Advances in High Temperature Directional Drilling

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ABSTRACT

Enhanced and advanced geothermal systems (EGS and AGS) are new methods of creating geothermal installations that will potentially increase electric power production by a factor of greater than 10 when compared with more conventional methods. Many such systems are emerging, and they are attracting a lot of funding and excitement. But compared with conventional hydrothermal wells, they are technically challenging to drill. Accurate well positioning, generally including horizontal wells, will be required for the most advanced well designs to succeed. The oil and gas industry can already drill accurate directional wells and this capability is directly transferable to some of the first EGS and AGS wells because they are likely to be drilled at temperatures familiar to oil and gas drillers. But to make EGS and AGS wells more economically interesting, they will need to be drilled at higher temperatures which are currently beyond the capabilities of oil and gas drilling, completions, and production equipment.

Even the claimed 175°C operating capability of oil and gas technologies is challenging for the economics of geothermal drilling because equipment operated at this maximum temperature limit exhibits low main time between failure and/or service. Therefore, the industry needs a step change in its approach to the temperature capabilities of downhole equipment. This presentation will outline just such an approach to the temperature resistance of the electronics and sensors needed.

Showing in detail a new approach to tool design, it will describe how a combination of component selection, a completely reimagined approach to downhole electronics, and multiple cooling strategies will allow measurement and control to be reliably implemented at higher temperatures, initially above 200°C and ultimately as high as 300°C. This will finally make reliable drilling at high temperature a reality and the presentation will conclude by showing results achieved to date during high temperature testing.

1. INTRODUCTION – UNCONVENTIONAL GEOTHERMAL

Although geothermal wells have been drilled for electric power for more than 100 years, since the first power station was built at Lardarello in Italy in 1924 (Clegg and Krase, 2022), the industry has long been associated with hydrothermal reservoirs, whereby hot fluid is found in naturally fractured formations and can be exploited by drilling wells to transport the hot water and/or steam to the surface. Where such reservoirs exist, they can be a very effective source of heat for power generation, but they are not geographically abundant. They tend to be confined to parts of the world where there is heat close to the surface which itself is combined with said fractured formations and water reservoirs. Unless solved, this geographic confinement would prevent the exploitation of geothermal energy for power at a global scale, with only a small number of "lucky" countries benefiting.

Recently, though, the picture has changed. Numerous different styles of enhanced and advanced geothermal systems (EGS and AGS) have been funded, and some have already been demonstrated at pilot scale. Although the design and principle of operation of each style is unique, they all share one binding characteristic: they create an artificial reservoir instead of relying on a natural, hydrothermal one.

Pioneers such as Fervo and Eavor are demonstrating that EGS and AGS can be made to work, with Fervo demonstrating for the first time that electricity can be reliably generated from an EGS well in Nevada in 2023 (Think Geoenergy, 2023).

Although their modes of operation are very different, both companies, and the vast majority of their potential competitors, rely on accurate directional drilling techniques, placing wells a precise distance apart and in some cases connecting them together at the end, many kilometres below the surface. That might seem like an extraordinarily difficult thing to do, but the directional drilling techniques that have been developed by the oil and gas industry over the last 100 years now allow wells to be placed very accurately (Clegg, 2021).

2. UNCONVENTIONAL OIL AND GAS

In a striking parallel with unconventional geothermal, the unconventional oil and gas industry also emerged by creating artificial reservoirs. In this case, the reservoirs were created by fracturing shale, normally thought of as the source rock for conventional oil and gas reservoirs. The most important of the technologies that enabled unconventional oil and gas wells to be drilled at scale were horizontal drilling and hydraulic fracturing. The directional well profiles that will be required to make unconventional geothermal a success are very similar to those used in unconventional oil and gas: increasingly long horizontal sections to maximise exposure of the well to the premium resource. In the case of oil and gas wells, the premium resource is hydrocarbon. In the case of unconventional geothermal wells, the premium resource is heat. Geometrically, the wells look very similar in either case. The most significant difference is temperature, and this will be discussed further in section 5.

The similarity with unconventional oil and gas is important, because of the cost savings that have been made in that industry over the last 15 years. These cost savings should be directly applicable to the unconventional geothermal industry.

