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Technical Conference Paper

Sounds Well System: Non-intrusive Monitoring of Leaching

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Sounds Well System:

Non-intrusive Leaching Monitoring

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Abstract

There are currently several systems available on the market for continuous blanket-level measurement, but all are intrusive — i.e., something has to be set up downhole to obtain the measurement. The first non-intrusive blanket measurement system was installed at Bad Ischl, Austria, in June 2016. This system, *Sounds Well*™, allows real-time measurement of cavern-roof and cavern-bottom depths along the well axis, as well as remote monitoring of all other leaching parameters.

Key words: leaching, well logging, instrumentation and monitoring, computer modeling/software, level monitoring, blanket control, depression wave, gas dynamics, remote control

1. Background — Blanket Measurement in Austria

Blanket-level measurement

There are currently several systems on the market for continuous blanket-level measurement. Some systems work on the capacitance principle and use a rod-shaped tool (Hasselkus et al., 2005). Others utilize conductivity and use a ring-shaped tool. Both methods involve the transmission of an electric signal from a cable into the blanket annulus (Saalbach, 1997). Systems using optic fibers have been introduced recently (Grosswig and Vogel, 2015). All these systems are intrusive and may need a maintenance workover from time to time.

Mining at Bad Ischl

Austrian salt has a high content of insolubles, of the order of 30 to 50%, and the height of caverns mined by Salinen Austria in Bad Ischl ranges normally between 5 to 20 m (15-60 ft). The solution process precludes leaching in large vertical steps (Gaisbauer, 2000). Wide thin slices of salt are mined slowly at the cavern roof. The maximal upward displacement rate of the cavern roof is about 2 cm per day (1 in/day). The leaching process includes raising the diesel-blanket level in relatively short intervals of one to several days. Therefore, precise control of the blanket level is essential in the process.

From 1971 to 1991, wellhead pressures were used to estimate the blanket level, but this technique was not very accurate (Figure 1), especially because of large variations of frictional forces in the production string depending on gypseous deposits (unstable pressure drop). From 1991 to 1994, a tool based on electric conductivity was implemented in several wells. This system was effective, but it was necessary to raise the pipe string in relatively short intervals to follow the rise of the blanket level (Gaisbauer, 2000).

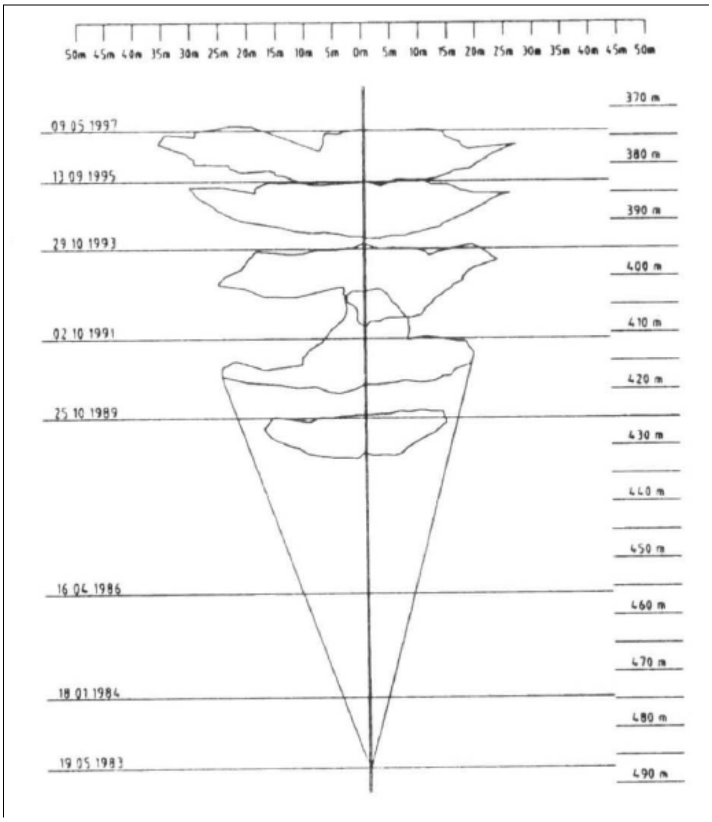

Figure 1 – Cavern history with an ineffective sump leaching phase before 1991 (after Gaisbauer, 2000).

In 1994, another system was introduced that consists of a measuring rod with 16 contact rings attached to the outer production string. This system works properly on many wells, but it gives odd results on others. In some cases, it is suspected that wires may have been damaged during workovers.

In 2013, a testing campaign of a new type of the tool for non-intrusive level monitoring was organized at Bad Ischl with Brouard Consulting. The testing results were promising, and Salinen Austria supported the development of an industrial prototype.

In 2016 the system Sounds Well™ was installed on one of the wells to monitor permanently the well integrity and to measure cavern roof and bottom levels without interruption of active leaching flow.

2. *Sounds Well*

Pressure pulse and other periodic phenomena observed at the wellheads of salt caverns have been analyzed for a long time (Bérest et al. 1996, 1999). It has been demonstrated that useful information related to the wellbore and/or the cavern can be obtained by analyzing the dynamic pressure signals. More recently, new tools have been designed and tested for level monitoring or damaged-casing detection (Brouard et al., 2012ab). Brouard Consulting, with support of Ecole Polytechnique, first developed a prototype called *Sounds Good*. This first system was designed for spot measurement as an alternative to a relatively expensive logging operation when checking inner-string integrity (Brouard et al., 2012a) or for blanket-level measurement during leaching (Brouard et al., 2012b). The next generation of *Sounds Good,* dedicated to underground storage, is called *Sounds Well*™.

Sounds Well is a comprehensive data-acquisition and dynamic pressure-analysis system that includes a manifold, including electrovalves to trigger the depression wave, very sensitive pressure sensors, a high-frequency data acquisition system and a user-friendly software program to analyze and report the data. *Sounds Well* is a connected object in the sense that it can be monitored remotely, provided that a GSM 3G or 4G network is available on site. Much more than a level-measurement

system, *Sounds Well* is a tool that incorporates 20+ years of expertise in the field of underground storage in salt caverns, especially in integrity testing and pressure dynamics.
Application configurations are numerous and not identified fully:

- air/nitrogen/diesel blanket monitoring during cavern leaching,
- nitrogen/brine interface during MITs,
- light liquid/brine interface during LLTs (Van Sambeek et al., 2005),
- gas/liquid level monitoring in annuli (works in narrow/large and shallow/deep interface), and
- detection of damaged strings

Sounds Well has several significant advantages compared to other logging tools. These include the following:

Non-intrusive: The system can be easily and quickly plugged at the wellhead.

Non-interruptive: Measurement in the outer annulus can be made while there is an active flow in the inner spaces. There is no need to stop or even reduce production.

