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Decommissioning and Abandonment Procedure of LPG Caverns at Carresse (France)

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Abstract

Total E&P France has decided to decommission its Carresse LPG storage facility located in the southwest of France, 30 kilometers west of the Lacq gas field. They comprise three solution-mined caverns (SPR1, 2 & 4) capable of storing a total volume of 44,000 cubic meters of liquid propane. A fourth cavern of about 10,000 cubic meters (SPR3) was used for brine production and re-saturating.

Since 1962 till 2002, the caverns have been operated continuously as a buffer-storage for the propane produced at the Lacq gas treatment plant. The propane was pumped out for the last time in 2002, leaving the caverns filled up with brine. At that date, Total E&P France launched an extensive decommissioning project with the objective of abandoning the site. This project, which is now completed, comprised three main tasks:

- To recover the propane trapped inside the irregularities of the cavern walls (geometrical traps) by using an innovative and cost-effective methodology.
- To carry out a large program of investigations and experiments in order to determine a safe and environmentally sound procedure for well and cavern abandonment.
- To prepare the administrative files in accordance with the regulations of the French Mining Authorities.

For recovering the propane remaining in the caverns geometric traps, an innovative methodology (so-called "de-trapping" process) has been developed and implemented. Nitrogen is injected under pressure into the well in order to withdraw brine out of the cavern. By this way the brine level is lowered below the roof of the cavern, down to a pre-determined level. The nitrogen is then depressurized until the pressure in the traps decreases below the propane vapor pressure. Therefore, the liquid propane vaporizes and gaseous propane is expelled out of the traps. It is collected on surface and burned. After the recovery is complete, the cavern and the well are again filled up with brine.

Before the operations, numerical simulations have demonstrated the stability of the caverns under the very low internal pressure conditions that will be encountered. A permanent microseismic monitoring system, which had been specially installed on the site, did confirm the cavern stability during the whole duration of the operations. The recovery operations started in June 2003 and should be completed in September 2004. About 1,650 m^3 of liquid propane have been recovered from the three caverns.

This innovative methodology has been proved efficient and cost-effective. It differs from others, which require the complete filling of the cavern with nitrogen to replace the trapped product. Such operations imply the use of a huge quantity of nitrogen and are of very high cost.

For predicting the long-term behavior of the caverns after plugging, an extensive program has been carried out. Its objective was to evaluate the combined effects of salt creep, temperature increase and brine permeation. Temperature measurements were done in 2003, which showed that caverns are not far from the thermal equilibrium with the surrounding salt rock, so that the difference of temperature should be less than 1°C at the expected plugging date. A one-year in situ creep test on SPR3 cavern and numerical simulations have shown that for the equilibrium pressure of the caverns will be far below the geostatic pressure. Therefore, it will be no risk of fracturing the rock.

From this program, which was designed for Carresse and was successfully applied, a methodology for the prediction of the post-abandonment behavior of solution-mined caverns has been developed. This methodology can be easily adapted for application to other cavern abandonment cases.

As the result of the program, the plugging of the wells and the dismantling of the Carresse facilities should be carried out as soon as in 2005. At the request of the French Mining Authorities, a period of observation of three years after plugging should have to be respected. Should no significant event occur during this period, the French Ministry of Industry should grant an Abandonment Permit to Total E&P France.

Key words: LPG storage, solution mined caverns, liquid propane, France, abandonment, traps, propane recovery, in situ creep test.

1. INTRODUCTION

Total E&P France has decided to decommission its Carresse LPG storage facility located in the southwest of France, 30 kilometers west of the Lacq gas field. They comprise three solution-mined caverns (SPR1, 2 & 4) in salt formation capable of storing a total volume of 44,000 cubic meters of liquid propane. A fourth cavern of about 10,000 cubic meters (SPR3) was used for brine production and re-saturating.

The caverns have been operated continuously from 1962 to 2002, as a buffer-storage for the propane produced from the Lacq gas treatment plant. In 2002 propane was pumped out for the last time and the caverns were left filled up with brine. At that date, Total E&P France launched an extensive decommissioning project in order to close the storage and to abandon the site in a safe and environmentally sound way.

The first important task was the recovery of the propane remaining in the caverns geometric traps after the last withdrawals. This process commenced in June 2003. It is expected to be completed in September 2004.

In the same time, Total E&P France undertook an extensive investigation program for predicting the long-term behavior of the caverns after well plugging. This was done with the collaboration of Géostock, Brouard Consulting and the Laboratory of Solids Mechanics in Ecole Polytechnique (LMS). This program consisted of in situ measurements, laboratory measurements, a long duration pressure test on one cavern, and numerical simulations.

As the result of this program, the final closure of the caverns should be effective as soon as in 2005: the wells will then be plugged and the surface installations will be dismantled. At the request of the French Mining Authorities, a period of observation of three years after plugging should have to be respected. Should no significant event occur during this period, the French Ministry of Industry should grant the Abandonment Permit to Total E&P France. This will be in France the first case of abandonment of a storage facility in solution-mined caverns.

2. CAVERNS AND SITE DESCRIPTION

The Carresse facility is located in the southwestern part of France, 60 km west of the city of Pau and 3 km from the city of Salies-de-Béarn. The storage site comprises three caverns SPR1, SPR2 and SPR4 used as storage for propane, and one cavern SPR3 used for brine production and re-saturating.

The caverns were solution-mined in a diapiric structure of the Pyrenean foothills. The salt formation is made of relatively thin salt layers of Triassic age. It contains inclusions of anhydrite, clay and dolomite, with a percentage of insoluble materials varying from 20% to 30%. Caverns SPR1, SPR2 and SPR4 are located at a depth of 300 to 400 m whereas SPR3 is located at a depth of about 700 m. The inner volume of caverns ranges from about 5,000 m^3 to 24,000 m^3. Their main geometrical characteristics are given in Table 1 and profiles from the latest sonar surveys are shown in Figures 1 to 6.

Propane cavern wells consist of a 9 5/8” last cemented casing completed with a 4” inner tubing for operation (4 1/2” for SPR4). The last cemented casing of the brine cavern well (SPR3) is 7” and is completed with a mixed 4” and 3 1/2” inner tubing.

