Novel "Directional Steel Shot Drilling“ – technology from Canopus Drilling Solutions B.V. – Preparation and results of an extensive lab and field test

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Summary

Directional Steel Shot Drilling" (DSSD), a novel directional drilling technology developed by Canopus Drilling Solutions B.V., offers an innovative solution to enhance the productivity and cost-effectiveness of geothermal drilling. Conventional drilling often faces uncertainties related to reservoir quality, primarily due to low permeability in the reservoir area. The DSSD technology allows for the construction of multilateral wells and innovative "closed loop systems". Multilaterals can tackle the challenges of reservoir heterogeneity by enhanced reservoir contact. The same technology can deliver cost-effective closed loop system utilizing the advanced steering principle. Hence, DSSD delivers solutions for shallow, medium, and deep geothermal projects. It combines conventional mechanical drilling action with the impulse of pressure accelerated steel shots. The steel shot action can be controlled with respect to the orientation of the drilling bit resulting in a novel rotating directional drilling system that simplifies the creation of complex borehole geometries. As part of the EU GEOTHERMICA project Canopus’ DSSD technology underwent extensive lab and field testing and a prototype for a live well test is under development.

In a very ambitious but productive first year of the project, Canopus Drilling Solutions B.V. laid the foundation for the system's development, created initial concepts, and built a prototype. Extensive laboratory testing and optimizations were conducted in collaboration with Well Engineering Partners (WEP) and the Rijswijk Centre for Sustainable Geo-Energy (RCSG) of TNO under laboratory conditions. A field trial took place in the Hagerbach test site (VSH) in Switzerland, led by ETH Zurich in cooperation with WEP, SCHENK AG, WellGuidance, TorqueWavez, SiG and the University of Calgary. Two directional wells were drilled using the DSSD technology and surveyed to examine system performance, borehole quality, and control mechanisms.

The obstacles to the first commercial implementation of the deployment concept are diminishing due to a carefully planned path taking manageable but challenging steps in terms of progress versus risk. These steps mark the way via additional field trials towards well-managed and successful deployments in geothermal projects of varying depths.

1. Introduction into a novel Directional Steel Shot Drilling (DSSD) Technolgoy

The Canopus "Directional Steel Shot Drilling" (DSSD) – technology represents an innovative combination of alternative rock breaking mechanism and a novel rotary steerable system (RSS). It offers improved functionality compared to conventional drilling methods through the directional steel shot drilling technology in combination with a mechanical Polycrystalline Diamond Cutter (PDC) drilling bit. Development of such new technology requires a detailed plan together with a carefully chosen team and experienced partners to cover all aspects of drilling tool development. This plan is the base of a series of checks, tests and trials leading to a novel but reliable and fit-for-purpose drilling system.

The Canopus DSSD technology comprises following technical components:

Fig. 1: CANOPUS PDC-bit

- During the drilling process, rock destruction is achieved by the erosive effect of a fluid jet loaded with steel shots. The steel shots are expelled at high speed from the nozzles of a special Steel-Shot-Jet bit or a modified PDC drill bit, (see Fig. 1) at the lower end of the drill string.

- The Steering sub, integrated into the lower part of the drill string, and the steel shot injection unit (SIU) including the control system (see Fig. 2) are used for directional control. The Steering Sub utilizes the abrasive jet erosion for direction changes by controlling the timing at which higher concentrations of the steel shot particles exit the bit to enhance erosion in the direction of drilling. The SIU provides the steel shot concentration to the drill bit and impact thereby the rate of penetration as well as the maximum built rate that can be archived.

Fig. 2: Surface steel shot injection unit

- A high-pressure pump and a steel shot recovery system are also part of the surface equipment. These units ensure that the drilling fluid circulates in a closed loop with the steel shot and separate the steel shots from the drill cuttings, returning them to the injection system (SIU).

The complete advanced drilling system comprises of the steel shots (#1), the steel shot injection unit (#2), the steering sub (#3) and the Canopus bit (#4); compare Fig. 3.

A detailed explanation of the technology's operation can be found in Jan Jette Blangé, et al 2022.

