Mechanical integrity testing of cavern wells in a salt solution mining in Portugal. First tests analysis and lessons learned

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Mechanical Integrity Testing of Cavern Wells in a Salt Solution Mining in Portugal – First tests analysis and lessons learned

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Abstract

The Matacães site is a solution mining salt production field located in Portugal, 40 km (25 mi) north of Lisbon. Operated by Solvay since 1954, this field comprises 22 caverns created in a salt dome. The cavern depths range from 300 to 1200 m (1000 to 4000 ft) and their geometrical volumes from 80 000 to more than 1,2 million m3 (3 to 42 MMft3).

In a perspective of securing the caverns before final closure, a vast study program was defined including collection of geological data, hydrogeological studies, geomechanical modelling, acquisition of temperature profiles, sonar imaging and microseismic monitoring. In this context, an ambitious program of well mechanical integrity tests was defined, with the objective of testing the tightness of cavern wells before their plugging and abandonment.

This test program started in November 2016. The method used is the fuel-oil leak test. The test was designed with the objective to remain simple and adapted to industrial constraints. A web monitoring system was set-up to enable remote analysis and control of the tests in real time.

To date (August 2019), 11 tests have been conducted. This paper presents the design, site implementation, analysis and interpretation of these tests. All of them have concluded to the integrity of the wells, with a maximum leak rate of ~ 3 L/day (~ 1 gal/day), i.e. at the limit of the resolution of the method.

Beside characterizing the well tightness, it is shown that the fuel-oil mechanical integrity test may provide a wealth of additional information on the well geometry, the cavern compressibility and the long-term equilibrium pressure of the cavern. It thus appears as an interesting method to implement in the context of a solution mining field before closure.

Key words: well mechanical integrity, tightness tests, MIT, abandonment, salt caverns, Portugal

1. Introduction

The mechanical integrity of wells is a primary requirement for the safety and sustainability of production and storage activities underground. The recent years have seen a growing concern of industrials and regulators about the management of well integrity throughout their lifecycle, from drilling to post-abandonment. Standard practices and guidelines for well testing have long been developed in oil and gas and hydrocarbon storage activities. Other mining industries now tend to transfer and adapt these practices to their domain with their proper objectives and constraints.

The fuel-oil leak test (FLT) is one example of the well tests that have long been implemented in the salt cavern hydrocarbon storage industry and were largely documented in the frame of the Solution Mining Research Institute (e.g. Crotogino, 1996; Bérest et al., 2002, Schulte et al., 2013). Solvay decided to implement this test in the context of a solution mining concession (Matacães in Portugal) in the perspective of its final closure. More precisely, the objective is to test the integrity of cavern wells before their plugging and abandonment (P&A).

The verification of well integrity before P&A is especially relevant in such saline, and therefore corrosive, environment where some wells were left inactive and brine filled for decades with very limited maintenance. It is expected that these tests will help locating and characterizing potential leaks and defining more appropriate P&A programs for each well. From a more general point of view, it is also an opportunity to collect quantitative information on the sealing properties of brine production wells up to 60 years after their construction.

The test program started in November 2016. To date, 11 cavern wells have been tested. This paper presents the design, site implementation and preliminary results of these first 11 tests.

2. Context

The Matacães site is a solution mining salt production field located in Portugal, 40 km (25 mi) north of Lisbon. Created in a salt diapir, this site was operated by Solvay since 1954. It comprises 23 production wells from which 22 isolated caverns were developed. The caverns are spread over two mining concessions, Matacães 1 and Matacães 2, at 500 m (0.3 mi) from each other (Figure 1).

The depth of cavern roofs ranges from 300 to 1200 m (1000 to 4000 ft) and their geometrical volume from 80 000 to 1,2 million m^3 (3 to 42 $MMft^3$) (see Table 1). Their average diameter is 45m (150 ft). Several caverns were developed in successive chambers separated by insoluble layers. Some chambers may be hydraulically connected.

The first caverns were developed between 1957 and the mid-seventies and the most recent ones between year 2000 and 2014 (Table 1). After their activity period, the caverns were left in brine and very little maintenance was done on the wells, except regular purges.

In 2014 Solvay decided to end the production of brine from Matacães to its industrial site of Povoa, located 40 km (25 mi.) south-east. Matacães then entered a phase of post-mining surveillance with the perspective of abandoning the site at term.

A study program was defined with the aim of defining the conditions of site closure that would best ensure long-term safety and environmental protection. This program includes collection and analysis of historical mining data, analysis of the hydrogeological context, implementation of geodesic, microseismic and seismic surveillance, thermal logging and sonar imaging of the caverns, conduction of specific tests on wells and caverns and finally, numerical modelling of the long-term evolution of caverns before and after their closure (Thoraval et al., 2018).

The fuel-oil leak tests reported in this paper are part of the specific tests defined in this program, which also include discharge tests, abandonment tests and interference tests between caverns.

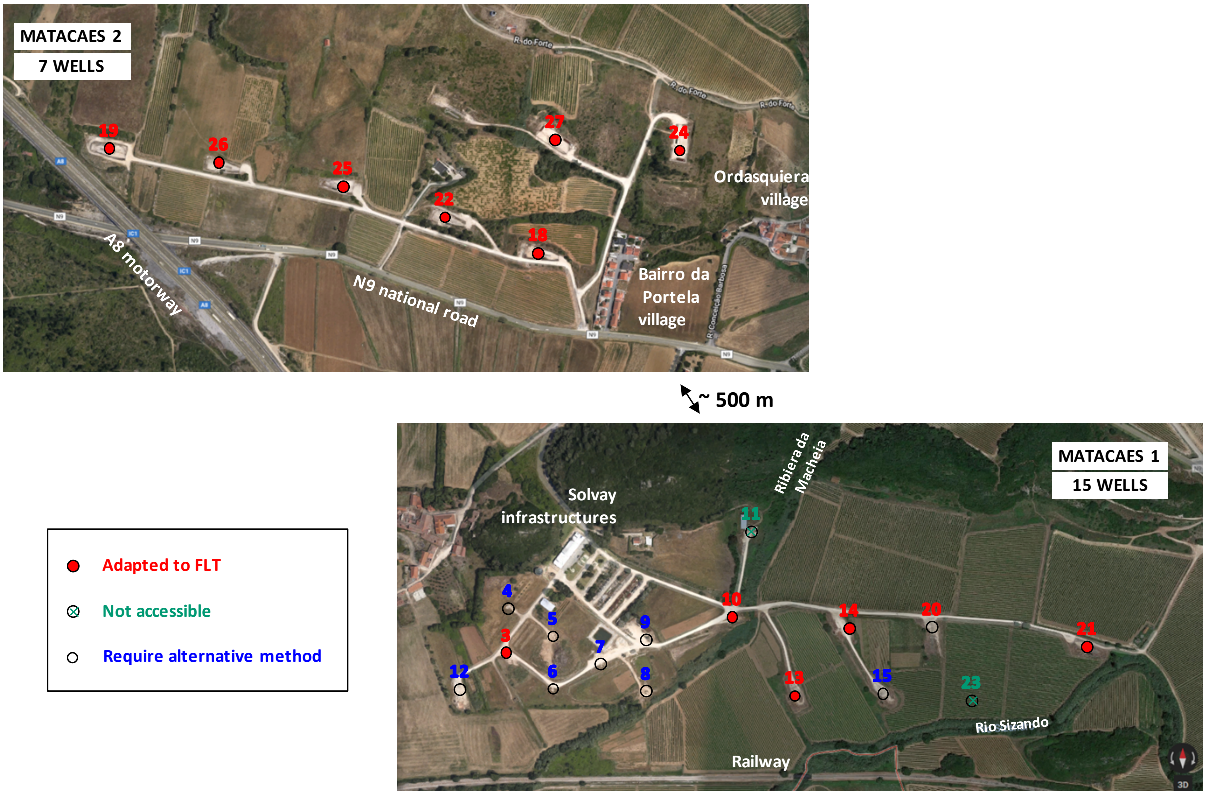

Figure 1. Map view of Matacães 1 and Matacães 2 concession with their 23 production wells

Table 1. Main characteristics of caverns and cavern wells – in colored lines the wells for which integrity tests are impossible (dark color) or require specific procedures (light color)