Depth values are below ground level	**SPR1**	**SPR2**	**SPR4**	**SPR3**
Top of salt formation (m)	253.00	259.00	266.00	352.00
Last cemented casing shoe (m)	348.00	286.60	363.10	677.45
4" inner operation tubing (m)	380.00	319.70	417.00	-
Cavern roof (m)	357.00	304.40	387.10	691.00
Cavern bottom (top insoluble) (m)	380.00	321.00	426.00	707.00
Maximum cavern diameter (m)	465.00	37.00	51.50	36.00
Free cavern volume asmeasured by the latest sonar survey (m^3)	12,516	9,080	24,190	4,600

Table 1: Geometrical characteristics of the Carresse caverns

The caverns were operated according to the brine compensation method (any propane injection or withdrawal movement is compensated by the opposite brine movement). Three brine ponds exist on the site with a total volume equal to the total volume of the caverns. The SPR3 cavern has been used until 1988 to re-saturate the brine diluted by rainfalls during its storage in the ponds. In 1988 liners and protective covers were installed on the three ponds and SPR3 was no longer operated.

Surface installations consist mainly of a centralized control room, a metering unit, a water separator, a flare, four pumps for brine injection in the caverns and propane send-back to Lacq gas plant, three brine ponds, two fire water ponds, and three fire water pumps.

The operating cycle of the storage facility was primarily an annual cycle: filling of the caverns during the spring and summer seasons, withdrawal from the caverns during the autumn and winter seasons. The storage facility was connected to the Lacq gas plant through a 4”-diameter pipeline of 36.5-km length. The facility has been operated continuously from 1962 to 2002. No significant incidents or technical problems were reported during this period. Sonar surveys have been performed on a regular basis and did not show significant changes on SPR1, SPR2 and SPR4 caverns used as storage. Meanwhile SPR3 used for brine production and re-saturating did exhibit major changes in shape and volume until its stop in1988.

In the recent years, because of the declining production of the Lacq gas field, the quantities of propane extracted on Lacq plant have dramatically decreased. In 2002 Total E&P France decided to close the site of Carresse, the quantities having become too small to justify to keep operating the facility.

