Light Drilling, Well Completion and Deep Monitoring

J. Carlos de Dios, Juan A. Marín, Carlos Martínez, and Alberto Ramos

Abstract Drilling is within the core activities of CO_2 geological storage since the more wells are drilled the higher amount of data is managed for site characterization and for a successful decision making on project viability. Most of commercial projects worldwide are at the early stage where the costs related to exploration play a key role, as is the case of the traditional drilling techniques from Oil and Gas industry that are usually expensive for on-shore projects whose business model still has to be proven. How to save drilling costs is addressed in the chapter, showing the experiences gained during the construction of the on-shore pilot: Hontomín Technology Development Plant (Burgos, Spain). Hontomín well drilling/completion was a success as the depth of 1600 m was reached using light drilling rigs (mining technique), achieving cost saving close to 60% in comparison to traditional techniques. Some experiences exist in the use of these rigs for mining, shale gas and oil and geothermal recovery, but for CO_2 geological storage they are limited to the Hontomín case. The existing technological drilling gaps identified during the plant construction and the future works for improving these rigs to reach the depth of 2500 m with a well geometry adequate to install advanced monitoring, are also addressed in this chapter.

Keywords On–shore CO_2 geological storage · Light drilling · Hontomín TDP · Cost savings · Target: 1600/2500 m depth · Advanced monitoring

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J. C. de Dios (✉) · J. A. Marín
Foundation Ciudad de la Energía-CIUDEN F.S.P, Avenida del Presidente Rodríguez Zapatero, 24492 Cubillos del Sil, Spain
e-mail: jcdediosgonzalez@gmail.com; jc.dedios@ciuden.es

C. Martínez · A. Ramos
School of Mines and Energy, Technical University of Madrid, Calle de Rios Rosas 21, 28003 Madrid, Spain

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1 Introduction

Well drilling is a core activity in the site characterization for CO_2 geological storage, and undoubtedly the more costly exploration work that impacts directly the project viability [1]. Therefore, the right election of drilling technique and equipment to use plays a key role that conditions the project as a whole.

For on-shore sites [2], the traditional techniques from Oil and Gas industry are usually expensive for an activity whose business model is still to be proven. The use of light equipment for drilling adapted from the mining industry offers the ability to achieve fully cored and completed wells with significant cost savings in comparison to the petroleum techniques [3]. Some experiences exist in the use of these rigs for mining exploration, shale gas and oil and geothermal recovery, but for CO_2 geological storage they are limited to Hontomín Technology Development Plant (TDP) case [4].

Hontomín is the unique on-shore injection site in Europe, located close to the city of Burgos in the north of Spain and operated by Foundation Ciudad de la Energía (CIUDEN). It has been recognized by the European Parliament as a “key test facility” to move forward the CCUS technologies to become a proven mitigation tool for the harmful effects produced by the emissions of greenhouse gases that cause climate change [5].

Two wells were drilled at Hontomín using mining technique to reach 1600 m depth with adequate geometry dimensions of completion and planned well trajectory, one intended for injection and the other for observation. The original plan was to use conventional rigs from Oil and Gas industry, but finally the light equipment was selected which meant cost saving of up to 60%. This was undoubtedly the main challenge to overcome during Hontomín pilot construction.

The use of light drilling rigs at Hontomín TDP construction was useful as wells were completed and monitored according to the planned design. This technology not previously used, also allowed relevant cost savings in comparison to traditional petroleum techniques as mentioned above. Undoubtedly these achievements are among the most relevant of Project “Compostilla OXYCFB300” [6], and they lead to think that light equipment can be used to reach depths of up to 2500 m with a well geometry adequate to install advanced monitoring, improving the effectiveness of the traditional drilling techniques.

However, relevant technological gaps were detected during well drilling at Hontomín related to safety and efficiency of the works performed. Preliminary studies have been carried out in ENOS Project [3] to analyze industrial solutions for improving the works conducted by these rigs.

Drilling techniques used at Hontomín, well completion and deep monitoring are addressed in this chapter, tackling the efficiency and safety of the works conducted on site, and the relevant cost savings that have been a success of Compostilla Project. Likewise, the current technological gaps associated with the use of these rigs are analyzed, as well as, the new technology development lines needed to improve light drilling technology.

2 Hontomin Well Drilling

Hontomín is a deep saline aquifer formed by naturally fractured carbonates. The main reservoir/seal pair is composed by Jurassic limestones and seal rocks belonging to the Lias and overlying Dogger formations, of which the primary hemipelagic seals are marls and black shales of Pliensbachian and Toarcian age. The site is a structural dome with the reservoir and seal rocks being located at a depth from 900 (top of the dome) to 1832 m (flanks). The main seal is the Marly Lias and Pozazal formations (highly carbonated marls, 160 m thick) and the reservoir is the Sopeña Formation (limestones and dolomites, 120 m thick) [7]. Both have a high level of fracturing in different geological blocks, but this does not affect the seal integrity.

The seal is formed by rock massifs with high uniaxial strength values close to 130 MPa and Young modulus values between 15 and 30 GPa. These data reveal that it is a hard rock with elastic-plastic deformation. The limestones and dolomites that compose the upper and down parts of the reservoir show uniaxial strength values between 180 and 190 MPa and Young modulus values in the ranges of 30–60 GPa and 60–80 GPa respectively. Hence, they are rigid rocks with brittle behavior which justifies the existence of fractures in the Sopeña Formation.

Figure 1 shows Hontomín geological column with main formations of seal-reservoir pair.

2.1 Goals and Constrains

The target formations to reach by drilling were Marly Liassic and Sopeña, main cap rock and reservoir respectively, which are located in the depth range of 1270–1550 m at Hontomín site. Two wells were designed with the completion and deep monitoring shown in Fig. 2.

The injection well (HI) is used to pump CO_2, brine and other fluids from surface to the reservoir in order to assess the fluid transmissivity in fractured carbonates, and the evolution of reservoir parameters as bottom hole pressure (BHP), temperature (BHT) and gas saturation. Hence, the following well completion and monitoring devices were installed in the well: super duplex tubing anchored to the liner by a hydraulic packer (1433 m MD), two P/T sensors located below the packer, one Distributed Temperature Sensing system (DTS) and one Distributed Acoustic Sensing system (DAS) joined along the tubing, six ERT electrodes and one U-tube device for fluid sampling from the bottom hole.

