Drilling in supercritical condition: the DESCRAMBLE project

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ABSTRACT

The DESCRAMBLE project, a proof-of-concept test of reaching deep geothermal supercritical resources in non-volcanic continental-crust, have demonstrated novel drilling techniques to control high temperature/pressure conditions and gas emissions expected from the deep fluids. The test site has been an existing dry well in Larderello, Italy, already drilled to a depth of 2.1 km and temperature of 350 °C, which was deepened to about 2.9 km depth and reached supercritical conditions. The usefulness and efficiency of the project were ensured by the combination of industrial and research participation and by the recognized expertise of the consortium in geothermal R&D as well as oil and gas drilling, combining excellence in both sectors. DESCRAMBLE's results will be presented, covering all the main aspects of the drilling activity: drilling procedures, material, well control, mud logging, and well testing.

Drilling operations in extreme conditions were carried out safely with very good performance of the new materials selected, although drilling conditions in some sections were even more extreme than expected, especially in terms of temperature. In consideration of the extreme static temperature (450°C) and pressure (450 bar) expected at bottom hole, the drilling would have been completely out of standard drilling conditions, and required a careful selection of materials and procedures for safety drilling conditions. A special cement and other material solutions (rock bits, casing…), were designed or selected among commercial and high performance products. Reached the last drilling phase, was important to have a diagnostic capability to be able to preview and anticipate loss of circulation and more important gas kick. The drilling into impermeable layers, so that drilling fluid returned to surface, was somewhat unusual for geothermal, where wells are typically drilled with complete loss to the formation. The target of the well was the exploration of the “K” seismic horizon, with the envisaged top at about 3 km. Due to mechanical characteristics of the formation encountered and hydraulic well conditions, drilling activities reached the final depth of 2.9 km, crossing the layer of reflections settled just above the targeted “K” marker. At that depth, drilling stopped because of the impossibility to deepen further the borehole in total safety, considering the high pressure expected, caused by the unexpected presence of a fractured zone above the target and the well was left idle after the execution of a temporary plug and abandonment.

1. INTRODUCTION

The project DESCRAMBLE aims at drilling a deep geothermal well, in order to investigate the properties of the fluids beneath a deep seismic horizon (K horizon), where fluids in supercritical condition are expected to be found.

The extrapolation made in some existing well present in this area predict bottom hole temperature about 450 °C and bottom hole pressure about 450 bar.

Related to these extreme conditions ENEL decided to implement the technology usually used, by some special equipment projected for this specific well, in order to minimize safety risk and increase the performance.

To develop this project the existing well Venelle 2 was selected.

2. WORKOVER, PLUGS AND NEW BRANCH REALIZATION

Drilling activities of the well Venelle 2 branch 1 began on 28th April 2017.

After having killed the well by water, a smooth 12 ¼” BHA was RIH revealing a maximum practicability at 1625 m of depth. Inert materials were pumped, catching the top at 1165 m. Above it two cement plugs were realized, in order to stop the residual absorption. Cement plug was milled until 1054 m of depth, where it was left to act as support for the realization of new branch.

Deviation started with directional drilling in sliding and rotary mode (KOP at 1054 m), by the use of an 8 ¼” mud motor with MWD and a 12 ¼" RB with the purpose to keep an inclination lower than 10° (pseudo vertical well). Since 1180 m of depth, some little losses (0-7 m^3/h) occurred drilling with water as drilling fluid. Directional drilling continued up to 2275 m of depth, when some problems of torsion occurred. Drilling continued in rotary with a 12 ¼" stabilized BHA encountering a TLC at 2334 m, after it reduced in an absorption of 25 m^3/h. At 2422 m a DP rupture occurred, losing all the BHA in the wellbore. Fishing operations were successful.

Drilling continued up to 2470 m, where it was stopped to set the 9 5/8" liner. Casing shoe was set at 2468 m of depth, whit the hanger anchored at 993 m. During the first cementation job, the slurry did not reach the liner top because of the presence of a loss, so it was decided to set an ogive above the hanger and to proceed with an inert materials and cement plug in order to give support to the 9 5/8" casing, avoiding to use the tie-back configuration originally foreseen. The casing shoe was set at 985 m, leaving the possibility to the liner to expand in case of heating.