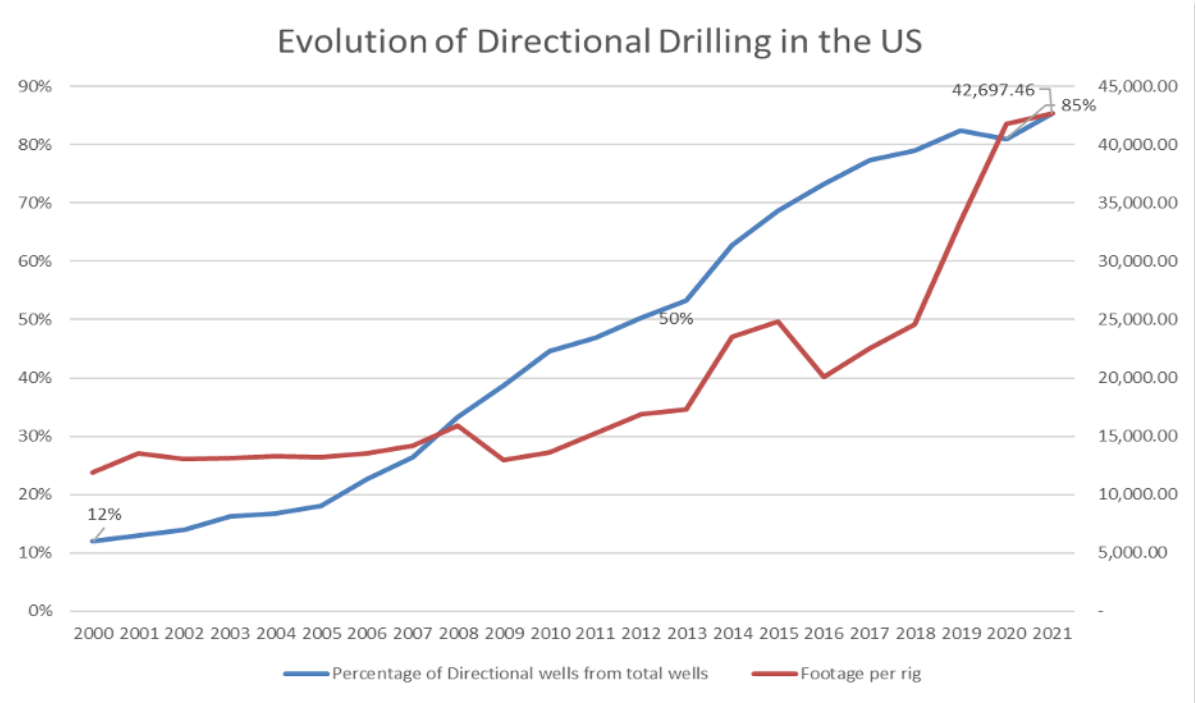


Figure 1: Evolution of the prevalence of directional drilling, and its cost, in the United States.

Figure 1 includes an amalgamation of data from Baker Hughes (bakerhughes.com, n.d.), the United States Energy Information Administration (eia.gov, 2022), and St. Louis Fed (stlouisfed.org, n.d.). It clearly shows how directional drilling has grown from a relatively small niche to the vast majority of wells drilled in the United States during the unconventional shale revolution. It also illustrates how the cost of drilling these wells has come down, with the footage drilled annually per rig increasing by a factor of more than three.

Similar cost savings will be available to the unconventional geothermal industry.

3. TARGETS FOR GEOTHERMAL TO SCALE

In its "Enhanced Geothermal Shot" initiative (energy.gov, n.d.), the United States Department of Energy identified five key areas where technical challenges need to be solved in order to create pathways to a 90% reduction in the cost of EGS by 2035. Two of these are related to subsurface modelling and one to completions and production. The other two are directly related to well construction and include the following specific targets:

- "drill the wellbore at 4X speed"
- "reduce well construction cost by 60%"
- "enable access to 50% more hot rock".

The technology developed for unconventional oil and gas can directly influence these targets. Figure 1 above shows how drilling speed has improved in the unconventional oil and gas industry – the number of feet drilled per rig per year is in inverse proportion to the speed at which the well is drilled. Well construction costs have reduced in line with this. Additionally, the horizontal drilling techniques pioneered in the unconventional oil and gas industry will allow increasingly long directional or horizontal geothermal wells to be drilled, significantly increasing exposure to hot formations. Based on the progress that the oil and gas industry made over the last 15 years, 50% seems like a very conservative target.