Intrinsically safe: The wellhead is kept closed; there is no need for any risky workover. Furthermore, an explosive-proof certified version of the system is available for hazardous areas (e.g., natural gas).

Quick set-up: The system has been designed to be Plug & Play and can be installed very easily.

Quick measurement: The measurement results are given within minutes locally at the wellhead and also remotely, when the system is connected to Internet.

Permanent monitoring is possible: The system can monitor continuously and without intervention for days, weeks, months etc.

Low power consumption: The power supply can be an electric outlet or a solar panel. The system also embeds a battery in case of a power cut.

Remote control: When a GSM network is available, the system can be controlled remotely, and data are displayed almost **at real time** on a very secure virtual machine in the Azure Cloud. (The synchronization delay at Bad Ischl is 30 minutes, adjustable). It allows 24/7 alarm triggering through email and/or SMS when a problem is detected.

Deep wells: There are no limitations related to depth, contrary to other intrusive tools.

Shallow interface: Levels less than 10 m (30 ft) in protecting annuli are measurable.

Deviated wellbores: The wellbore may be highly deviated — or even horizontal in some parts.

Much more than a simple measurement tool: *Sounds Well* software integrates data from other management tools, providing comprehensive management environment that can collect various data and measurements related to multiple wells.

Cost effective: The costs are reduced because no workover is required for set-up or maintenance. The required number of wireline loggings for blanket/roof control can be reduced. Rental programs are possible, reducing the initial investment. *Sounds Well* was designed mainly as a long-term or even permanent monitoring system, but it also can be used for spot measurements — for example, during an MIT or control of the protection annulus of a gas cavern. The system does not limit the using of other common measurement techniques; it can operate both as exclusive monitoring tool and as in addition to traditional approaches.

3. Cavern Monitoring System

A version of the *Sounds Well* system has been designed for cavern displacement monitoring in a configuration with diesel blanket. This system is shown in Photo 1; it is composed of a manifold (44 × 32 × 12 cm, 17 × 13 × 5 in) to be plugged to the diesel annulus at the wellhead, and a data acquisition system (DAQ) in a box (52× 43 × 20 cm, 21 × 13 × 8 in).

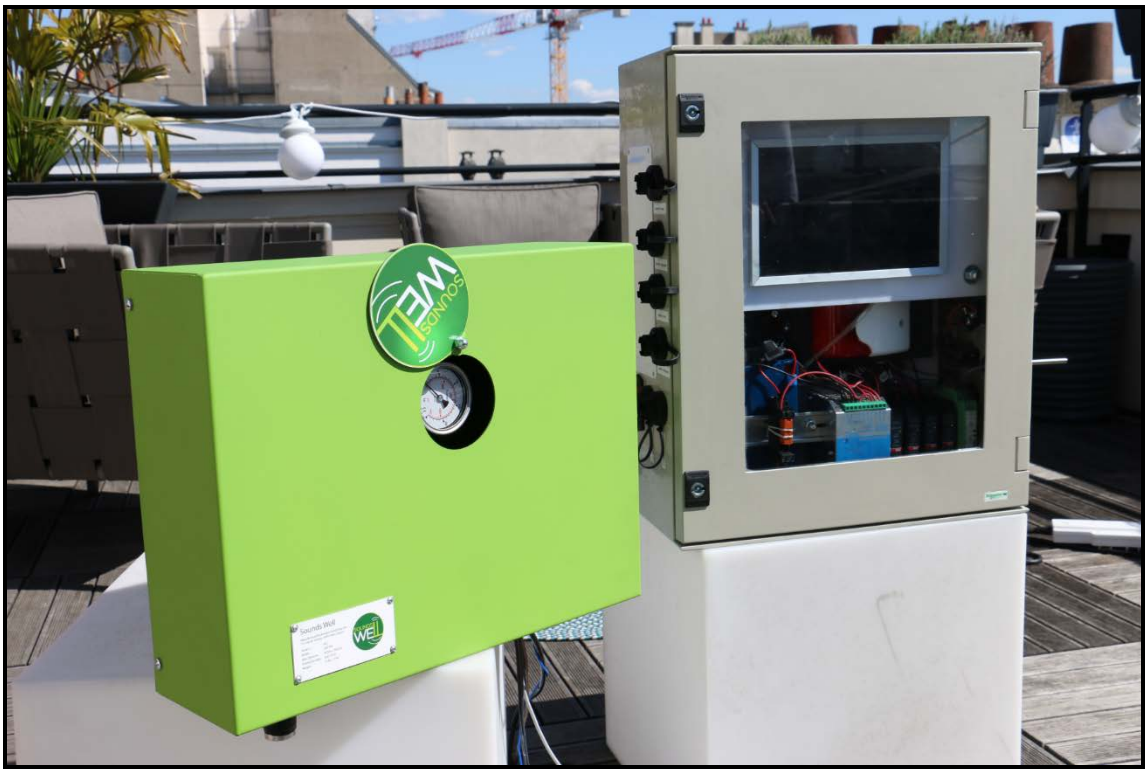

Photo 1 – The *Sounds Well* system designed for blanket monitoring: a manifold to be plugged to the wellhead (green box on the left) and a data acquisition box (right).

The testing configuration at Bad Ischl is quite challenging, as the leaching process implies a slow vertical displacement of the cavern that must be monitor carefully to optimize salt production.

The system periodically triggers series of disturbance pulses by means of the withdrawal of few tenths of a liter of diesel (less than 10 fl oz). The signals are analyzed quickly on an embedded mini-pc and displayed locally on a screen. The system also records other static data: brine pressure, water pressure, diesel pressure, water and brine flowrates, diesel temperature in the manifold, atmospheric pressure, and temperature. It also records data relative to the DAQ itself, such as electronic-card temperature and available memory for data storage to ensure proper functioning on the long term. Pulse generation and data acquisition are automated and can be easily tuned remotely. An industrial prototype is installed at Bad Ischl since mid-June 2016.

The DAQ is connected to the Internet through a 3G/4G mobile network (Figure 2). Acquired data are strongly compressed and encrypted before being synchronized with a dedicated server in Microsoft's[1] Azure Cloud. This remote data storage is extremely secure; it also enables deep mathematical and statistical data analysis in the Cloud and real-time reporting to granted users worldwide. In case any unexpected event is detected, the *Sounds Well* software program, running 24/7, is able to send alarms automatically through SMS and/or emails.

Photo 2 shows the system as it is situated in the cabin well at Bad Ischl. The whole system was installed within a couple of hours.

[1] Microsoft is a partner of the *Sounds Well* project through its BizSpark program for startups.