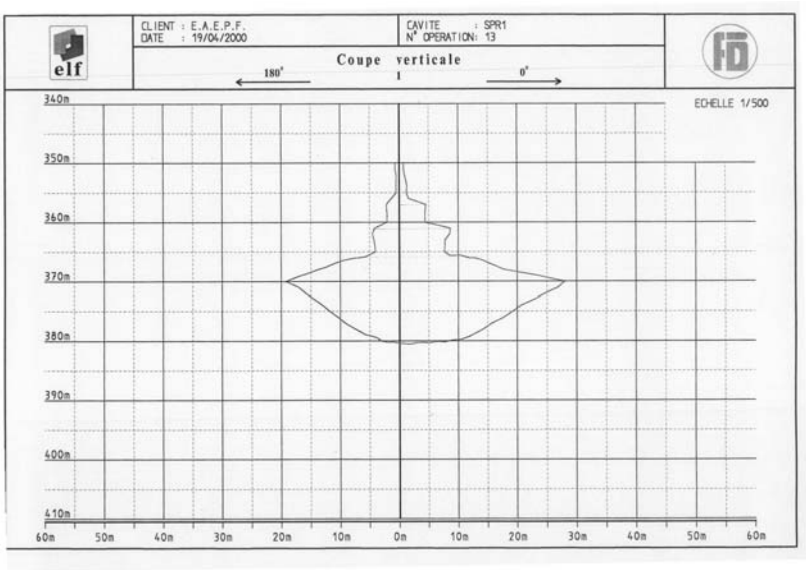


Figure 1 : Cavern SPR1 – sonar survey

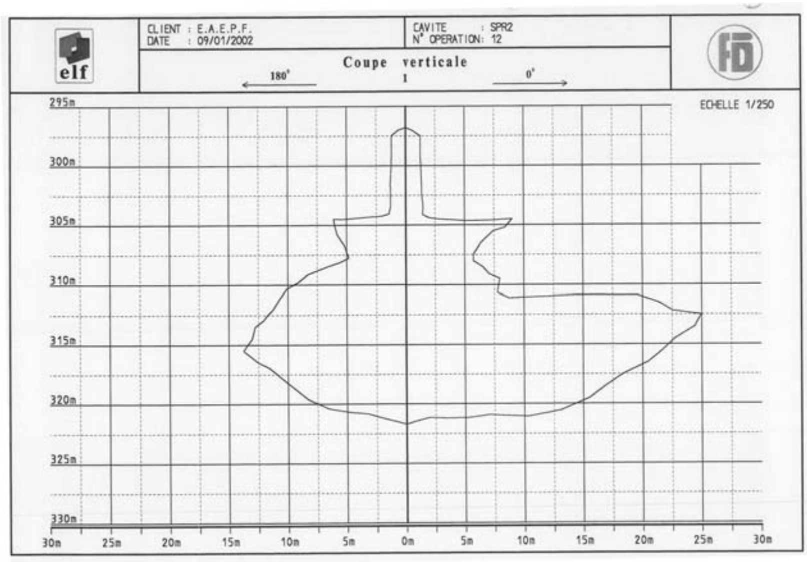


Figure 2 : Cavern SPR2 – sonar survey

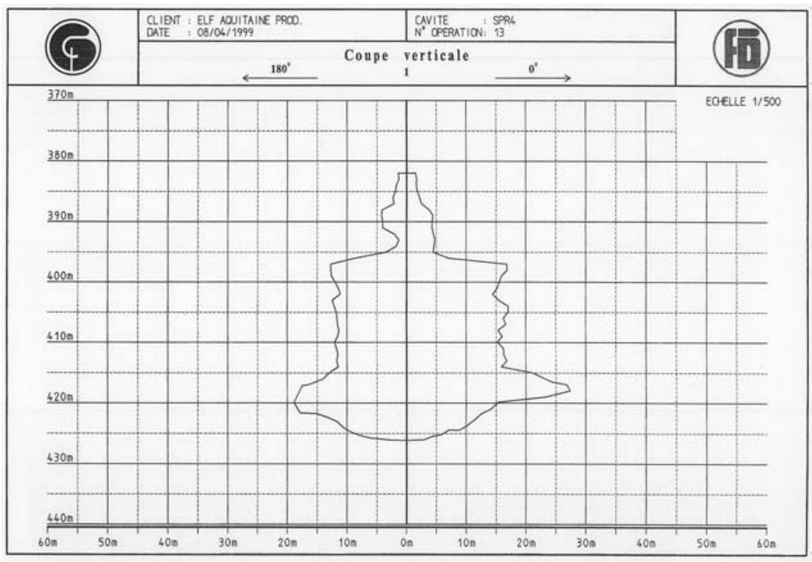


Figure 3: Cavern SPR4 – Sonar survey

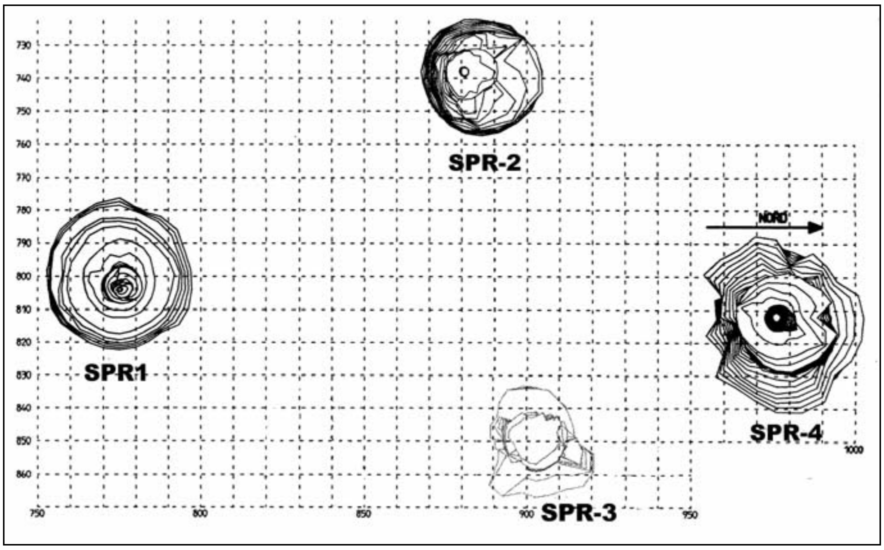


Figure 4: Caverns location map

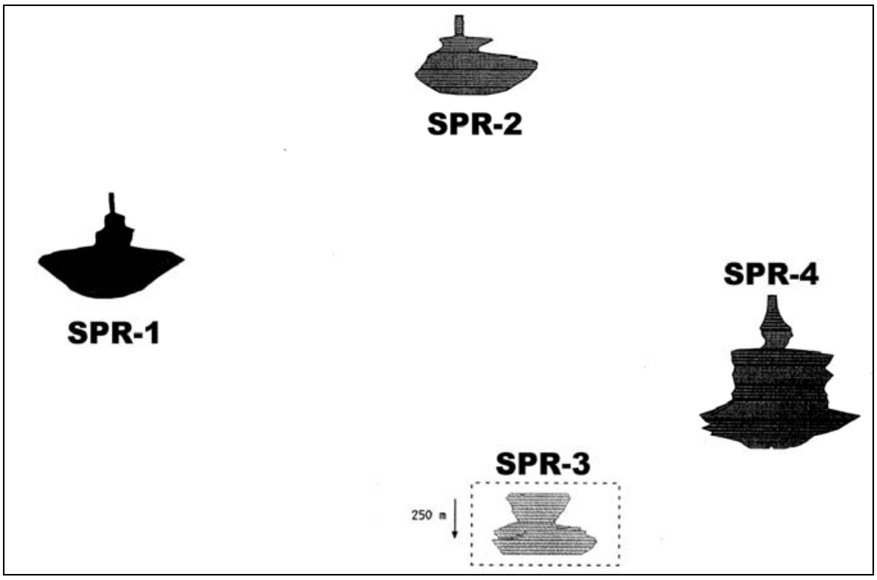


Figure 5: Caverns SPR1, 2, 3 & 4 - Vertical projection of sonar surveys

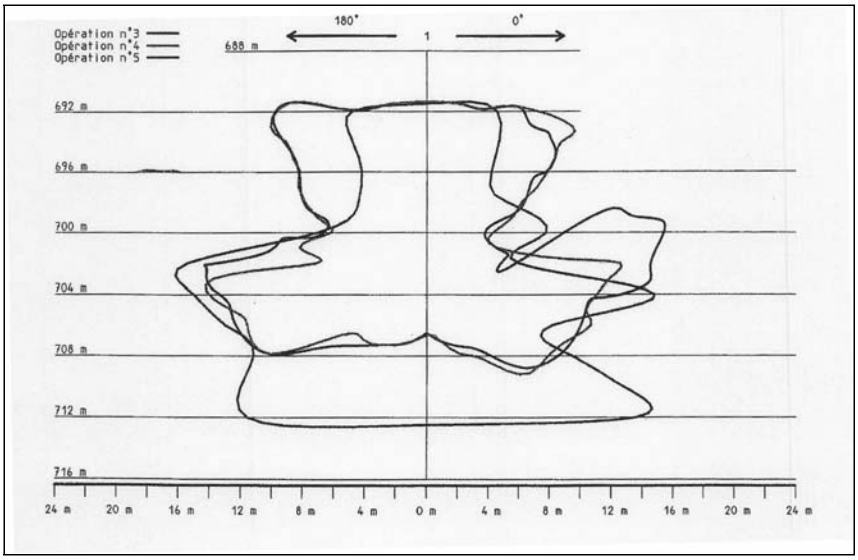


Figure 6 : Cavern SPR3 – superposition of sonar surveys (1982, 1994, 1995)

3. DECOMMISSIONING AND ABANDONMENT PROGRAM

The program for the decommissioning of the Carresse facility and the abandonment of the site is summarized below (dates after 2004 should be considered as tentative).

1)	Cavern last propane withdrawal	2001 to 2002
2)	Brine temperature measurements inside caverns	2002 to 2003
3)	Hydrogeological survey to check that no brine or LPG is present in the site area and to establish the initial hydrogeological balance	2002 to 2003
4)	Removal of trapped propane ("de-trapping")	2003 to 2004
5)	Program of studies, laboratory tests, in situ tests and numerical simulations to predict the long-term cavern behaviour after abandonment	2002 to 2004
6)	Validation of predictive model with a pressure test on cavern SPR2	2004
7)	Caverns sonar survey	2005
8)	Well integrity survey by logging	2005
9)	Dismantling of surface installations: pipelines, buildings, brine ponds, etc… and site remediation for future agricultural use	2005 to 2006
10)	Cement plugs setting inside the four wells	2005
11)	Observation period : subsidence monitoring and hydrogeological surveys	2005 to 2008
12)	Abandonment Permit granted to Total E&P France	2008

4. REMOVAL OF THE TRAPPED PROPANE: "DE-TRAPPING" PROCESS

Although the shape of the caverns is rather smooth, some geometrical traps may exist in their overhanging parts. These traps may have remained totally or partially filled of liquid propane after the last withdrawal operation. A rough estimate of the volume of liquid propane likely to be trapped indicated a range of 1 to 2% of the volume of the cavern. Since this estimate is directly linked to the accuracy of the sonar survey, which is in the order of 3 to 5 % in volume, the level of uncertainty is very high. In addition, liquid propane may have migrated into the insoluble materials, which are embedded within the salt formation.

