 Relation Between Actual Leak and Apparent Leak in an NIT 128
  13.4.5 Relation Between Actual Leak and Corrected Leak in an LLI Test 128
  13.4.6 Relation Between Actual Leak and Corrected Leak in an NIT 128

14.0 NOMENCLATURE 129

15.0 REFERENCES 137

LIST OF TABLES

TABLE PAGE

1 Depths of Temperature Gauges in the SPR3 Well 32
2 Typical Salt Creep Parameters 69
3 Typical Munson-Dawson Creep Parameters 71

LIST OF FIGURES

FIGURE **PAGE**

1 Underground Pressure Distribution 4
2 Water-Filled Annular Space in a Natural Gas Storage Facility 7
3 Nitrogen (Left) Versus Liquid (Right) Integrity Tests 9
4 Measurement of Cavern Compressibility 20
5 Tersanne TE04 Cavity (Gaz de France) 22
6 Cavern Shape Factor for a Spheroidal Cavern 23
7 Three Cavern Compressibility Measurements for the Carresse SPR1 Cavern 26
8 A Compressibility Test on the Carresse SPR3 Cavern 27
9 Injection of Nonsaturated Brine in the Central Tube 28
10 Iso-Underestimates of Cavern Compressibility βV When Injecting Undersaturated Brine 30
11 SPR3 Wellhead 33
12 Temperature Measurements in the SPR3 Wellhead 33
13 A Correlation Between External (i.e., Ground) Temperature and Oil-Filled Tubing Pressure Is Clearly Visible 35
14 Measured Wellhead Pressure and Air Temperature Variations 36
15 Geothermal Profile in the Gaz de France EZ53 Cavern and Well 37
16 Temperature Evolution in the EZ53 Cavern 40
17 Measurement of Brine Flow Expelled From the EZ53 Cavern 41
18 Pressure Build-Up Due to Brine Thermal Expansion in a Small, Big, and Medium Size Cavern 43
19 Cavern Temperature Evolution as Measured in a Large Oil-Filled Cavern 49
20 Numerical Computation of Relative Pressure History After a Rapid Pressure Increase 52
21 Evolution of Brine and Hydrocarbon in the Well at the End of EZ53 Transient Creep Test 64
22 Cavity Pressure History (MIT Performed 2,000 Days After the End of Leaching, p_i^1 =+2 MPa) 75
23 Cavity Pressure After Pressure Build-Up (MIT Performed 2,000 Days After the End of Leaching, p_i^1 = +2 MPa) 75
24 Cavity Pressure History (MIT Performed 2,000 Days After the End of Leaching, p_i^1 = +4 MPa) 76
25 Cavity Pressure After Pressure Build-Up (MIT Performed 2,000 Days After the End of Leaching, p_i^1 = +4 MPa) 76

LIST OF FIGURES

(Continued)

FIGURE PAGE

26 Cavity Pressure History (MIT Performed 2,000 Days After the End of Leaching, p_i^1 = +9 MPa) 77

27 Cavity Pressure After Pressure Build-Up (MIT Performed 2,000 Days After the End of Leaching, p_i^1 = +9 MPa) 77

28 Pressurization Data During a Pressure Observation Test in Kansas 80

29 Two Different Curves Are Plotted Associated With Two Observation Cycles 81

30 The 0-1 Curve is the Wellhead Pressure Difference Versus Injected Volume as Observed at the End of the Pressurization Period 83

31 EZ53 Sonar Survey 91

32 Evolution of Brine and Hydrocarbon in the Well at the End of EZ53 Transient Creep Test 93

33 EZ53 Transient Creep Test 95

34 SPR3 Cavern Mesh Used for Numerical Computations 96

35 Comparison of as-Measured and as-Calculated Cavern Pressure Evolution 97

36 Cavern Pressure Evolution 98

37 EZ58 Test 99

38 LOOP Cavern 11 MIT From 2002 (ΔP Is the Crude Oil Pressure Minus the Brine Pressure Both Measured at the Wellhead) 100

