Eavor Technologies Inc.

Insulated Drill Pipe Trial Results

FORGE Project

June 2023

Contents

Executive Summary

Insulated drill pipe (IDP) restricts counter-current heat transfer between drilling fluid inside the drill string and hotter returning fluid in the annulus, thereby ensuring the bottomhole assembly (BHA) remains submerged in cool fluid. Eavor has several versions of the IDP in operation, testing, and development. The performance of the IDP in high temperature geothermal settings was successfully tested at Eavor's Eavor-Deep project in New Mexico in Q3/Q4 2022.

FORGE rented 350 joints of IDP which was run in two consecutive BHAs at the FORGE 16B (78)-32 well in May 2023. The objective of the pilot was to demonstrate the IDP's capacity to reduce the BHA temperatures, reduce temperature related equipment failures and observe any potential drilling performance improvement with the IDP.

In the first run, a full string of the IDP was utilized. In the subsequent run, a partial IDP string (~70% IDP) was utilized, with the remaining ~30% comprised of regular non-insulated drill pipe. The benefit of the IDP was empirically estimated (against prior and subsequent bit runs) to be 47-75°F for the full IDP string and 30-55°F for the partial IDP string. This range was validated by thermodynamic modelling.

Eavor regards the FORGE IDP trial as a success, with predicted bottomhole circulating temperatures in-line with expectations and matching the results observed at Eavor-Deep, providing additional empirical validation of the performance of the IDP.

Background

Eavor Technologies Inc. has developed insulated drill pipe (IDP) technology to reach depths and temperatures previously seen as impossible while using conventional downhole drilling components. Previously, the limiting factor for drilling in high temperature geothermal geologies was the temperature rating of different bottomhole assembly (BHA) components such as measurement while drilling (MWD) and rotary steerable systems (RSS), typically limited to 300-350°F. By insulating the drill pipe, the heat transfer between the cool mud travelling down the drill pipe and the hot fluid travelling up the annulus is reduced, resulting in cooler fluid being delivered to the BHA.

Eavor has several versions of the IDP in operation, testing, and development. The performance of the IDP in high temperature geothermal settings was successfully tested at Eavor's Eavor-Deep project in New Mexico in Q3/Q4 2022. A full string of the IDP used at Eavor-Deep is capable of drilling through >750°F resources with downhole equipment rated to 300°F.

FORGE is a US Department of Energy (DOE) funded geothermal research project run by the University of Utah. The DOE hired Eavor to run the IDP for two bit runs in May 2023 as a pilot to test the technology. 350 joints of the internally and externally coated IDP were provided to FORGE for this trial which consisted of different versions, grades and coating types. The pilot's objectives were to demonstrate the IDP capacity to reduce the BHA temperatures, reduce temperature related equipment failures, and observe any potential drilling performance improvement with the IDP.

IDP Trial Operational Summary

Eavor's IDP was deployed in the BHA 11 and 12 which consisted of 100% and ~70% of the total drill string length respectively. For the BHA 12, regular drill pipe was run below the IDP string.

Prior to runs with the IDP

- Eavor understands that while tripping in hole at ~4700ft in a previous run to the IDP deployment, one of the MWD batteries failed under temperature recording of 327°F.
- To avoid damaging external coating of the IDP while pipe handling, the forklift on the drilling rig was outfitted with plastic socks for the forks.

BHA 11 – Full IDP String

- For the first BHA run of the IDP trial, the same BHA as the previous run (BHA10) was used (with a new motor), however the flow rate was increased from 600GPM to 700GPM and mud chillers were initially shut off, providing a change in the wellbore hydraulics and therefore cooling efficiency.
- Towards the end of the BHA 11 run, one mud chiller was brought online, decreasing the inlet temperatures from approximately 130°F to 110°F.
- At 8400ft, mud loggers were reporting that an internal coating of the drill pipe was caught in shakers, with noticeable amount of coating parts in the mud samples.
- Depth in for the BHA11 was 8085ft, depth out was 8585ft.