WELL #	END OF DRILLING	ACTIVITY PERIOD	CAVERN VOLUME[1] (m^3)	NUMBER OF CHAMBERS	THERMAL EQUILIBRIUM	CASING SHOE DEPTH (m)	CAVERN DEPTH[2] (m)	TUBING DEPTH (m)
				Matacães 1				
3	1952	1957 - 1980	326820	2	Equilibrated	296.20	302.50	314.00
4	1955	1957 - 1975	78764	1	Equilibrated	432.71	434.00	No tubing
5	1957	1957 - 1974	177056	2	Equilibrated	364.00	368.00	394.60
6	1957	1960 - 1989	499502	1	Equilibrated	300.63	300.63	No tubing
7	1969	1970 - 1990	427533	1	Equilibrated	289.48	289.48	No tubing
8	1969	1971 - 1980	279115	1	Equilibrated	376.00	376.00	No tubing
9	1970	1971 - 1993	425589	1	Equilibrated	390.52	400.00	425.90
10	1976	1977 - 2002	474084	1	Equilibrated	482.60	576.00	583.20
11								
12	1977	1978 - 2008	370392	2	Not equilibrated	273.40	298.00	No tubing
13	1978	1980 - 2014	809806	1	Not equilibrated	353.10	486.00	493.60
14	1979	1979 - 2014	600922	1	Not equilibrated	511.80	548.00	554.00
15	1979	1981 - 2014	534316	2	Not equilibrated	311.10	346.00	362.00
20	1985	1985 - 1998	154601	1	Equilibrated	410.90	410.90	No tubing
21	1988	1989 - 2013	133039	1	Not equilibrated	669.86	673.10	684.20
				Matacães 2				
18	1984	1986 - 2014	1235590	1	Not equilibrated	481.12	595.00	600.40
19	1985	1988 - 2006	603733	1	Not equilibrated	454.25	723.50	729.20
22	1989	1990 - 2006	428912	2	Not equilibrated	450.46	571.00	711.60
23								
24	1999	2000 - 2013	440765	1	Not equilibrated	595.00	1150.00	Not measured
25	1990	1991 - 2014	593789	2	Not equilibrated	467.74	590.00	599.70
26	1991	1992 - 2014	875692	2	Not equilibrated	466.94	522.00	523.00
27	1999	2001 - 2013	467119	1	Not equilibrated	575.00	1156.00	1168.00

[1] Total geometrical volume deduced from salt tonnage

[2] Top of cavern or cavern neck in the axis of borehole as deduced from last sonar

3. Method

3.1 Principle

The fuel-oil leak test (FLT) owns to the family of mechanical integrity tests called “liquid-liquid interface” tests (Diamond, 1989). The principle of a FLT is illustrated in Figure 2. The cavern is initially brine-filled and the well is equipped with a central column (tubing). High-precision pressure sensors are installed at the head of tubing and annular columns before the test. Brine is then pumped in the cavern up to a predefined pressure gradient at shoe depth, γ_{test}, ranging from 1.7 and 2.0 bar/10m (0.75 and 0.9 psi/ft). A fuel blanket is then lowered in the annular column, below the last casing shoe. A small amount of fuel (not displayed in Figure 2) may also be lowered in tubing for checking potential leaks of the tubing head.

The pressures at tubing and annular heads are then monitored during a period that may range from a few days to several weeks, depending on the time for the well to get back to thermal and chemical equilibrium and the desired precision of the test. Due to the lower density of oil relative to brine, any leak (or filling) of oil in one of these columns induces a higher pressure change at the head of this column. Monitoring the differential pressure between tubing and annular through time is thus a way of detecting and characterizing potential leaks along the well.

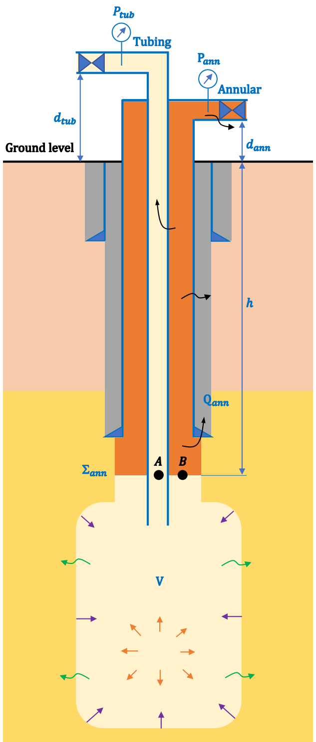

Figure 2. Principle of the fuel-oil leak test - arrows symbolize the main phenomena that influence wellhead pressures, namely brine thermal expansion, salt creep, brine permeation through salt and well leaks. Only the latter induces a different pressure change in tubing and annular.

3.2 Interpretation

The interpretation of a FLT relies mainly on three expressions.

The first one expresses the equilibrium of pressures in the tubing and annular columns. If one considers the simplest case where fuel is present only in the annular, i.e. no fuel cushion has been introduced in the tubing, the equality of static pressures in tubing and annular at the depth of the brine-fuel interface (points A and B in Figure 1) may be written:

$$P_i = P_{tub} + \rho_b g(h + d_{tub}) = P_{ann} + \rho_o g(h + d_{ann}) \quad (1)$$

where:
h is the depth of the brine-fuel interface from ground surface
d_{tub} and d_{ann} are respectively the elevation of tubing and annular valves above ground
ρ_o and ρ_b are respectively the density of oil and brine
P_i is the pressure at the depth of the brine-fuel interface
P_{tub} and P_{ann} are respectively the pressures at the head of tubing and annular
g is the gravitational constant.

After derivating with time and neglecting at first order the variations of oil and brine densities with pressure and temperature, one obtains the following expression relating the rate of fuel leak, Q_{ann}, to the rate of change of the differential pressure between tubing and annular:

$$\dot{P}_{ann} - \dot{P}_{tub} = (\rho_s - \rho_h)g\dot{h} = -(\rho_s - \rho_h)g\frac{Q_{ann}}{\Sigma_{\mathrm{ann}}} \quad (2)$$

where Σ_{ann} is the section of the annular at the depth of the brine-fuel interface.

The last important expression for the interpretation of a FLT is the relation between the volume of fluid ΔV injected in, or removed from, the cavern, and the corresponding pressure change ΔP at the wellhead:

$$\Delta P = \frac{\Delta V}{\beta V} \quad (3)$$

where:
β is the cavern compressibility factor
V is the cavern geometrical volume.

4. Tests design

4. 1 Selection of wells suited to mechanical integrity tests

A pre-requisite for conducting FLTs in Matacães was to check whether the concerned wells were adapted to such test.

Out of the 23 production wells in Matacães, two wells (#11 and 23) are no longer accessible, i.e. already plugged or stoppered, so they were immediately discarded.

Nine other wells (#4, 5, 6, 7, 8, 9, 12, 15, 20) are still accessible but are not technically adapted to the conduction of a FLT. For instance. some wells have no tubing anymore. Assessment of their mechanical integrity thus requires the application of alternative methods.

Finally, 12 wells (white lines in Table 1) appeared as immediately suited for FLT.

4.2 Review of information on wells and caverns

A thorough analysis of well logs was carried out to get as precise information as possible on the well geometry.

The design of Matacães wells is globally the same but slight variations may be found from one well to another. Most wells are lined with a 9"5/8 production casing (except two of them in diameter 10"3/4) with a linear weight of 36 lb/ft. The production casing is cemented from the surface to a "shoe" depth and then prolonged with an alternation of uncemented slotted casings (in front of productive formations) and cemented plain casings (in front of sterile formations). The "openhole", i.e. the section of the borehole between the casing shoe and the first cavity encountered along the borehole, whether it be the cavern itself, the cavern neck or a cave due to uncontrolled leaching, is in diameter 12"1/4 or 8"1/2, depending on the wells.

For the wells that are still equipped with a tubing, the latter is in diameter 7". The depths of the tubings were measured by logging in 2015; these are reported in Table 1. In 2015 was also performed a 3D sonar imaging of the caverns, from which the depth of the caverns could be precisely determined (see Table 1).

Gamma-ray logs and temperature profiles acquired by Solvay between 2015 and 2017 were also analyzed in order to detect possible caves along the borehole.

The elevation of tubing and annular valves above ground were also measured for each well. These values are integrated in the calculation of pressures in the well.

4.3 Prior estimation of the cavern compressibility

Prior estimation of the cavern compressibility, βV, was important for predicting the evolution of pressures and the volume of brine needed at each phase of the test.