4. UNCONVENTIONAL GEOTHERMAL CASE HISTORIES

There is already evidence that techniques imported from oil and gas drilling are reducing the cost of unconventional geothermal wells.

Results from the Frontier Observatory for Research in Geothermal Energy (FORGE) drilling site in Utah, United States, have shown that drilling speed improved from 14 ft/h to 71 ft/h, a five-fold improvement, between 2017 and 2022, simply by applying oil and gas drilling technologies (US Department of Energy, 2024). The same reference stated that there is still a two-to-three-fold improvement available if the drilling speeds typically achieved in oil and gas can be transferred.

Earlier in 2024 (El-Sadi, *et al*, 2024) Fervo reported significant improvements in drilling performance from their initial wells in Nevada and Utah, United States. Like FORGE, they demonstrated sustained drilling rates of 70 ft/h, resulting from the use of modern drilling techniques imported from the oil and gas industry. Their paper contrasted this with the 25 ft/h baseline estimated by SANDIA (Lowry, et al, 2017) as recently as 2017.

5. THE IMPORTANCE OF TEMPERATURE CAPABILITY

The findings above suggest that the cost targets set by the Department of Energy "Enhanced Geothermal Shot" are very achievable. But as well as reducing the cost of an installation, there are also gains to be found in increasing its value. The leverage of temperature in terms of the value of the well is very high.

A number of scenarios were modelled using the US Department of Energy Geothermal Electricity Technology Evaluation Model (US Department of Energy, 2016). When normalised, they revealed a constant pattern in that the cost of electricity reduces significantly as the temperature of the rock exploited increases. This is clearly shown in Figure 2 below.

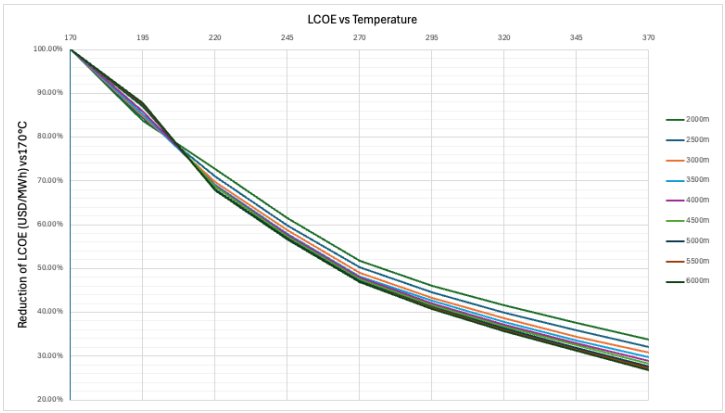


Figure 2: LCOE as a function of reservoir temperature.

The graphs show a consistent and significant reduction in levelized cost of electricity (LCOE) as a result of temperature for EGS systems modelled using GETEM. Results are not shown here for AGS, but increasing temperature has a very similar impact on their economics.

Compared with a baseline (100%) at 170°C, increasing the reservoir temperature to 210°C will reduce the LCOE to approximately 75% of the baseline value. At 300°C, LCOE is only about 30% of baseline. This demonstrates extremely important economic value that will come from deeper and hotter geothermal wells.

170°C was chosen because it is close to the claimed temperature rating of drilling and measurement tools currently used in the oil and gas industry. Typically, this might be 175°C. Occasionally it can be higher, up to 200°C, for a fairly small number of (most likely) expensive tools.

However, this temperature rating is no guarantee that tools will work reliably at such temperatures. The environment in which they are deployed is harsh and difficult, and they often fail prematurely at temperatures lower than their rating.

Research based on drilling a high temperature field in the United States shows a correlation of measurement while drilling (MWD) failures with temperature, but at lower temperatures than would have been expected.