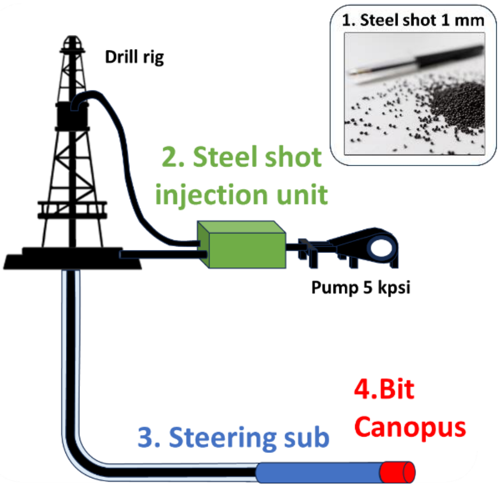

Fig. 3: Components of DSSD-technology

2. Time for a novel drilling technology

DSSD offers a variety of advantages that can make a significant contribution to the successful development of geothermal reservoirs at different depths (see Fig. 4). Projects involving rapid drilling with single or multilateral boreholes in the field of shallow (up to 500m), deep geothermal (between

500 - 4000m), and ultra-deep geothermal energy (over 4000m) can potentially benefit from this technology. This opens previously untapped resources, particularly in the context of the sustainable utilization of geothermal energy.

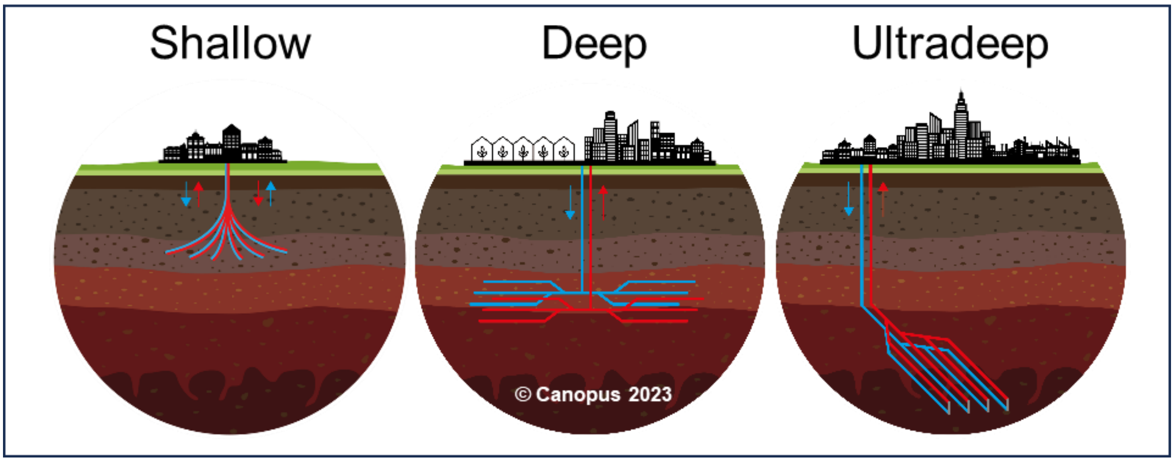

Fig. 4: Geothermal applications

For instance, in shallow geothermal applications, Curved Bore hole Heat Exchangers (BHE) with a length up to 450 m can be utilized with producing three times more heating/cooling than standard, much shorter vertical BHEs (TNO, 2022)/ (Frank Michels, 2021). The Canopus design has the benefit to require just a small footprint and enables drilling of high doglegs in soft formations. This allows to access large subsurface volume with less BHEs, reduced overall construction cost, and a higher energy efficiency per BHE.

DSSD has an excellent drill rate performance in any rock type. The mechanical forces on the drill bit are much lower than required for conventional PDC-drilling. Beside that it reduces vibration of the entire drilling string and the wear of and torque on the drill bit due to lower weight on bit (WOB). The overall concept of the technology enables precise at-the-bit directional control, formation independent steering for short radius well bores, the creation of a sidetrack in the open borehole without the need of cement plugs, and, furthermore, a very high drilling progress while steering. All those points are favorized for the construction of highly productive reservoir sections which are longer to be drilled and may include multiple branches like the multilaterals for deep geothermal projects. Beside the beforementioned technical advantages especially the technology's ability to handle high temperatures makes it suitable for i.e., challenging drilling ultra-deep projects into carbonates or the basement.