Here the cavern compressibility was estimated from the measured pressure drop, ΔP_{purge}, and the volume of brine collected, ΔV_{purge}, during the periodic purges of the caverns, using expression (3). An illustration of the purges carried out on well #26 and of the compressibility determined from purges on wells #24, 25 and 26 are presented respectively on the left and right graphs of Figure 3. The values of the compressibility determined for all caverns may be found in Thoraval (2018). These range from 4.4 to 56.7 m^3/bar (10 to 138 ft^3/psi).

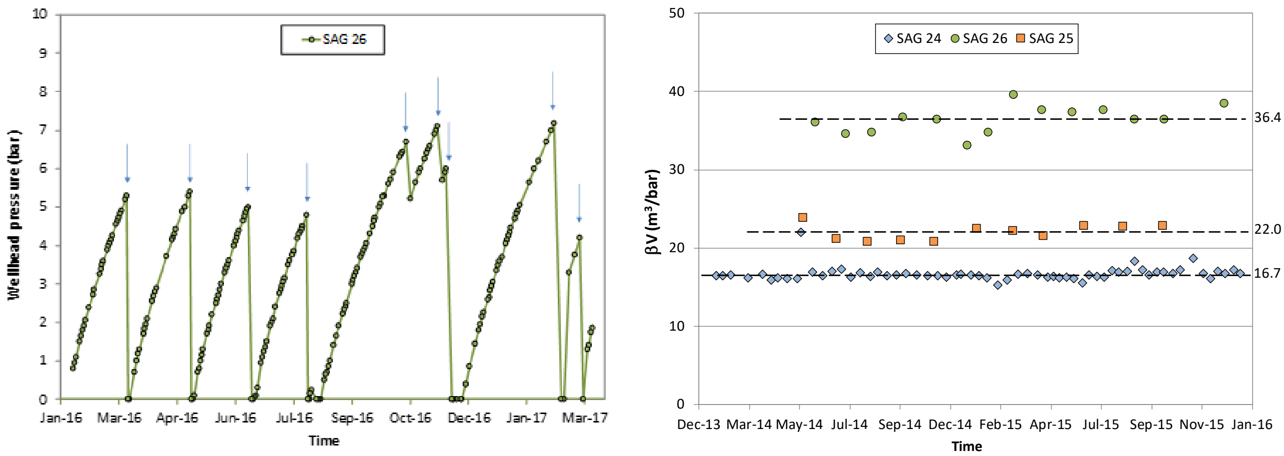

Figure 3. Estimation of the cavern compressibility from purges

4.4 Definition of the test procedure

The procedure defined for these tests consisted in three phases: (1) fuel injection in the annular until the brine-fuel interface is positioned in the optimal (i.e. deepest and narrowest) section of the openhole, (2) brine injection in the tubing up to the predefined test pressure gradient at shoe depth γ_{test}, (3) observation of the well until the variations of pressures in tubing and annular reach a permanent regime. The pressure was then released at a maximum rate of 20 bar/day in order to avoid damage of cavern walls.

It must be noted that because of the low-pressure working range of the fuel pump, the fuel injection (phase 1) had to be carried out before pressurization of the cavern (phase 2). The drawback of this phasing is that the depth of the brine-fuel interface may change during brine injection and move into a "bad" section of the borehole. One of the tests (on well #14) had to be redone for this reason.

For the sake of simplicity and because of the low-pressure working range of the fuel pump, no fuel cushion was lowered in the tubing. More fundamentally, the detection of tubing leaks was not a priority:

in the perspective of well abandonment, the primary aim of the test was to detect leaks of the well, not of its completion.

In order to best characterize the borehole geometry and determine the optimal position for the fuel-brine interface, the fuel injection was proceeded in two phases: first, the brine-fuel interface was lowered as deep as possible in the borehole, possibly down to the cavern or the upper cave along the borehole; second, fuel was progressively removed until the fuel interface reaches its optimal position.

4.5 Definition of the test pressure gradients

For each well, a specific test pressure gradient, γ_{test}, was defined based on the following criteria:

(1) it must not exceed 2.0 bar/10m (0.88 psi/ft) in order to avoid damage or fracturing of the shoe;
(2) it must be such that the wellhead pressure remains under the maximum allowable wellhead pressure (MAP), i.e. 64 bar (930 psi);
(3) it must be such that the pressure in the cavern is above its predicted long-term equilibrium pressure after plugging. For assessing this long-term equilibrium pressure, we first used the analytical solution proposed by Bérest et al. (1997) for a spherical cavern subjected to salt creep and brine permeation and adapted to the case of a cylindrical cavern by Lahaie & Thoraval (2013). In addition, we used the results of the numerical modelling of the long-term behavior of Matacães caverns (Thoraval, 2018).

Note that this third criterion could not be always respected. For instance, the center of cavern 27 is at a depth of 1310 m, i.e. more than two times the depth of the casing shoe (575 m). The application of the third criterion above would have led to apply a pressure gradient at shoe, γ_{test}, superior to 2.5 bar/10m (36 psi/10m), i.e. far above the lithostatic pressure gradient.

4.6 Predictive calculations of volumes and pressures

From the information collected on the well geometry (section 4.2), the cavern compressibility (section 4.3), the targeted test pressure gradient (section 4.5) and using equations (1) and (3), predictive calculations of the volume of fuel and brine to be injected as well as the evolution of pressures (in tubing and annular) at each phase of the FLT were performed. In those calculations, a density of 1200 Kg/m^3 and 960 Kg/m^3 (data provided by Solvay) were assumed respectively for brine and fuel. The Matacães wells are nearly perfectly vertical (loss of depth between MD and TVD inferior to 30 cm), so no pressure corrections were done from borehole deviation.

These predictive numbers were communicated to the operational people on site so that they could prepare all the logistics needed for the tests accordingly.

4.7 Maximum admissible leak rate

The maximum admissible leak rate (MALRs) has no absolute definition; it depends on the context and the vulnerability of the environment.

In the context of a salt cavern storage, the reference value of 150 kg/day (330 lbs/day) has been proposed for nitrogen leak tests (Crotogino, 1996). For a more viscous test fluid as fuel-oil, the same author recommends applying a reduction factor of 3, which comes down to a MARL of 50 kg/day. For a density of the test fluid of 960 kg/m^3 (density of the fuel-oil used in Matacães), one obtains a MALR of 52 L/day (14 gal/day).

The hydrogeological and hydrochemical analysis of the Matacães site does not reveal sensitive aquifers or vulnerable surface waters in the environment of the site (Charmoille, 2018). A MALR of 52 L/day thus appears as quite conservative in this context. Nevertheless, we will adopt this value in a first approach. To express it more concretely, if we consider the most pessimistic scenario where the 21 unplugged Matacães wells would leak with a rate of 52 L/day and where all brine would reach the surface and spill into a river or a stream at a single point, the corresponding mass flow of salt added to the water would be about 4 g/s (1 oz/s).

5. Tests implementation

5.1 Experimental layout

The characteristics of sensors used for the mechanical integrity tests are presented in Table 2. Beside sensors, the experimental layout comprises (Figure 4):
- a fuel tank and a low-pressure pump for fuel injection,
- a brine tank for buffering the brine taken from underground pipelines as well as a high-pressure pump for brine injection,
- an acquisition unit to which all sensors are connected. The unit comprises a datalogger as well as a GSM modem for data transfer on a web server and remote control of the acquisition parameters.

Table 2. Main characteristics of sensors deployed in Matacães

Designation	Range	Precision	
		% of full scale	Physical unit
Annular head pressure sensor	0 - 50 bar	± 0,075 %	± 37,5 mbar
Tubing head pressure sensor	0 - 50 bar	± 0,075 %	± 37,5 mbar
Atmospheric pressure sensor	0 - 2 bar	± 0,075 %	± 1,5 mbar
Atmospheric temperature sensor	-40°C to 65°C	-	± 0.5 °C
Fuel Mass flow meter	0 - 300 Kg/min	± 0,1 %	± 0,3 kg/min
Brine volumetric flow meter	0 - 150 L/min	± 0,2%	± 0,3 L/min
Brine volume totalizer	2.5 L/pulse	± 0,2%	± 5 mL/pulse