39 Annular Space and Tubing Pressure During a Well Leak 105

40 Annular Space and Central-Tubing Pressure Drops 107

41 Kansas Well #6 Architecture 109

42 Kansas Well #25 Architecture 110

43 Kansas Well #6 Compressibility βV Measurement 111

44 Kansas Well #25 Compressibility βV Measurement 112

45 Kansas Well #6–Pressure Observation Data During a POT 113

46 Kansas Well #25–Pressure Observation Data During a POT 114

47 Kansas Well #6–Pressure Observation Data During the Last 48 Hours of a POT 115

48 Kansas Well #25–Pressure Observation Data During the Last 48 Hours of a POT 116

1.0 INTRODUCTION

Almost all solution-mining wells and storage caverns in rock salt are tested on a regular basis to prove their mechanical integrity, typically upon commissioning and then again every 5 years. Technologies for Mechanical Integrity Tests (MITs) for caverns filled with a liquid are reasonably well advanced and established; however, this research project investigated how the MIT technology could be improved to increase test accuracy and reliability and/or to decrease test cost and time-out-of-service for the cavern. Potential improvements in the technology were investigated by reviewing aspects of MIT methods and protocols, test results interpretation, and formulation of cavern tightness conclusions. The research was intentionally biased toward MITs for bedded salt caverns because they are more difficult to test; however, the research results are equally valid for domal salt caverns.

This research report is organized as follows. Chapter 2.0 presents a concise review of solution mining of salt whether for mineral production or for creating storage, and introduces the MIT and the factors that affect an MIT. Chapter 3.0 describes key concepts required to understand the MIT and how testing errors might be introduced. Chapter 4.0 presents the theoretical aspects of an MIT; differentiates between measured (apparent), corrected, and actual leakage rates; and introduces the phenomena that disguise or contribute to measured leakage. Chapter 5.0 presents a detailed description of cavern compressibility and the factors that influence cavern compressibility. Chapter 6.0 discusses the ways that temperature changes occur in the caverns, consequences of such thermal effects, and their characteristic times. The consequences of brine (or stored product) permeation and additional dissolution and their effect on MIT results are discussed in Chapters 7.0 and 8.0, respectively. Chapter 9.0 describes how salt creep is altered by the MIT and its influence on test results. Chapter 10.0 provides more detail on the Liquid-Liquid Interface Test (POT and PDO), and Chapter 11.0 provides more detail on the Nitrogen Interface Test (NIT). Chapter 12.0 presents eight case histories where the interpretation follows the methodology given in Chapters 3.0 through 9.0. Chapter 13.0 is a summary of the conclusions from Chapters 3.0 through 9.0. In Chapter 13.0, distinctions are reaffirmed as to which cavern conditions cause certain phenomena to be significant in the MIT and which conditions might be relatively unimportant. The report concludes with a nomenclature and cited references.

2.0 BACKGROUND

Salt caverns are created by solution mining in both bedded and domal salts. These caverns can be used to provide chemical plants with brine (mineral production) or for storage of hydrocarbons (both gaseous and liquid), compressed air, and waste productions. For almost all applications, tightness of the cavern and external well components is a fundamental requirement. Tightness testing is required to ensure that a leak is not causing contamination of drinking water resources or the unreasonable escape of storage products to the surface. In that regard, tightness or leakage testing (referred to as a Mechanical Integrity Test or MIT) is a regulatory requirement that must be performed at various times during a cavern's life-cycle.

In most cases, from an engineering perspective, the salt surrounding a cavern can be considered as being nearly perfectly tight. From a scientific perspective, some leakage from the cavern and into the salt must occur, albeit usually at very slow rates. The real problem is usually the "piping;" that is, the cemented well that connects the cavern to the ground surface. While correct and robust well designs prevent most leakage, full-scale testing is necessary to ensure that acceptable tightness exists. MITs used to measure the integrity of the casing shoe area and the cemented casing are called External MITs (e.g., Crotogino [1995]; CH2M-HILL, Inc. [1995]).