In consideration of all technological aspects, the drilling process becomes significantly more economically attractive compared to conventional drilling methods.

3. Lab test at the Rijswijk Centre for Sustainable Geo-Energy (RCSG) of TNO in the Netherlands

3.1 Aim of the laboratory test program

GEOTHERMICA project DEPLOI the HEAT - The main objective of this project is advance Canopus' DSSD system towards the prototype status by testing the main components separately and as full system in various realistic environment. The project shall **DE**monstrate **P**roduction enhancement through **LO**w-cost d**I**rectional steel shot drilling for **HEAT** production. The foundations for the DSSD system development were established during the laboratory tests at TNO's Rijswijk Centre of

Sustainable Geo-Energy and resulted in the first Field Acceptance Test 1 (FAT1) of the complete system.

The goals of this phase were to assess the performance and functionality of individual subsystems and provide evidence of the complete integration of Directional Steel Shot Drilling (DSSD) technology into an efficient operational and functional system. The lab test program, which commenced in November 2022 and concluded in June 2023, can be divided into four phases, the results of which are summarized below.

3.2 Results

3.2.1 Phase 1 – Bit testing and SIU injection control @ 50t drilling simulator (50TDM)

Fig. 5: RCSG's 50t drilling simulator

In this phase, conducted from November 2022 to March 2023, the focus was on testing the drill bits in the 50-ton drilling simulator (50TDM) (see Fig. 5) and controlling the injection of the SIU.

The SIU injection rate control has been advanced, a comparison between mechanical PDC (Polycrystalline Diamond Cutter) bits and steel shot drilling action has been performed. This phase included the evaluation of different types of steel shots, different bit-nozzle combinations have been investigated, and the impact of rock types and formation pressures on drilling performance was analyzed.

A total of 30 tests were conducted, including both circulation tests (without drilling) and drilling tests in different types of rock samples. Control of the SIU injection rate was successfully achieved, with stability maintained at rates below 400 liters per minute. The addition of steel shots led to increased aggressiveness and enhanced rate of penetration (ROP). As expected, different nozzle combinations, rock formations, and formation pressures had varying effects on drilling performance (see Fig. 7) or borehole gauge (see Fig. 6).

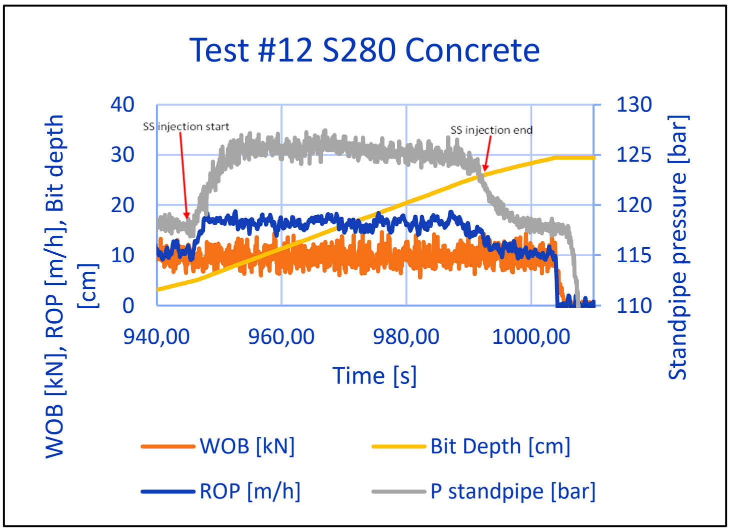

Fig. 7: Test example (Pressure response to added steel shot. Correlation with ROP can also be observed)

Fig. 6: Borehole gauge (50TDM)

3.2.2 Phase 2 - Steering sub testing (horizontal test 1)

Phase 2 aimed to test the functionality of the downhole control unit within the intended operational range for the first field test in the Hagerbach test site. Additionally, an update to the steel shot injection unit (SIU) was implemented to enhance user control and visualization while optimizing response times and automation. Several tests were conducted, with a focus on aspects such as actuator functionality, sensor functionality, and communication with the tool.