CO_2 plume tracking and other reservoir fluids evolution are monitored in the observation well (HA) that is equipped with fiberglass tubing anchored to the liner with 3 inflatable packer (1.275 m, 1.379 m and 1.479 m MD) that distribute the open hole in intervals with different permeability, four pressure/temperature (P/T) sensors and 28 ERT electrodes installed in the seal and reservoir formations.

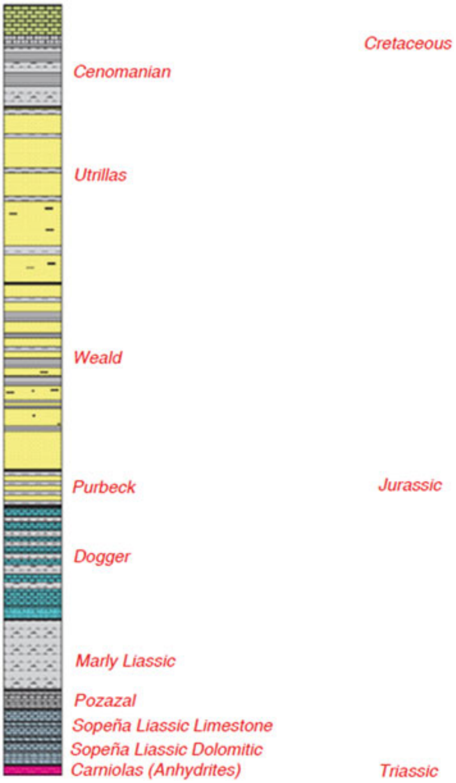


Fig. 1 Hontomín geological column

As mentioned above, the main challenge to overcome was to reach the depth of 1600 m according to the well geometry designed to install deep monitoring devices, using light drilling rigs. Never before these rigs had been used to do a work as planned at Hontomín. So, doubts raised previously the work startup like if finally the rigs would be able to reach the reservoir bottom, and in that case, if the well inner space to install the monitoring devices would be enough, and particularly, how the work efficiency would be and if drilling could be conducted accordingly existing safety standards. Relevant collaboration efforts were necessary between the drilling company staff/crew and CIUDEN engineering team to overcome daily problems during well drilling.

2.2 Drilling Rigs

Well drilling was performed at Hontomín with two light rigs: SEGOQUI 1900 and SEGOQUI 2000 (Fig. 3) using mining technique. SEGOQUI 1900 drilled first 600 m

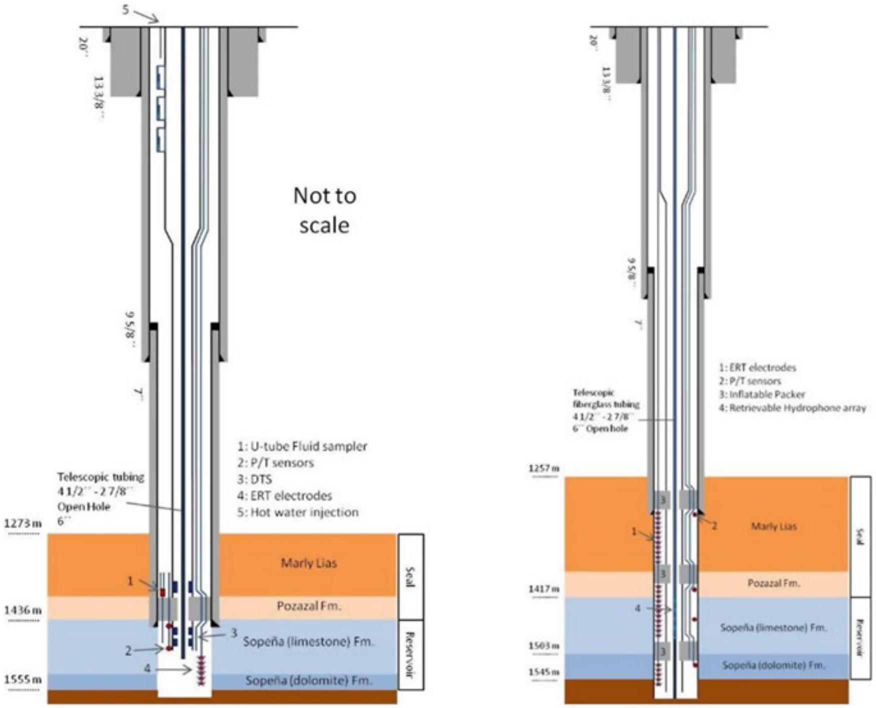


Fig. 2 Well completion/monitoring schemes of injection (left side) and observation (right side) wells of Hontomín TDP

depth and SEGOQUI 2000 was used to reach the target of 1600 m depth. Main technical characteristics of SEGOQUI 2000 are the following [8]:

- Mast height: 15.5 m.
- Engine power: 300 HP.
- Maximum torque: 4000 kg m.
- Rotary table opening: 150 mm.
- Cylinder hoisting load: 50 t.
- Winch load: 60 t.
- Total load (cylinder + winch): 110 t.
- Maximum push load: 20 t.
- Maximum speed: 120 rpm.
- Drill pipe: φ 140, 152 mm L 6 m.
- Rig mounted on truck 8 × 8.

Following auxiliary equipment and infrastructure were also necessary (Fig. 4):

- 2 Compressors Atlas Copco XRVS 455, 25 bar and 25 m^3/min.
- 1 Booster HURRICANE M 41C-870, 60 bar and 50 m^3/min.
- Mud pump GARDNER-DENVER Mod 7 1/4″ × 14″ × 10″ and 5″ × 10″.

Fig. 3 Rig SEGOQUI 2000 drilling at Hontomín TDP (Courtesy of CIUDEN)

Fig. 4 Drilling on-site panoramic view with the rig and auxiliary equipment (Courtesy of CIUDEN)

- Mud pump EMSCO F-500. Triplex Mud Pumps (API-7K) 500 HP.
- Screen and double cyclone MODELCO model MD 190 D 200 m^3/h.
- 2 mud pools. Total capacity 75 m^3.
- Electricity generator: 25 kVA for lighting.
- Mud logging cabin.
- Geological control cabin, equipped with chromatograph for gases and masterlog software.
- H_2S and CH_4 continuous monitoring.
- BOP (Blowout Preventer): WP 5000 psi.
- Choke manifold and torch.
- Crane and auxiliary vehicles.
- Pipe for direct and reverse drilling.
- Core sampling pipe and bits (OD 80 mm and 7 m length). OD 6″ cores.