When a cavern is filled with liquid (e.g., brine or crude oil), an MIT is performed by conducting an overpressurization test. In such a pressure test, an overpressure situation is created by pumping a test fluid into the cavern and then monitoring the cavern pressure evolution. The fluid pumped into the cavern during this pressure build-up might be brine, the stored product, or a gas.

One method of measuring the cavern pressure evolution during the MIT is to monitor the position of an interface between the brine and an immiscible fluid such as nitrogen–the so-called interface test (Nitrogen Interface Test or NIT). Interface tests have become the worldwide standard method for MITs when the conditions are suitable. Another method of measuring the cavern pressure evolution during the MIT is to simply measure the wellhead tubing or annulus pressure using sensitive pressure transducers (sometimes referred to as a Pressure Observation Test or POT) or the difference between the annulus and tubing pressure (referred to as the Pressure Difference Observation or PDO). In the following discussion, these methods are referred to a Liquid-Liquid Interface (LLI) tests. There are variations on these methods where the interface position or surface pressure is adjusted by pumping more test fluid into the system to maintain predetermined values.

By any method of testing, the presumption is that an unexplained pressure drop (or test fluid addition to maintain the pressure) can be attributed to leakage from the cavern or wellbore. The key question thus becomes how to ensure that observed pressure drops or interface movements are explained properly to avoid suggesting a leak when none exists, but also how to recognize an actual leak when it might be explained away as something else.

Bérest et al. [2002] describe the pressure drop in a POT (or interface rise in an NIT) in terms of: (1) the "apparent" leak, directly deduced from the observed pressure decrease; (2) the "corrected" leak, obtained by accounting for quantifiable factors contributing to pressure changes; and (3) the "actual" leak, which, in some cases, can differ greatly from the apparent leak (and even the corrected leak). The purpose of this research project was to determine specific information and develop guidelines for explaining how to convert an apparent leak to a corrected leak, and further to provide sensitivity on how the corrected leak probably relates to an actual leak.

Factors that potentially influence test results include the following:

- Salt creep that changes the cavern volume (cavern creep)
- Cavern-filling liquid temperature changes (brine or product warming or cooling)
- Liquid micropermeation into the surrounding salt (salt micropermeability)
- Wellbore temperature changes from recent injection/withdrawal activities
- Ground or surface-air temperature-induced pressure changes
- Barometric or earth-tide-induced pressure changes
- Cavern volume change from salt dissolution
- Cavern compressibility and hysteresis between loading and unloading (transient creep).

Factors are distinguished as those existing before testing and factors that are transient phenomena triggered by the MIT itself (i.e., pressure increase at the beginning of the test).

3.0 MAIN FACTORS CONTRIBUTING TO WELL TIGHTNESS

Three main factors contribute to the problem of leakage in wells: pressure distribution, geological environment, and well architecture. These factors are discussed below.

3.1 PRESSURE DISTRIBUTION

Fluids flow only from an area of "high" pressure toward an area of lower pressure. Figure 1 shows an example of underground pressure distribution as a function of depth. The terms used in the figure are explained below. Instead of the "pressure" at a certain depth, it is often convenient to speak of the associated "gradient" (or density) of a fluid column that produces a specific pressure at a specific depth (e.g., the casing shoe depth).