BHA 12 – Partial IDP String

- After the BHA 11 was pulled out of hole, wireline logs were run, resulting in more time for wellbore thermal recovery (vs. the BHA 10 and 11).
- The BHA performed within expectations, it achieved higher penetration rates and showed a lower building tendency requiring less sliding, even with lower weight on the bit than the previous BHAs, limited by the bit manufacturer to 57 klbs WOB (weight on bit) (vs. 70klbs WOB for the BHAs 10 and 11).
- Depth in for the BHA12 was 8585ft, depth out was 9255ft.
- A different BHA was used for the BHA 12 (vs the BHA 11); the table below highlights the differences between the BHA and drill string.

Table 1: the BHA and Drill String Comparison

	BHA-10	BHA-11 – Full IDP	BHA-12 – Partial IDP	BHA-13
Bit	9 ½" PDC -TKC83	9 ½" PDC -TKC83	9 ½" PDC – D406V	9 ½" PDC -TKC83
BHA + NMDC (ft)	130.84	130.84	132.28	132.33
Drill Collars (DC), (ft)	278.27	278.27	0	0
HWDP (joints)	28	28	28	30

Non-IDP (ft, end of run)	6821.91	0	2378.5	8748.63
IDP (ft, end of run)	0	7317.66	8264.49	0
End of run depth (ft)	8085	8585	9255	9800

Thermal Performance of the IDP

Empirical Results

Figure 1 below shows the measured MWD temperatures plotted against the circulation rate and inlet temperature (Manifold temperature). Other than the level of drill pipe insulation, these two parameters are the primary drivers of MWD temperature variation. The BHAs 8, 9, 10 and 13 used regular non-insulated drill pipe, while the BHAs 11 and 12 used 100% and ~70% of the IDP respectively.

