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Innovative Reeled Drilling System: Enabler of "Factory Drilling" for Onshore Geothermal Applications

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ABSTRACT

Despite the differences in size and sustainability between the O&G and geothermal sectors, they both face similar challenges. These challenges are nearly identical when drilling long horizontal or inclined sections, or drilling in hard and abrasive formations. This is why a development team led by the authors of this paper has partnered with Petrobras, one of the world's largest national oil companies, to develop a Reeled Drilling System for their planned ultra-deep offshore wells. The Reeled Drilling System leverages the benefits of coiled tubing (CT) deployment, which allows for tripping speeds 3-4 times faster and reduces manual handling hazards compared to standard drill pipes. Previously, the limitations for coiled tubing drilling were the torque and weight capacities of the reeled pipe. These limitations are addressed by an innovative Downhole Anchor and Drive unit, which provides torque isolation and axial thrust capability downhole close proximity to the drill bit as opposed to at the surface with conventional drilling methods. The system can be further enhanced by integrating innovative drill bits, such as combined electro-mechanical 'hybrid' plasma-assisted drill bits. The core elements of the Reeled Drilling System under development can be adapted for onshore geothermal applications. In such cases, the technology could facilitate "factory drilling," ideal for high-volume drilling operations and repetitive complex well designs essential for engineered geothermal reservoir management. The system offers significant benefits for high-temperature geothermal applications, including continuous circulation to maintain downhole tools within the desired temperature range. Additionally, high-speed wireline communication improves drilling efficiency and decision-making capabilities. The multi-year development contract was signed in June 2024, and this paper summarizes the achievements of the first project year.

1 INTRODUCTION

Reservoir Independent Geothermal Energy (both Enhanced / Advanced Geothermal Systems - EGS / AGS) wells and deepwater pre-salt wells present some of the most technically demanding drilling environments in the world. These wells are characterized by:

- Extreme total vertical depths; in the case of pre-salt wells multiplied by a necessity to be drilled from 6th / 7th generation drill ship in >2,000 m water depth
- Hard carbonate or crystalline formations that are abrasive, can be fractured, and are considered very challenging to drill cost effectively
- Very slow Rate of Penetration (ROP), often 3–5 m/hr, particularly in the 8.5” section
- Frequent drill bit wear, requiring multiple trips to replace that adds time and cost
- Shock and vibration and drilling dysfunctions e.g. stick-slip, whirl, and axial loading resulting in high wellbore friction and - in the case of ultra-deepwater drilling from a vessel -poor vessel heave compensation
- Lost circulation, especially in fractured formations, necessitating cement squeezes and the inclusion of additional drillstring tools such as circulation subs
- Steep well costs driven by rig rates, inefficiencies, and long tripping times – 43% of well drilling time can be spent tripping

To address these challenges mainly in offshore pre-salt wells, the multi-year Reeled Drilling Project was initiated with the goal of relocating drilling control and force application to the Bottom Hole Assembly (BHA) and utilizing a disruptive and innovative rock destruction mechanism. This is achieved through three innovative components:

- Downhole Anchor and Drive (DAD) unit which allows high Weight on Bit (WOB) to be applied locally within 200ft of the drilling bit and allowing drilling torque to be reacted into the borehole walls rather than along the drillstring.
- Reeled pipe drillstring and associated deployment system for 8.5in hole size, which eliminates connection-related flat time and simplifies tripping.
- Optional electro-mechanical drill bit, which reduces cutter load, increases efficiency of the mechanical drilling process and potentially extends bit life.

Together, these innovations promise a step-change in drilling performance, if associated challenges are properly addressed.

2 CHALLENGES

The Reeled Drilling Project should resolve typical limitations of Coiled Tubing Drilling (CTD) that typically constrain its current use to shallow or slimhole operations (e.g. mineral exploration and well sidetracks) rather than full-depth geothermal or deepwater wells. Teodoriu and Falcone (2011) state several CTD limitations in the context of hard-rock drilling. The most relevant are:

- Limited WOB - Unlike conventional drill pipe, CT is usually a smaller diameter, continuous steel coil that tends to buckle under compressive load. This greatly limits how much WOB can be applied to the bit before the tubing starts to buckle and lock up. In hard crystalline rock, insufficient WOB leads to poor ROP, since the bit cutters cannot efficiently engage the formation. Historically, CTD has compensated for the lack of WOB by using high bit rotation speeds (with downhole motors) to improve ROP, but this is an imperfect solution for hard rock and accelerates bit wear
- No Rotary Torque from Surface - CT cannot be rotated from surface, so it cannot transmit significant rotary torque to the bit. All torque must be generated downhole by drilling motors or turbines, and the CT string can only passively endure the reactive torque. Based on Brillon (2007) this means drilling torque is limited, and importantly, the inability to rotate the string makes it more likely to get stuck and more difficult to free .The lack of surface rotation and resultant “slide drilling” mode tends to reduce drilling performance and directional control due to higher levels of drillstring to wellbore friction when stationary vs rotating. Any reactive torque that does develop in the string can also lead to dangerous torsional oscillations, as CT’s elasticity allows torque to build up and release suddenly.
- Directional Control: Steering a wellbore with CT is inherently more difficult. Conventional directional drilling often relies on rotating the drill string to orient toolface or to reduce friction between the drillstring and the wellbore. With CT, the directional bottom-hole assembly (BHA) must function without continuous rotation of the string. While there are CT-compatible directional tools (e.g. downhole orienters or rotary steerable systems sized for CT), they are constrained by the small tool diameter and the need for specialized /control systems e.g. hydraulic orienters that require hydraulic supplies from surface. As a result, achieving precise trajectory control and adequate dogleg capability in hard rock has been problematic. Based on Brillon (2007), directional CT wells have typically been limited to small hole sizes and shorter reach, which is insufficient for many geothermal targets
- CT Fatigue and Depth Limitations: The CT string undergoes repeated bending as it is spooled off/on to the working reel and into/out of the CT injector, causing cumulative metal fatigue. Each trip in/out consumes fatigue life, and the high tensile strains and circulating pressures encountered in deep wells exacerbate this problem. Fatigue limits and the risk of string failure impose a practical depth limit on CTD – historically on the order of only a few kilometers. Additionally, the small diameter of CT limits the achievable depth due to friction and pressure losses in the long, narrow conduit. As a result, conventional CT units have struggled to reach the depths required for commercial geothermal wells. This has been a fundamental barrier for deploying CT in deep geothermal projects.

Given these constraints, innovative downhole solutions are needed to unlock CTD for geothermal applications that require long, large diameter boreholes (8.5in hole size and above) to be drilled cost effectively through very hard rock . The project´s focus is on overcoming the lack of WOB and torque capacity in CTD. The introduction of the DAD eliminates reliance on surface-applied WOB and surface torque, delivering up to 30,000 lbf axial thrust to the BHA and 14,000 ft-lbf torque anchoring into the formation per gripping unit. It is possible to multiply this capacity by integrating more gripping units into BHA. The Reeled Drilling Project is centered around this component which was originally designed as a torsional anchoring tool and tested in a shallow test well as stated by Whitfield (2023).

3 METHODS

The Reeled Drilling Project is a multi-phase development program led by authors of this paper in collaboration with Petrobras, South American national O&G operator and supported by a network of commercial and academic parties. The project´s concept was described for the first time by Lines (2024). Its objective is to develop a fully integrated reeled pipe drilling system capable of delivering transformational performance improvements in offshore wells - particularly in deepwater pre-salt formations. In parallel to this, the development team works on its customization and deployment for onshore geothermal wells. A visualisation of the system in onshore conditions is shown in Figure 1.



Figure 1. Autonomous Coiled Tubing Drilling System for Long Geothermal Wells with DAD system zoomed in the bottom right corner. Lines (2025).

The program is structured around three primary development phases:

- Phase 1: Conceptual design, feasibility analysis, requirements development, and early experimental testing
- Phase 2: Full-scale subsystem prototyping, factory acceptance testing, and subsystem testing in a simulated lab-based environment
- Phase 3: Targeting onshore integration and full-system field validation in provided onshore test well with associated drilling infrastructure.

The project offers fundamentally different architecture than conventional drilling techniques, with the potential to:

- Eliminate drilling dysfunctions like stick-slip via stable downhole anchoring as explained by Wisinger (2025)

- Apply significantly more WOB and torque than is possible with conventional string weight transfer and allow for faster drilling with further reach
- Improve bit life through deeper, more consistent cutter engagement and optimized drilling dynamics
- Enable automation and real-time downhole control through power and telemetry
- Maintain downhole temperature in a sensible range by continuous circulation

Reduce total drilling days through a combination of higher ROP, fewer and faster trips

Primary objectives of the recently concluded Phase 1 were:

- Establish and verify conceptual designs aligned with clients' application-specific needs
- Define comprehensive functional requirements and interface requirements for each subsystem and establish a cohesive vision for the commercial offshore integrated marine Reeled Drilling System.
- Identify and de-risk critical areas through analysis, simulation, and early lab-scale tests
- Create an initial Product Integration Plan and Infrastructure Requirements Plan for later phases

During Phase 1, components of the Reeled Drilling System were developed and tested using different test procedures and methods. These components are shown in Figure 2.