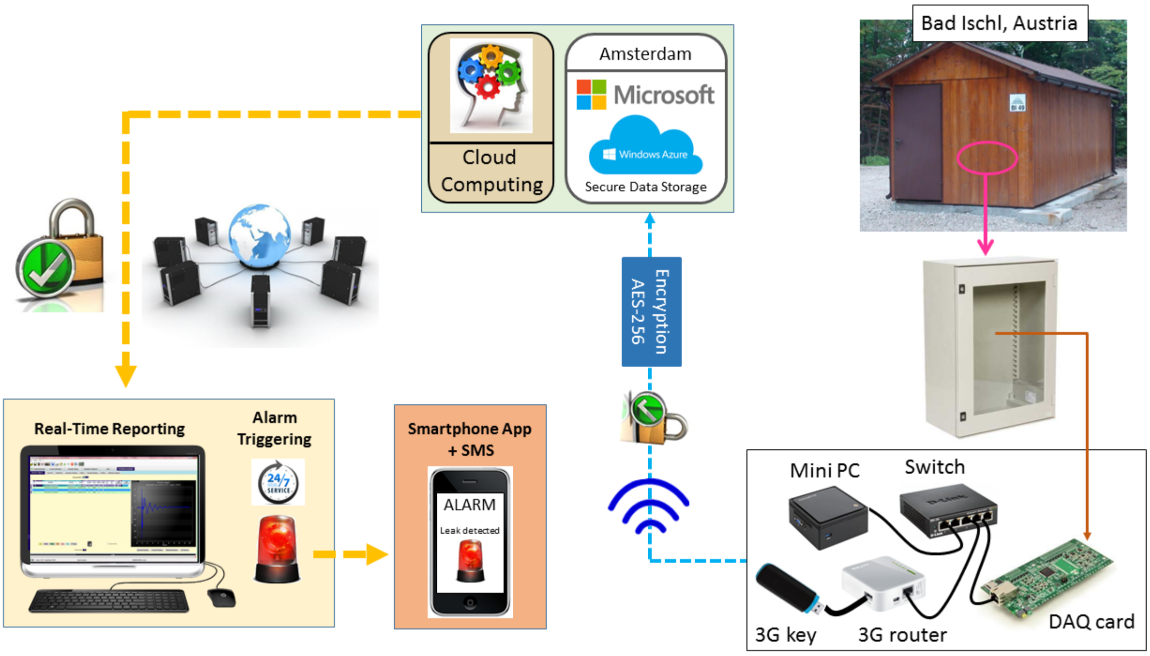

Figure 2 – Data acquisition system.

Data available locally on the field

Figure 3 shows the display of the screen in the data acquisition box.

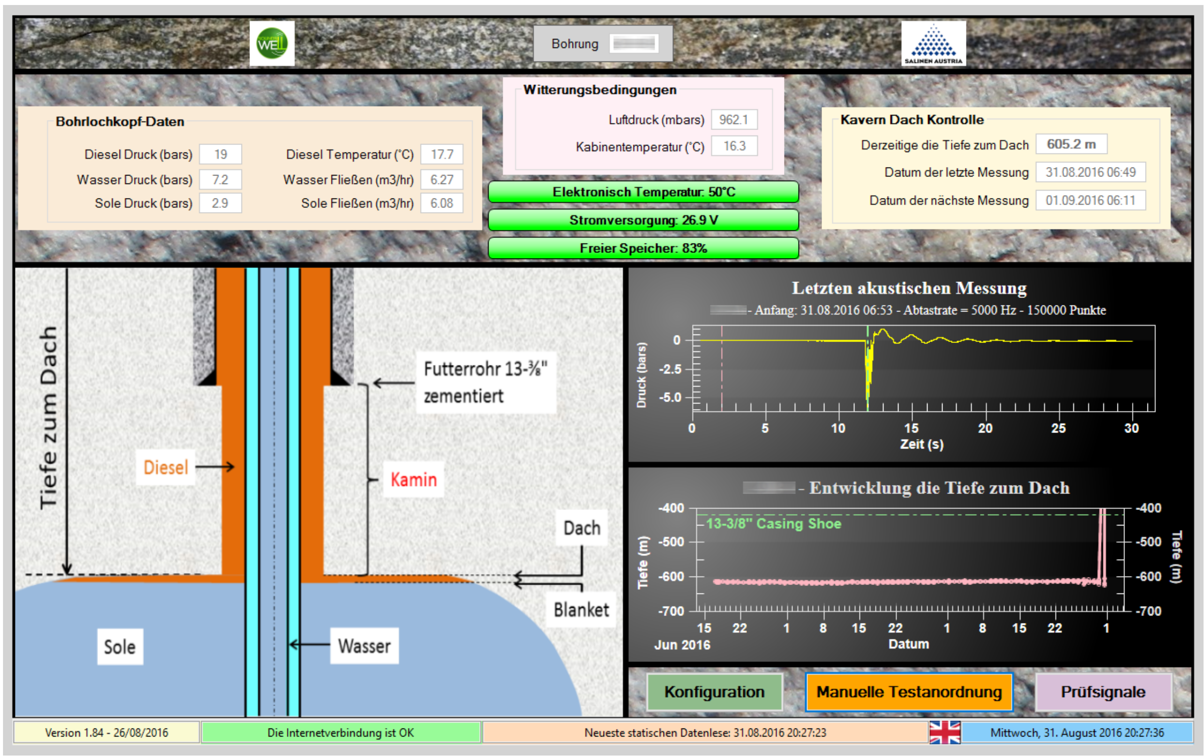

Figure 3 – Display available on the DAQ screen at wellhead.

Photo 2 - System installed on the well at Bad Ischl.

Data available remotely

Figure 4 to Figure 11 show screenshots of the software program available in the cloud. Figure 4 shows the first tab, which embeds a fully interactive Google map, giving an overview of the facility.