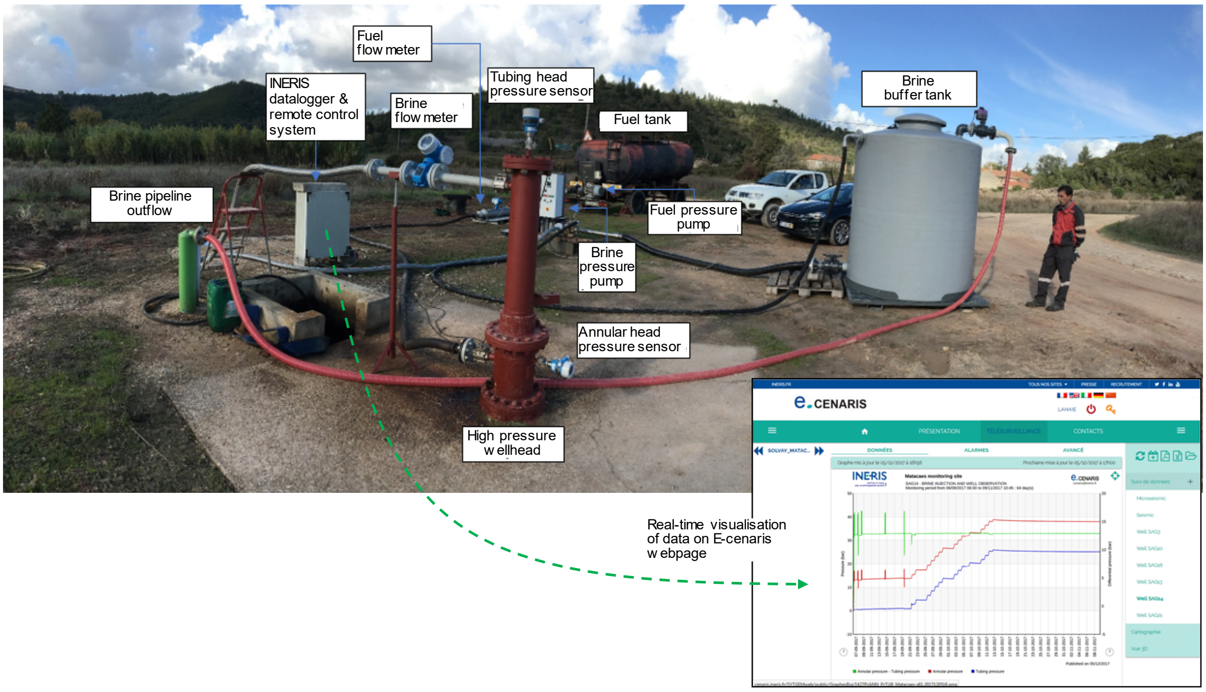

Figure 4. Experimental layout used for mechanical integrity tests in Matacães

5.2 Timeline and organization

The first mechanical integrity test was conducted in November 2016 on cavern #3. For this first test, Ineris was present on site for assisting the Solvay staff in the installation, testing of equipment and implementation of the test. The objective of that first week was to provide the local staff with the minimal information and training needed for being able to conduct the following tests with remote assistance only.

A periodic transfer of data on the web infrastructure e-cenaris (cenaris.ineris.fr) was set up and a dedicated webpage was created on which measurements could be consulted and analyzed in near-real time, enabling fast decision-making at critical moments of the tests.

From a safety perspective, the wellheads were checked before each test and an automatic alarm was set up to alert designated persons in case of anomalous pressure changes. Fresh water was also circulated in the well before the test to dissolve salt plugs and avoid excessive peaks of pressures.

To date (august 2019), 11 tests have been carried out. The time periods of the tests as well as their length are shown in Figure 5. The tests lasted between 20 days and 3 months, with a mean duration of 58 days. Note that fuel and brine injections were done only during working days, 8 hours a day, so the effective duration of the tests was probably closer to 1 month in average.

If we look at a finer scale, the fuel injection phase (blue bars in Figure 5) was globally the shortest one. This is not surprising as the volume of fuel that needs to be injected in a FLT, i.e. usually between 5 and 30 m^3 (200 to 1000 ft^3), remains modest. In fact, the length of this phase is essentially determined by the time needed for analyzing the pressure vs volume measurements (from which the well geometry is inferred) and for searching the optimal position of the brine-fuel interface. For some wells with a particularly complex and unexpected geometry (e.g. well #22), several cycles of fuel injection and removal may be necessary for fixing the optimal position of the fuel interface; this could take a lot of time.

The length of the brine injection phase is much more predictive as it is essentially determined by the cavern compressibility and the value of the targeted test pressure gradient. In Matacães, this phase ranged from 1 to 51 days (red bars in Figure 5).

Lastly, the length of the observation phase depends essentially on the time needed for well pressures to equilibrate after brine injection and on the desired precision of the test. In Matacães, this length was quite variable and ranged from 11 to 83 days (green bars). Note that the exceptionally long test performed on cavern 18, with an observation period of nearly 3 months, was intended to determine the time after which the pressures at wellhead are no longer influenced by transient phenomena (see section 6.3).

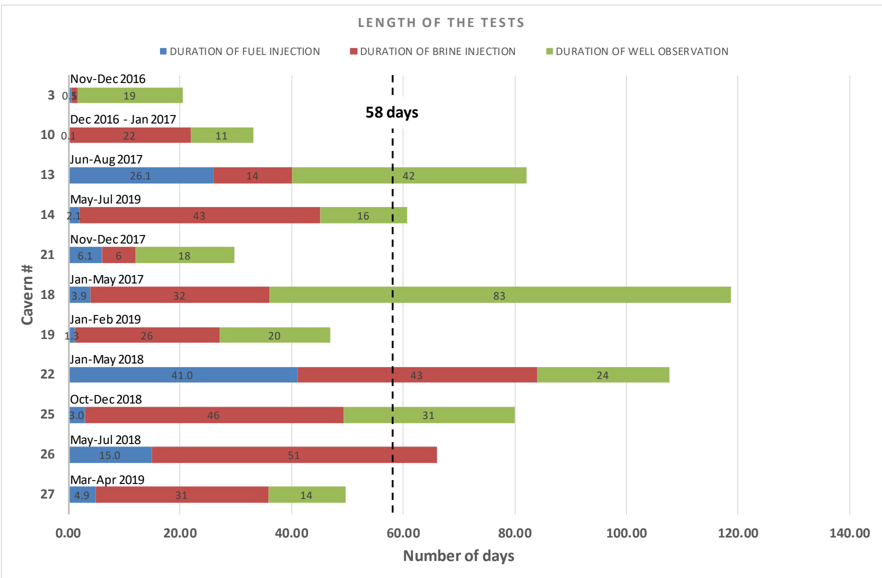

Figure 5. Time periods and length of Matacães tests

6. Results

Beside characterizing the well tightness, which is the primary goal of an FLT, it is also an opportunity to collect valuable information on the well geometry, the compressibility of the cavern or its long-term equilibrium pressure. These side results are detailed in the following sections (6.1 to 6.3), while the MIT test results in their strict sense are presented in section 6.4.

6.1 Information on the well geometry

The fuel injection phase offers the opportunity to check the depth and diameter of the different sections of the well as the fuel interface is lowered in the annular, first along the casing and then in the openhole.

An example of the wellhead pressure measurements recorded during a fuel injection phase, as a function of the volume of fuel injected, is presented in Figure 6. The depth of the fuel interface, inferred from the tubing and annular pressures using equation (1), is also plotted on the graph. One clearly sees two inflexion points, corresponding to two changes of diameter, first the passage of the casing shoe at 350.9 m and second, the point where the fuel interface reaches the chimney at 488.5 m. From the depth and the volume of fuel corresponding to each of these points and using equation (2), one may estimate, first, the average inner diameter of the casing and second, the average diameter of the openhole.

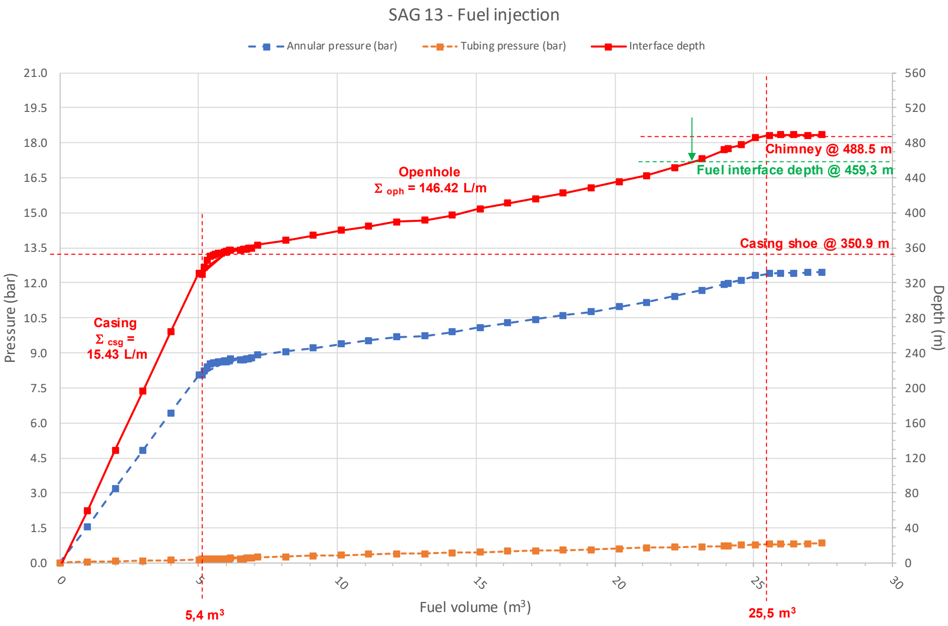

Figure 6. Example of measurements recorded during the fuel injection phase - cavern 13

Figure 7 shows a comparison between the depths and diameters of the casing and openhole deduced from the interpretation of the fuel injection measurements with the ones predicted from prior information (well history reports, well logs, sonars, gamma ray, temperature profile, etc.).