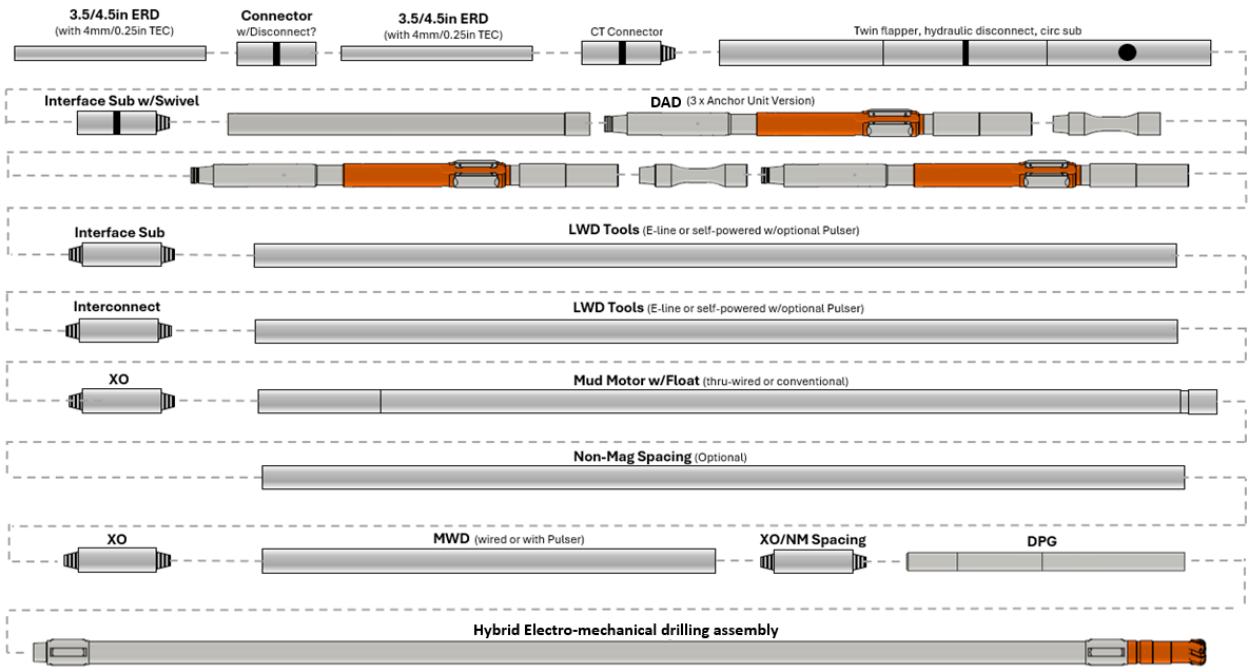


Figure 2. Main sub-surface components of Autonomous Coiled Tubing Drilling System. ERD-Electrified Reeled Drilling; LWD-Logging While Drilling; MWD-Measurement While Drilling; DPG-Downhole Power generator.

Key components of the system enabling deployment using CT are CT-BHA Connector and Mid-String CT Connector. Both are shown in Figure 3 and their functionality is described in Lines (2025).

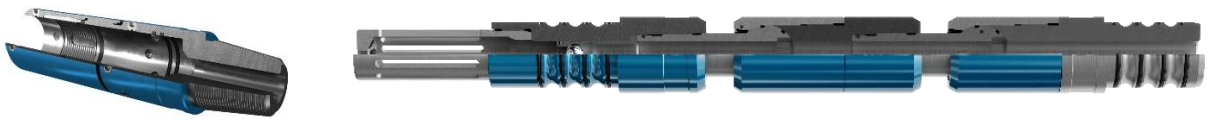


Figure 3. CT-BHA Connector (left); Mid-string CT connector (right). Lines (2025).

3.1 DAD Concept Design

DAD´s (shown in Figure 4) main parts are gripper housing and smart shaft that integrates a range of electrical and hydraulic control and actuation modules that are all housed in the up-hole (UH) end of the assembly.

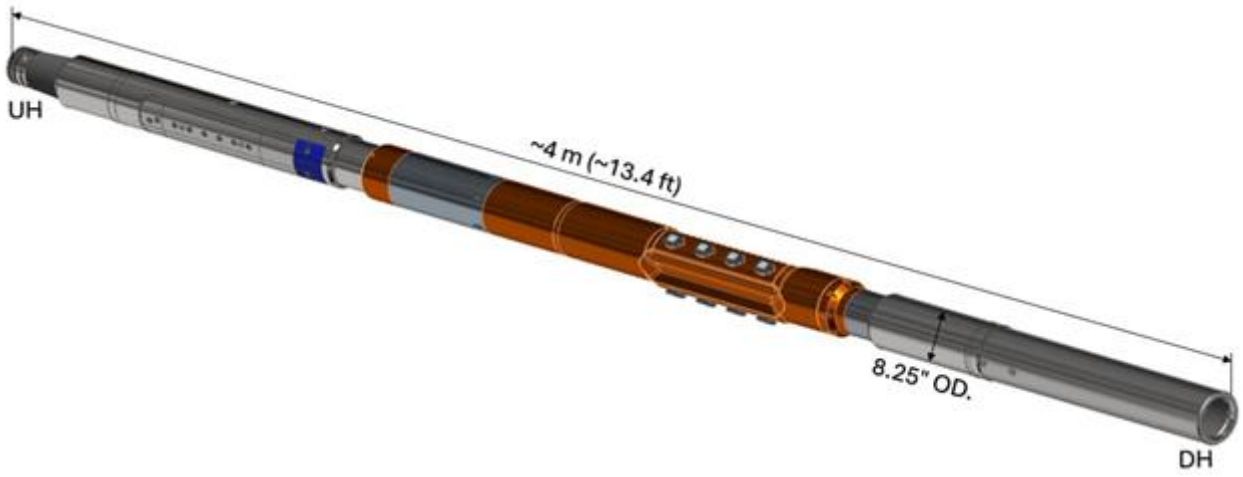


Figure 4. DAD´s Assembly.

The radial bearings guide and constrain relative motion between the gripper housing and the smart shaft, allowing the shaft shown in Figure 5 to rotate (in the non-CT version of the tool) and slide within the housing as needed for deployment and retraction.