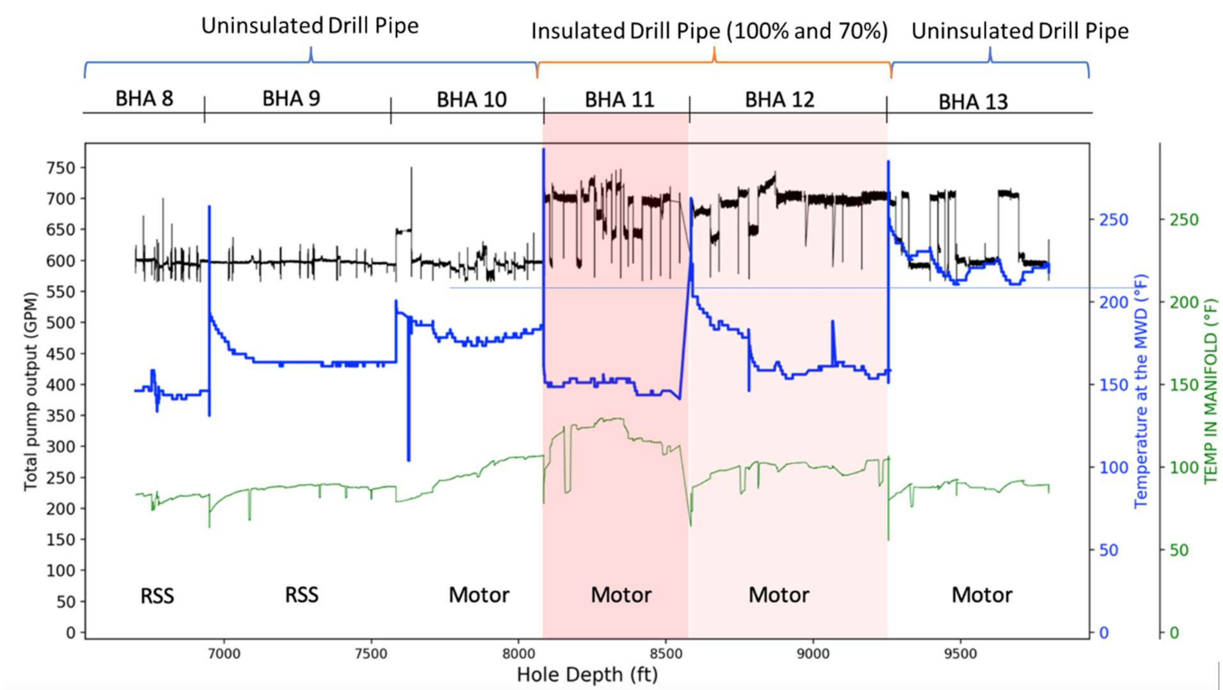

Figure 1: Pump output, Inlet Temperature and MWD Temperature vs Depth

The following sections provide commentary on the measured data outlined in the above chart:

BHA 10 (non-insulated regular drill pipe)

- Average MWD temperature of 180°F while drilling.
- Baseline run to gauge MWD temperatures without the IDP.
- By maintaining a constant flowrate and considering the gradual increase in inlet temperatures, the specific impact of inlet temperatures on MWD temperatures could be isolated for regular drill-pipe. It is estimated that a 1°F change in inlet temperature has an approximately 1°F impact on MWD temperatures.

BHA 11 (Full string of the IDP)

- Average MWD temperature of 149°F while drilling (a reduction of 31°F relative to the BHA 10 without the IDP).
- The same BHA 11 was used as the BHA 10.
- Throughout the entire run, the temperature profile of the MWD measurements remained relatively uniform when employing the full string of the IDP.
- The circulation rates were increased from 600GPM to 700GPM (vs the BHA 10), which does provide an additional cooling effect. However, the BHA 13 run managed to attain nearly identical circulation rates with regular drill pipe, establishing a benchmark for empirically estimating the impact of circulation rate on MWD temperature.
  - The data suggests that 12-14°F of cooling was attributable to the higher flowrate in the BHA 11 vs the BHA 10. See the BHA 13 section below for more detail on the empirical estimation of the impact of circulation rate.
- The inlet temperature was increased from an average of 98°F in the previous run without the IDP to an average of 121°F. Based on the data collected during the BHA 10 which suggests that a 1°F change in inlet temperature corresponds to a 1°F change in MWD temperature, it is estimated that the change in inlet temperature increased MWD temperatures by ~23°F.
- Correcting for different inlet temperatures and flowrates, empirical estimates (from the BHAs 10 and 13) suggest that for every 500 feet of increased vertical depth, MWD temperatures at FORGE rose by approximately 7°F owing to the elevated temperature of the rock (~16°F/500ft geothermal gradient).
- The empirically estimated impact of the IDP alone is 47-49°F for the BHA11 vs the BHA 10, normalized for all variables below, calculated as follows:
  - 31°F observed reduction in MWD temperature.
  - Minus 12-14°F reduction in MWD temperature attributable to increasing circulation rate.
  - Plus 23°F increase in MWD temperature attributable to increased inlet temperature
  - Plus 7°F attributable to drilling through higher temperature rock.
  - Note this empirical estimate neglects the transient MWD temperature profile during initial drilling; thus this factor will increase the relative benefit of the IDP. Therefore, this empirical estimate is deemed to be conservative.
    - See *Temperature modeling by Eavor* Temperature modeling by Eavor which incorporates calibrated simulation results accounting for transient effects.

BHA 12 (Partial string of the IDP)

- Average MWD temperature of 164°F while drilling, with high temperatures observed initially but ultimately leveling off at ~150-160°F.
- A different BHA design to the BHA 11
- Wireline logs were run between BHAs 11 and 12, providing more time for thermal recharge of the near wellbore rock temperatures, a contributing factor towards the higher observed MWD temperatures during initial drilling.
- Higher MWD temperatures during initial drilling were observed with the partial IDP string (70 % in the BHA 12) than with a full string of the IDP (100% of the IDP in the BHA 11). This transient effect can be attributed to the positioning of regular non-insulated drill pipe near the BHA.