One sees on the two upper graphs that the casing depth and the casing diameter estimated from the fuel injection measurements fit globally very well with their prior values, with a precision of the order of 1% (i.e. ~5 m for the depth of a 500 m-deep casing and ~2 mm for the inner diameter of a 9”$^{5/8}$ casing). For two wells (# 22 and 26), however, the measured casing depth is inferior to the predicted one, i.e. an enlargement of the well section is encountered respectively 22 m and 73 m (72 ft and 240 ft) before the depth of the casing shoe reported on well logs. We interpret this as the result of a breach in the cemented casing, which may have caused uncontrolled leaching of the salt outside the casing and thereafter, an enlargement of the borehole.

Looking now at the depth of the openhole (left lower graph on Figure 7), the measured depth is consistent with the predicted one for 5 wells (out of the 8 for which the openhole depth could be measured). For 3 wells, an unexpected cave (well #22) or the onset of a chimney (wells # 14 and 26) were found before the predicted depth of the cavern as determined by sonar.

Regarding the diameter of the openhole (right lower graph on Figure 7), a strong discrepancy is globally observed between the predicted and the measured diameter. In most cases (6 out of 9), the openhole diameter is larger, sometimes by a factor 2 (e.g. cavern # 13), than the nominal one as indicated in well logs. This is symptomatic of an uncontrolled leaching of those wells. More surprisingly, 3 wells (#10, 19 and 26) show a measured openhole diameter inferior to their nominal one, sometimes by a reduction factor of 25%, i.e. well above the precision of the method (1%). These three openholes are all reported on well logs as drilled with a 12"$^{1/4}$ nominal diameter. It is likely that the diameter mentioned on the log be erroneous and that they were drilled with a 8”$^{1/2}$ nominal diameter, as many other wells in Matacães.

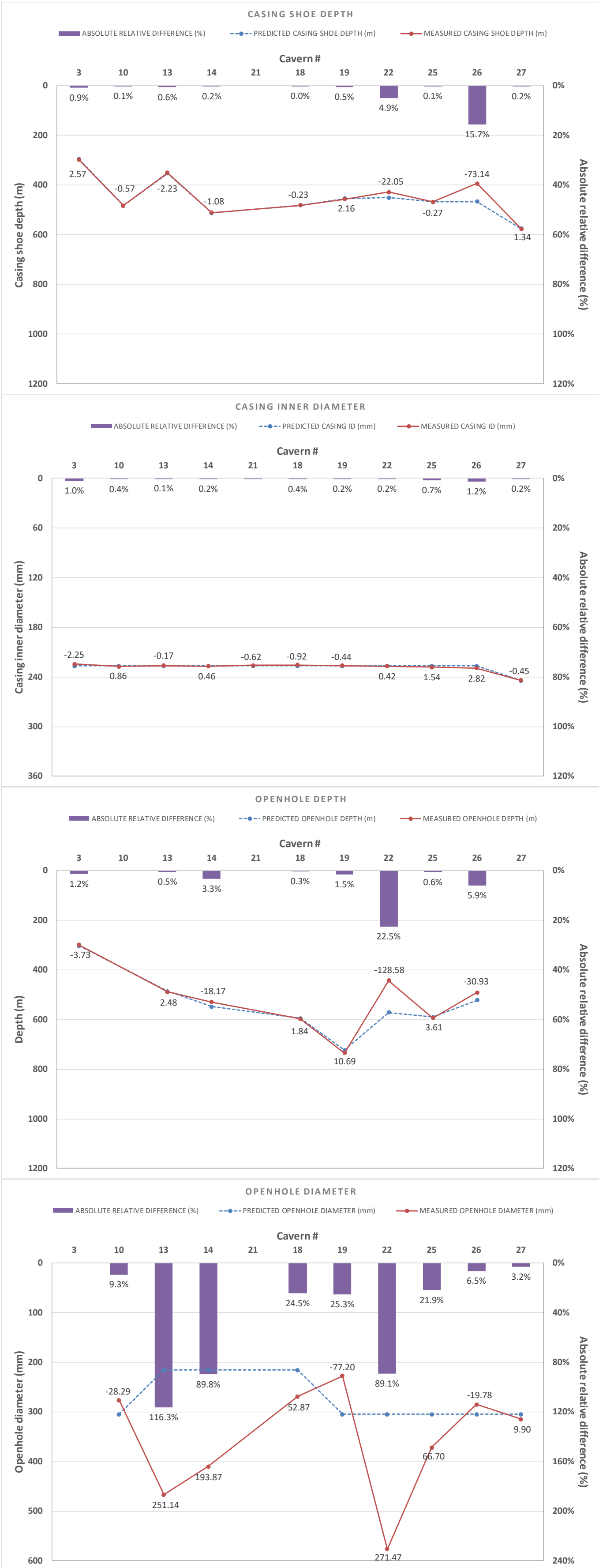

Figure 7. Comparison between predicted and measured geometrical parameters of the wells. The tagged numbers on red curves are the absolute difference between measured and predicted values

Another unexpected result arising from fuel injection measurements is illustrated in Figure 8. It concerns the well #21. The fuel injection was in progress and the fuel interface was around 617 m when an inflexion point was observed on both the annular and tubing pressure curves, indicating a fuel invasion in the tubing. After checking recent well records, it was found that the tubing was moved up during the last sonar measures and was now positioned at a depth of 647 m, i.e. 37 m above the expected depth.

As a result of the new depth of the tubing, which is shallower than the casing shoe, the fuel interface could not be lowered in the openhole and the tightness of the well was tested only on the cased section of the well. The same was done on well #3, for which the cavern roof is at the same depth as the casing shoe.

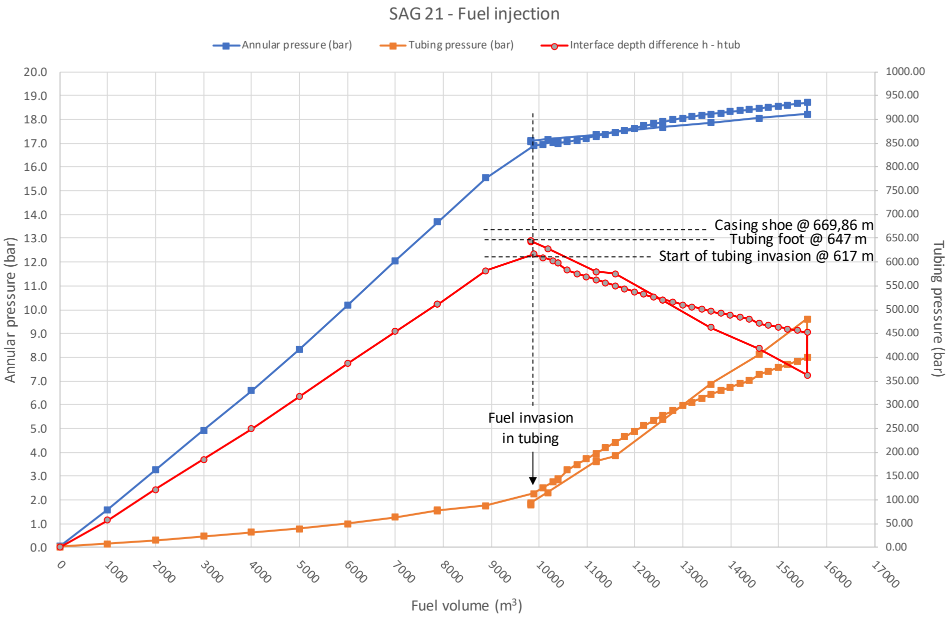

Figure 8. Invasion of fuel in tubing during mechanical integrity test on well #21

6.2 Information on the cavern compressibility

The pressurization of the cavern exerted during a FLT is an opportunity to estimate the cavern compressibility on a wide range of pressures and in conditions that may be more representative of the behavior of the cavern in the long-term (e.g. in response to brine thermal expansion) than the purge test.