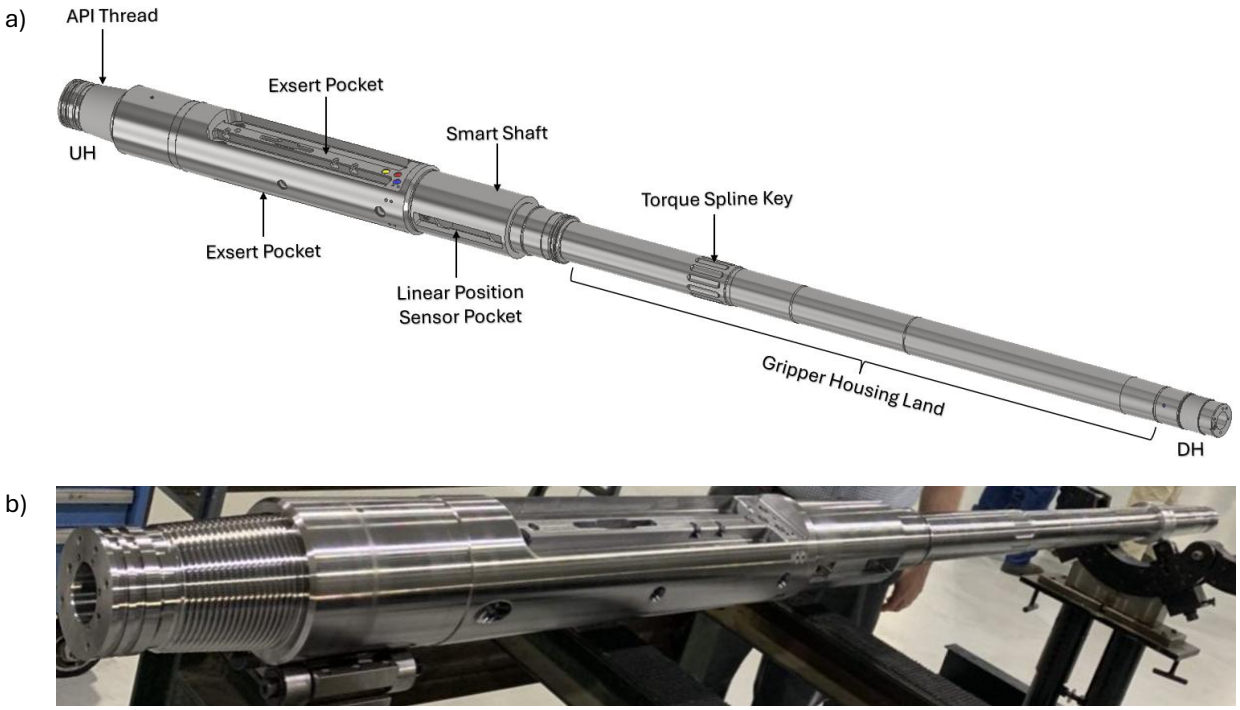


Figure 5. a) Key parts of Smart shaft; b) manufactured Smart shaft.

Each Anchor Unit incorporates hydraulically energized gripping elements. Figure 7 illustrates two design approaches: piston-style and blade-style gripping elements. Each design offers distinct advantages and trade-offs in terms of performance, reliability, and manufacturability.