3. DRILLING PHASE 8 ½"

Collars, cement and shoes of both section of casings were milled and drilling continued with an 8 ½" BHA not stabilized. At 2500 m of depth some test were conducted, in particular a temperature log and a Leak Off Test. Just because the 9 5/8" liner was not perfectly cemented in the upper part, it was decided to set a retrievable RTTS packer in proximity of the casing shoe, allowing the execution of the LOT not pressurizing the entire casing string set.

Once the Packer was extracted, drilling continued again with 8 ½" stabilized BHA up to 2600 m. Since 2520 m of depth water was substituted with sepiolitic water based mud as drilling fluid.

The Mud Program has been based on the expected well conditions and all the tests performed in Newpark (mud supplier) Laboratory while tender and during the pre-spud studies. As the environment expected while drilling this well was unknown and critical, many assumptions had been taken while planning the fluid design. At the end of the tests performed to achieve the best drilling fluid for this project, it was decided to proceed with a Water Base Mud weighted up with Ilmenite (Microdense™) and with Sepiolite as suspending agent. In particular, this fluid had better performance in term of temperature resistance looking to the fact that also once aged, the fluid did not present any sagging and still keep the fluid loss under control. This helped the operations because had not been required a displacement with a heavy brine while tripping.

It had been tested, as weighting agent the Ilmenite, Microdense™, which, thanks to its particular particle size distribution (average 5 µm) offer an auto suspending properties, which could help to prevent sagging, and settlement of the weighting agent.

During drilling, even with very low viscosity, fluid has not decanted and the weight of the mud has been stable. During the activity it has been verified a speed polymer depletion and a high evaporation that has been made necessary a continuous reintegration of water. The phenomenon of mud products deterioration due to the high temperature is shown by gas peaks as CO_2 and H_2S registered in the bottom pillows.

From 2600 m to 2601 m a core was performed, it was very short because coring operations were interrupted for some top drive blockages.

At this moment a crucial aspect was represented by the knowledge of the formation fracture gradient, information required in order to set the 7" liner shoe.

Getting this kind of information was possible by the execution of Leak Off Tests in proximity of the bottom of the wellbore. Just because the formation fracture gradient varies with the change in formation and with depth, in order to be sure to refer the acquired data to the desired section, it is important to use an open hole packer to insulate the last section of the well (typically 10-20 m) and pressurize only it.

The new LOT was performed, using an 8 ½" swallable packer. It was set at 2585 m and LOT was executed about 60 hours after the packer RIH.

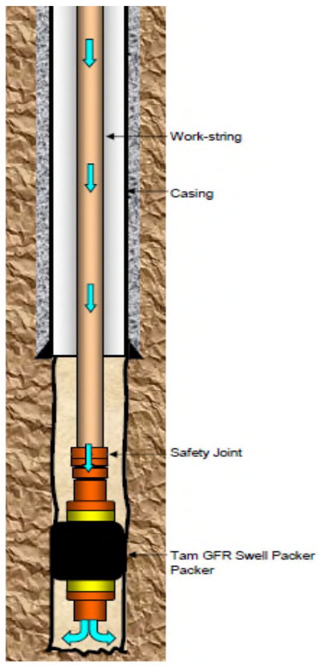

Figure 1 : Swallable TAM packer assembly

This kind of tool, developed in partnership with TAM, has a high-temperature elastomer that swells when is in contact with hot fluids and is able to seal the annulus in any open or cased hole application. So, when the packer is RIH it has a diameter lower than the open hole and starts to grow when it is set in placement. Initially the fluid circulation is kept for some hours before to stop it in order to reach the complete swelling effect that is faster as higher is temperature. Swellable packers have also the opportunity to grow even more than the nominal open hole diameter, allowing to be anchored also when a caving effect is present.

The LOT gave a fracture pressure of the formation at 2685 m of 513 bar. Taking in account the results of the LOT, it was decided to stop deepening and proceed to set the 7" casing, dividing it in 3 sections. The deep liner was placed with shoe at 2601 m and hanger at 2299 m. The intermediate liner was placed with the tie-back at 2299 m and the top at 1409 m than the column was reintegrated up to the surface. In agreement with the project assumptions, an important activity of design was developed in cooperation with the casing supplier (TENARIS). In particular, the casing string design was designed to produce fluid (steam) in supercritical condition a final temperature at well head of 300°C. Moreover, for the design it was considered the presence of a very corrosive fluid, with a high content of H_2S and CO_2. The stress check string design was realized using a specific software. Casing strength calculations has been based on API Bulletin 5C3. Thermal yield de-rating has been used for load cases at elevated temperatures.