Figure 9 shows the record of wellhead pressures and the cumulated volume of brine injected during the pressurization of cavern 14. The graphs show a staircase evolution with an alternation of injection periods (during daytime) and rest periods (during nights and weekends). During the rest periods a pressure relaxation is visible, probably due to the combined effect of reverse salt creep and additional dissolution of salt.

Figure 10 shows, on the left, the evolution of the annular and tubing pressures as a function of injected volume and on the right, the evolution of the cavern compressibility as calculated from the inverse of the derivate of the annular pressure vs volume relationship shown on the left. At the beginning of each injection cycle, the compressibility starts from a higher value (around 31 m^3/bar, 75 ft^3/psi), decreases to a minimum (22 m^3/bar, 53 ft^3/psi) and then rises back toward an asymptotic value (25 m^3/bar, 60 ft^3/psi). This trend repeats at each injection cycle.

This apparent non-linear elasticity of the cavern implies that the compressibility to consider for a cavern is not the same depending on the problem of interest. To support this idea, Figure 11 shows a comparison of the compressibility value deduced from the brine injection measurements with the one deduced from purges. We note that the compressibility deduced from brine injection is globally inferior, by a factor of 12% in average, to the one deduced from purges.

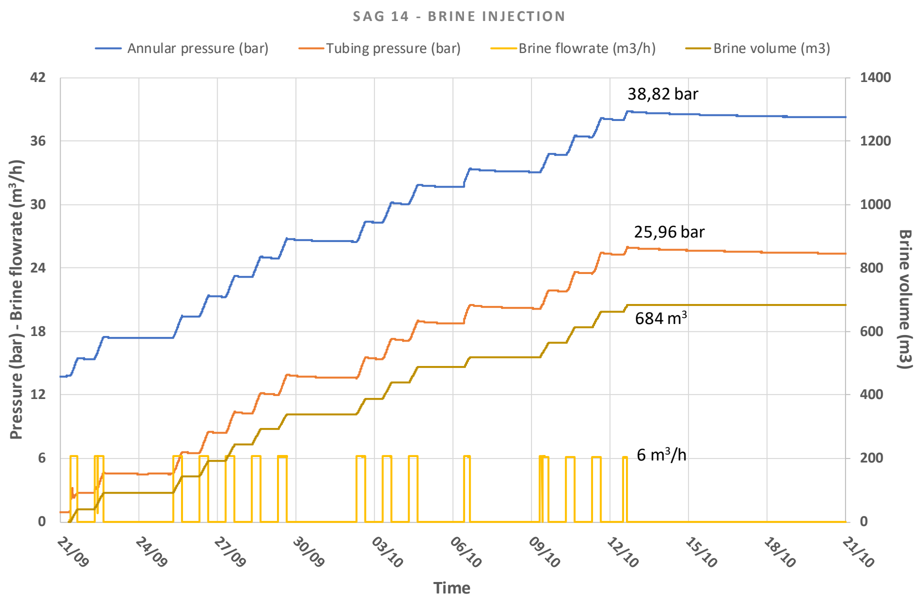

Figure 9. Example of measurements recorded during the brine injection phase - cavern 14

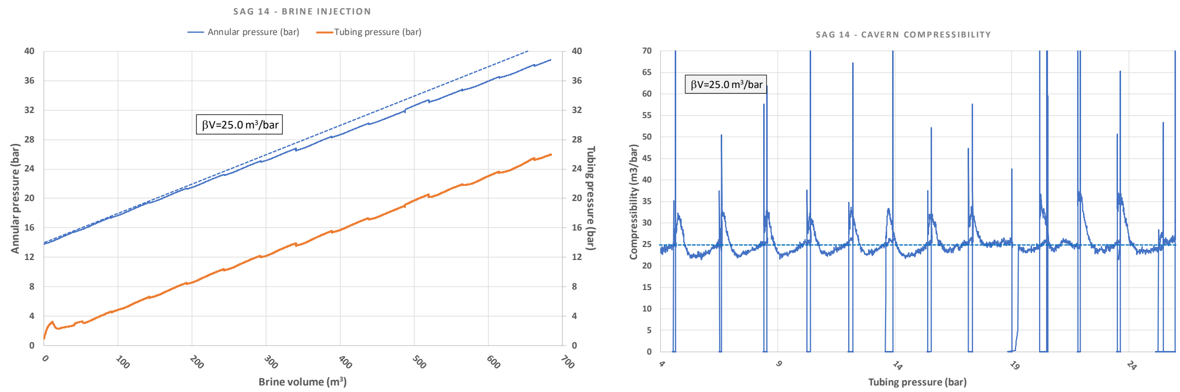

Figure 10. Determination of cavern compressibility from the brine injection data - cavern 14

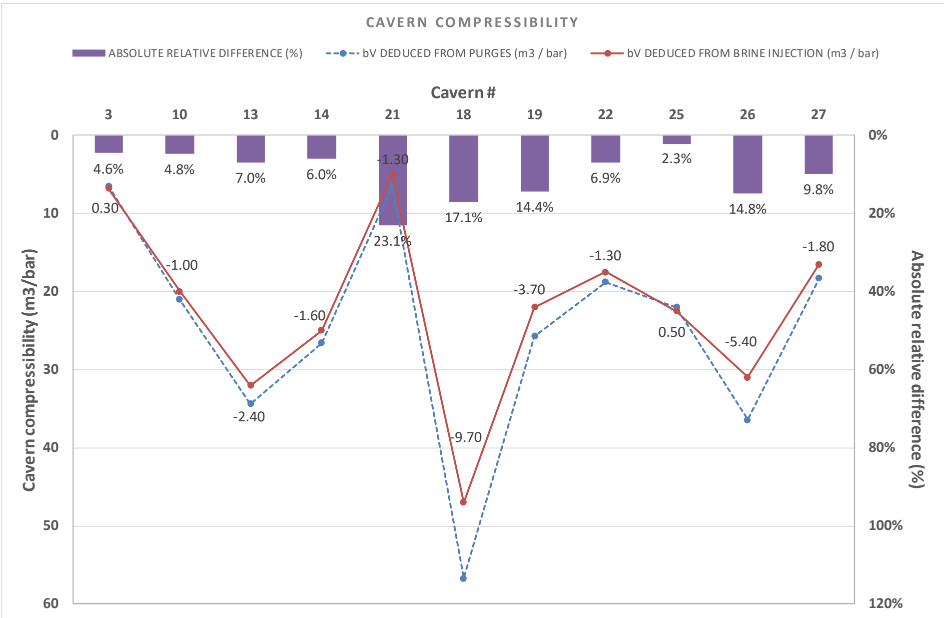

Figure 11. Comparison of cavern compressibility deduced from brine injection and from purges

6.3 Information on the long-term equilibrium pressure of caverns

The determination of the final equilibrium pressure of a cavern after plugging is fundamental for assessing its conditions of stability in the long-term. The most appropriate test for determining this pressure is the so-called abandonment test (e.g. Brouard et al., 2006). It consists in observing the wellhead pressures of a cavern for different pressure gradients and finding, by dichotomy, the pressure gradient that leads to a constant value of wellhead pressures. In the case where the cavern is not thermally equilibrated, the principle is the same but the interpretation is more delicate since the effect of brine thermal expansion on wellhead pressures has to be modelled.

A mechanical integrity test may be viewed as a partial abandonment test, corresponding to the application of a unique pressure gradient, γ_{test}. From the observation of the evolution of wellhead pressures after the application of γ_{test}, one may determine if the long-term cavern equilibrium pressure is above or below γ_{test}. The condition is that the period of observation be sufficiently long for the transient phenomena affecting the cavern during brine injection (reverse salt creep, additional dissolution of salt, etc.) no longer be effective. The characteristic time for these transient phenomena depends on various parameters but it usually varies between several days and a few weeks.