RSI-1476-05-005

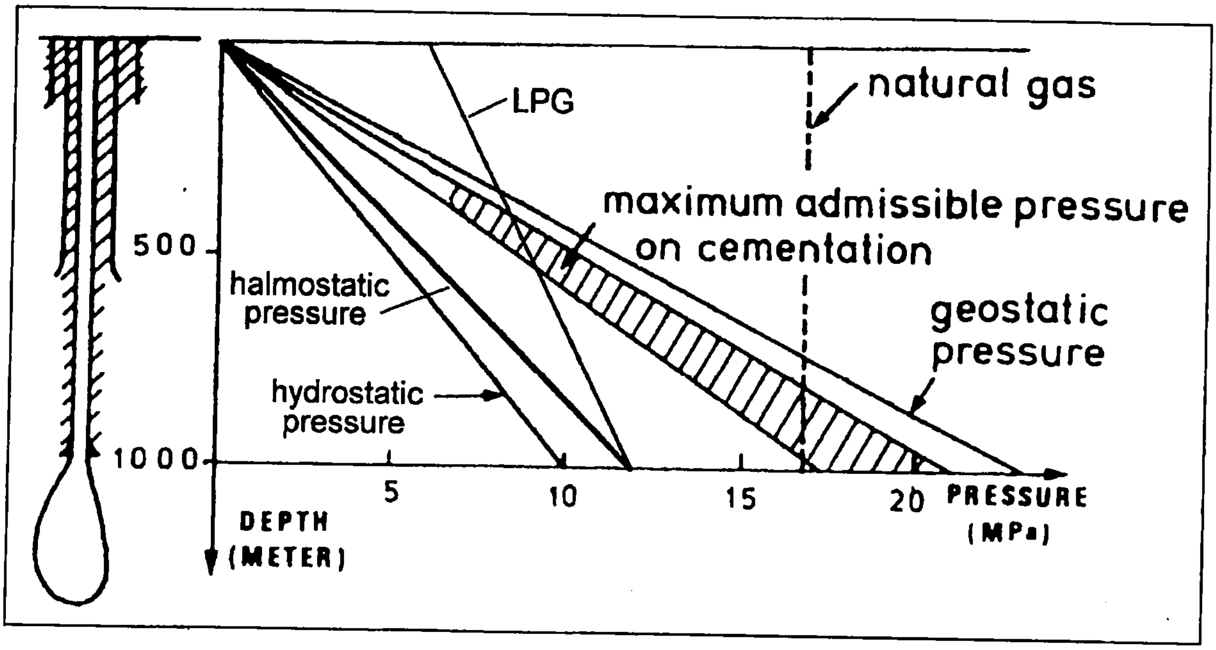


Figure 1. Underground Pressure Distribution.

- The geostatic (also called lithostatic) pressure (P_{∞}, gradient 2.2) is the natural rock stress expected in a sedimentary formation with a rock density of 2,200 kg/m^3. Occasionally, anomalous stress can be encountered, especially in salt dome flanks, but 22 MPa at a 1,000-meter depth (slightly less than 1 psi/foot depth) is a standard engineering value.

- The hydrostatic pressure (gradient 1) is, in principle, the natural pressure of groundwater in water-bearing strata, although this figure is only an average value, because dissolved minerals and tight permeability can influence the gradient.
- The halmostatic pressure (P_o, gradient 1.2) is the pressure in a salt-saturated brine well open at ground level.
- The pressure of the stored liquid or liquefied products at cavern depth (P_i) is equal to the halmostatic pressure whenever a brine-filled tubing is present. For natural gas storage caverns, the gas pressure is kept smaller than the geostatic pressure. (Typical maximum gradients are from 1.8 to 2.0 compared to the geostatic gradient of 2.2.)
- The maximum admissible pressure on cementation, below which a cement-filled annular space will not leak significantly (gradient 1.8–2.0), is a purely empirical and site-specific notion. This pressure must not be exceeded at the casing shoe, where the cement is in direct contact with the stored product. Any stored fluid must never exceed this pressure, and there must be a safety margin; otherwise, there is a risk of fracturing or of drastic permeability increase [Durup, 1994; Rummel et al., 1996; Rokahr et al., 2000].