    - Initially, the hot fluid from the drill pipe is displaced with cooler fluid from the upper sections. However, the section of regular non-insulated drill pipe near the BHA facilitates high heat transfer between the hot annulus fluid and colder drill pipe fluid, resulting in prolonged higher BHA temperatures.
    - A sharp decline in temperature occurs at approximately 8,700ft when sufficient circulation has occurred to displace the hot fluid from both the drill pipe and annular side of the regular non-insulated drill pipe section.
    - This transient effect is minimized when drilling with a full string of the IDP evidenced by the flat measured MWD temperature profile in the BHA 11.
- The sharp MWD temperature increase between the BHAs 12 and 13 highlights the cooling impact of the partial IDP string, estimated to be 30-55°F.

BHA 13 (non-insulated regular drill pipe)

- Average MWD temperature of 220°F while drilling.
- Baseline run to gauge MWD temperatures without the IDP.
- Inlet temperature was relatively consistent throughout the run, providing a good baseline for estimating the impact of circulation rate.
- The figure below shows a zoom-in of the temperature profile for the BHA 13. The two blue arrows indicate steady state MWD temperatures at 700GPM (both 211°F), while the two red arrows indicate steady state MWD temperatures at 600GPM (225°F and 223°F). This data suggests that an increase in circulation rate from 600 to 700 GPM results in an MWD temperature reduction of 12-14°F.
- The configuration of the BHAs 12 and 13 are very similar, with only 2 extra joints of HWDP (heavy weight drill pipe) in the BHA 13, and an identical PDC bit to the BHA 10.

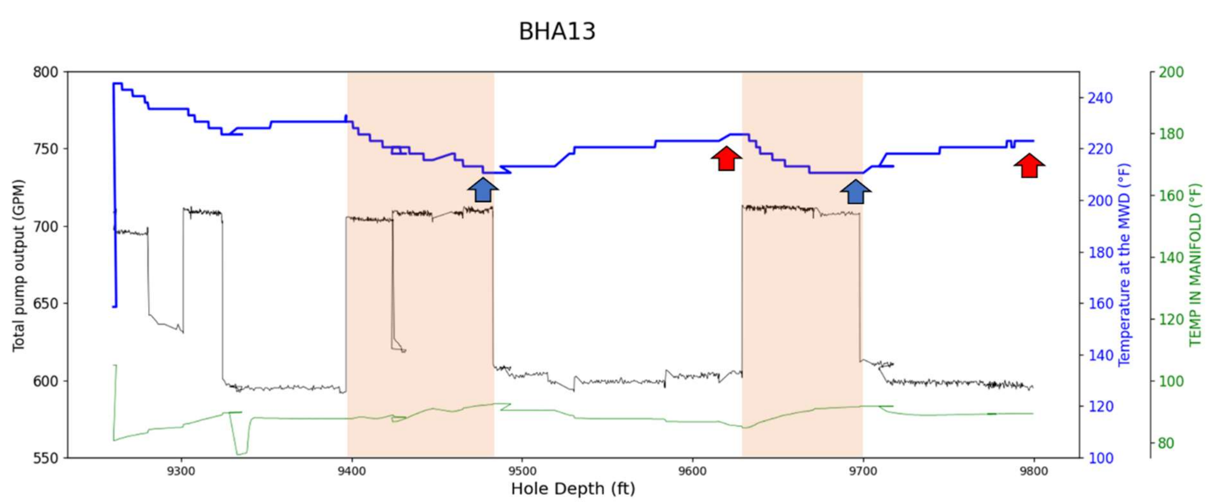

Figure 2: Impact of flow rate on MWD temperature

Temperature modeling by Eavor

Eavor has developed a proprietary transient drilling model to evaluate the effectiveness of IDP and predict the temperature profile along the wellbore, both inside the drill pipe and in the annulus. Inputs to the model include:

- Inlet temperatures, flow rates and pressures were exported from Pason.
- Temperature gradient and geology were estimated from the offset wells.
- Drill pipe thermodynamic properties were measured in the lab (insulated or regular drill pipe).
- Assumptions for mud properties and the BHA as detailed data for each BHA were not available.
    - A water-based drilling mud was used to drill the FORGE well - solids content was minimal (<1%). Modelled as pure water.
    - If provided to Eavor, detailed mud reports and the BHA spec sheets can further improve the match presented below.