In order to estimate the characteristic time of these transient phenomena in the context of Matacães caverns, a long-duration test was conducted on cavern 18. This cavern is the largest one in Matacães (1,2 million m^3 or 42 $MMft^3$) and its production was stopped recently (2014) so it is expected that the thermal expansion of brine be very active in this cavern. As a result one should observe, after the brine injection phase, first a pressure decrease due to transient phenomena, then a pressure increase due to brine thermal expansion. The time when the wellhead pressure goes through a minimum may provide an estimation of the transient phenomena characteristic time.

Figure 12 shows the evolution of wellhead pressures on cavern 18 after applying a test pressure gradient of 1.70 bar/10m (0.75 psi/ft) at shoe depth. The expected minimum of pressures is encountered after approximately 5 days, but it takes approximately 15 days before the wellhead pressures start to increase again significantly. A waiting time of 15 days thus appears as reasonable for considering that transient phenomena are no more significantly active in the cavern.

Except well #10, all FLTs in Matacães were carried out with an observation period superior to 15 days (see Figure 5). The evolution of pressures after this delay may thus be used for assessing the long-term equilibrium pressure. If wellhead pressures are diminishing after this delay, this may indicate that the equilibrium pressure of the cavern is below the applied one. Reversely if wellhead pressures are increasing after this delay and if the cavern is thermally equilibrated, this may indicate that the equilibrium pressure of the cavern is above the applied one. If the cavern is not thermally equilibrated (see e.g. cavern 18 on Figure 12), modeling of thermal effects is necessary before being able to conclude, like in an abandonment test.

As most caverns on which a FLT has been done to date are not equilibrated (see Table 1), some modeling work would be necessary for interpreting these tests in the purpose of estimating the long-term equilibrium pressure of caverns. This work has not been done so far. The only test performed on an equilibrated cavern for which the observation period was long enough (> 15 days) is the one on cavern 3. The corresponding evolution of wellhead pressures after applying a pressure gradient of 1.70 bar/10m (0.75 psi/ft) at shoe depth is shown on Figure 13. The pressures are still decreasing after 19 days of observation, which means that the equilibrium pressure gradient at shoe is probably below 1.70 bar/10m or equivalently, that the equilibrium pressure gradient at the center of the cavern is below 1.55 bar/10m (0.68 psi/ft).

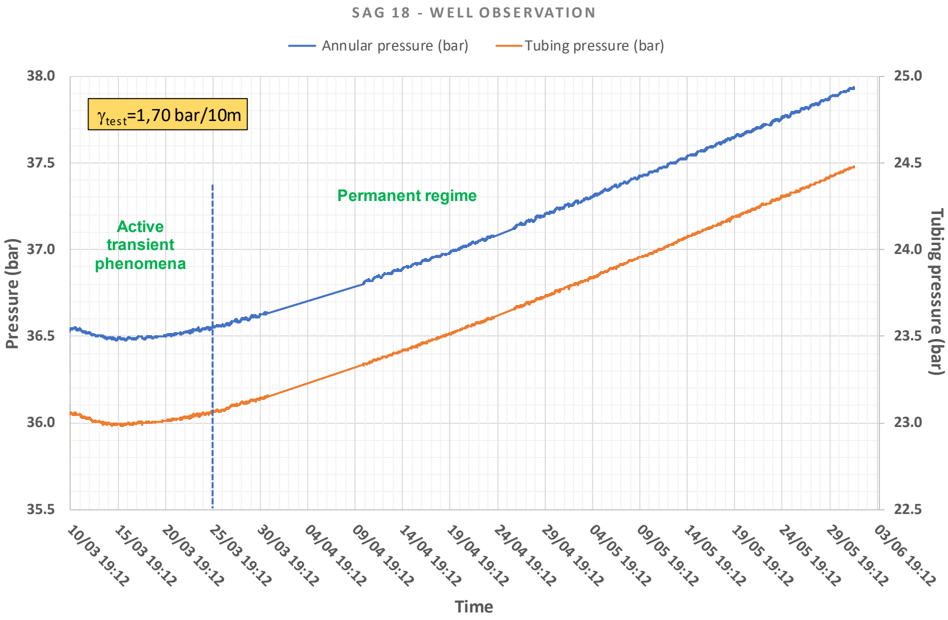

Figure 12. Evolution of wellhead pressures on cavern 18 during the observation period

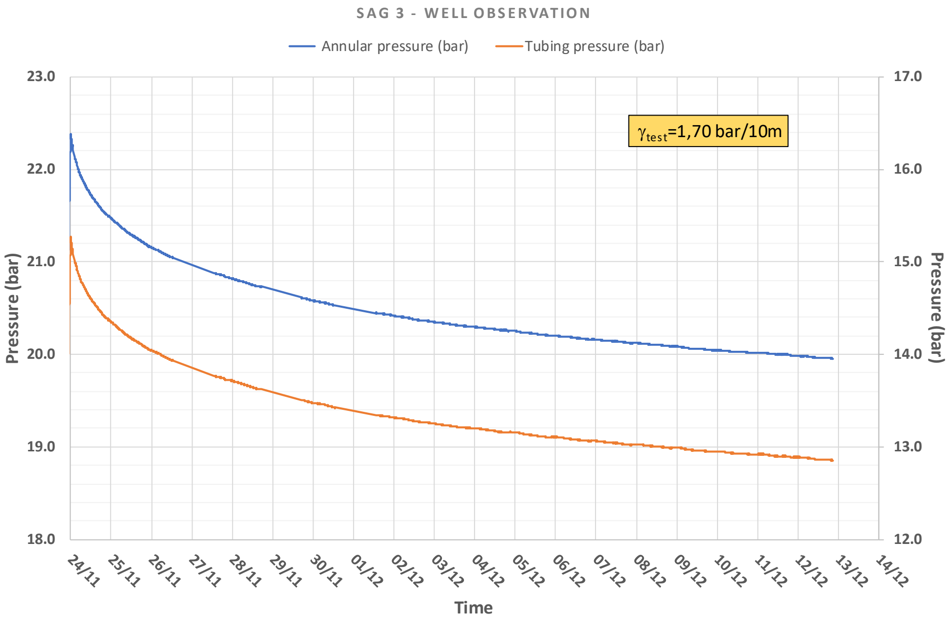

Figure 13. Evolution of wellhead pressures on cavern 3 during the observation period

6.4 Integrity of the wells

10 MITs were proceeded up to the end of the observation phase and could thus be interpreted in terms of well leak rates. The series of charts in Figure 14 represent, for each of test, the variations of the differential pressure $P_{ann} - P_{tub}$ and the fuel interface depth h (deduced from $P_{ann} - P_{tub}$ using equation (1)), during the observation phase. The pressure gradient γ_{test} applied at shoe depth is mentioned in the title of each chart. To ease comparison, all charts have the same scale in ordinate.

After a transient period of equilibration of the well, the differential pressure follows a linear trend whose slope, $\dot{P}_{ann} - \dot{P}_{tub}$, is used to infer the rate of variation of the interface depth $\dot{h}$ and the leak rate Q_{ann}, using equation (2). The numbers obtained for these variables are mentioned on the charts.

One first observation is the presence of daily oscillations of the differential pressure, which correlate well with the variations of atmospheric temperature, as shown in Figure 15. This phenomenon is wellknown and its origin has been thoroughly studied (Brouard et al., 2006). Here it is worth mentioning that the amplitude of these oscillations varies according to the wells, from almost no oscillations (well #14) to oscillations of nearly 200 mbar (well #18).

Concerning the slope of the differential pressure curve, it shows to be either zero or slightly negative for most wells (6 out of 10). The maximum negative slope observed for the differential pressure is -0.6 mbar/day (-0.0087 psi/day), which corresponds to an elevation of the brine-fuel interface in the annular of about 2.5 cm/day (1 in/day). The maximum corresponding leak rate is 3.1 L/day (0.82 gal/day) (well #13), which is two orders of magnitude under the MALR defined for this study (52 L/day). This result is very encouraging from a safety point of view. It must be noted, however, that two wells (#3 and 21) were tested only in their cased section (see section 6.1).

For the other wells (#10, 19, 22, 27), the slope of the differential pressure curve is positive, which indicates an “inverse” leak. The maximum positive slope observed for the differential pressure is +2.1 mbar/day (+0.03 psi/day), which corresponds to a descent of the brine-fuel interface in the annular of about 8.9 cm/day (1 in/day). The maximum corresponding “inverse” leak rate is 8.0 L/day (2.1 gal/day)(well #22). The most plausible origin of this phenomenon is the liberation of fuel trapped at the roof of the cavern or in local caves during the first “sweep” of the openhole by the fuel interface. It is noticeable that the wells which are the most concerned by this “inverse” leak are the ones whose borehole geometry is the less regular (presence of caves) or for which several operations of injection and removal of fuel had to be done before finding the optimal interface depth. Even if this phenomenon is not desirable and hinders the possibility to detect very small leaks, it is not sufficiently important to hide significant leaks so it does not question the tightness of the concerned wells.