2.3 Workflow

Drilling process for both injection and observation wells was as follows:

1. Percussion drilling for first 130 m depth.
2. Rotary drilling by reverse mud circulation up to reach the bottom of Utrillas Formation (600 m depth).
3. Rotary drilling by direct mud circulation up to reach the top of Keuper Formation (close to 1600 m depth).

Percussion drilling was performed using a trepan for first 130 m, in order to ensure the well alignment and verticality. Afterwards, considering that first shallow relevant formation crossed was Utrillas (see Fig. 1), which is comprised of sand, gravel and little cohesive material in general terms, the reverse mud circulation drilling was conducted due to the good performance of this technique for this ground. Finally, direct mud circulation drilling was used from 600 to 1600 m depth, crossing the upper seal formations: Weald, Purbeck, Dogger, Marly Liassic and Pozazal, the reservoir Sopeña Formation and finally reaching the Carniolas (anhydrites) at the top of Keuper (see Fig. 1).

Reverse mud circulation technique [9] was performed insufflating compressed air in the inner part of the drill pipe OD 220 mm and 6 m length, through a valve installed to the depth of between 200 and 250 m. The compressor Atlas Copco XRVS 455, 25 bar and 25 m^3/min was used for this maneuver. Below the valve, standard drill pipe 5 1/2″, 9–10″ loading bars and 17 1/2″ or 12 1/4″ bits were installed. This maneuver produces the air-lift effect, lightening the hydrostatic column above the valve and inducing the extraction of the mud along the inner part of drill pipe. The process scheme for reverse circulation is shown in Fig. 5.

A Blowout preventer valve (BOP) [10] 11″ 5000 psi was installed previously to start 3rd drilling phase (exploration of cap-rock and reservoir formations) for avoiding the risk of gas eruption from the bottom hole, as shown in Fig. 6. The

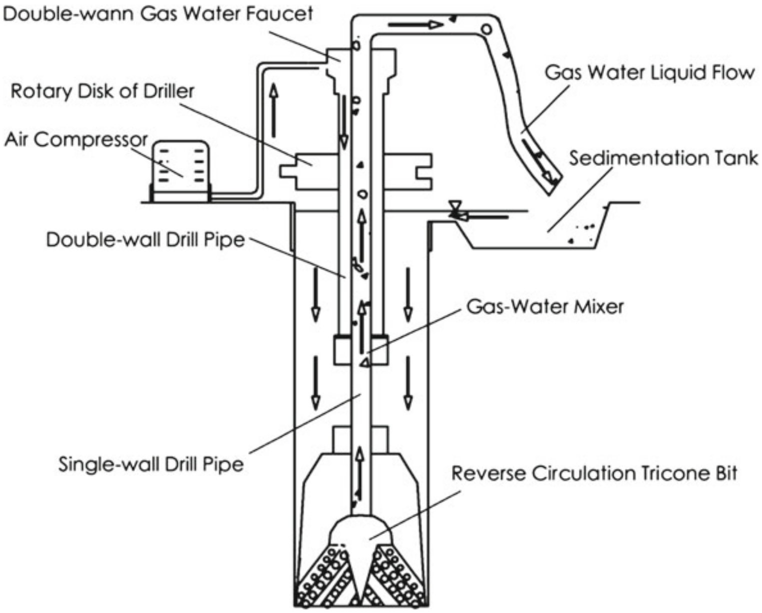


Fig. 5 Reverse mud circulation drilling scheme

Fig. 6 Installation of BOP and spools during HI well drilling (Courtesy of CIUDEN)

spools, pressure lines and BOP were tested by hydraulic pressure of 70 bar held constant for 15 min. No variations were detected during the period. Subsequently, direct circulation drilling started for the length range 600–1600 m depth.

As mentioned above, direct mud circulation drilling [11] was used to cross the seal (Marly Lias and Pozazal) and reservoir (Sopeña). It was conducted pumping the mud through the inner part of drill pipes to reach the bottom hole, producing the bit cooling and lifting the rock cuttings to the surface. The cake around the wellbore

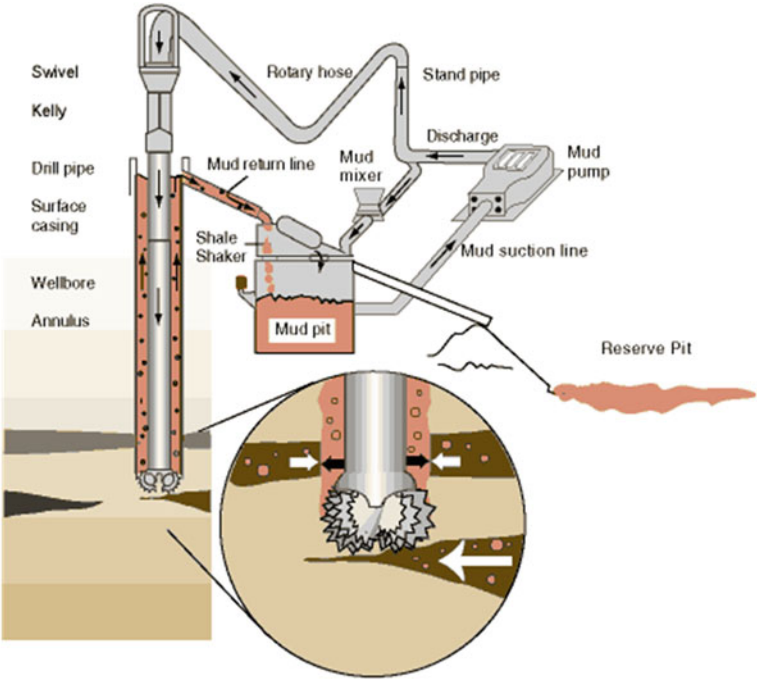


Fig. 7 Direct mud circulation drilling scheme (Courtesy of Massenza drilling rigs)

was also built during the maneuver to avoid the collapse of wellbore wall and acting as a first barrier in gas release case, as shown in Fig. 7.