The transient model used for this analysis is covered in detail in the "Enablement of High-Temperature Well Drilling for Multilateral Closed-Loop Geothermal Systems", presented at 2023 Stanford Geothermal Workshop.

Figure 3 below summarizes the history match simulation using Eavor's transient model (blue line) plotted alongside the measured MWD temperatures, both with the IDP (green points) and without the IDP (orange points).

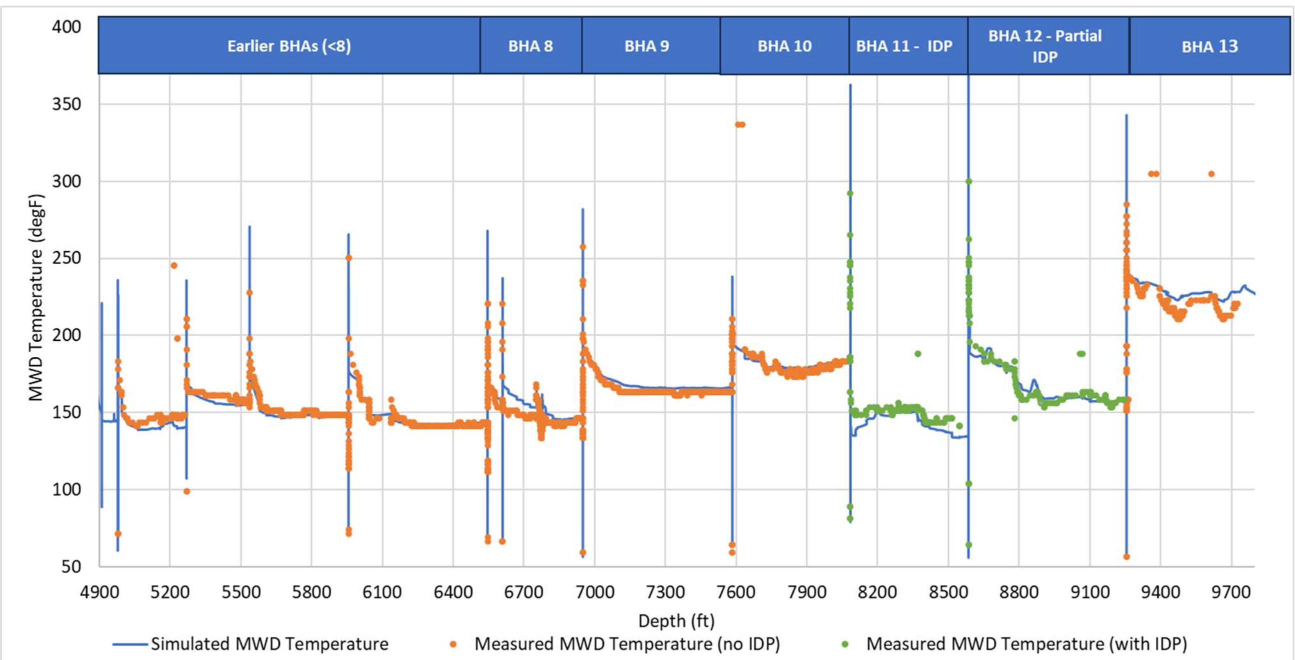

Figure 3: the BHA temperature prediction using Eavor's Transient Drilling Model

The overall match was considered satisfactory, as the predicted BHA temperatures for both insulated and non-insulated drill pipe scenarios closely aligned with the measured values. To assess the impact of the IDP, simulation of the BHA 11 and 12 runs were repeated assuming regular drill pipe properties instead of the IDP. All other parameters were held constant between the simulations. The impact of the IDP is apparent, with the simulation drastically over-estimating the observed MWD temperatures when using non-insulated regular drill pipe (blue line vs. green points in the BHAs 11 and 12).