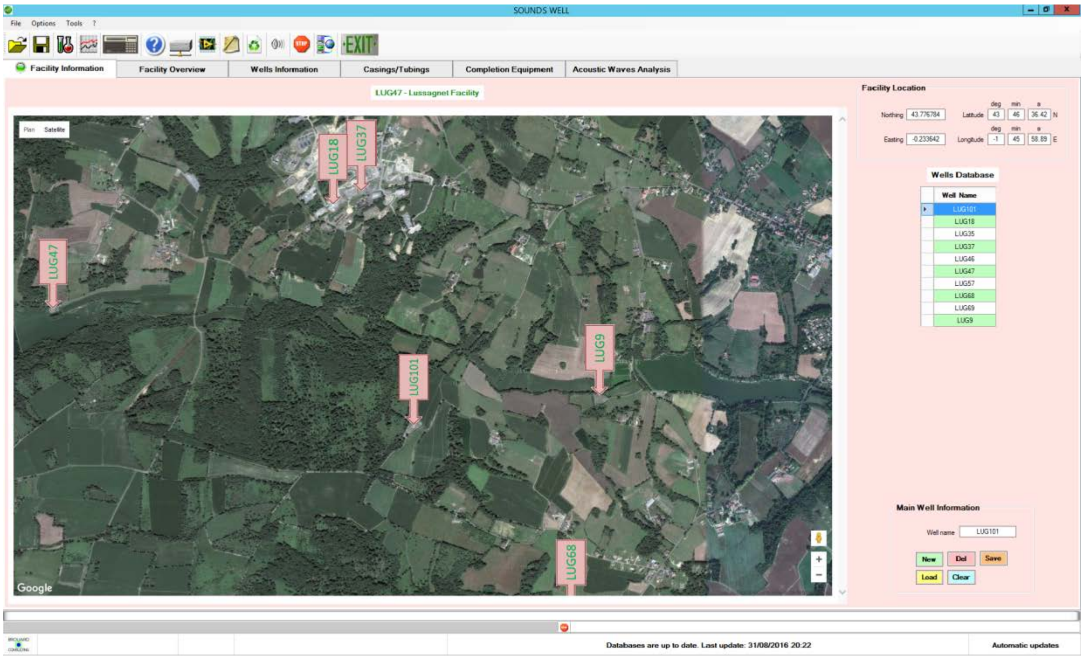

Figure 4 – *Sounds Well* — Interactive Google map embedded in the software.

In addition to static and dynamic data, a very comprehensive set of information about the facility and the wells can be archived in the software program. For each well, it includes, for instance, location, completion, trajectory, pressure/flowrate/temperature histories, loggings history, sonar surveys, pictures etc. Figure 5 to Figure 7 respectively show tabs displaying well location, a picture viewer, a casings/tubing database, and wellbore completion that can be built from an embedded casings database. Wells tabs are automatically generated allowing easy adding or removal of wells. The system can work with several facilities and dozens of wells simultaneously.

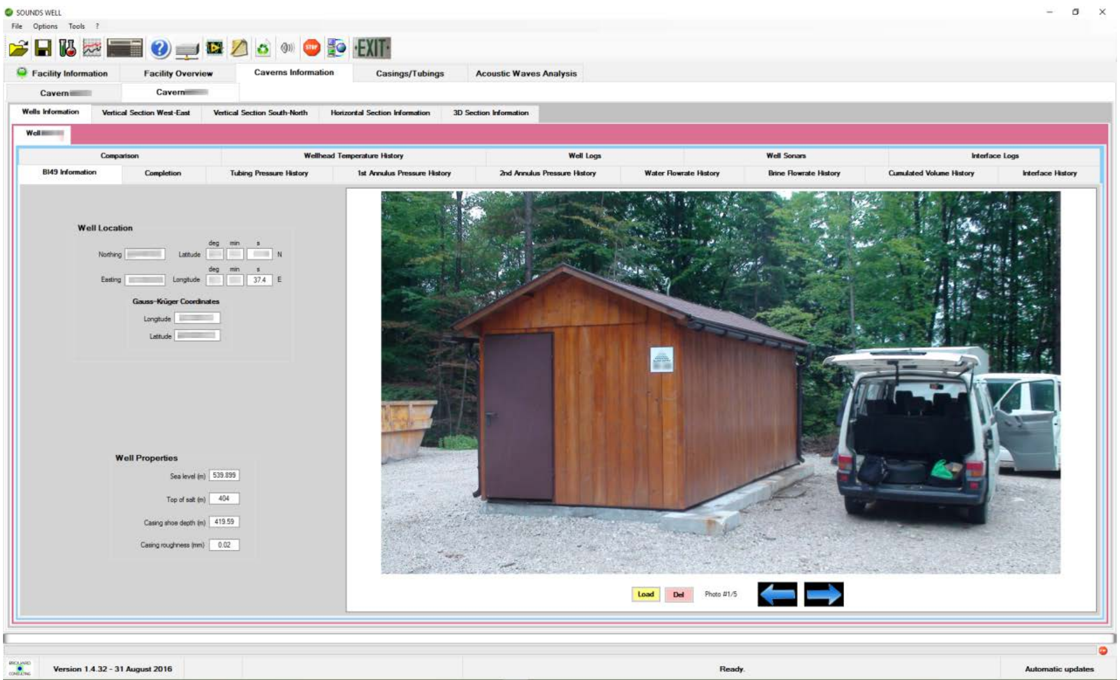

Figure 5 – *Sounds Well* — Well characteristics. (A comprehensive set of information can be saved in the software program.)

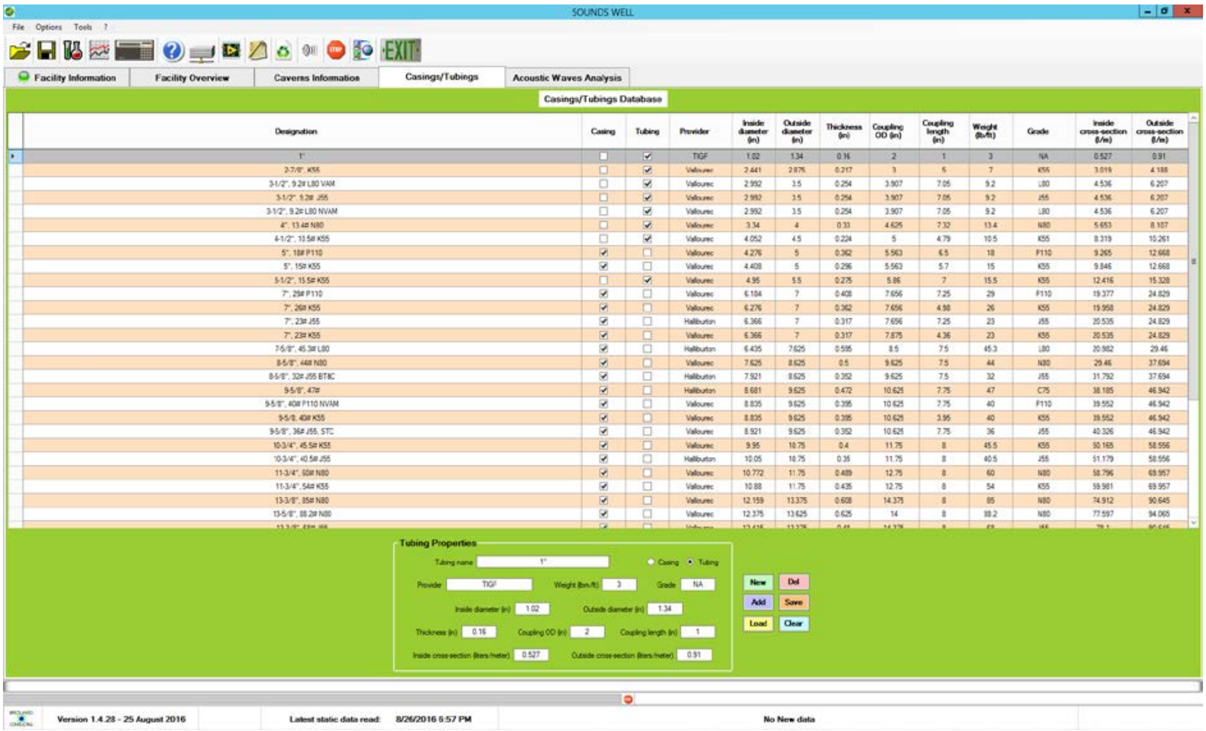

Figure 6 - *Sounds Well* — Casings/Tubings database.