The possible presence of H_2S, potentially in high concentrations, could lead to sulphide stress corrosion phenomena especially during drilling stages in which system temperature cools down due to the mud circulation. For this reason, in order to be on safe side against any short term catastrophic failures, material selection for 9 5/8" and 7" casings could be restricted to full sour services grades (L80 or T95). Nevertheless, being the compressive load the "governing load", it was necessary increase the grade of the steel in the tie-back section. Particularly, the TN125SS™ material was chosen to its elastic behaviour with the compression load applied during the model running. Against, this steel grade was not full sour but it could be utilized with the presence of H_2S if the environmental temperature was greater than of 80°C.

Furthermore, the fact that the well could be producing for few days only (testing period) suggested that CO_2 corrosion phenomena typically taking place in a long time frame, could be disregarded.

Connections for the production casing (7") were metal-to-metal seal, in order to avoid any elastomeric inner part and to ensure gas seal even under high pressure. In particular TSH BLUE DOPELESS were chosen for the application. In the end, the chosen casing string was:

- 7" Liner in T95 with TSH BLUE DOPELESS connections (metal seal connections)
- 7" intermediate liner and tie back in sour service steel grade TN125SS™ with TSH BLUE DOPELESS connections (metal seal connections).

The entire column had been completely cemented using Thermalock™, a particular slurry developed in partnership with Halliburton for this specific project.

Based on the expected static temperature profile and the simulations for 9 5/8" liner and the 7" liner, it was proposed that cement be cured at 199°C to simulate placement and then subsequently tested after exposure to 450°C for seven days to test its resistance at temperatures similar what might be experienced when producing from 3000 – 3500 m depths.

From these tests, Portland cement should not be used. In fact, silica is deleterious to the stability of high alumina cements at temperatures exceeding 300°C, its mechanical properties drastically fell after the exposure at 450°C. Due to this, it was abandoned as solution for the slurry design.

Instead, Thermalock™ blend shew good results in tests after high temperature exposure. However, it had to be tested also its behaviour coupling high temperature and pressure.

For this reason, other tests were designed with the ovens and autoclaves that were available in Halliburton Laboratories. In particular:

Wet curing at 371°C (ambient pressure) and following exposure at 310 bar (at ambient temperature);

Combined wet curing at 250°C and 310 bar with further dry curing at wet at 550°C and ambient pressure.

This kind of tests could provide more detailed and reliable information about the behaviour of mechanical properties and chemical composition changes of the slurry, allowing also to vary the blend composition and its density in order to identify the best solution.

These tests shew that Thermalock™ was able to resist to the compressive and tensile strength in so hard conditions, the most similar to real well conditions that could be simulated in Laboratory.

On the column of 7" casing string was placed a well head 7 1/16" with rating API 10k. Due to the extremely high expected temperature, the choice of the well head equipment required an important preliminary study in order to consider the de-rating resistance of the materials in such conditions.

Well head equipment have been object of study by Enel Green Power that has been defined the best well head quality/cost compromise act to find the right equipment to operate in safe in these conditions.

The purpose of the Descramble project was to verify the existence of supercritical fluids with an unknown chemical composition. Due to this, being the possibility to encounter a potentially corrosive fluid, it was decided to realize the base flange of corrosion high resistance material. At the same time, an overlay of alloy was realized on the parts of the valves and spool crossed by the fluid.

4. DRILLING PHASE 6"

Collars, cement and shoes of both section of casings were milled and drilling continued with a 6" smooth BHA, that was used also to drill a short section of open hole. At 2616 m a new LOT was realized and at 2620 m it was registered a static log (temperature build up). At this stage, the MPD (Manage Pressure Drilling) equipment was set to guarantee the best safety condition in terms of well control. The most important parts of this system are the RCD (Rotating Circulation Device) and the Coriolis's flow meter. The flow meter can detect all the minimum difference between flow in and flow out, and trough the RCD, MPD's software controls choke valves and regulates the Surface Back Pressure. This action allows keeping the pressure balance at bottom hole, working into the set point range. The 7100 RCD Bearing Assembly API 2000 was installed above the 7 1/16" BOP stack.