Several techniques have been considered for removing this trapped propane out of the caverns:

- To pump out the whole cavern volume (brine and propane) either with submerged pumps or by nitrogen injection.
- To operate a releaching in the cavern in order to eliminate the geometrical traps.
- To depressurize the cavern below the propane vapor pressure.

After a technical and economical evaluation of the three techniques, Total E&P France has decided to implement the depressurization method proposed by Géostock.

4.1 Process description (see figure 7)

In current operating conditions, the pressure inside the cavern is halmostatic (i.e. created by the weight of the brine column). Thus it depends of the cavern depth, but it is high enough for maintaining the propane as a liquid. For SPR1, 2 & 4 it varies from 38 bar to 49 bar while the propane vapor pressure at cavern temperature (around 19°C) is about 7 bar (relative).

The basic principle of the method is to lower the pressure inside the traps below 7 bar allowing the propane to vaporize and to be expelled out. For this purpose, brine has to be withdrawn out of the cavern with the objective to drastically reduce the height of the brine column. Practically, the gas-brine interface has to be lowered under the cavern roof. Its level will be determined by taking into account the deepest traps as these will be kept pressured by the weight of the remaining brine column, in the range of 3 to 5 bar, depending of the cavern height (20 to 40 m).

The operation consists in injecting nitrogen under a pressure ranging from 40 bar to 50 bar into the well annulus and in simultaneously evacuating the brine through the tubing. After the pre-determined volume of brine is evacuated, the nitrogen is depressurized down to 7 bar. At this moment, the liquid propane trapped above the brine-gas interface begins to vaporize and to be expelled out of the traps. The gaseous propane is evacuated to the surface through the well annulus, then to the flare where it is burned. A further decrease of gas pressure will be necessary to deal with the traps located under the brine-gas interface.

4.2 Cavern stability

Prior to deciding the operation it had to be demonstrated that the caverns might experiment a depressurization to almost the atmospheric pressure without any impact on their stability. This short-term behavior of the cavern was checked on the basis of a literature survey and of 2D numerical simulations performed with ABAQUS, a finite elements model (FEM). The necessary mechanical parameters were obtained from the laboratory tests and from the in situ SPR3 pressure test (see section 5).

4.3 Microseismic monitoring

Before entering into the operation phase, a microseismic monitoring network had been installed on the site in order to check the cavern stability during this phase. It consisted of:

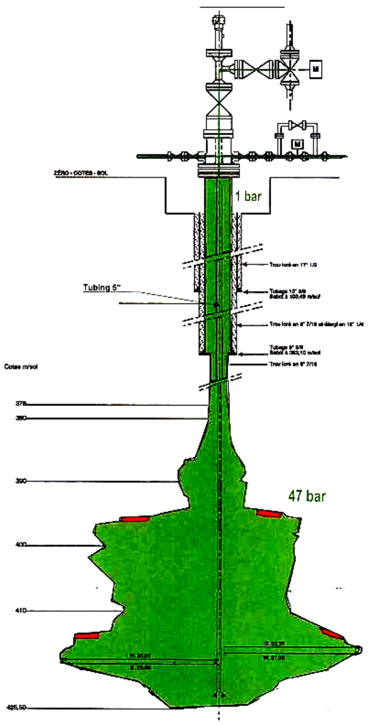
- One triaxial geophone located above SPR4 at a depth of 26 m.
- One triaxial geophone and three uniaxial geophones located above SPR2 at depths of 95 m, 75 m, 65 m and 55 m.
- A remotely controlled computer for data acquisition, data processing and data transfer, installed inside the site control room.

In addition two geophones were installed on surface in order to detect possible cracks in the vicinity of the casing shoe.

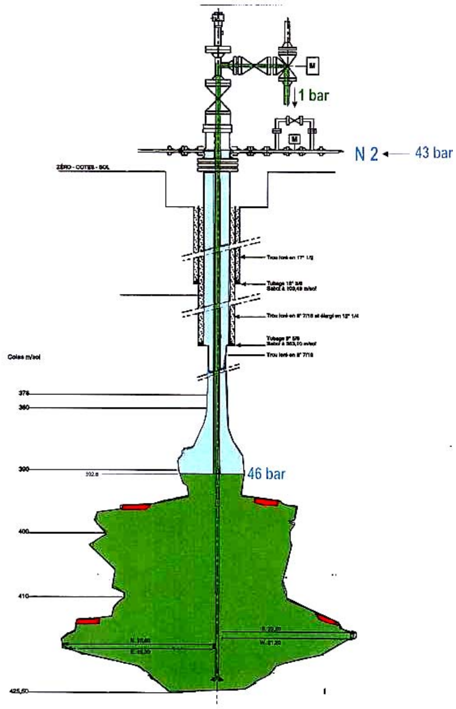
- One geophone attached to wellhead casing.
- One geophone at ground level installed close to wellhead, to cope with surface noises.

This system did continuously operate during the whole duration of the operations. During the phases of nitrogen injection and depressurization, data records were remotely analyzed and a report was sent every hour. Out of these critical phases, the analyses and reporting were done on a daily basis. An alert procedure was set up for the case of a signal detection originating from cavern vicinity. No microseismic signal interpretable as a sign of instability or movement at cavern depth was detected during the operations.

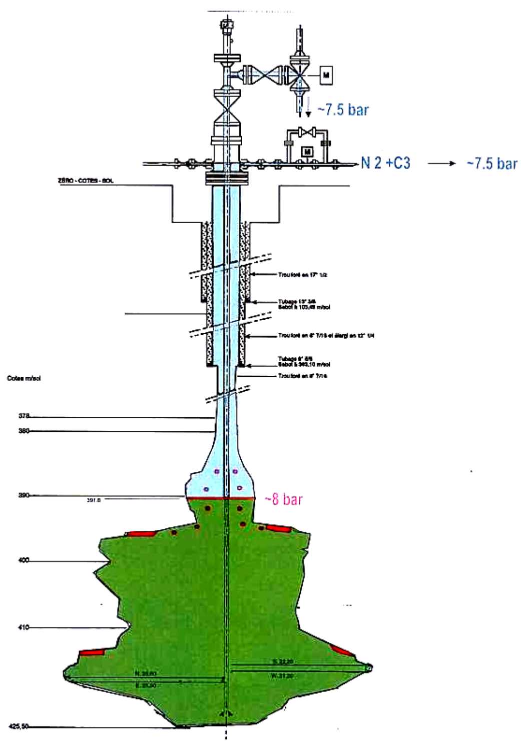
Both the installation of the system and the analyses of data records have been contracted to Magnitude, a company specialized in microseismic monitoring.