Figure 7 – *Sounds Well* — Well completion.

Figure 8 shows the database of all the dynamic signals that have been recorded by end of August, including a plot of the selected pressure signal. During the initial testing period, from June to August 2016, a series of 10 successive pulses at a sampling rate of 2 to 5 kHz were triggered each day. In addition, whenever necessary, the system is able to record signals over several seconds at a sampling rate up to 100 kHz.

At this time, in a diesel/brine configuration such as at Bad Ischl, the system mainly is able to monitor the depth of the cavern roof. Acoustic monitoring of the diesel/brine interface is much more challenging, as the contrast of acoustic impedance between diesel and brine is relatively small. Nevertheless, this situation enables the measurement of the cavern bottom level along the well axis. The diesel/brine interface is estimated by the software based on wellhead pressures and flowrates. At Bad Ischl there is no mean to calculate mass balance as no density and temperature are available for water and brine yet. These additional data will be very useful to drastically improve the accuracy and deliverables of the system.

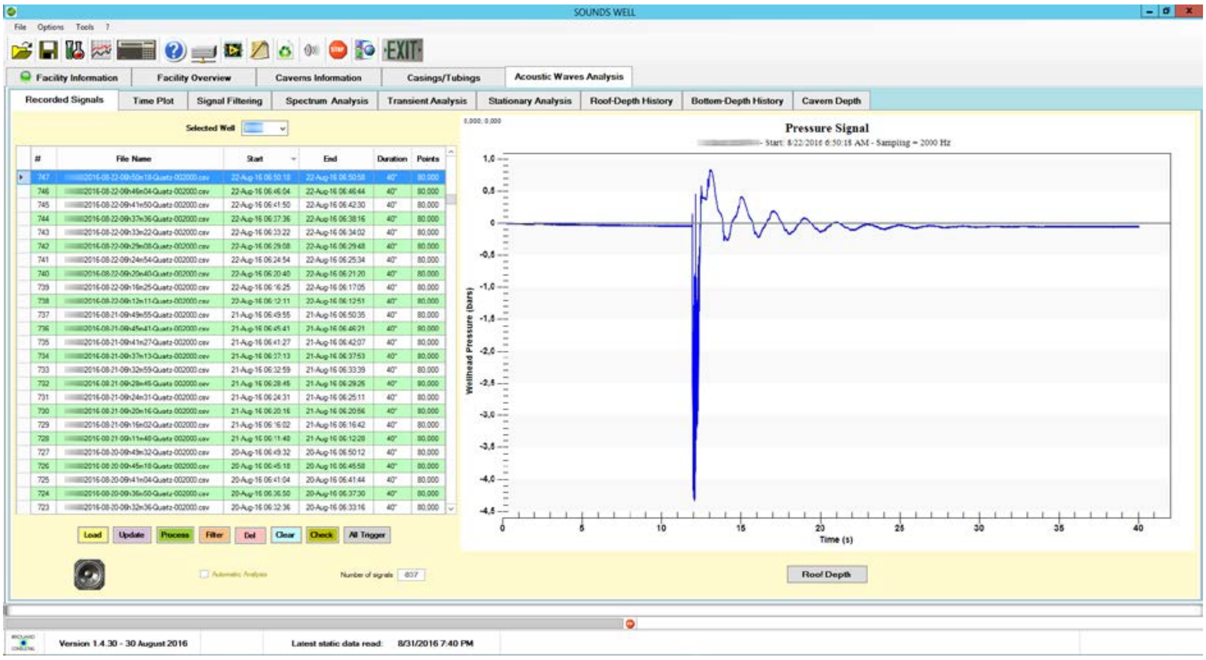

Figure 8 – *Sounds Well* — Database of all acoustic signals recorded.

Figure 9 shows the computed evolution of cavern-roof (openhole bottom) and cavern-bottom evolutions as displayed on the virtual machine available in the Cloud (the system was not calibrated yet to display proper absolute values, so a constant offset is likely).

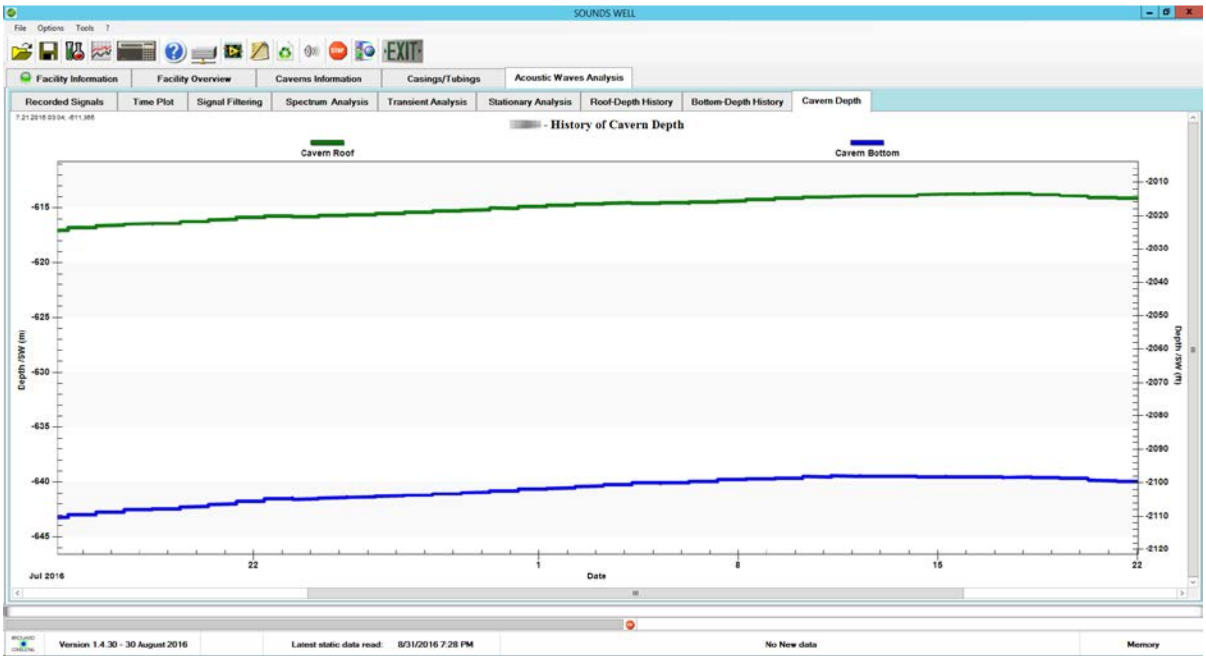

Figure 9 – *Sounds Well* — Evolutions of cavern roof and bottom depth.