The tests included the assembly and pressure testing of the lower part of the control unit, flow tests without steel shots, as well as low-pressure (LP) and high-pressure (HP) flow tests with steel shots. The pressure tests at 300 bar were successful. Flow tests demonstrated communication with the tool and the robustness of the subsurface control unit could be improved further.

3.2.3 Phase 3 – Rig testing (vertical test)

Phase 3 ensured the full-system integration and readiness of the DSSD technology prior shipping to the field test location in Switzerland. The multi-stage experimental program included a risk assessment and the creation of a risk register, preparation of the test area around the test drilling rig at TNO's Rijswijk Centre for Sustainable Geo-energy (see Fig. 8), installation of the test setup, circulation tests, and the retrieval of the downhole Bottom Hole Assembly (BHA), its inspection, and cleaning.

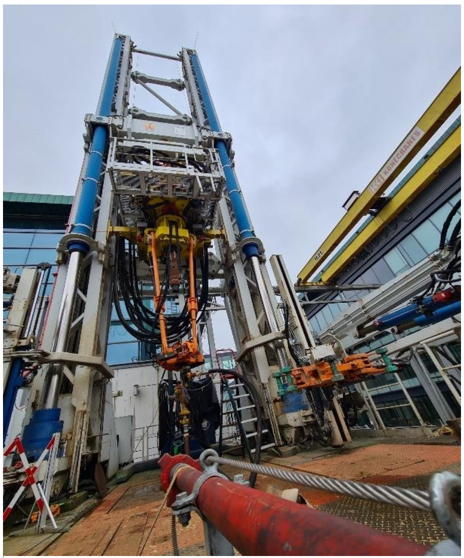
Fig. 8: Rig test at TNO's RCSG

The main objectives included the successful operation and integration of the Canopus systems including rig floor handling and conducting all tests without Health, Safety, and Environment (HSE) incidents.

System integration was evaluated as successful, with no visible wear on the downhole drilling assembly at maximum flow rates. Operational challenges included high-pressure fluctuations, issues related to cleaning steel shots at the outlet, pump failures, and difficulties in maintaining stable injection rates.

3.2.4 Phase 4- Steering sub, DM- and EM-testing (horizontal test 2)

The final phase aimed to demonstrate the readiness of the downhole electronics for the field test. This included the assembly of key components and electronic connections, including the Directional Module (DM) and the electromagnetic (EM) telemetry module/receiver/transmitter. Assembly and communication tests confirmed functionality and operational control. During the lead-up to the field test, the robustness of the control module was further improved.

3.3 Summary

In summary, the laboratory tests at RCSG served to test individual components as well as the entire DSSD technology at full scale. Already in this phase, the advantages of DSSD compared to conventional drilling methods could be demonstrated, and operational envelope for the drilling parameters for the field test were defined. Risks related to the subsurface control unit were identified and mitigated. The automation control of the SIU was strengthened.

It is worth mentioning that the effort required during the entire laboratory testing phase exceeded the initial expectations. This presented challenges, but it is expected that this additional effort will lead to more efficient subsequent phases.

4. Field test in the Versuchsstollen Hagerbach (VSH) / Switzerland

In the next stage of the DEPLOI the HEAT project, the consortium consisting of ETH Zurich, the Hagerbach test site (VSH), SiG, SiL, Grob, TNO, Tullip Energy, University of Calgary, Well Guidance, and Canopus Drilling Solutions B.V. supported by WEP for the project management, tool design & construction and supervision part aimed for the field-testing phase. The primary objective of this phase was to demonstrate that the system is suitable for addressing the next generation of drilling challenges and can potentially contribute to the exploration and assessment of geothermal resources at varying depths.

4.1 Goal of the field test

The scope of this field test includes the deployment of a fully functional Directional Steel Shot Drilling (DSSD) system and its associated components, enabling directional drilling, in the tunnel terrain of the Hagerbach test site (VSH) (see Fig. 9). Two or three horizontally deviated multilateral boreholes (see Fig. 11) with a total length of up to 150 meters each are planned to be performed in a hard limestone formation using a 4 1/8-inch DSSD system. In addition to the steering sub and other internal elements for control electronics and direction control, a variety of external drill string components were prepared for the downhole system (see for example Fig. 10). The string could be modularly assembled or adapted depending on the intended borehole trajectory.