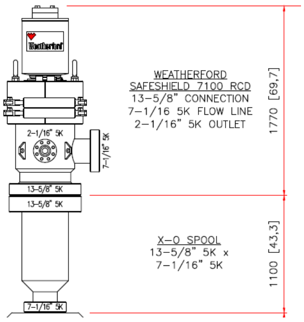

Figure 2 : RCD bearing assembly

Figure 3 : Automatic choke with Coriolis' flowmeter

In this 6" phase, working with 3 ½ DPs, the circulation flow rate was low, causing a very high working temperature at bottom hole. In such conditions, the risk to damage the elastomer of the bits increased significantly. Therefore, proper studies involving bits manufacturers were developed in order to choose the best solution to drill the 6" section across the H and K Horizon. The chosen one was the PDC Full Stinger type provided by Smith.

This type of bits, named StingBlade™ bits, had a Stinger conical diamond elements across the bit face designed to significantly increase footage and ROP in tough-to-drill formations. In particular, this kind of bits have not elastomer inner parts, being only metallic, so they are able to operate with extremely high temperatures. Due to this, a quite long working life was expected for this kind of bits.

The chosen one bit has six blades with the cutters elements on the surface of the blades.

This type of bit was already tried in an Enel Green Power well few years ago. The results had been great, the bit increased ROP in the "Filladi di Boccheggiano" formation so, seeing the high temperature and the hard working conditions, it has decided to try again this type of drilling bit.

Figure 4 : StingBlade™ 6" bit

Two StingBlade™ 6" bits have been used in the Graphitic phyllites, obtaining very good performances both in terms of ROP (higher than 5 m/h) and durability. They were used to drill about 300 m, from 2620 to 2900 m.

The great result has been due to the match between the characteristics of the formation and the type of the bit.

At this stage water was substituted with sepiolitic mud and specific weightener called Microdense™.

The mud was cooled in a plate type heat-exchanger by means of a glycol/water mixture which in its turn is cooled down by two radiators with electric driven ventilators. The glycol/water mixture was circulated through the radiators and heat-exchanger by means of an electric driven centrifugal circulation pump.

The circulation pump will be used to pump the ethylene glycol mixture through the plate heat-exchanger and radiators in a closed circuit system. This system had the purpose to control and manage the drilling fluid temperatures, allowing to maintain the maximum mud out temperature below 90 °C. In such case, mud boiling was avoided, decreasing also the safety risks for the operators.

Figure 5 : Mud cooling system

Mud early origin an important rise in WH pressure when circulation was stopped and the well was shut in. In fact, especially for high mud density (1.5 kg/l), it had a big thermal expansion in case of circulation stop and consequent thermal recovery. Problems occurred after the break due to the running out of the string. When the circulation restarted in fact, the fluid was circulating with difficulty and it has been necessary pump Microdense™ and water based pillows to improve the rheological characteristics of the fluid maintaining the same fluid weight. Afterwards the mud density has been increased up to 1.6 Kg/l against a possible overpressure but problems about circulating got worse: the mud weight gain made difficulty the fluid management. A very important issue of very high bottom hole temperature occurred, causing operative problems in the mud use. In fact, it had a very high thermal expansion, avoiding the possibility to get the Shut In Pressure stabilized, with huge problems to apply the standard well control Driller's Method. It has been necessary to find a way to continue drilling safely so it has been decided to decrease the mud weight to 1.5 Kg/l. Even in such conditions important problems of stuck pipes occurred.

Due to this, many problems were experienced in the application of the standard well control procedure by means the use of the Driller's Method. However drilling continued with mud of 1.5 kg /l density, with return of circulation, using a 6" Full Stinger Bit, obtaining a high ROP value up to 2695 m, depth of the first stuck pipe for differential pressure.

Because it was not possible to release the BHA by jarring and pull up, the density was decreased up to 1.35 kg/l and it was pumped a special additive able to break the mud's panel. As soon as the drilling started again, at 2708 m the well goes into TLC, after stabilized with a small absorption and at 2709 m there was a second stuck pipe. In order to decrease the differential pressure between the well and the formation, the mud present into the well was fully displaced by pumping water to decrease the hydrostatic pressure, in that situation no losses were present. Clearly, this obliged to review the well control procedures, because of the lower fluid density. When the BHA was free, the drilling continued with water up to 2721 m with total return of circulation. Pressure tests were performed in order to estimate the absorption increasing the WH pressure.