Figure 10 shows the computed evolution of the cavern roof (openhole bottom) as measured during the July to August period.

Figure 10 – *Sounds Well* — Evolution of cavern-roof (openhole bottom) depth.

Because the height of the caverns at Bad Ischl is relatively small (Figure 1), it is also possible to monitor cavern bottom (Figure 11).

Figure 11 – *Sounds Well* — Evolution of cavern-bottom depth.

4. Acquired Static Data

Evolutions of static data as measured from June 15 to August 21, 2016 are shown in Figure 12 and Figure 13. As a stress test, data were recorded every 10 seconds — i.e., 600,000 data points for each sensor over this 2-month period. The whole system worked perfectly without any interruption, demonstrating that the system can work for years on a slower rate.

The so-called "water pressure" is changing over time, because it was not soft water that was pumped in, but under-saturated brine coming from the well nearby, complicating the data analysis. The density of this under-saturated brine was changing over time depending on operations performed on this other well. Note that the system also can record water/brine temperatures and/or densities from existing sensors; however, these were not yet available at Bad Ischl.

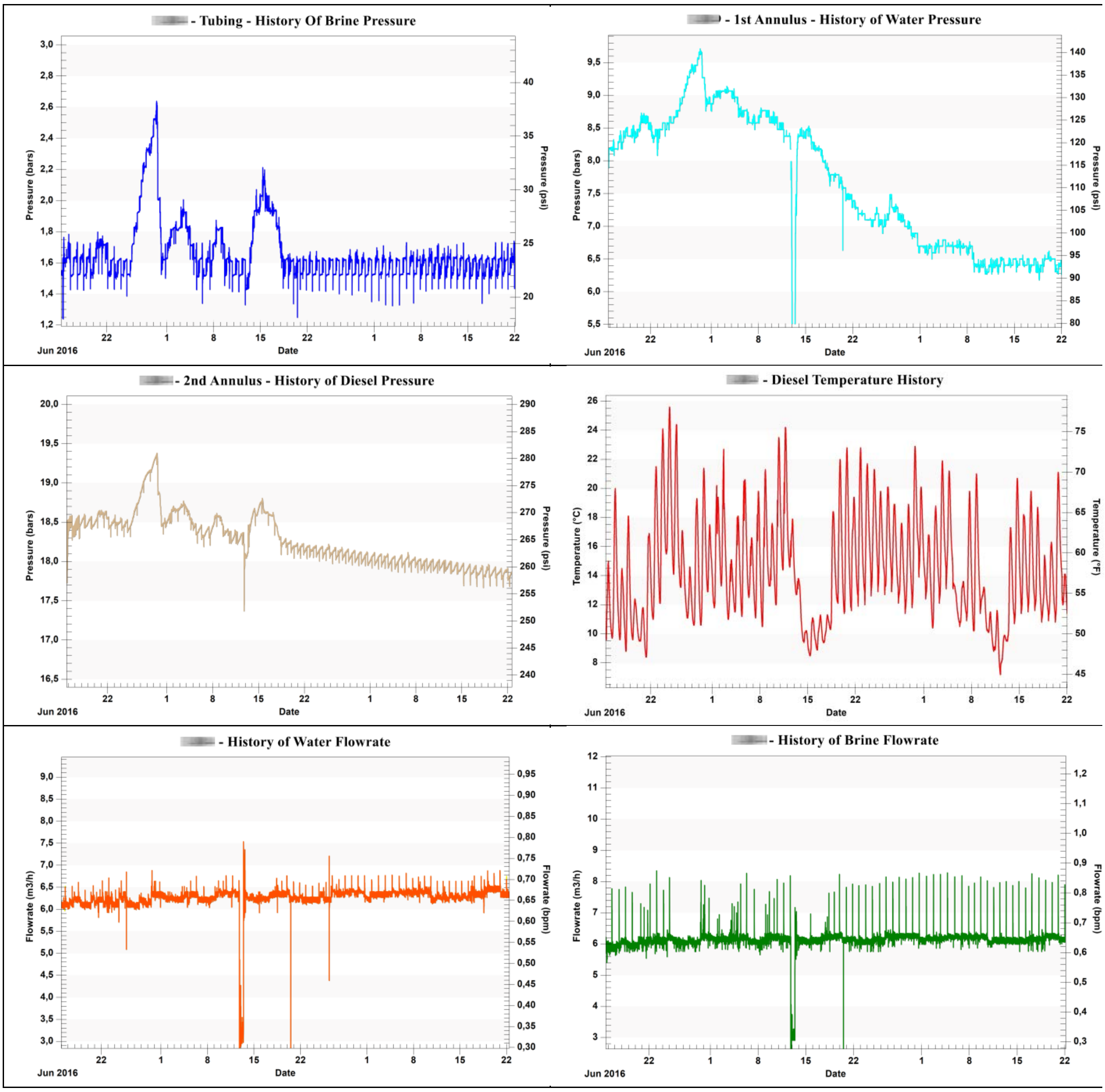

Figure 12 – Data recorded at the wellhead: brine pressure (top left), water pressure (top right), diesel pressure (middle left), diesel temperature (middle right), water flowrate (bottom left), and brine flowrate (bottom right).

Figure 13 shows the other data measured by the system, which helps provide better control of the whole system. Atmospheric pressure variations, for instance, may have a significant effect on interface displacements in gas/brine-blanket systems, but much less on liquid-filled wells (Brouard et al., 2010). The power-supply plot shows that there were two power cuts due to heavy storms during the monitoring period, but the battery ensured measurement to continue.