Table 1 shows drilling bit diameters used and depth reached in each process phase (Fig. 8).

The drilling mud was made with the following components:

- Bentonite to increase the density and viscosity of the fluid.
- Calcium carbonate to increase the density.
- Carboxy Methyl Cellulose for filtering and viscosity control.
- Sodium Hydroxide to control the alkali and pH.
- Sodium carbonate for density control.
- Dry polymer to reduce the friction.
- Agent for rheological control.
- Antifoaming.

Its main characteristics are:

- Density: 1.01–1.09 g/cm^3.
- Funnel Viscosity: 41–48 s.
- Apparent Viscosity: 14–21 cp.
- Yield Point: 10–18 lb/100 ft^2.

Table 1 Drilling phase, bit OD and depths

Drilling phase	Injection well (HI)		Observation well (HA)	
	Bit OD (″)	Length MD (m)	Bit OD (″)	Length MD (m)
1st phase: percussion				
Percussion 1	25 1/4	0–20	22	0–20
Percussion 2	19	20–130	19	20–132
2nd phase: reverse mud circulation				
Reverse 1	17 1/2	130–210	17 1/2	132–220
Reverse 2	12 1/4	210–591	12 1/4	220–600
BOP installation				
3rd phase: direct mud circulation				
Direct 1	8 1/2	591–1441	8 1/2	600–1286
Direct 2	6	1441–1570	6	1286–1580

Fig. 8 Drilling bits used at Hontomín (Courtesy of CIUDEN)

- pH: 9–10.
- Cake: 0.5 mm.

Mud circulation features were: flow rate between 1000 and 1200 l/m and pressure ranges of 5–10 bar and 15–25 bar for 2nd and 3rd drilling phases respectively.

2.4 Well Completion and Deep Monitoring

Figure 9 shows the following completion components (according to API standards) and monitoring devices installed in the injection and observation wells.

Completion

- **HI Well**:
  - 20″ conductor, S235JR (20 m depth), 13 3/8″ casing, 61 lb/ft, K55, BTC (207 m depth), 9 5/8″ casing, 43.5 lb/ft, N 80, BTC (586 m depth) and 7″ Liner, 29 lb/ft, N80, BTC (from 483 to 1437 m depth, last 200 m L80Cr13).
  - Tubing 4 1/2″, 13.5 lb/ft, CR22-140, VAM TOP, R2/R3 (408 m depth), tubing 2 7/8″, 7.8 lb/ft, 22 CR-125 (from 408 to 1466 m depth).
  - Tubing hanger (L = 0.76 m) (GL at bottom of the TH) and X-over 4 1/2″ EUE pin × 4 1/2″ EUE pin (L = 0.30 m).
  - 7″ RDH Dual Hydraulic-Set/Retrievable Packer, 5000 psi WP, 13Cr and Nitrile element, Primary connection 2 3/8″ API-EU box × 2 3/8″ API-EU pin + X-Over pin × pin (L = 2.80 m) (1431 m depth).
  - Otis 1.875″ X Selective Landing Nipple, X20Cr13, 2 3/8″ API EU pin × pin (L = 0.26 m) and choke (1003 m depth), Sliding Side-Door Circulating Device, 1.875″ X Profile, 13Cr, 2 3/8″ EUE pin × pin (L = 1.02 m) (1417 m depth), Otis 1.875″ X Selective Landing Nipple, X20Cr13, 2 3/8″ API EU pin × pin (L = 0.27 m) (1444 m depth), Otis 1.875″ XN Landing Nipple (Bottom No-Go), X20Cr13, 2 3/8″ API EU pin × pin (L = 0.31 m) (1456 m depth) and RH Catcher Sub Bell Type, X20Cr13, 2 3/8″ EUE box up (L = 0.15 m) (1466 m depth).
  - 3 Sidepocket Mandrel, 13Cr, with RD-2 Dummy Valve, 4 1/2″ EUE box × pin (L = 3.02 m) (176, 281 and 383 m depth).

- **HA Well**:
  - 20″ conductor, S235JR (20 m depth), 13 3/8″ casing, 61 lb/ft, K55, BTC (216 m depth), 9 5/8″ casing, 43.5 lb/ft, N 80, BTC (594 m depth) and 7″ Liner, 29 lb/ft, N80, BTC (from 490 to 1281 m depth, last 200 m L80Cr13).
  - 4 1/2″ tubing, 7.6 kg/m, EPOXY/FG, Serial number 2500, T&C EUE 8 RD (371 m depth), tubing 2 7/8″, EPOXY/FG, Serial number 2500, T&C EUE 8 RD (from 371 to 1561 m depth).
  - Tubing hanger (L = 0.76) (GL at bottom of the TH) and X-over 4 1/2″ pin × 4 1/2″ EUE box (L = 0.21 m).
  - 3 Inflatable Packers, SS 316L and HNBR Nitrile, 2 × 1/4″ infl/des. lines (2 7/8″ EUE box × box) (L = 2.79 m) (1275, 1380 and 1498 m depth).
  - 1.875″ XN Landing nipple (Bottom No-Go), 13 Cr, 2 7/8″ 6.5 API EUE (L = 0.45 m) (1508 m depth).