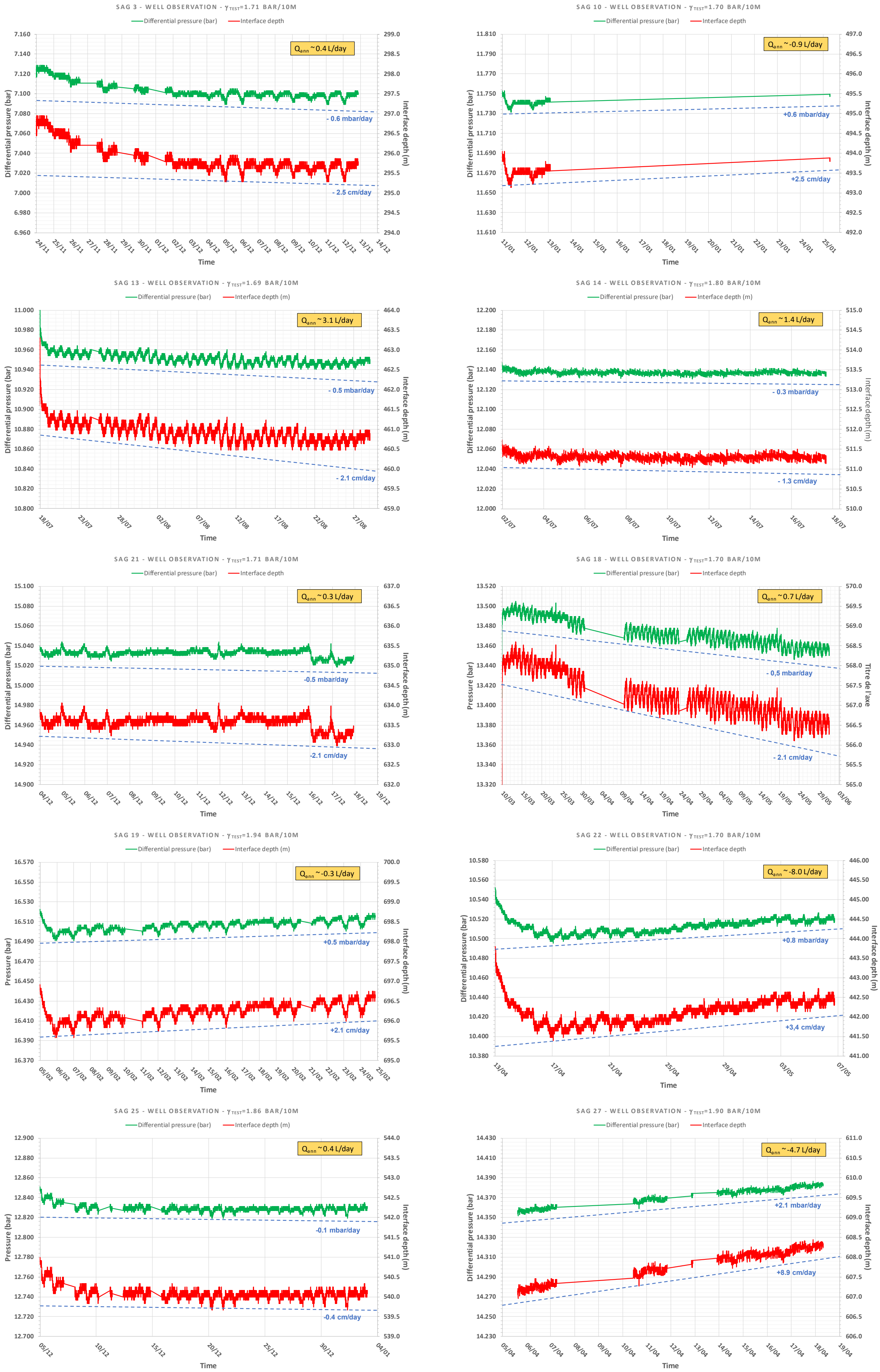

Figure 14. Evolution of wellhead pressures and interface depth during the observation periods

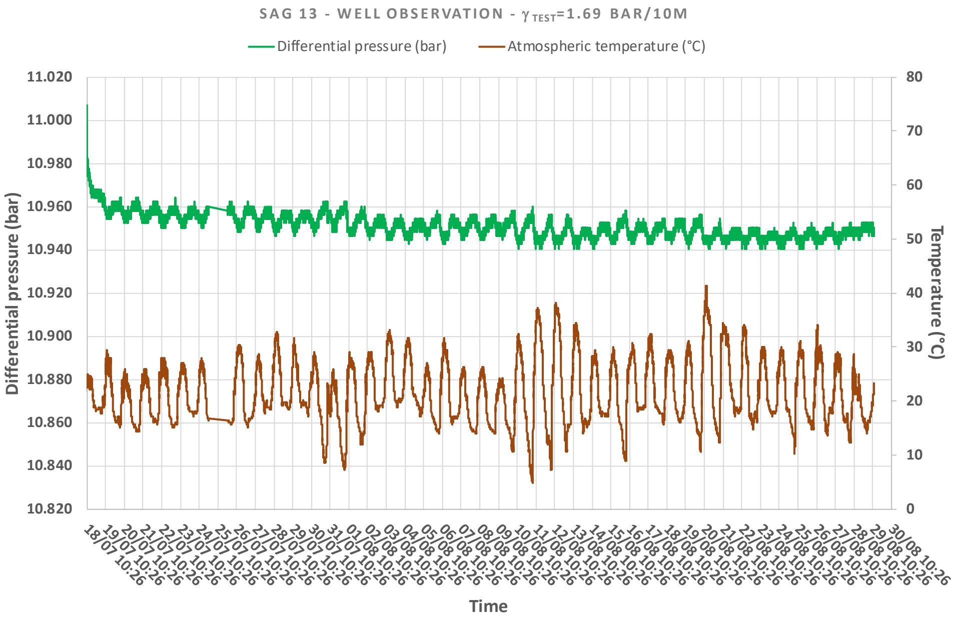

Figure 15. Correlation of the differential pressure oscillations with external temperature – cavern 13

7. Conclusion

An ambitious program of fuel-oil mechanical integrity tests is being implemented in a salt mining concession in Portugal. The test procedure was designed with the objective to remain simple and adapted to industrial constraints. Except for the first test, no specialists are present on site. The tests are monitored at distance and oriented in near-real time thanks to a web monitoring system and a close collaboration between the local staff, the Solvay headquarters in Brussels and Ineris consultants in France.

Out of the 11 tests performed so far, 10 were conclusive and demonstrated the integrity of the wells (maximum leak rate of 3.1 L/day, 0.82 gal/day) at pressure gradients varying from 1.69 to 1.94 bar/10 m (0.75 to 0.86 psi/ft) at shoe depth. Eight tests were conducted with a fuel interface below the casing shoe while the two others only tested the tightness of the cemented casing.

These first results are encouraging from a safety perspective and show that the integrity of salt production wells may still be ensured up to 60 years after their drilling, despite a highly corrosive environment and very little maintenance on the wells since the end of their activity.

Beside characterizing the well tightness, the FLT was shown to provide valuable information on the well geometry. The depth and the inner diameter of the casing could be determined (or confirmed) with a precision better than 1% using this method. Unexpected geometries were detected for some wells: enlarged diameter of the openhole, presence of caves or chimneys, uncontrolled leaching around the cemented casing, openhole diameter inferior to one expected, errors in the tubing depth, etc...

The brine injection phase could also be valued for estimating the cavern compressibility on a wide range of pressures and in conditions that may be more representative of the behavior of the cavern in the long-term than other methods. The compressibility estimated from brine injection measurements was shown to be 12% inferior in average to the one deduced from purges.

Lastly the mechanical integrity test may be used as a partial abandonment test, i.e. a way to estimate the long-term equilibrium pressure of a cavern from the observation of absolute wellhead pressures. This needs to observe the well on a time period longer than the characteristic time for the transient phenomena affecting the cavern after brine injection (reverse salt creep, additional dissolution of salt) to vanish. In Matacães, this delay was estimated to be around 15 days, thanks to the conduction of an exceptionally long test where the well pressures were observed during almost 3 months.

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