3.2 GEOLOGICAL FORMATION

When the well crosses impervious rock formations, the tightness of the rock formation is, of course, extremely favorable. Salt domes are frequently overlaid by a permeable zone (called caprock), where brine easily circulates between the pieces of rock left over from solution of the top-of-the-salt dome. A loose caprock requires special cement treatments.

In contrast, soft impervious formations can have a very favorable effect on tightness in that they naturally creep and tend to tighten around the well, improving the bond between the cement and the casing. For example, the salt layer in which the Tersanne natural gas facility is sited in France is overlain by 600 meters of predominantly clayey ground. So-called "Cement Bond Logs" have revealed a significant improvement with the passage of time, which is attributed to clay creep.

3.3 CEMENTING WORKMANSHIP AND WELL ARCHITECTURE

Cementing in gas and oil wells is a "rough-and-ready" operation, but underground storage engineers work to a higher standard than is typical in ordinary oil-industry operations. This has led to many improvements in the techniques usually employed in oil drilling (e.g., use of admixtures, recementing, and leak tests). The various logs kept provide information for the assessment of the cement-steel or cement-rock quality bonding [ATG Manual, 1985; Jordan, 1987; Kelly and Fleniken, 1999].

The architecture of the borehole into salt caverns is also important, and potential errors are easy to identify. Oil wells usually do not have only a single casing cemented into the ground; drilling proceeds in stages and, in each stage, a casing is run and cemented into that level, with each casing having a smaller diameter than the preceding one. By the time the hole has reached its final depth, there are several concentric casings at the top, gradually decreasing in number lower down.

A similar situation exists for solution caverns, which is obviously beneficial for safety in a storage environment. The positive pressure differential of products in a well increases toward the surface (Figure 1). It is equally true that, near the surface, any leakage starting at the junction between two casing lengths will be channeled in the cemented annular space between the inner casing and the outer casing. Any leak thus rises up the cemented annular space between the two casings and comes out at the surface at the hole collar, where it is easy to detect and treat.

The architecture of the well and the number and length of steel casings are generally selected with reference to the actual objectives of the drilling operations. These may be to shore up the hole through weak strata or to prevent communication between two aquifers at distinctly different pressures. Quite clearly, the objectives must also include leakage prevention, which may require a more complicated architecture to isolate a stratum that was not troublesome for the driller but which might later promote leakage through a single damaged casing. In particular, the last two cemented casings are ideally anchored in the salt formation (or in the overlaying formation, when this formation is impermeable.) As Thoms and Kiddoo [1998] state, *"Once in the porous sand formations, the gas can readily migrate (...) This has happened in US Golf Coast wells (...) Thus two casing strings are now 'cemented' into the salt."* In Texas, Rules 1995-97 of the Texas Railroad Commission, which is the authority in charge of oil matters in the area, make this design mandatory for wells completed later than 1993.

Several companies have opted for the most comprehensive solution by specifying double-tubing at all natural gas sites with a central string inside the inner casing (Figure 2). The annular space between them is plugged at the bottom and may or may not be filled with liquid. Any gas leak from the central string immediately results in a pressure build-up in the annular space, which is easily detected at ground level.

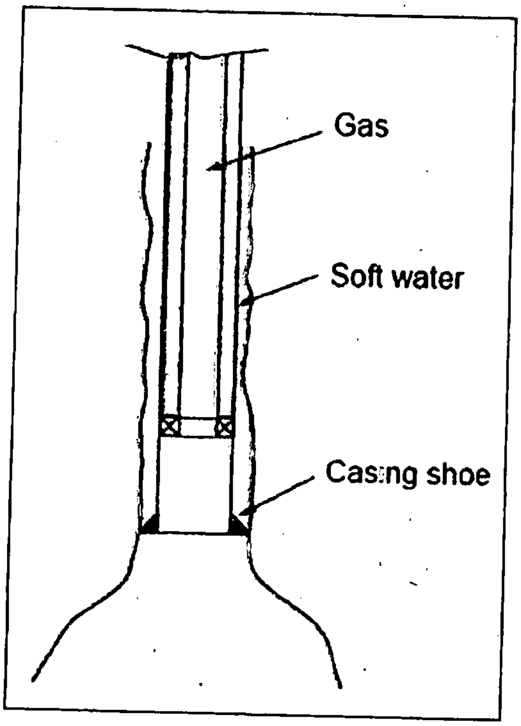


Figure 2. Water-Filled Annular Space in a Natural Gas Storage Facility.