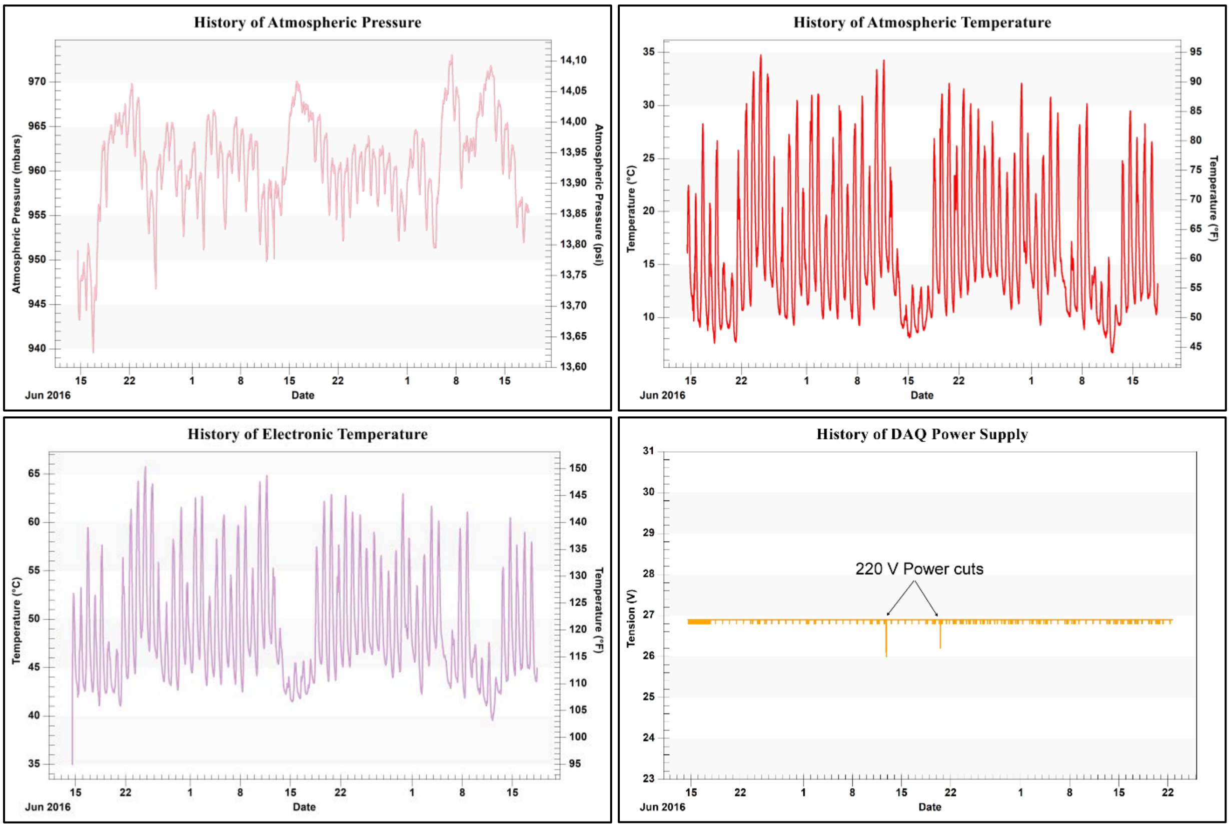

Figure 13 – Other data measured by the system: atmospheric pressure (top left), atmospheric temperature (top right), temperature of data acquisition card (bottom left), and power supply voltage (bottom right).

From mid-June until mid-August 2016, 800+ disturbance pulses were triggered by a small diesel withdrawal, and the corresponding number of dynamic pressure signals were recorded (see an example of signal in Figure 14). During this period, the *Sounds Well* DAQ was tweaked to optimize the parameters of pulse generation in diesel. Adjustments on pulse series, acquisition frequency and data logging were performed and refined.

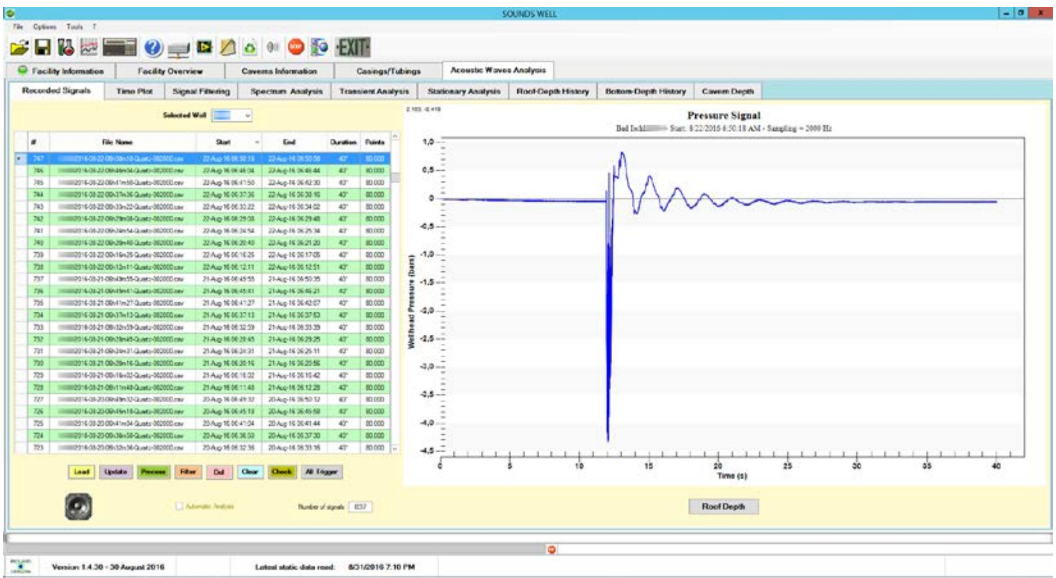

Figure 14 - Example of dynamic pressure signal registered in August 2016.

5. Analysis Results

A complex analysis

The *Sounds Well* system developed for diesel/brine monitoring records high-frequency dynamic pressure variations besides controlling static parameters in the inner tubing and annuli. Enhanced analysis of this signal allows estimation of the condition of the well, evaluation of the location of the cavern roof and bottom with reasonable accuracy, and extraction of additional information for further modeling.

Fast pressure variations are triggered by depression pulses that are produced automatically following defined sequences and at given frequency. In order to guarantee the fulfilment of general requirements to disturbance-pulse generation, special type of electrovalves is used, along with a dedicated electronic management system. This last one is essential for pulse optimization and good reproducibility between the series of pulses. The depression-pulse generation and pulse structure itself, which can be represented as a wave packet of multiple waves of various frequency and intensity, depends strongly on characteristics of the wellhead and, in particular, diesel properties. A wave packet arising from the wellhead propagates in the annulus with the speed of sound, which may vary in a large-scale and a complex manner with diesel pressure, temperature, composition, dissolved gas, and the occurrence of gas bubbles, strings and borehole stiffness, etc.

Evolution of the temperature in the wellbore also is a relatively complex topic, but modeling is possible providing that the inlet and outlet temperatures of the water and brine are available (Manivannan et al., 2015). The influence of only some of these factors was studied before, but only for few well-known diesel types. Diesel fuel used in Bad Ischl salt-production wells is not very common, and its properties evolve with time; thus, it should be considered largely as an “unknown” media. The analysis gets even more complex when the annulus is filled partially with brine, as it adds additional uncertainty in the wave-transport process.

The complexity faced in monitoring cavern mining that uses diesel blanket points toward using extended techniques of data computing, including complex mathematical methods, numerical and statistical analysis. This should go together with precisely controlled hydraulic components of the system in order to get the required accuracy of the measurement. This implies several calibration procedures, and accumulation of sufficient data is essential for efficient statistical analysis. The data acquired during this period will reduce drastically the learning phase in future installations of Sounds Well system.