In order to try to increase the formation resistance and reduce the risk of losses, various squeeze of clogging materials and barite were performed, with the purpose of clogging the absorbent zone, but after each job, the pressurization tests gave negative results.

Drilling started again with water and controlled parameters, with the purpose of reach the final depth of 2900 m. The Geothermal centre of excellence calculated that, considering the K horizon at 3000 m, and the mechanical characteristic of the formation at this depth, 2900 m with 100 m of residual formation above an over-pressured zone at 450 bar are the safe limit. Beyond that depth the risk of underground blow out would increase dramatically.

At 2830 m of depth a core was performed (9 m), after that a series of static temperature logs, using instruments both of ENEL and CNR property were performed.

At 2900 m of depth a further core was realized (9 m), after that a static temperature log was performed. With the purpose to realize a new LOT a 6" swallable packer was run in hole and set at 2898 m, however the attempt to anchor the tool failed, so the packer was pulled out after many hours of waiting and some verifies.

In the end a last static temperature log was realized using a SINTEF tool.

At this point, it was decided to proceed with a temporary mining closure of the well.

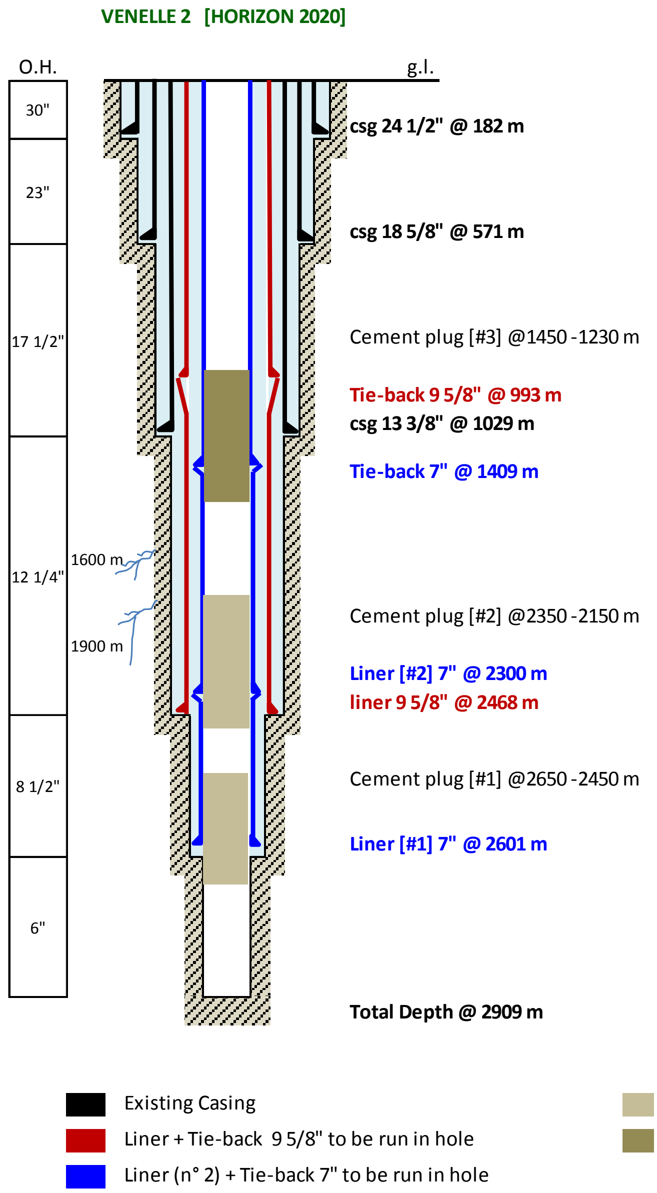

Figure 6 : Final well profile

5. CONCLUSIONS

Nevertheless, the drilling activity resulted in a relevant operative success, improving dramatically the geological knowledge of the deep part of the Larderello geothermal system and providing valuable scientific information.

Copious new technology were tested in this project, many of those were designed specifically for that application in partnership with the main drilling contractor worldwide. Most of the solutions existing in the drilling market belonged to the Oil and Gas environment. Never before an amount of resource like in this case was allocated searching new solution or developing existing technology for a geothermal application.