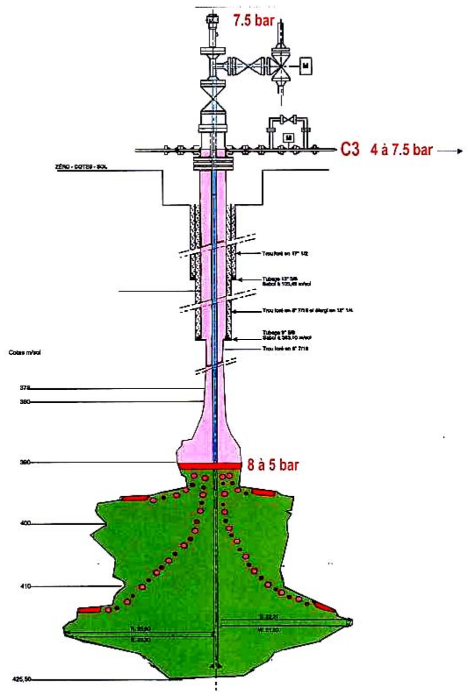
Step 0: cavern is full of brine, traps are filled with liquid propane



Step1: Nitrogen is injected in the annulus, brine is evacuated through inner tubing



Step2: nitrogen is vented and at 7 bar propane begin to vaporize



Step3: liquid and gaseous propane goes up to cavern top and is evacuated to the flare

Figure 7: The de-trapping process

4.4 Description of operations

At the end of June 2003, nitrogen under pressure was injected in caverns SPR1, 2 & 4, expelling brine out of the caverns. Liquid nitrogen was pumped from a tank and vaporized, utilizing a nitrogen pumping and heating unit. Gaseous nitrogen was then injected into the caverns at a pressure of 42 to 46 bar. The existing facilities were used with only minor adaptations for the nitrogen injection, for the metering of expelled brine and for the depressurization of nitrogen to the flare. The operation was contracted to Schlumberger Oildfield Services.

The brine volume to be expelled out of the cavern was determined as the "free volume" to be created above the gas-brine interface in the upper part of the cavern. This volume should be large enough to be able to receive the whole volume of liquid propane to be expelled from the traps. The cavern diameter at the gas-brine interface should also be large enough (i.e. of the order of or greater than 5 m) to allow that liquid propane vaporizes: this endothermic process will indeed require a large transfer of heat from the brine and from the cavern walls. The volume calculation has been based on a trapped volume of 1% of the total free volume.

Depth values are below ground level		**SPR1**	**SPR2**	**SPR4**
Brine volume expelled	m^3	202	157	387
Nitrogen volume injected	Nm^3	8,770	5,780	18,270
Brine-gas interface depth	m	360.7	304.8	391.8

Table 2 –Brine and nitrogen quantities needed for the "de-trapping" process

4.4.1 De-trapping of SPR2

The de-trapping operations began with the depressurization of the smallest cavern SPR2 from 37 bar to 7 bar, by venting nitrogen to the flare. The depressurization had to be slowed down to avoid an excessive temperature drop and was achieved within two days. When the pressure reached 7 bar a mixture of nitrogen and gaseous propane began to burn at the flare. It took four days, at a flow rate ranging from 1 to 3 t/h for 6 to 8 hours a day, to release and evacuate the liquid propane from the geometrical traps. A period of about one week has been then necessary to evacuate the gaseous propane, produced by brine degassing. A total of 22 metric tons of propane, representing 44 m^3 of liquid propane i.e. 0.5% of cavern volume, has been evacuated from SPR2. The cavern has been refilled with saturated brine in August 2003.

4.4.2 De-trapping of SPR1

SPR1 exhibited a very different behavior from SPR2. At mid-August 2003, SPR1 was depressurized and the gas began to burn at 5 bars. During the first days, significant quantities of propane were evacuated at a rate of 4 t/h for 6 to 8 hours a day. After three weeks of de-trapping, a total of 182 tons had been produced. At that time the flow was stable at a rate of about 1 ton a day. It has then remained constant for nearly one year. In mid-July 2004, it started to decrease. At the end of August 2004, it had become very low (of the order of 0.1 ton a day or less) and irregular. It is expected to stop during the month of September 2004. The cavern will then be refilled with brine.

This phenomenon has been explained by the presence of significant dolomite and anhydrite inclusions in the salt formation surrounding this cavern. This has been corroborated by permeability and porosity measurements done on core samples. Over the 40-years operating period, liquid propane has been injected and trapped in the porous space of these insoluble materials. During the de-trapping, the pressure conditions into the cavern did allow the “production” of this “liquid gas rich formation”. Due to the low permeability values of these materials, this process has been rather slow.

During this one-year de-trapping, a total of 480 metric tons of propane has been flared, representing 960 m^3 of liquid propane. In this volume, it is estimated that 360 m^3 were released from geometrical traps, i.e. 2.9% of cavern volume, while the remaining 600 m^3 have probably been "produced".

4.4.3 De-trapping of SPR4

SPR4 exhibited another interesting behavior. It was depressurized in mid-September 2003 and the gas began to burn at 4 bar. As for SPR1, a flow rate of 4 t/h has been observed during the first days. Until mid-October, a total of 164 tons has been evacuated. At that time, the flow rate drastically decreased, down to only 0.1 ton a day.

It was then noticed that the gas-brine interface level, which initially was just below the cavern roof at a depth of about 392 m, had risen in the cavern well up to about 370 m. Meanwhile, the pressure at the bottom of the cavern stabilized at around 7 bar. During several weeks, this pressure remained constant, close to the propane vapor pressure. It then became clear that the de-trapping process of the lower part of the cavern had stopped.

The observed rise up of gas-brine interface, and the resulting increase of the pressure at the bottom of the cavern, were explained by the existence of some geometrical traps which initially were resting incompletely filled with liquid propane. When propane began to vaporize it expelled the brine present inside the trap, which accumulated at the cavern top part. The consequences have been the rise up of the gas-brine interface, resulting in increasing the pressure at cavern bottom.

In April 2004, a new nitrogen injection operation was carried out and an additional volume of 1,500 m^3 of brine was expelled out of the cavern. As a result of this operation, the gas-brine interface was again lowered down below the cavern roof and the pressure at cavern bottom level dropped, down to around 4 bar. This allowed the remaining propane to be released. The de-trapping process on SPR4 has been completed at the end of June 2004 and the cavern will be refilled with brine in September 2004.

During the two de-trapping period a total of 325 metric tons of propane have been evacuated, of which 65 tons during the second period. It represents a total of 650 m^3 of liquid propane, i.e. 2.7% of the cavern volume.