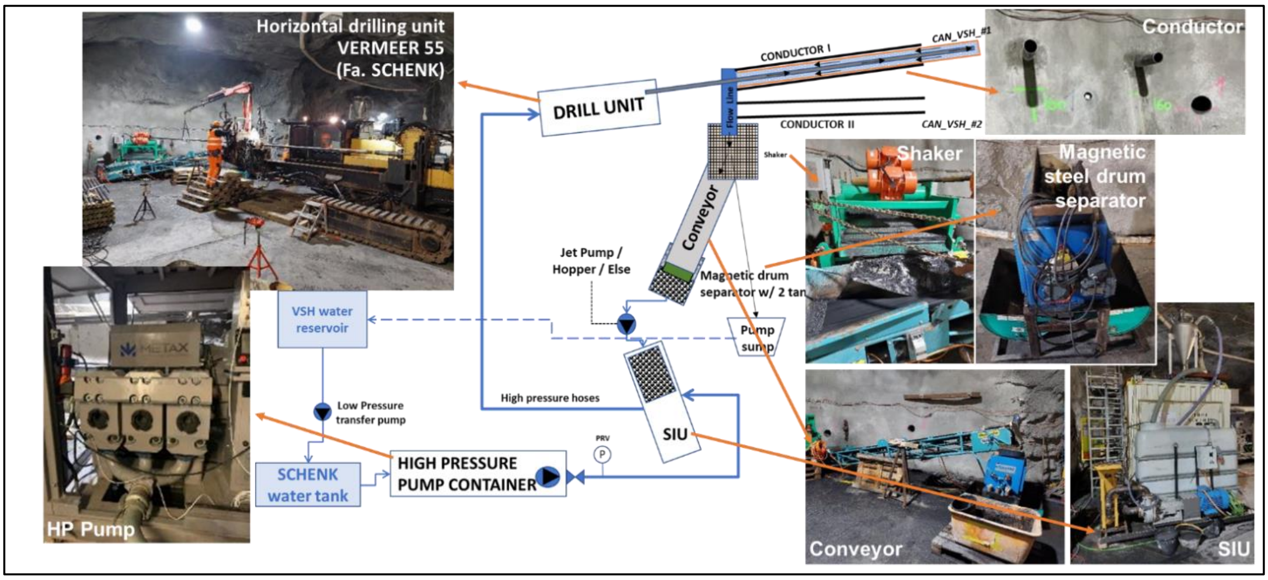

Fig. 9 Surface equipment P&ID / fluid-circulation system

The deflections from the main boreholes are intended to start from a shallow, inclined wellbore and then follow a predefined curvature before continuing straight to form a fork-like multilateral structure (see Fig. 11). The construction of this structure allows for the evaluation of relevant drilling parameters such as the rate of penetration (ROP), the achievable bending radius (known as Dogleg Severity, DLS), control of the borehole trajectory, and challenges related to borehole cleaning.

For this test phase, a drilling rig from SCHENK typically used for shallow horizontal drilling was used in combination with a surface-based overall system as displayed in Fig. 9. The system is designed to handle high pressures of up to 350 bar and is prepared for steel shot circulation. Conducting the test with a horizontal drilling rig allows for the assessment of expected operational performance through system integration, including tool handling, tool communication, handling of steel shots for transport in drilling fluid and separation, and high-pressure requirements. The results will be used for the further development of larger DSSD tools and their implementation in future tests and/or projects.