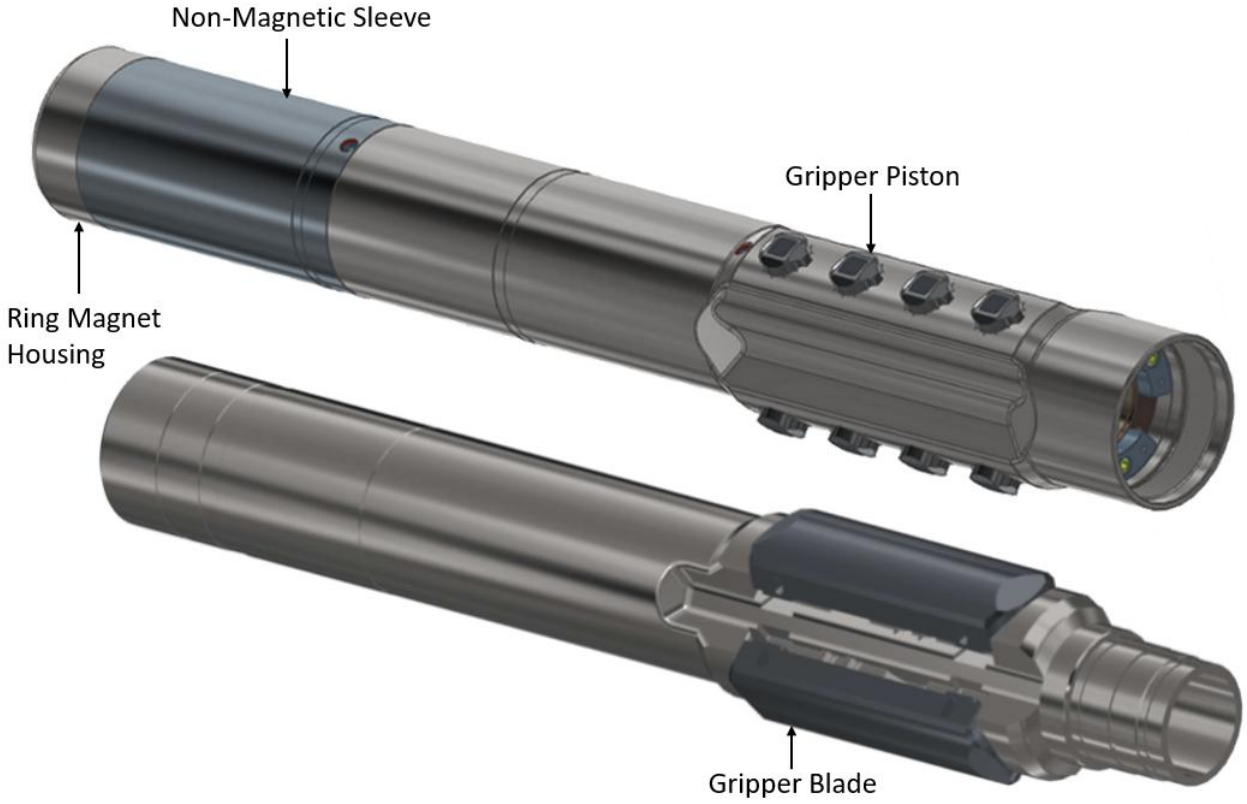


Figure 6. Gripper Piston and Gripper Blade.

The Anchor Unit is lubricated using drilling fluid, following the same design principles as mud-lubricated bearing packs found in conventional drilling motors. This ensures efficient operation and extended service life in harsh downhole environments. The manufactured Anchor Units are shown in Figure 7.

a) b)

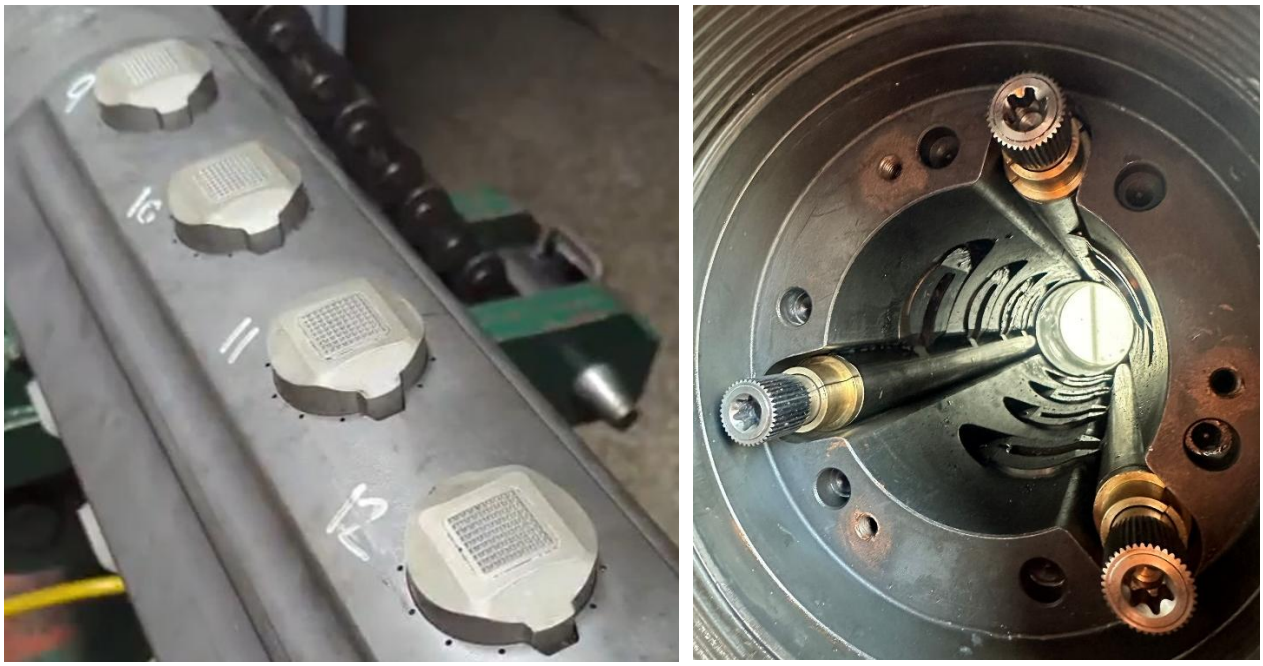


Figure 7. a) External view on manufactured Anchor Unit; b) Internal view on manufactured Anchor Unit.

A small amount of drilling fluid 4 GPM, or less than 1% of the total flow at 400 GPM for all Anchor Units combined is diverted from the internal bore of the BHA into each Anchor Unit. This diverted fluid is used to expand the gripping elements and generate axial thrust to push or pull the BHA via WOB Chamber or pull out of hole (POOH) chamber, after which it is expelled to the annulus.