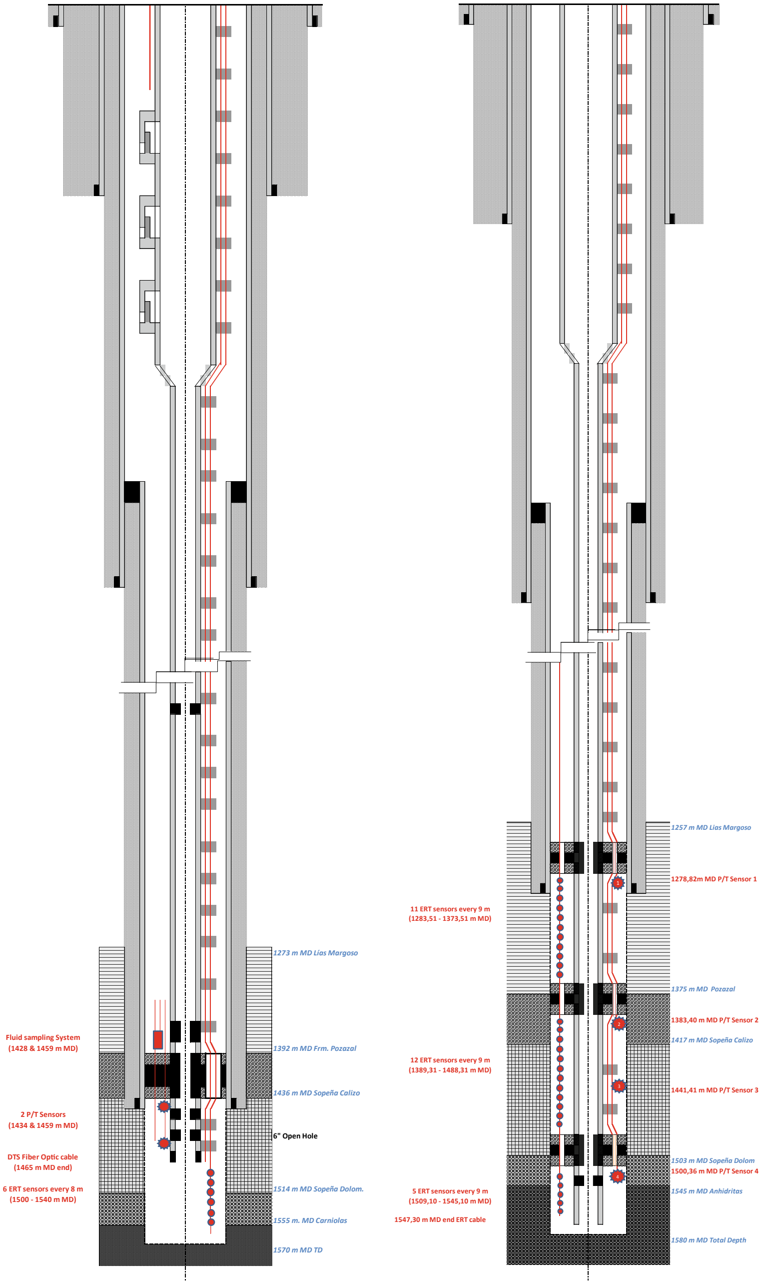


Fig. 9 Schemes of well completion and monitoring of the injection (on the left) and observation (on the right) well

Monitoring

- **HI Well**:
  - U Tube sampling system (1459 m depth).
  - Distributed Temperature Sensing System (DTS) (along the tubing, 1465 m depth).
  - Distributed Acoustic Sensing system (DAS) (along the tubing, 1465 m depth).
  - P/T sensors (1434 and 1459 m depth).
  - 6 ERT (from 1500 to 1540 m depth).
- **HA Well**:
  - 4 P/T sensors (1279, 1383, 1441 and 1500 m depth).
  - 11 ERT sensors (from 1283 to 1373 m depth).
  - 12 ERT sensors (from 1389 to 1488 m depth).
  - 5 ERT sensors (from 1509 to 1545 m depth).

Note. The data to locate the components of completion and monitoring are measured in depth units (m MD).

Casings and liners were cemented using CO_2 resistance cement for avoiding damages due to the acidification produced by the mixture of carbon dioxide and reservoir saline water. CBL (Cement Bond log) logging device was used for checking the cementing grade.

2.5 Coring

The extraction of rock samples during well drilling, known as coring, is a key activity to reduce uncertainty in the seal-reservoir evaluation by providing data representative in situ conditions [12]. Samples are used to perform laboratory scale tests to determine the reservoir injectivity, storage capacity and long term trapping [13].

Drilling and extraction of rock samples are part of the drilling report, as shown in Tables 2 and 3, which include the information of coring activity conducted during the injection and observation well drilling.

Coring was conducted by ID 6″ drilling tool and piping for sample recovery, as Fig. 10 shows.

Finally, 13 core samples were acquired from well drilling, 10 from the observation well (HA) and 3 from the injection well (HI), of which 7 correspond to the caprock (Marly Lias and Pozazal Formations) and 6 to reservoir (4 from Limestone and 2 from Dolomitic Sopeña Formations) (Fig. 11).

Petrophysical routine and specific lab tests [4, 13] were carried out using these rock cores to determine the ability of formations to be cap-rock and reservoir respectively. Lab procedure description and analysis of results to determine petrophysical properties, injectivity, impacts of hydrodinamic, mechanical and geochemical effects due to injection and trapping will be addressed in Chapter “Laboratory Scale Works”.

Table 2 Observation well (HA) coring information

Core sample	Recovery		Drilling interval (m)
	Length drilled (m)	%	
1	7	100	1307–1314
2	3.5	100	1320–1323.5
3	6	85.7	1343–1349
4	4	100	1401–1405
5	5.10	72.8	1405–1410
6	6.77	97	1442–1449
7	1.38	100	1449–1450.38
8	5.87	0	1457–1462.87
9	0.12	60	1464–1462.1
10	6.91	98.7	1515–1522

Table 3 Injection well (HI) coring information

Core sample	Recovery		Drilling interval (m)
	Length drilled (m)	%	
1	7	100	1355–1362
2	0.96	19	1467.74–1468.7
3	6.96	99.12	1531–1538

Fig. 10 Drilling tool and pipe for coring used at Hontomín (Courtesy of CIUDEN)

Fig. 11 Core sample from limestone Sopeña Formation in the observation well (Courtesy of CIUDEN)

2.6 *On-Site Tests*

Well logging works [14] conducted at Hontomín site were performed using petrophysical probes and other running tools along the completion and open hole of both wells, in order to achieve the following goals:

- Data acquiring for a better knowledge of geophysical characteristics and more accurate location of the pair seal-reservoir.
- Check well drilling geometric parameters as its azimuth, inner diameter and vertical deviation.
- Perform quality control of well completion, particularly the cementing grade and existence of leakages.

Well logging works focused to increase the knowledge of geological formations conducted within the site characterization were as the following:

- Gamma ray (natural gamma ray and gamma log) to locate the top and bottom of each geological formation, the clay amount existing in their composition and existing density.
- Temperature to determine the thermal gradient related to depth.
- Neutron to determine rock matrix porosity of each formation.