System initial test - Diesel withdrawal on June 15

Sounds Well is designed to be installed easily and quickly on the wellhead following the Plug & Play principle. After the first security and functionality tests were executed, some quick stress tests also were performed: the system was operated for several hours with intensive pulse triggering and in high-frequency acquisition mode.

After this initial phase, a first calibration operation was conducted through diesel withdrawal. To optimize the opening sequences of electrovalves and to study propagation of the depression pulse in diesel at various pressures and temperatures, a significant amount of diesel was withdrawn from the annulus on June 15. The procedure consisted of six successive diesel withdrawals, 2 m^3 each, and the subsequent triggering of several pulses. Withdrawal of each 2 m^3 of diesel resulted in diesel-pressure decrease, temperature increase, and an upward displacement of the diesel/brine interface by approximately 20 m in the borehole (see Figure 15).

Both pressure, temperature and blanket level influence frequencies in recorded signals. The fundamental frequency decreases with pressure and temperature while the diesel/brine-interface level raises. Moreover, high damping of the disturbance pulse in its propagation through the diesel column does not allow a standing wave to develop. Thus, it is irrelevant, in this case, to consider a stationary analysis of the signals to determine cavern-roof depth. A more complex analytic approach is essential.

Continuous automated monitoring – Learning phase

Since the initial tests performed in June 2016, the *Sounds Well* system has been operating a fully automated monitoring of the well in learning mode. The monitoring sequence included 10 daily pulses automatically triggered by the system. In parallel, all static data were recorded every 10 seconds with an automated synchronization with the server in the Azure Cloud.

Preliminary analysis of the data acquired during the initial tests and during a 2-month learning period allows a relatively rough estimation of the cavern-roof and cavern-bottom levels (see Figure 9). The estimated accuracy of calculated depths at that time is of the order of 2 to 2.5 m (6 to 8 ft). The system has not been calibrated through a sonar survey yet; thus, a constant offset may be observed in level evolution. Because roof and bottom velocities are very slow, it is known from sonar surveys that they are of the order of 0.5 to 1 m/month (1.5 to 3 ft/month), the period of data acquisition needed for an efficient statistical analysis of this first ever tested well should take several months. Application of statistical methods and mathematical modeling when analyzing static and dynamic data will allow a significant improvement on measurement accuracy; it will be possible to obtain the cavern roof (openhole bottom) level measurement accuracy of a few decimeters or less in diesel.

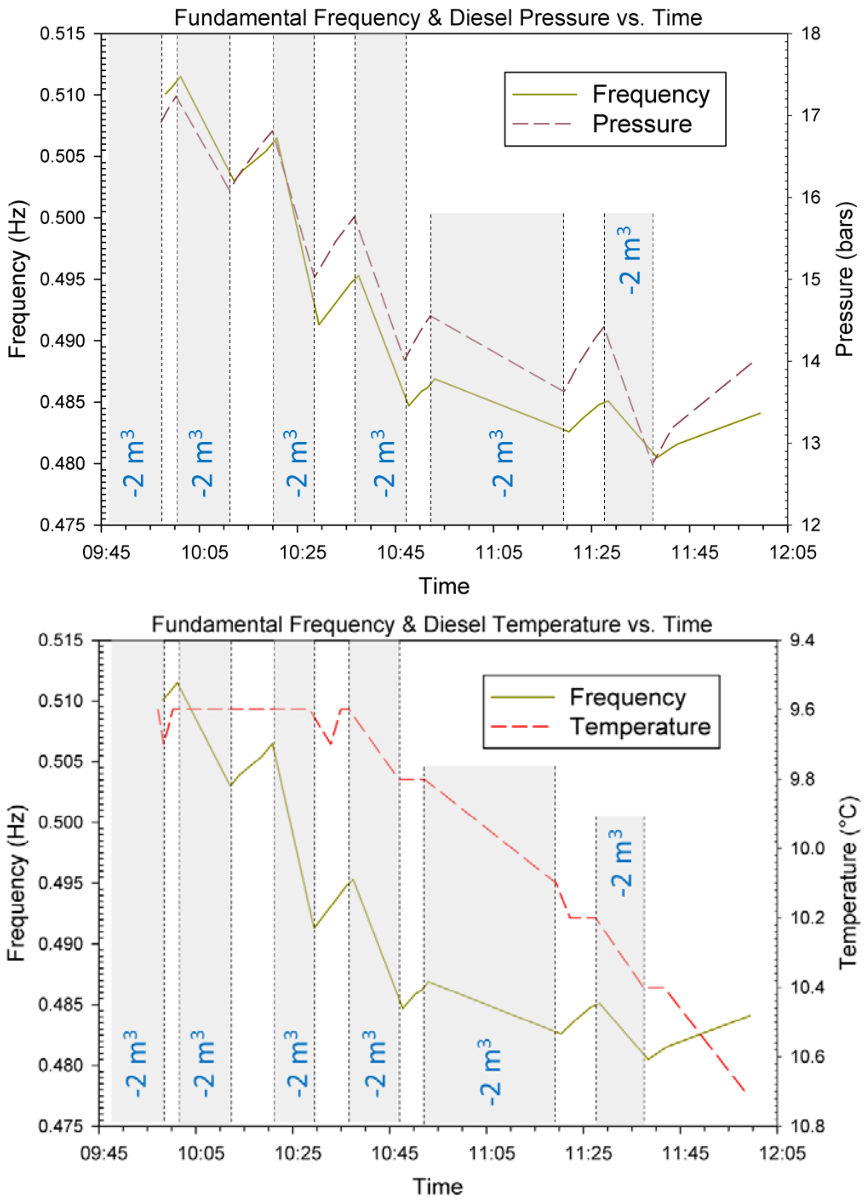

Figure 15 – Evolution of fundamental frequency in dynamic pressure signal, diesel pressure and temperature during withdrawal.

6. Conclusions – Path Forward

Diesel/brine-blanket control can be difficult in some circumstances, especially in deep and narrow annuli. All the currently available tools are intrusive and may require heavy investments and periodic workovers for maintenance.

An industrial prototype of the first non-intrusive blanket measurement system was installed at Bad Ischl, Austria, in June 2016. This system, ***Sounds Well*** *, allows real-time monitoring of the cavern roof, as well as a record of all the leaching parameters. A learning period is necessary, as a poorly documented diesel blanket is used at Bad Ischl, and no recent sonar survey is available yet for calibration. The initial accuracy is of the order of 2 m (6 ft), and it should be improved significantly to a few decimeters (a couple of feet) after the learning phase.

The next industrial validation of the system will be performed for the monitoring of the gas/brine blanket for leaching control or during integrity testing. Such configurations with gas are much easier than with diesel; much better accuracy and a significant reduced learning phase are expected.

ACKOWLEDGMENTS

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* Patent pending.