A slightly different test procedure is possible in deep salt caverns. The cavern-plus-well system is similar to the ball-plus-tube system used in a standard thermometer or barometer. Compared to a huge cavern, the well appears as a very thin capillary tube, and tracking movements of a fluid-fluid interface in the well allows high sensitivity to cavern fluid-volume changes. When measuring interface displacement, an accuracy of δh = 15 centimeters (6 inches) for a Σ = 20–l/m well cross section is achieved easily, which means that in a cavern neck corresponding to a 20 l/m cross section, even a brine loss of $\delta V_b = 0.03$ m^3 (0.2 barrels (bbls)) is detectable, even though the cavern volume might exceed 100,000 m^3 (0.6 million barrels (MMbbls)).

4.2 TIGHTNESS TESTS IN SALT CAVERNS

A Mechanical Integrity Test (MIT) is used to test cavern tightness. Two types of the MIT are currently used; these are described below and illustrated in Figure 3.

RSI-1476-05-007

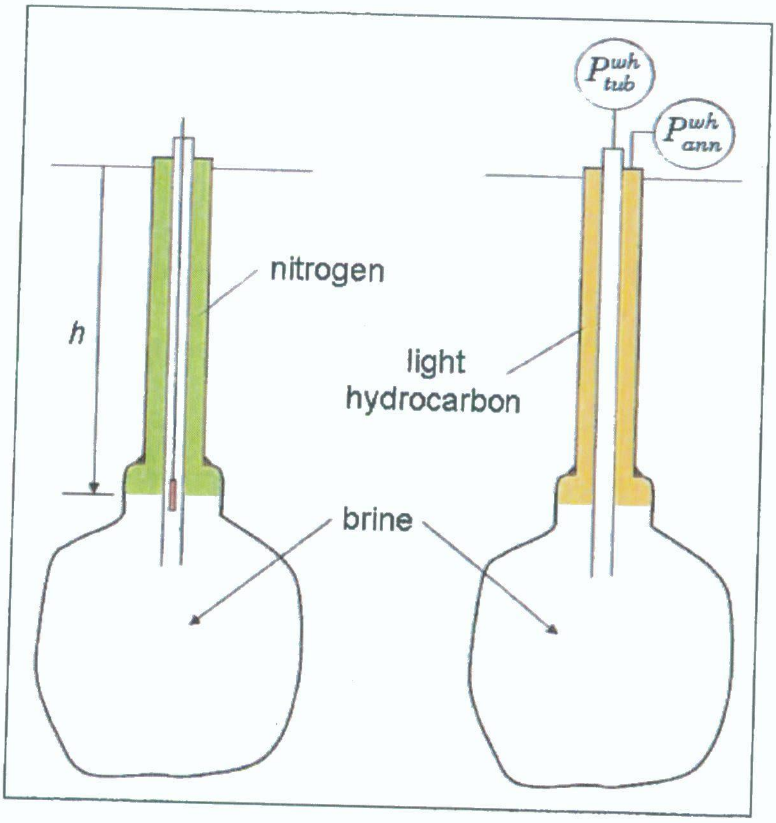


Figure 3. Nitrogen (Left) Versus Liquid (Right) Integrity Tests. (In the former, the nitrogen/brine interface is tracked through a logging tool. In the latter, tubing (P^{wh}_{tub}) and annular (P^{wh}_{ann}) pressures are continuously recorded at the wellhead during the test.)