The system is designed to operate within a bore to annular pressure drop range of 500 to 3,000 psi, with a target value of 1,500 psi. These pressures are typical for a BHA configuration consisting of a drill bit, drilling motor, and MWD/LWD system. The flow of drilling fluid into the gripper and thrust chambers is precisely managed by electronic control assemblies located within each Anchor Unit. These assemblies operate rotary valves that open and close internal hydraulic pathways. The electro-hydraulic actuation and control system adjusts valve positions in real-time to control the force output and movement of the Anchor Unit.

Each Anchor Unit is designed with a fixed range of axial movement, allowing the housing to move back and forth along the central shaft. The maximum stroke length is approximately 200 mm. Once the housing reaches the end of its stroke, the gripper elements automatically disengage, and the housing is hydraulically retracted to its initial position, where it re-engages with the wellbore to begin the next thrust cycle.

Each Anchor Unit is equipped with smart electronics and sensor feedback systems that coordinate the movement, gripping, and thrusting sequences to ensure synchronized operation across all units. This coordination is essential for delivering continuous and stable axial thrust to the drill bit and maintaining consistent movement of the BHA. Each unit currently integrates up to five pressure transducers, distributed as follows:

- One transducer for each of the three hydraulic circuits: thrust down, gripper actuation, and thrust up.
- One transducer for measuring internal bore (ID) pressure.
- One transducer for measuring annulus pressure.

This sensor configuration enables precise control and real-time monitoring of hydraulic performance. However, it is anticipated that the number of pressure transducers may be reduced in future tool iterations, as system understanding improves and sensor fusion techniques or optimized control algorithms are implemented. The position of the Gripper Housing on each Anchor Unit is monitored using an innovative patent pending non-contact magnetic linear position sensor. This sensor tracks the motion of the gripper housing on the central shaft and, when the Gripper is engaged with the borehole, the measurement is a good indicator of ROP. The sensor is accurate to the sub 1mm level and therefore gives a very high resolution, near real-time measurement of ROP that can be utilized for control purposes.

Many of the DAD testing work packages have been performed using a dedicated test frame specifically designed for evaluating downhole drilling equipment. This test frame is described by Lines (2025) and consists of two 60ft long beams braced together, with bespoke carriages and bulkheads mounted between them to secure the test assemblies. The test frame can apply axial, torsional, bending, fatigue, and vibration loads. From the extensive testing matrix we have chosen tests confirming ability of DAD to apply thrust during gripper piston actuation.

3.2 Test of DAD applying thrust during gripper piston actuation

The main objective was to verify key DAD operations such as WOB, POOH, and gripper piston actuation. The target was set to achieve continuous axial force WOB of 30,000 lbf as well as ROP of 150 ft/hr. (200mm stroke in 15.75 seconds). DAD system contains a manifold block which distributes hydraulic fluid from the inlet port, through the rotary valves (shown in Figure 8), to the thrust and gripper pistons, and then out to the outlet ports.

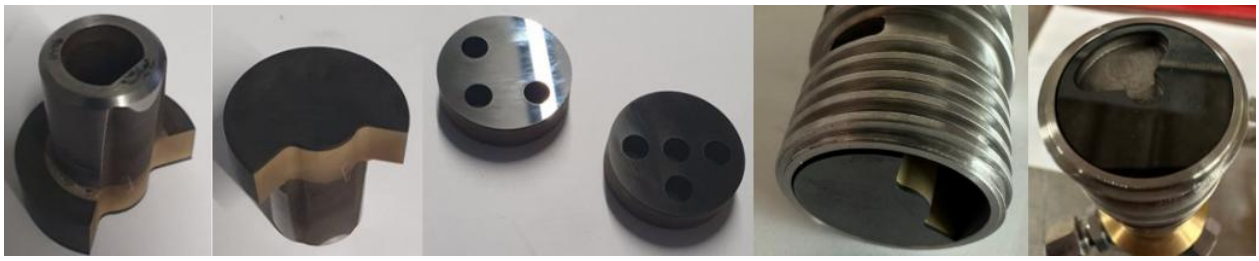


Figure 8. Rotary Valve Carbide Components.

The testing confirmed that the thrust and gripper pistons are sufficiently pressurized and vented as expected when the rotary valves were actuated. Pressure Response vs. Valve Position Variation is shown in Figure 9.