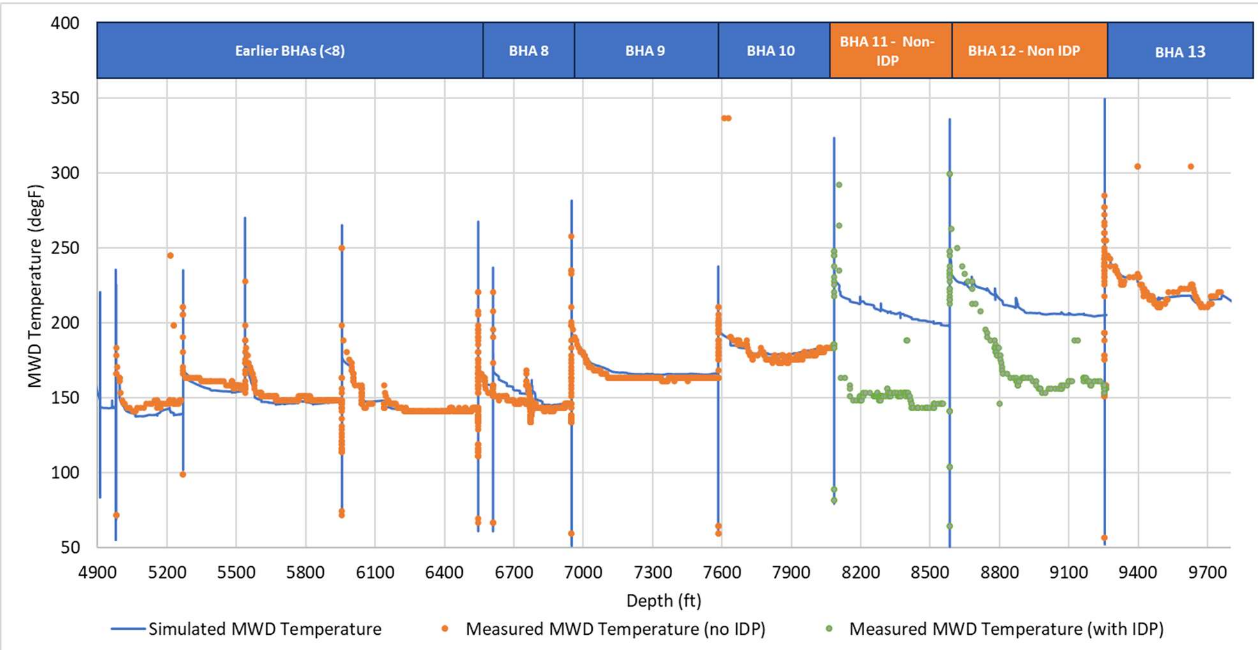

Figure 4: the BHA temperature prediction, assuming non-insulated Drill Pipe

Zooming into the BHA 11 and 12 sections (simulation assumes the non-IDP is used):