4.5 <u>Gas-brine interface level measurement</u>

A method to measure the brine-gas interface level has been developed for the de-trapping operations. It consists in injecting gaseous nitrogen in the inner tubing until observation of the overflow of nitrogen at the tubing shoe, whose level is known (the tubing pressure will remain constant). The interface level is then calculated from the difference between the tubing pressure and the annulus pressure, measured on the wellhead. The measurement is easy to carry out and is accurate enough (1 to 2 m) for the needs of the operation.

4.6 <u>Measurement of the propane quantities</u>

The determination of the gas volume evacuated from the caverns was achieved by measuring the pressure losses in the piping between the wellheads and the flare. This method was of poor accuracy but it has been proved to be sufficient for the operation needs (the main objective was to ensure that all trapped propane had been expelled out of the cavern, but was not to precisely determine the quantity of propane that had been released).

5. PREDICTION OF CAVERNS POST-ABANDONMENT BEHAVIOR

In the aim of predicting the long-term behavior of the abandoned caverns, Total E&P France launched an extensive program, which was carried out over two years over years 2002 to 2004. It has included laboratory tests, in situ measurements and tests, and numerical simulations of the combined effect of creep, thermal expansion and brine permeation.

The long-term behavior of sealed and abandoned caverns has been discussed in several papers, particularly in Ratigan, (2003) and Bérest *et al.* (2001).

5.1 Laboratory tests

Lab tests on core samples were conducted in Palaiseau by the Laboratory of Solids Mechanics of Ecole Polytechnique (LMS) and in Pau by the Laboratory of Geomechanics of Total E&P (Scientific & Technical Center). The objective was to determine the creep properties of the salt. Both primary creep and secondary (stationary) creep have been tested on five samples: three of them have originally embedded at a depth of 300 to 400 m, the two others at a depth of 700 m.

The interpretation of the secondary creep is based on the Norton-Hoff law, whose uniaxial formulation is:

$$\frac{d\varepsilon}{dt} = A_o \ \sigma^n$$

From the lab tests, the creep parameter values have been determined:

- For the salt laying at 700 m depth:
  $n = 3.42$ and $A_0 = 0.63\ 10^{-13}\ s^{-1}\ MPa^{-3.42}$

- For the salt laying between 300 m and 400 m depths, two sets of values were calculated:
  $n = 2$ and $A_0 = 2.5$ to $5.5\ 10^{-12}\ s^{-1}\ MPa^{-2}$
  $n = 3$ and $A_0 = 6\ 10^{-13}\ s^{-1}\ MPa^{-3}$

These creep rates are in the upper range of those known on other sites: see Brouard and Bérest (1998).

5.2 Temperature and pressure measurements in caverns

In 2002 and 2003 in situ temperature measurements were performed in the four caverns. For each of them, the temperature well and cavern profile was measured. The measurements on SPR3, for which temperature equilibrium had already been reached, gave the reference profile for the geothermal temperature. Inner-cavern temperature increasing was also recorded by downhole memory gauges, which were let at tubing bottom level for periods of two to four months. In order to predict the cavern temperature rise, a thermal exchange model has been developed which was calibrated with the measurements. The results are shown in Table 3. They clearly indicate that the thermal rise, thus the induced thermal expansion, should be very small after the plugging of the wells, which should be done in 2005.

Cavern	2003	2004	2005	2010	Geothermal temp.
SPR1	18.3	19.0	19.3	19.8	20.0
SPR2	18.5	18.9	19.1	19.2	19.3
SPR3	24.0	24.0	24.0	24.0	24.0
SPR4	16.9	17.6	18.4	19.5	20.4

Table 3: Prediction of cavern temperature rise (in °C)

In addition, the three caverns SPR1, 2 and 4 were left closed for two months in 2003. During this period, wellhead pressures were recorded. The pressure increase, which was then measured, was found consistent with the temperature rise predictions. However, it indicated that the creep rate was lower than what could have been expected from the lab tests and from the pressure test on SPR3 (see section 5.3). This conclusion presumes that the effects of the permeability and of the possible leaks in the well are low, what can be assumed because the cavern pressure value was close to the halmostatic value at the time of the measurements.

5.3 One-year pressure test on cavern SPR3

This cavern was selected because it had not been operated for 15 years and thus was no longer exhibiting thermal expansion. Moreover, as this cavern is deep, salt creep is more important and thus is easier to measure.

As displayed on Figure 8, the SPR3 cavern experimented during the testing program several steps at various cavern pressure values, each step lasting around one month to reach a steady state behavior. The test pressures varied from a rather high pressure (30 bar or 3 MPa above the halmostatic pressure) down to a pressure below the halmostatic pressure. Continuously along the test, the wellhead pressures values and the expelled brine flow rate were locally recorded and remotely monitored. The recorded data were periodically transferred for remote interpretation.

Assuming a Norton-Hoff law for secondary (stationary) creep, a back analysis allowed to determine the creep parameter values. The SPR3 salt creep appears to be faster than the in situ creep observed before in other sites.

The results also show that a long-term equilibrium between salt creep and brine permeation should be reached at a brine pressure value far below the value of the geostatic pressure. This is consistent with the permeability value of the salt formation, which appears to be rather high ($5.\ 10^{-19}$ to $9.\ 10^{-19}\ m^2$).

The description and the results of this test are detailed in Brouard *et al* (2004).