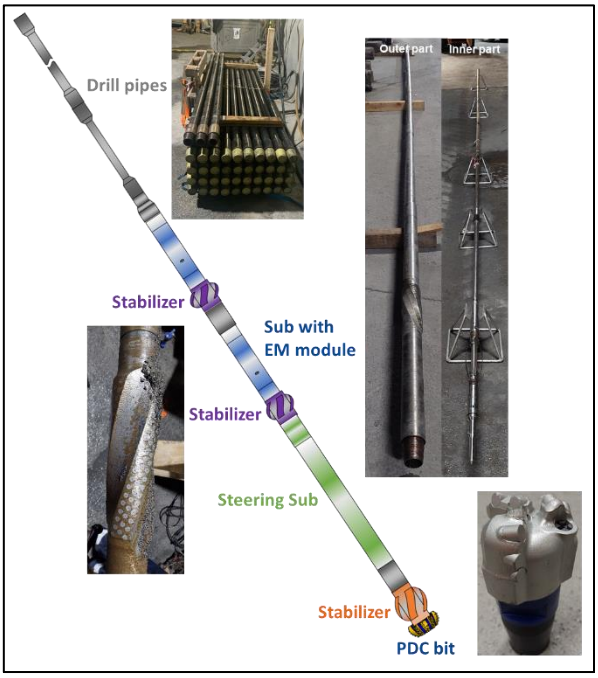

Fig. 10: String Components (Flex BHA)

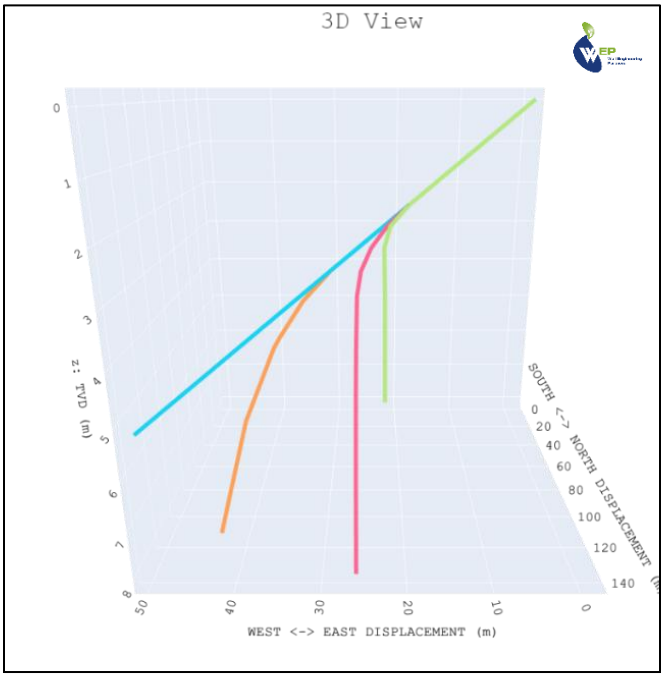

Fig. 11: Planned 3d well path

4.2 Progress report

4.2.1 Week 1

Overall, the first week involved extensive setup of the surface-based system and initial drilling operations. Unexpected challenges arose, leading to equipment and procedural adjustments.

At the end of the first week of the project, several key points were achieved:

- The operation of the drilling equipment and data acquisition (see Fig. 12) for various parameters proceeded smoothly.
- While the setup of the drilling equipment took some time, an optimal configuration was established and continually optimized.
- Checks for bidirectional EM tool communication were conducted, and the electronics of the drilling units were prepared for upcoming tasks.
- Initial drilling operations were carried out, and it was observed that the rock type in the first 25 meters primarily consisted of (softer) shale, necessitating an adjustment in the drilling strategy.

Fig. 12: Control room for data acquisition

Overall, the status at the end of the week indicated that equipment installation and testing were completed, with some tests and checks remaining for the second week.

4.2.2 Week 2

In the second week of drilling operations, several improvements and tests were carried out. These included optimizing and extending the conductor pipe, shaker screen, conveyor belt, and magnetic drum separator to create a more compact and efficient system. Pressure tests were conducted to ensure the performance of the surface system.

Fig. 13: Damaged bit (left) due non-optimal drilling parameters and new (right) drilling bit

Ongoing tests focused on evaluating the capabilities of the steering sub, including actuator performance, sensors, communication, battery consumption, and directional control calibration. During drilling operations, various operational challenges such as formation wash outs, bit damage, inefficient handling, were seen that required further optimization in terms of drilling parameters and operational procedures.

Overall, the second week marked the transition from system setup to operational testing and the learning process of effective drilling with the integrated system.