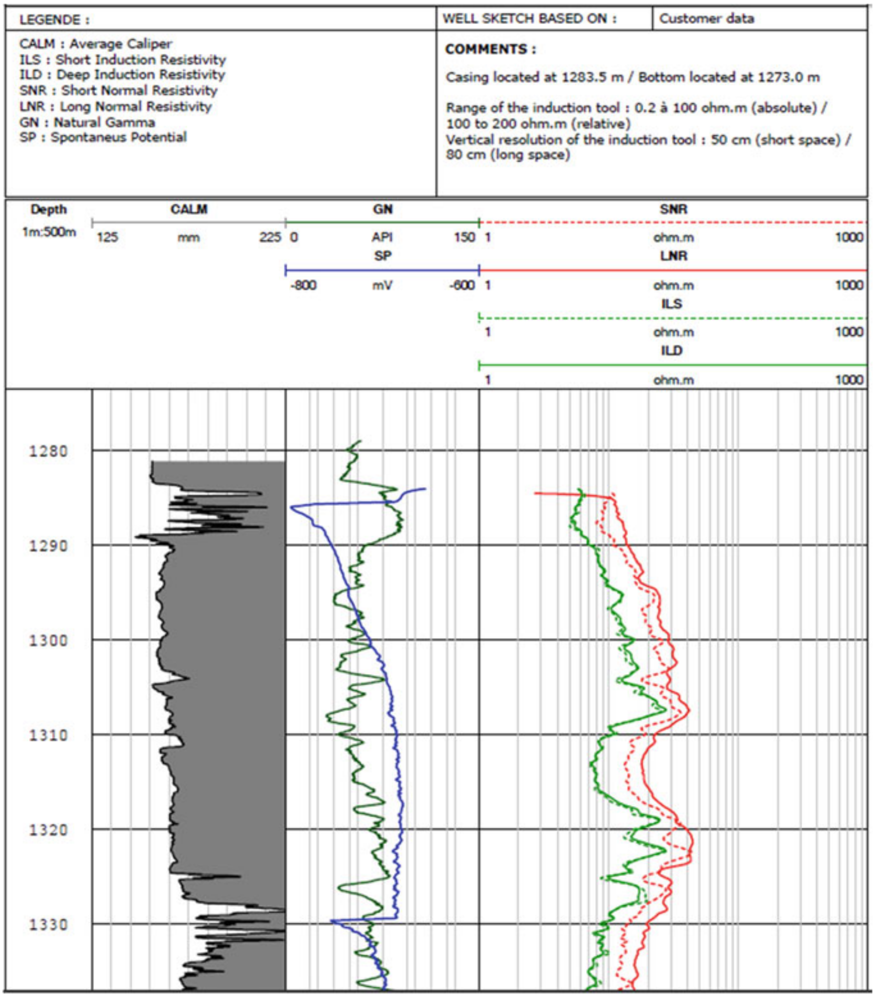
Spontaneous potential used promptly to identify the aquifer limits and brine movement direction.

- Resistivity to determine brine conductivity and its salinity.
- Sonic to determine the velocities Vp and Vs along the open hole and their correlation with geomechanical properties.
- Acoustic televiewer to identify the azimuth and dip of main fractures existing in the borehole.

Particularly, well logging works conducted to check well completion quality were the following:

- Caliper used to determine bottom-hole inner diameter.
- Gyroscope used to determine the azimuth and deviation of well drilling path.
- CBL (Cement Bond Log) used to determine cementing level of casings and liners.

Figure 12 shows results from several well logging probes run in the observation well (HA), plotted in the same scheme for its correlation and interpretation. This work was conducted in the depth range from 1280 to 1570 m combining the following tools:



LEGENDE :

CALM : Average Caliper
ILS : Short Induction Resistivity
ILD : Deep Induction Resistivity
SNR : Short Normal Resistivity
LNR : Long Normal Resistivity
GN : Natural Gamma
SP : Spontaneus Potential

WELL SKETCH BASED ON : Customer data

COMMENTS :

Casing located at 1283.5 m / Bottom located at 1273.0 m

Range of the induction tool : 0.2 à 100 ohm.m (absolute) / 100 to 200 ohm.m (relative)
Vertical resolution of the induction tool : 50 cm (short space) / 80 cm (long space)

Fig. 12 Observation well logging results

- Caliper
- Short and deep induction resistivity
- Short and long normal resistivity
- Gamma ray
- Spontaneous potential.

Other logging probe run at Hontomín wells was the acoustic televiewer [4, 15] used to give an oriented and continuous borehole-wall imaging for fractured-rock aquifer studies. This type of well logging will be addressed in Chapter "On-Site Hydraulic Characterization Tests". Finally, following on-site tests were performed during site hydraulic characterization [4], which will be also described and analyzed in Chapter "On-Site Hydraulic Characterization Tests":

- Permeability test at field scale (PTFS)
- Connectivity test inter wells (CTIW)
- Leak off test (LoT).

3 Performance Curves and Cost Saving

Drilling performance curve (DPC) [16] is the tool for assessing the operation performance for a specific well or for series drilled in an area with same technology and workflow. The graphic provides the information needed to analyze the working sequence in the well(s) and the time taken to reach a given depth.

Figure 13 shows the HI/HA Well DPCs which include planned works (in red line) and real execution (in blue line) of following activities:

- Percussion drilling.
- Reverse circulation rotary drilling.
- 1st completion.
- Direct circulation rotary drilling.
- 2nd completion.
- Well logging.
- Coring.
- Downtimes.

Tables 4 and 5 shows the correlation between each activity and time required during the drilling of both wells.