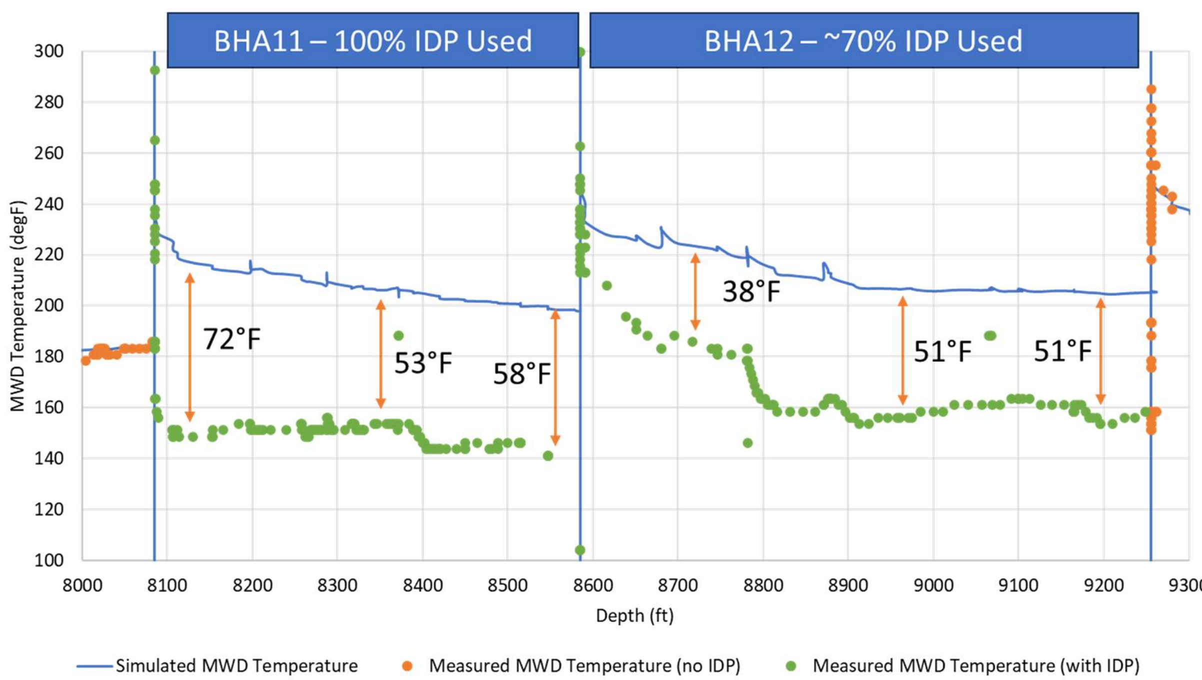

Figure 5: BHA temperature prediction, assuming non-insulated Drill Pipe (zoom into the BHA 11 and 12)

The benefit of the IDP can be quantified by the difference between the measured and simulated curves. The thermodynamic results align with the empirical measurements from the trial, showing the bottomhole circulating temperature impact of a full IDP string to be 50-75°F, and a partial IDP string to be 30-55°F.