4.2.3 Week 3

In the third week of operations, several significant developments could be implemented. The most important highlight was the directional drilling with the complete DSSD unit (directional drilling system using steel shots as a means of changing/influencing direction). Evidence of the control effect of the steering sub was observed for the first time. However, communication issues arose due to external noise at the underground test site. These communication problems were eventually resolved by changing the communication frequency.

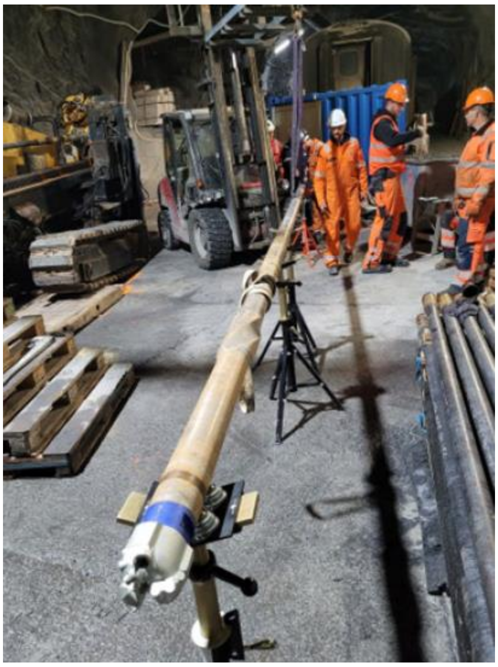

Fig. 14: New BHA – preparations for running in hole. Clearly visible the absence of any external steering aids.

Drilling continued throughout the week, with a focus on testing the entire DSSD system. Several batches of steel shots were circulated through the borehole, maintaining consistent parameters for the steering effect. Initial results showed some steering effect, although limited at this stage. Larger effects are expected in the subsequent tests with increased steel shot injection.

At the end of the week, memory data from both the directional module and the downhole control unit were downloaded and analyzed. The directional data indicated a change in azimuth and inclination, at 5˚ / 30m over a length of over 6m, suggesting active steering. For comparison, an intentional straight section length of 18m was successfully drilled with continuous steel shot injection with reported DLS of 0.3˚ / 30m.

In summary, the third week marked the successful operation of the complete DSSD system, with progress made in exploring its steering capabilities. Despite technical challenges, the team continued to work on optimizing the system and preparing for the most extensive tests in the fourth week.

4.2.4 Week 4

In the fourth and final week of the field test, two drill strings with different components were prepared - one stiff assembly and one flexible. At the end of the third week, a straight borehole of 25 meters in length had already been created as a start. The main goal of the last week was to gather experience with the complete, i.e. above and below surface, DSSD system, use bidirectional EM communication and collect information on various performance aspects of the tools.

During the week, minimal equipment and bit wear was observed after inspection and active steering over significant borehole length could be achieved. On the last day of drilling, higher concentrations of steel shots resulted in significant increased progress rates. Despite challenges in separating drill cuttings from steel shots for steel shot reinjection, the field test was very successfully completed.

In summary, the last week resulted in further experience with the entire DSSD system in a real drilling environment. Due to persisting communication problems with the EM tool no real-time survey data was acquired. Steering was executed with pre-programmed azimuth and inclination settings. The tool memory data highlighted, two successful steering actions with consistent built rates of 6˚ / 30m and 7˚ / 30m DLS over a measured borehole length of 15m and 21m, respectively.

4.3 Specific achievements

4.3.1 System integration

The setup of the Canopus DSSD system and its connection to the Vermeer 55 horizontal drilling unit from SCHENK was executed smoothly but required some unique and specific modifications. Changes were made to the shaker and the steel shot return system to improve solids handling. The high-pressure pump, SIU, surface high-pressure lines, power swivel of the drilling unit, and drill string all performed well and showed no signs of wear due to the use of steel shots. A high-pressure bypass was added to the injection system to effectively control the injection rate.

In the first borehole, some losses occurred, especially when circulating off-bottom and cleaning the borehole before the pump had to be stopped for adding the drill pipe. It was also evident from the subsequent survey of the open borehole area that borehole cleaning and circulation during connection had to be performed with special care and following a specific procedure. The quality of the second borehole including the hole cleaning was significantly better.