Although drilling performance is lower than case where oil and gas rigs are used [17], well light drilling was a success as the depth of 1600 m was reached at Hontomín, which had not been done before, achieving cost savings close to 60% in comparison to traditional techniques. Main reason is the associated costs to light drilling are considerably lower than those corresponding to Oil and Gas drilling, since both the availability, transport and operation of light rigs is less expensive. Nevertheless, several technological gaps were identified during Hontomín construction, as well as the necessity to find solutions that make more reliable operations, increasing the

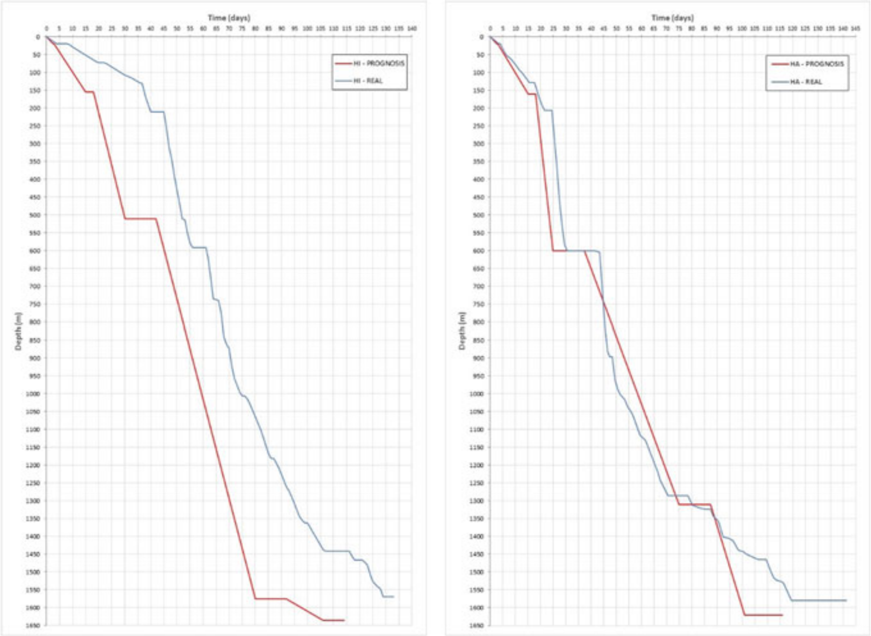


Fig. 13 HI/HA drilling performance curves

Table 4 HI well drilling and completion, associated works and time

HI well activities	Time (days)	Well drilling average (%)
Drilling	74	48.88
Maneuvers	17	10.87
Equipment maintenance	1	0.79
Circulation/losses/mud manufacturing	4	2.44
Piping placement/cementing	13	8.88
Coring	6	4.2
Well logging	10	6.84
Staff rest	3	1.72
On-site tests	10	6.14
Final well completion (monitoring, well heads)	12	7.78
Downtimes (e.g. tool fishing, fault repair)	2	1.46
Total	152	100

Table 5 HA well drilling and completion, associated works and time

HA well activities	Time (days)	Well drilling average (%)
Drilling	54	33.17
Maneuvers	19	11.8
Equipment maintenance	2	0.94
Circulation/losses/mud manufacturing	3	1.9
Piping placement/cementing	6	3.91
Coring	18	10.68
Well logging	8	4.95
Staff rest	9	5.68
On-site tests	22	13.2
Final well completion (monitoring, well heads)	9	5.52
Downtimes (e.g. tool fishing, fault repair)	13	8.25
Total	163	100

safety and efficiency. Section 4 address this issue, classifying the gaps according to their impacts on drilling workflow and on work efficiency and safety.

4 Existing Technological Gaps

Technological gaps identified during Hontomín well drilling are related to the following topics:

- Operation efficiency and safety
- Well completion and the installation of monitoring devices
- Rig instrumentation and operation control
- Directed drilling.

The gap analysis described below will be used in future works as a reference to explore the existence of technological solutions.

4.1 Gaps Related to Operation Efficiency and Safety

Regarding well drilling efficiency, first general matter to analyze is whether it is possible that an unique light rig is able to develop the works performed in Hontomín by the following equipment:

- Percussion drilling rig for first 130 m depth.
- Rotary drilling with reverse mud circulation up to reach 600 m depth.
- Rotary drilling direct mud circulation up to reach 1600 m depth.

If so, downtimes due to rig placement and disassembly would be avoided.

On the other hand, having a look to Tables 4 and 5, drilling performance is a crucial parameter as it was in the range 33.17–48.88% of total well drilling period. Therefore, parameters such as the push, rotary speed, torque and pull, and related operations as mud pumping, must be analyzed for their improvement. Likewise, the drill pipe placement and disassembly must avoid as much as possible downtimes, so that, pull capacity and rig height play a key role. On one hand, pull capacity provides high lift velocity and the ability to support heavy loads at deep depths. On the other, higher rig height allows the use of longer drill pipe and install longer tubing parts than used at Hontomín works, which means a performance increase in piping handling operations. These improvements could reduce the maneuver time that corresponds to 11% of well drilling period.

Regarding safety issues, the capability to integrate the additional equipment (Fig. 4) in the rig is really important, taking into account the more components are needed to be installed and dissembled the higher probability of accident occurs. It is particularly relevant that the rig can assembles the blow-out preventer valve, for which, the elevation of the machine and a specific mechanical and hydraulic coupling design are needed. In the same way, an integrated equipment is more efficient since it is needed less time to install and disassembly components.

4.2 Gaps Related to Well Completion and the Installation of Monitoring Devices

Drilled diameter is a critical parameter because of the necessity to install deep monitoring devices inside the annular space between the casing/liner and tubing in some cases, and within the interphase between the rock and the external part of well completion in others.

Likewise, well diameter conditions tubing dimensions, being this fact more critical in the injection well case, since a nominal flow rate is planned and the diameter value is conditioned by the steady state injection in laminar flux. In any case, drilling diameter increase depends on rig capability determined by the parameters described above, mainly the push, rotary speed, torque, pull and mud pumping.

For industrial injections, tubing OD is planned to be equal or higher than 4–5 1/2″ that corresponds to 9 5/8″ OD casing/liner and 12 1/4″ drilled diameter. If well monitoring devices are decided to assembly in the outer completion part instead of the inner annular, drilling diameter should be increased. Diameters for Hontomín bottom holes were 8 1/2″ and 6″ in the completed and “open hole” areas respectively. This fact conditioned both the final tubing dimension (2 7/8″) and the installation process of monitoring devices, which was a risky operation due to the tight annular space existing between the tubing and the borehole wall.

On the other hand, the reason why cementing is crucial in drilling for CO_2 geological storage is the wells are main potential migration pathways if cementing grade is not as required. Besides this critical point, cementing is usually a well service provided by an external company. This fact involves the adversities of a contract, what supposes high budgetary conditions in this case and lack of immediate quality control if well logging is also performed by an external service. Well repair in case of faulty work is really difficult and costly. These reasons lead to thinking that cementing could be included as other activity to be conducted by own drilling staff.