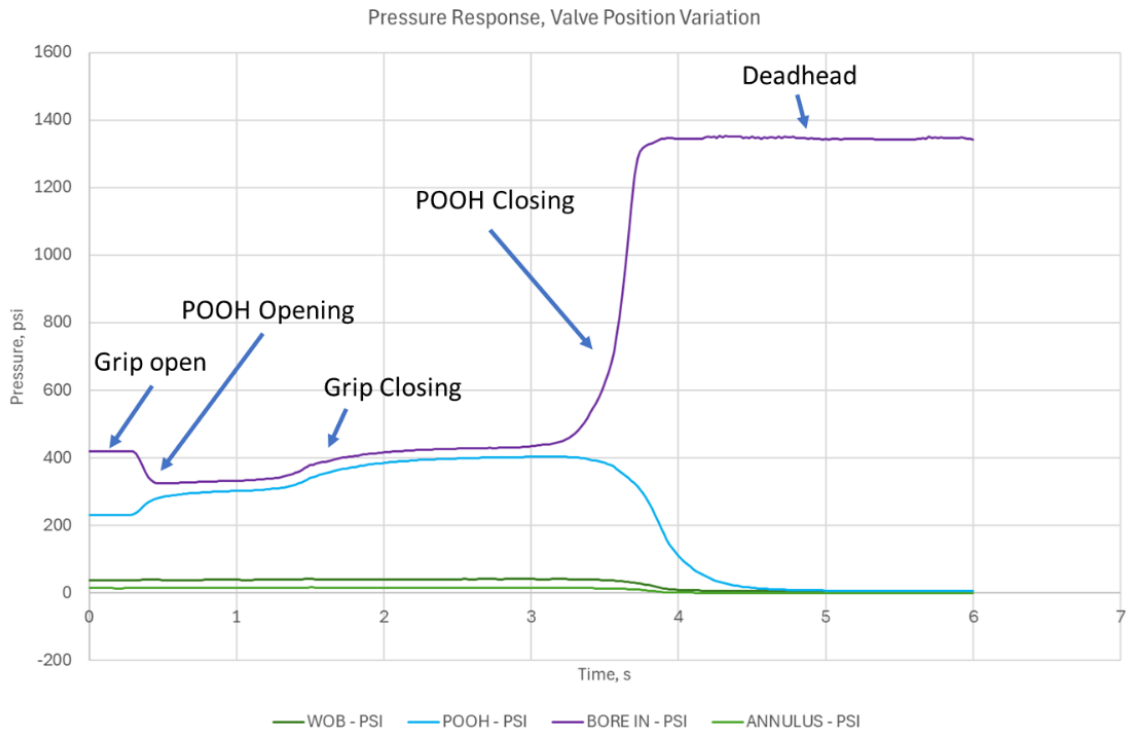


Figure 9. Pressure Response and Valve Position Variation.

The controller precisely controlled the thrust piston to specification with a 1,500-psi pressure drop. The piston achieved its full 200 mm stroke, exerted 30,000 lbf against the reacting system, and completed the 200mm stroke. The Gripper was confirmed to achieve 1" inch of extension at max extension. The control system successfully modulated the reacting piston's velocity by superimposing a sine-wave signal at instantaneous changes in ROP. The reacting control system confirmed that all sensors interfaced seamlessly with the data acquisition system, enabling reliable data capture as shown in Figure 10.

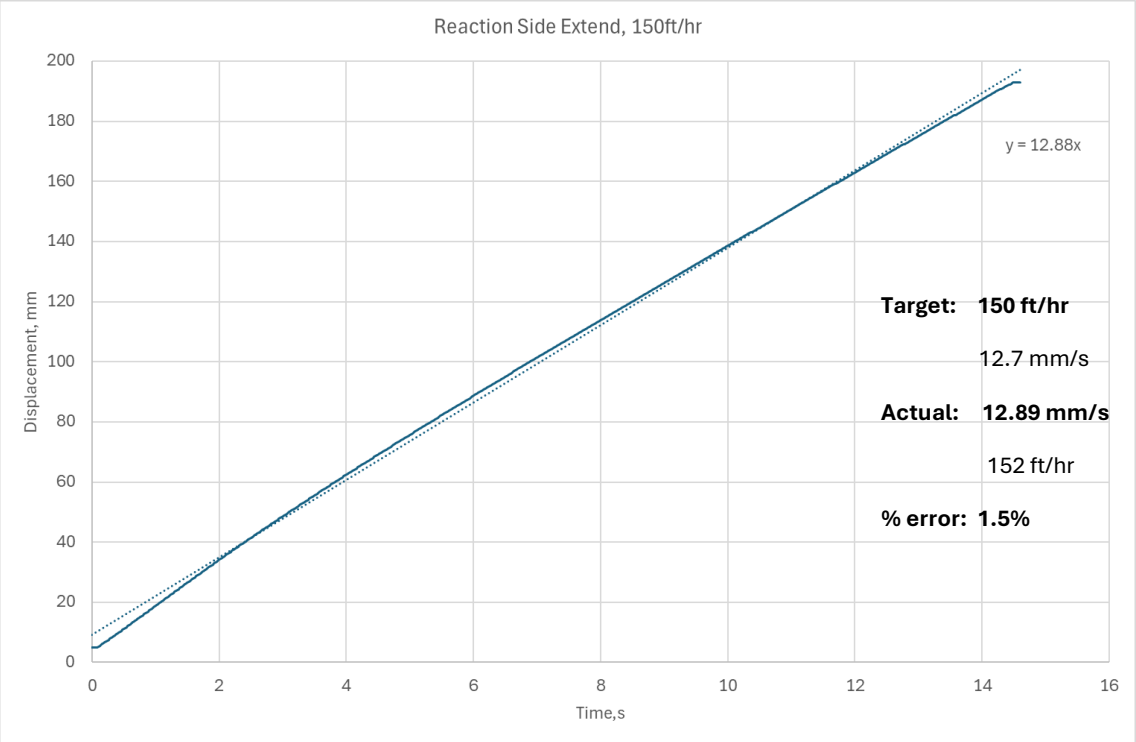


Figure 10. ROP Verification Test for 150 ft/hr.