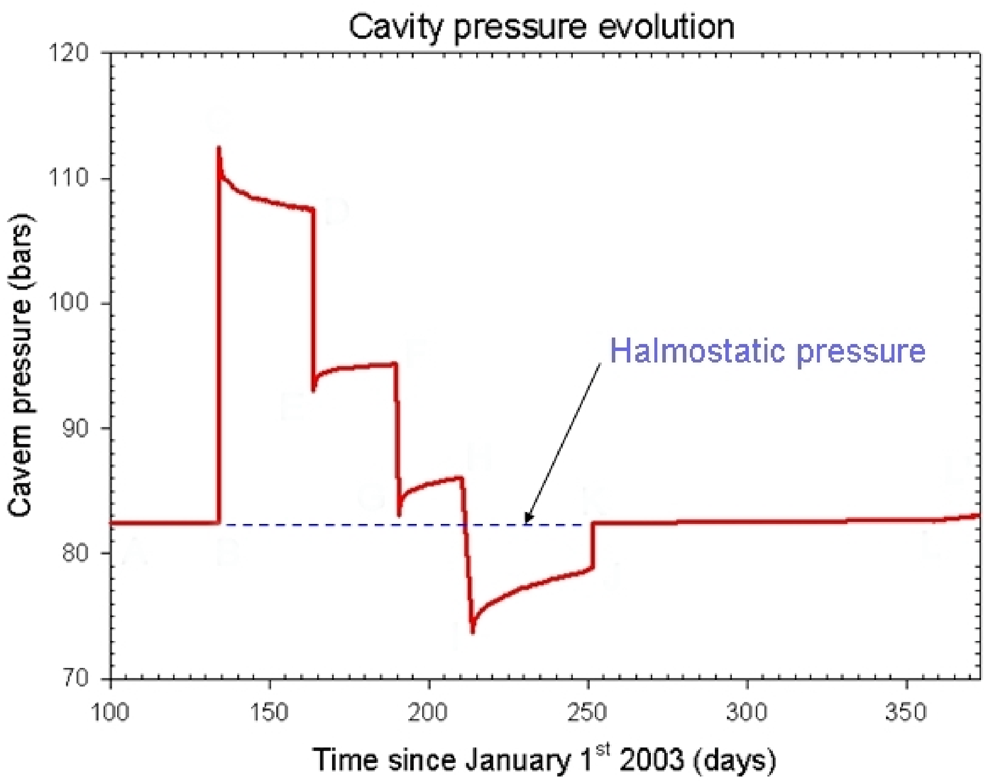


Figure 8 – Cavern pressure evolution during SPR3 in situ test.

5.4 Numerical simulations

Two different numerical models have been used to predict the long-term behavior of the caverns after abandonment.

- The semi-analytical part of LOCAS software from Brouard Consulting, which simulates the combined effects of secondary creep (Norton-Hoff law), thermal expansion, brine permeation and salt dissolution for an equivalent spherical or cylindrical cavern.
- A 2D finite elements model (FEM) which has been specially developed for this project under the supervision of Professor Attilio Frangi of Politecnico di Milano and Ecole Polytechnique. This model takes into account the actual 2D geometry of the cavern and the combined effects of primary and secondary creep (Munson-Dawson law), thermal expansion, brine permeation and salt dissolution (see Figures 9 and 10).

Since the time of the simulations the 2D Finite Elements Code has been integrated into the LOCAS software.

The simulations have been calibrated with the SPR3 test results and with the temperature measurements in the four caverns. In addition, the possible variations in creep properties and salt permeability have been considered for appreciating the sensitivity of the results to these parameters.

Both models gave similar results and concluded that the inner-cavern pressures should increase very slowly after the plugging of the wells. They should finally reach equilibrium after a period of 50 to 100 years, at a pressure corresponding to a pressure gradient of 1.4 to 1.6 10^{-2} Mpa/m. This pressure gradient is far below the geostatic gradient, of which the value is about 2.1 10^{-2} Mpa/m. Thus there should be no risk of fracturing at the cavern roof or casing shoe levels. Figure 10 shows the results of the 2D FEM simulation of the SPR2 long-term behavior.

Despite this favorable result, a worst-case scenario has been analyzed in order to fully account for the impact of the cavities closure on Health, on Safety and on the Environment. In this scenario, the rocks or cement would have been fractured, letting the brine leak out of the cavern toward the upper layers.

In this most pessimistic situation, the cavern pressure might drop to hydrostatic pressure. The brine quantities leaking out would amount for the four caverns to a total of 60 m^3 per year. These quantities would be quite acceptable with regards to the Carresse site environment: there is no aquifer above the salt formation and the top of the salt formation is already saturated with brine, which is currently exploited for salt production in the city of Salies-de-Béarn.

5.5 Model validation with an in situ test on SPR2

The predictive models of the caverns long-term behavior have been validated by a pressure test on the SPR2 cavern, the only cavern of which de-trapping had been terminated at the time of the test.

In May 2004 the SPR2 cavern was pressurized at a wellhead pressure value of 13 bar, which for the cavern is equivalent to a gradient value of 1.65 10^{-2} MPa/m., The tubing and the annulus have been equipped on the wellhead with highly accurate pressure gauges, and a data acquisition system has been locally installed, which can be remotely controlled.

At the beginning of September 2004 the test was continuing and the pressure values at wellhead had dropped to around 11 bar: the pressure values were decreasing slightly, indicating that despite the temperature rise inside the cavern, the pressure equilibrium value is lower. This confirmed that the cavern pressure gradient has an equilibrium value below 1.6 10^{-2} MPa/m.

In September 2004, the cavern should be depressurized to reach an equivalent cavern gradient value of about 1.5 10^{-2} MPa/m. The further evolution of the wellhead pressure values should give new indications on the equilibrium values.

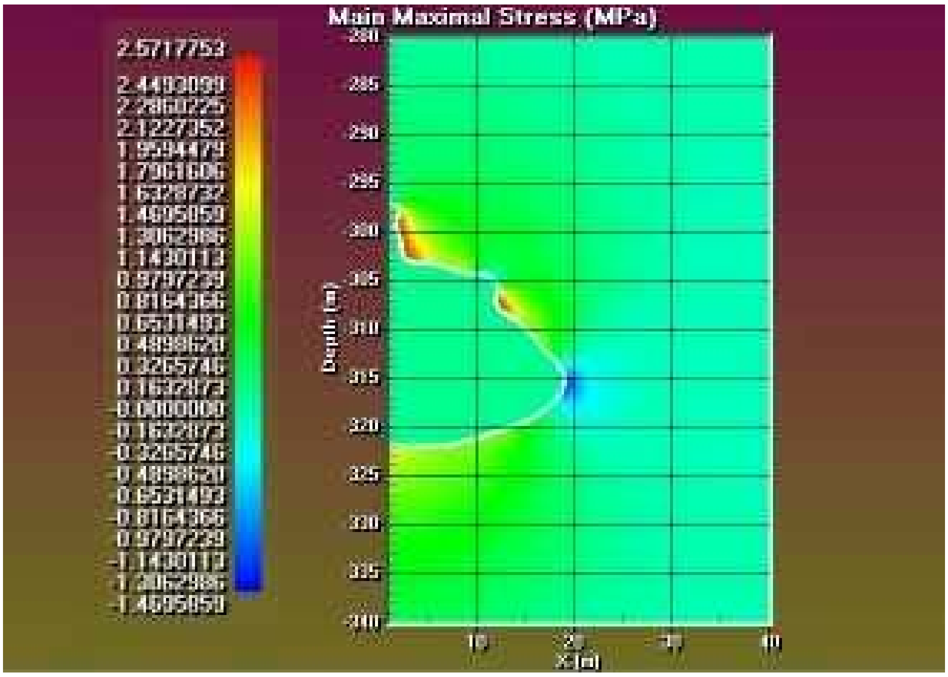


Figure 9 : Cavern SPR2 - Main maximal stress contour plot at the end of the depressurization step