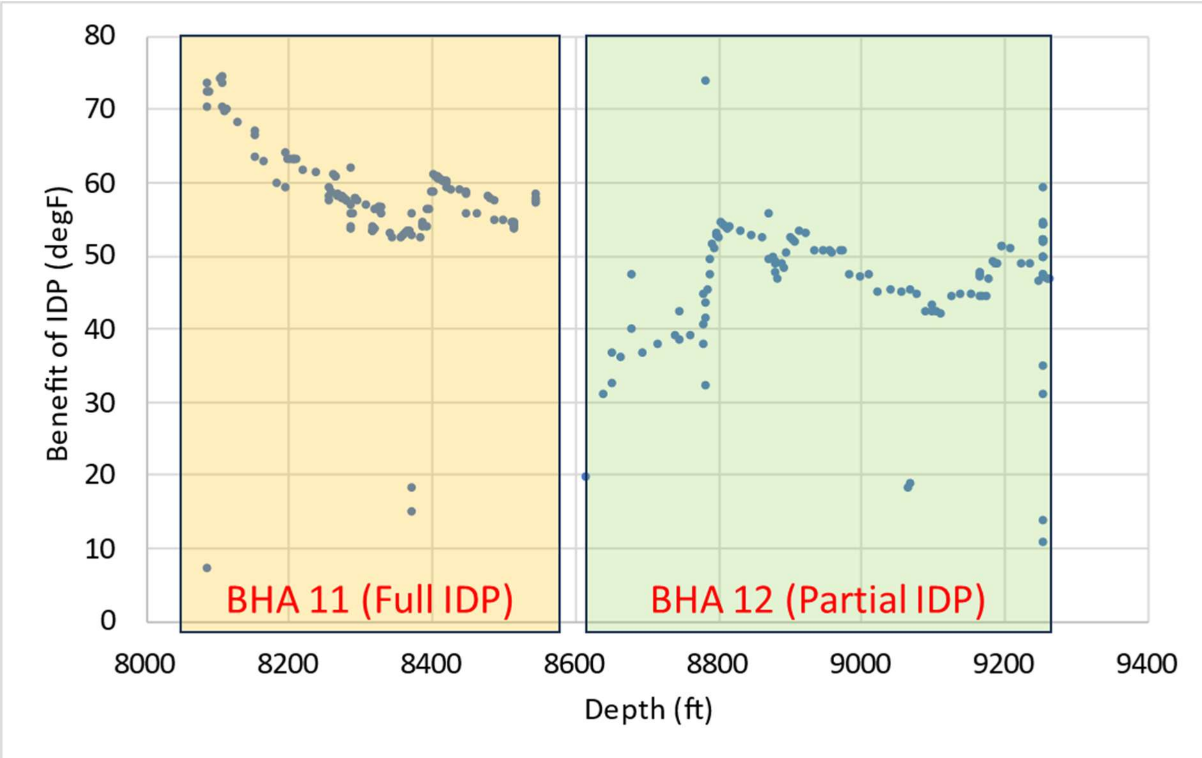

Figure 6: Benefit of the IDP (modelled bottomhole circulating temperature without the IDP minus measured bottomhole circulating temperature with the IDP)

IDP Mechanical Wear

The external coating of the IDP was inspected by Eavor on-site and showed negligible wear from the trial, however, there was minor damage to the internal coating of the IDP on a small number of joints; Small portions of the internal coating delaminated from the steel tubular, but no coating peels were found on the MWD tool or the drill bit nozzles. A subsequent inspection of the internal coating indicated that only few joints were affected by this damage, where applications of a thicker coating were trialed, and accounts for less than 0.01% of the uncoated coverage of the IDP. Eavor is working on solutions to this and improve the reliability of the insulative coating.

Figure 7: Coating pieces caught by the mud loggers

Figure 8: Drill pipe joints laid down with ID coating defects

Additional Benefits of the IDP

During the process of tripping in the hole and at the beginning of drilling a new section, the BHAs face heightened vulnerability due to the lack of circulation, resulting in the column warming up close to the temperature of the surrounding formation. While running in hole, the BHA encounters hot fluid, and without adequate circulation it will warm up very quickly, requiring frequent pauses to circulate and cool down the BHA. If the cool downs are not performed in time, the BHA is at risk of exceeding the maximum design temperatures. Eavor understands that an example of this operational concern occurred at the FORGE well, where while tripping in hole in a run prior to the IDP deployment, one of the MWD batteries failed with a recorded temperature of 327°F. With the IDP, heat transfer between the hot annulus fluid and cold fluid in the drill-pipe is reduced. This improves the effectiveness of a bypass sub (if used) and allows less time to spend on washing-in, thus eliminating the risk of exceeding the BHA maximum temperatures and reducing the time required to trip into the well.

Eavor believes that the IDP technology can lead to improvements in hard-rock drilling performance in high temperature formations through a thermal shock cooling effect. This effect is attributed to the introduction of cold fluid (enabled by the IDP) at the rock face, resulting in differential thermal contraction within the rock volume. Consequently, the rock weakens, leading to a significant increase in the rate of penetration and extended bit life. Due to the influence of numer4ous variables on drilling performance and the absence of a solid baseline run, the data obtained from the two conducted IDP runs do not offer conclusive evidence to either validate or refute the effectiveness of the shock cooling effect while drilling brittle rock. Despite the lack of conclusive evidence from this trial data, Eavor remains confident in the occurrence of this phenomenon, grounded in the fundamental principles to govern it as well as empirically from bench-level testing.

Conclusions

Eavor regards the trial demonstration of IDP technology at FORGE a success. The IDP was empirically proven to reduce the BHA temperature by 47-75°F for a full IDP string and by 30-55°F for a partial IDP string. Eavor's proprietary drilling model integrated measured data from the FORGE trial, along with other drilling and geology data, to accurately estimate the MWD temperatures both with and without the IDP and provide further validation to the empirical data from the trial.

The IDP trial at FORGE has shown that the BHA can be maintained at cool temperatures with the use of mud coolers and IDP alone. The delay in using mud chillers until later (and hotter) parts of the well allows for significant savings due to reduced fuel consumption.