4 RESULTS

The ability to test the critical elements of the DAD control and actuation system early in the development is essential to de-risk the project and confirm the fundamental ability of the hardware and control system to react as fast as necessary to control and optimize the drilling process. 21 prescribed tests were successfully completed, and the test rig performed according to specifications. The thrust piston delivered 30,000 lbf over a 200 mm stroke under a 1,500-psi pressure drop confirming ability to achieve 150+ ft/hr ROP. The gripper piston consistently achieved full 1" engagement.

5 DISCUSSION

The presented results are just a small sample of the whole testing matrix of DAD within the Reeled Drilling System. The pre-commercial version of DAD tool passed all necessary tests and is under assembly as of November 2025 for a drilling campaign in 2026 in challenging hard rock conditions in Norway. Beyond this, there are several geothermal projects in Europe and North America where the DAD tool should be piloted as stated in Jacobs (2024). This stage should serve as a confirmation of field operability of DAD and enabling its integration into the CTD system.

Once DAD is fully integrated within Reeled Drilling System, it can be a foundation for the Factory Drilling Concept (FDC) which originates from the idea of transferring manufacturing principles—standardization, automation, and high-throughput efficiency—into the process of well construction. Instead of treating each well as a standalone project, factory drilling envisions a continuous, repeatable, and scalable operation in which multiple wells are drilled sequentially or in parallel using standardized designs, specialized rigs, and automated systems. The objective is to achieve consistent performance and minimize the variability, downtime, and learning curve that traditionally slow down geothermal drilling campaigns.

In geothermal development, well construction is the single largest contributor to project cost, often representing 40–60% of total capital expenditure. Much of this cost stems from the custom nature of each well, lengthy mobilization and demobilization cycles, and inefficiencies arising from manual operations and variable geological conditions. FDC mitigates these challenges by focusing on process optimization rather than one-off performance.

By applying uniform well designs, repeatable drilling procedures, and modularized surface infrastructure, each subsequent well benefits from the operational learning and efficiencies of the previous one. The result is a step-change in drilling productivity, like the efficiency gains achieved in shale oil and gas developments through pad drilling and batch operations.

In practice, factory drilling for geothermal applications would involve the deployment of a mobile, integrated drilling unit - such as a Reeled Drilling System - designed to rapidly drill, complete, and move between wells with minimal reconfiguration. The system would operate continuously, maintaining a steady rhythm of drilling, completion, and relocation, much like an assembly line. Standardized BHAs, real-time data acquisition, and automated control loops would allow optimization of drilling parameters across wells, creating a feedback-driven operation that continuously improve efficiency.

A CTD system is particularly well suited to this model. Its rapid tripping speeds, compact footprint, and elimination of drill pipe connections significantly shorten the time between wells. When coupled with intelligent downhole tools—such as DAD, which provides autonomous downhole thrust and torque management—the system can maintain consistent ROP and performance in hard rock formations without constant surface intervention. This downhole autonomy enables operation with fewer interruptions and allows one team to manage multiple drilling units in parallel.

Furthermore, factory drilling emphasizes surface process integration: dedicated mud systems, power generation, and control modules are designed as standardized skids that can be quickly connected or disconnected during rig moves. Data from each well is aggregated into a central monitoring platform, enabling predictive maintenance, performance benchmarking, and drilling automation algorithms that progressively refine parameters with each successive well.

6 CONCLUSION

This paper addressed the persistent barriers to drilling in hard, hot rock for next-generation geothermal wells and deepwater pre-salt environments - low ROP, vibration-driven dysfunction, repeated trips, and the inherent WOB/torque limits of conventional CTD. We presented a reeled drilling architecture that relocates force application and control to the bottom-hole assembly and centers on the DAD unit. By reacting torque into the

borehole and delivering high, local WOB, DAD directly targets the root causes of poor ROP and instability in hard formations while CTD eliminates connection time and supports continuous circulation.

Phase 1 of the multi-year program established the system concept, requirements, and test methods, with a deliberate focus on de-risking DAD as the enabling subsystem. Extensive testing was conducted using a custom test frame capable of applying axial, torsional, bending, fatigue, and vibration loads.

Thrust Test During Gripper Piston Actuation was chosen to represent the extensive DAD´s testing matrix. The goal was to validate key DAD functions—WOB, POOH, and gripper actuation. The thrust piston achieved the full 200 mm stroke under a 1,500 psi pressure drop, delivering 30,000 lbf as required while the gripper extended to 1 inch at maximum. All sensors communicated effectively with the data acquisition system, ensuring high-quality measured data.

These results, together with the completed integration plans for Phases 2–3, support advancing to full-scale prototypes, environmental qualification, and onshore system validation. The pre-commercial DAD tool is assembled for a 2025–2026 hard-rock campaign, with additional geothermal commercial wells planned in Europe and North America.

Once integrated, the Reeled Drilling System provides a practical pathway to factory drilling in geothermal: standardized well designs and BHAs, rapid tripping, continuous circulation, autonomous downhole thrust/torque control, and centralized data/automation for closed-loop performance improvement across many wells. The expected impact is a substantial reduction in drilling days through higher, more stable ROP and fewer trips; improved safety from reduced manual handling; and materially lower well costs - the dominant component of geothermal CAPEX.

Acknowledgements

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