4.3.2 Drilling performance

The ROP exceeded expectations, partly due to the softer shale rock, reaching rate of penetration of over 80 m/hour. To test the DSSD system and avoid washouts due to high pressure, drilling conditions were stabilized with reduced system pressure and adjusted WOB.

Inspection of the Bottom Hole Assembly (BHA) showed minimal wear, but the drill bit repeatedly exhibited damage in the midsection of the bit blades due to abrasive quartzite layers crossing the borehole. The BHA was designed to have a neutral directional behavior and showed a tendency of less than 0.3˚ / 30m and a DLS between 5 and 7˚ / 30m was achieved when steering with steel shot action.

4.4 Summary

The achievements of this project in a very short time are impressive and underscore the progress and potential of the technology used:

- All operations were conducted safely and without damage, demonstrating the team's excellent safety performance.
- The successful integration of DSSD into the drilling rig marked a significant milestone in the development of this innovative technology.
- Drilling two horizontal sections, each about 125 meters in length, demonstrated the effectiveness of the system and its accurate directional drilling capabilities.
- Through the strategic use of steel shots, an impressive increase in drilling speed of up to three times was achieved, demonstrating the efficiency of the technology.
- The holding angle in the tangential section within only 0.3˚ / 30m and the ability to steer with 5 to 7˚ / 30m using DSSD technology demonstrate both the stiffness and controllability of the downhole part of the drilling assembly.
- Despite some challenges, adequate hole cleaning was achieved at a flow rate of 600 liters per minute, with the only remaining risk of creating washouts when adding drill string.
- The ability to maintain the normal flow rate and the potential to reduce the pressure to the range of 150-200 bar illustrate the adaptability of the system to different conditions.
- The stability of the SIU injection was successfully ensured using a pulsation dampener and a bypass.
- DSSD proved to be functional with a steel shot concentration of 0.5% and it was recognized that exploring higher concentrations has the potential to improve the performance and lifespan of the drill bit.
- The components of the downhole control unit, including actuators, sensors, downhole communication, and control unit, met all expectations.
- Furthermore, the downhole control unit exhibited low power consumption, with one assembly able to operate for at least 100 hours with a single standard downhole battery module.

5. Conclusions and outlook

A well-prepared plan was followed to bring the project within 1 year from concept design to a successful 4-week long field test. This showed the importance of planning for manageable steps in such complex developments and to use a team that is experienced in development and usage of downhole drilling tools.

Despite some operational adjustments, the novel DSSD technology offers a groundbreaking solution for directional drilling in geothermal projects. It primarily provides a better means of accessing previously difficult or inaccessible reservoir areas and improving productivity.

The tests conducted at RCSG marked a significant milestone in testing the technology under realistic full-scale laboratory and field conditions. Even during these tests, the remarkable advantages of Directional Steel Shot Drilling (DSSD) compared to conventional drilling methods became evident.

Furthermore, the test played a crucial role in determining the operational parameters, required modifications and procedures that should be applied during the subsequent field test.

In this next phase, the insights and progress made in development were put into practice, and the potential of the technology was practically tested in a field test. The field test took place in the Hagerbach test site and spanned over a period of 4 weeks. The integration of various hardware components into a functional drilling unit required teamwork, troubleshooting, dealing with unknown risks, and creativity. Despite these challenges, the team successfully operated the 4 1/8-inch Directional Steel Shot Drilling system, confirmed its steering capabilities and drilling potential, identified various system enhancements for the following 6-inch DSSD system, and, most importantly, maintained safety without harm to the environment.

Overall, the VSH pilot not only demonstrated the performance of a highly motivated and skilled team but also made significant progress in the development and implementation of an innovative drilling technology. This project lays a promising foundation for future developments and underscores the enormous potential of this technology for the drilling industry.

Canopus Drilling Solutions B.V. is ready to face further challenges with its DSSD system, whether they involve additional field tests or explicit field deployments in geothermal projects at shallow, deep or ultradeep depths. Well Engineering Partners, with its broad engineering expertise in supporting the development of new technologies, well engineering, project management, and extensive experience in drilling process management, is eager to continue working with Canopus Drilling Solutions B.V. or other pioneers in advancing novel technologies towards a more sustainable future.

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