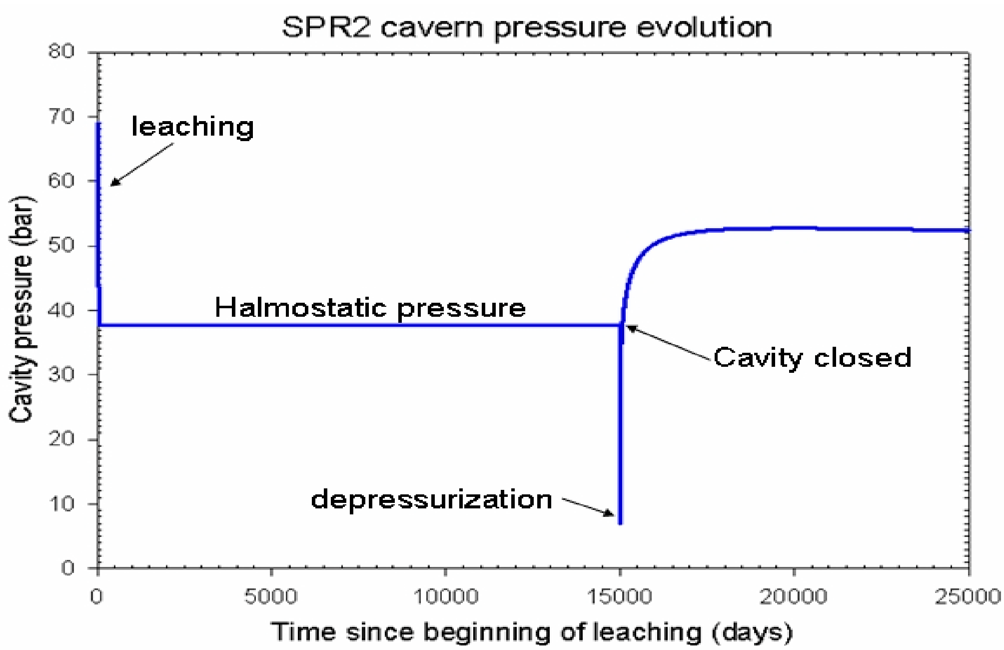


Figure 10 -Simulation with 2D FEM of pressure history in the SPR2 cavern, before and after closure (Depressurization before closure corresponds to the de-trapping period)**.**

6. ADMINISTRATIVE PROCEDURE

In France the underground storages are under the authority of the Ministry of Industry. In January 2003, a law relating to the gas market liberalization has changed the regulation applicable to underground storages. They are now governed by the Mining Code. Decrees have not been published yet but it is likely that the new rules will be very similar to those applicable to conventional mining activities, which include oil and gas production.

The administrative procedure to be fulfilled for Carresse first concerns the termination of the storage-related operations. It will be effective when the de-trapping process is completed, i.e. when there will be no more gas on the site. The Mining Authorities should then grant new rules relaxing the safety and control constraints. At this occasion, Total E&P France had to provide to the French Authorities a comprehensive storage closure file.

A first part of this closure file comprised the history of the storage, the description and the status of the facilities at the termination of the operations, especially for the caverns and for the wells. It included a statement of the final impact on communities and on the environment, of the 40-years operations. A second part of the file detailed the program that had been conducted to predict the long-term post-abandonment behavior of the caverns. It concluded on the conditions for a safe and environmentally sound abandonment of the storage, and it demonstrated the absence of risk regarding ground instabilities and contamination with brine of soil or underground layers.

Based on this file, the Mining Authorities should request an observation period, which should last three years after the plugging of the wells. During this period the site subsidence should have to be monitored, and the local hydrogeology regularly surveyed. Should no significant event occur during this period, the French Ministry of Industry should grant the Abandonment Permit to Total E&P France.

The Carresse will be the first case in France of storage in solution-mined caverns that will experiment an engineered abandonment program along with the related administrative procedure. To date, the May-sur-Orne diesel oil storage remains the only underground storage which has been decommissioned and abandoned in France: it was a disused iron mine converted into storage in the early 1970's and closed in the early 1990's.

7. WELL PLUGGING

The plugging technique will be similar to the technique currently used for the oil and gas wells of the Lacq field. First a cement plug of 100 to 125-m high will be set inside the cavern neck and inside the bottom part of the well casing, with a 50-m length of cement below the casing shoe. Then a bridge plug will be set up at the cement top for SPR1, 2 & 4 and at a depth of 300 m for SPR3. Finally a second cement plug will be set, up to a depth of 30 m below ground level.

After a period of observation of around 6 months, the wellhead will be dismantled and the top of the casings will be cut off, after having been filled up with cement.

8 CONCLUSIONS

The Carresse storage facility will be the first case of its kind to be decommissioned and abandoned in France.
The complete withdrawal of propane required carrying out a specific operation in order to remove the propane trapped inside the cavern. This operation proved to be necessary since a total of 1,650 m^3 of liquid propane has been removed at the end of August 2004. An innovative and cost-effective method based on cavern depressurization has been developed and satisfactorily applied. It should be noted that this method is applicable only to shallow caverns capable of remaining stable at the atmospheric pressure, and in addition, in the case of a storage of liquid propane, having a height limited to 50 m (or where the suspected traps are located in the upper 50 m of the cavern).

To predict the long-term behavior of the caverns after the plugging of the wells, an extensive program has been carried out. Its first objective was to estimate of the combined effects of salt creep, of temperature increase and of brine permeation.

The temperature measurements, which have been performed in 2003, have shown that the caverns are almost in equilibrium with the geothermal temperature and that the thermal difference will be less than 1°C at the expected plugging date. This favorable situation is due to the shallow depth of the caverns and to the temperature of the lastly pumped brine, which was in the range of 15°C to 20°C. Consequently long-term cavern behavior will be only dictated by creep and by brine permeation.

The creep rates, which resulted from the laboratory tests and from the in situ SPR3 pressure test, are quite high. They are higher than the in situ creep rates that have already been observed in other sites. Meanwhile the permeability of the salt formation is also quite high (it is of the order of $5.\ 10^{-19}$ to $9.\ 10^{-19}\ m^2$). This might be due to the high insoluble contents of the salt formation, especially to the presence of dolomite inclusions.

The one-year creep test on SPR3 and the numerical simulations have shown that for the four caverns an equilibrium pressure will be reached far below geostatic pressure. The equilibrium value of the pressure gradient ranges from 1.4 to 1.6. Mpa/m, which will avoid any risk of fracturation.

As a result of this project a practical methodology has been developed for the prediction of cavern post-abandonment behavior, which might be easily adapted to others cavern sites.

This work has been done through a close and efficient cooperation between the owner (Total E&P France) and his in-house experts (Total E&P), the specialists of an engineering company (Géostock) and of a consulting company (Brouard Consulting) and those of a laboratory (EcolePolytechnique/LMS assisted by Politechnico di Milano).

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