4.3 Gaps Related to Rig Instrumentation and Operation Control

The instrumentation of rigs used in Hontomín well drilling corresponds to usual equipment for shallow operations, as mining exploration and hydrogeological prospecting, being 1000 m depth the common barrier for this type of works. Therefore, the rig instrumentation must be improved to reach depths in the range 1600–2500 m in an efficient and safe manner.

Pumping facility and its control were not integrated as part of the rig, what means operation difficulties that produce inefficiency and working faults may occur. Hence, it would be advisable to analyze how integrate the mud facility on drilling equipment, and particularly, its operation control.

Regarding data of Tables 4 and 5, almost 5–7% of drilling period was used to conduct well logging works. These ones were performed by an external service company, what meant extra costs and coordination efforts regarding the availability to conduct the planned works. Particularly, borehole cross-section diameter is usually controlled by the caliper log, a running tool which determines the cross section deviation from planned for different well parts. Graphic of Fig. 14 shows the caliper logging results.

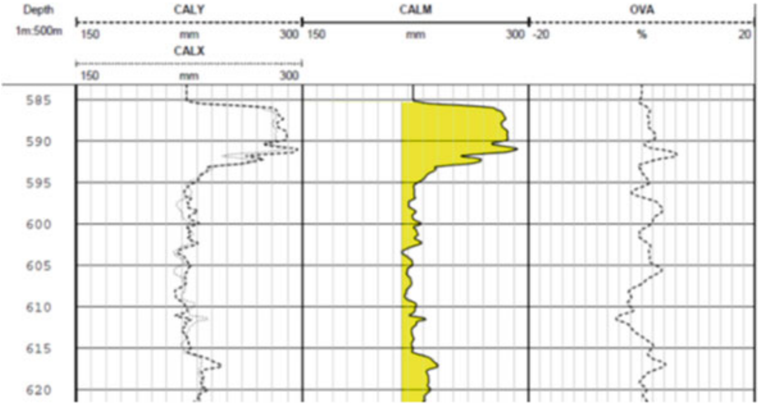


Fig. 14 Caliper logging results

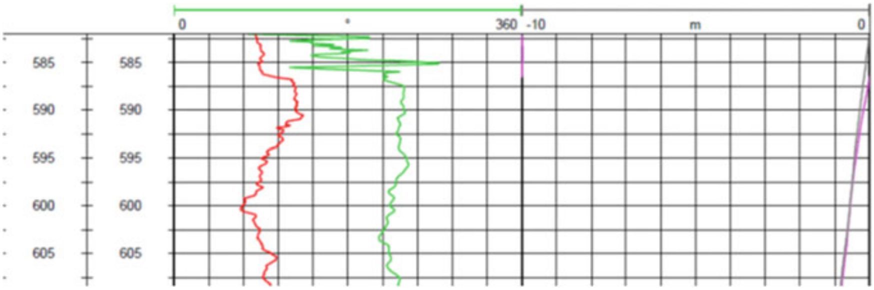


Fig. 15 Gyroscope logging results

In a similar way, borehole deviation control is developed by the gyroscope logging, a running tool which determines the well axis deviation from planned for different intervals in depth. Figure 15 shows the gyroscope logging results.

Clearly, if data logging can be conducted during drilling, less downtimes will occur, as drill pipe is located along the well and no need of maneuvers for place and replace. On the other hand, a quick information on drilling performance may be achieved which is crucial to take the right decision at the right time. Therefore, it is necessary to determine what type of monitoring devices would be suitable to install within the drilling array, in order to carry out logging and measuring while drilling (L/MWD), particularly to control the borehole cross-section and deviation [18, 19].

4.4 Directed Drilling

Directed drilling is more and more required. Initially, traditional Oil and Gas industry decided to use this type of wells for particular reasons, and mainly for unconventional hydrocarbon recovery techniques. More recently other activities as geothermal, energy storage and CO_2 geological storage have claimed the use of this technique. Unfortunately, the existing light drilling rigs are not able to perform this type of works, being needed to analyze technological solutions to perform directed drilling using these equipments.

5 Future Works

Drilling is within the core activities of CO_2 geological storage since the more wells are drilled the higher amount of data is managed for site characterization and for a successful decision making on project viability, since it is undoubtedly the more costly exploration work.

For this reason, a feasibility study to improve light drilling rigs used at Hontomín was carried out in ENOS Project [3], whose goals in this matter are the following:

- Reach depth of 2500 m at least
- Achieve enough inner space at well bottom hole to install monitoring devices.

Ciudad de la Energía Foundation (CIUDEN), Bureau de Recherches Geologiques et Minieres (BRGM) and Sotacarbo, as project partners, have counted on the technical collaboration and advice of HERRENKNECTH AG, company specialized in tailor made manufacturing of deep drilling rigs, that supports and promotes their use for geological exploration related with future energy needs.

6 Concluding Remarks

Main concluding remarks on light rigs use for deep well drilling regarding the experience gained during the construction of Hontomín Technology Development Plant for CO_2 geological storage are the following:

- Although light drilling had not previously been used in wells more than 1000 m depth, this was a success during Hontomín pilot construction.
- Final depth close to 1600 m was reached with well dimensions appropriate to install deep monitoring devices.
- Cost savings were up to 60% in comparison to those corresponding to traditional oil and gas techniques.
- The achievements described above lead to thinking that light drilling technique may be used to reach the depth of 2500 m with a well geometry adequate to install advanced monitoring.
- Drilling equipment improvement is necessary to achieve mentioned goals, since technological gaps that impact on drilling operations and on work efficiency and safety were identified during the pilot construction.

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Glossary

API American Petroleum Institute
BHP Bottom hole pressure

BHT Bottom hole temperature
BOP Blowout preventer
CBL Cement Bond Log
CCUS Carbon capture utilization and storage
CTIW Connectivity test inter wells
DAS Distributed acoustic sensing system
DPC Drilling performance curve
DTS Distributed temperature sensing system
ENOS Enabling on shore CO_2 storage in Europe
EP Resolution European Parliament Resolution
ERT Electrical resistivity tomography
HA Hontomín observation well
HI Hontomín injection well
LoT Leak off test
LWD Logging while drilling
MD Measured depth
MWD Measured while drilling
OD Outer diameter
P/T Pressure/Temperature
PTFS Permeability test at field scale
TDP Technology Development Plant

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