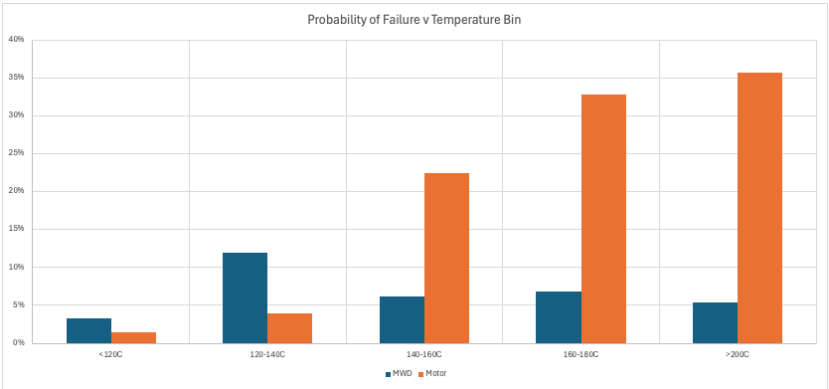


Figure 3: Probability of run terminating failure as a functional temperature.

Rather than working reliably to 175°C, Figure 3 shows that MWD reliability drops off 120°C and 140°C. The picture would probably be worse above 140°C, but for the fact that by then drilling motors, which have a significant elastomeric content in their moulded stators, start to fail even more rapidly than MWD – thereby masking what would otherwise likely be a higher number of run terminating MWD failures at higher temperatures.

This clearly demonstrates the difficulty of drilling at increasingly higher temperatures with equipment directly imported from the oil and gas industry.

6. A HIGH TEMPERATURE DRILLING SYSTEM

Figure 4 shows what a combined high temperature MWD and rotary stable system (RSS) will look like. This drilling system is being developed for operation initially at 210°C, but by 2030 it is anticipated that it will be working reliably at circulating temperatures as high as 300°C.

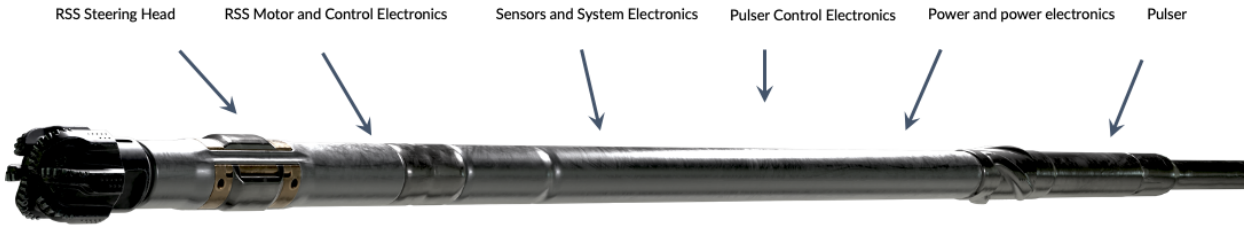


Figure 4: Combined RSS/MWD for high temperature operation.

Closest to the drill bit is the RSS steering head. This can be identical to the type of steering head used in oil and gas wells, with pads and/or pistons that extend once per revolution and urge the bit sideways. However, RSS tools used in oil and gas generally have their own sensor packs and control systems, independent from those used in an adjacent MWD tool – mostly for historic reasons. There is no technical reason why these two set of sensors and electronics cannot be combined. A high temperature drilling tool for geothermal should combine them in order to save on space, cost and technical risk.

Approximately halfway along the tool as illustrated there is a set of sensors and system electronics that is able to measure the direction and inclination of the well, and control a positive mud pulser to send this information to surface. The same sensors can also derive rotational position of the tool and drive electronics that control the steering head. Both the pulser and steering head are controlled with pilot valves that themselves are driven by brushless DC motors.

This drilling assembly can be driven directly from surface, from the top drive, or can be "motorised" in the same way as in oil and gas wells, where a drilling motor is placed above the tool in order to provide additional power downhole. However, conventional mud motors used in oil and gas will suffer at high temperature because of the use of elastomers in their stator assemblies. Options to resolve this include all metal motors (Stefánsson *et al,* 2018) or geared turbines (Jones, Feddema and Sugiura, 2016), both of which can avoid the temperature limitations of the elastomeric stator.

If RSS is not required, the MWD is capable of being used with an oriented directional motor, again very much like oil and gas drilling. As above, the orientation could be of a motor with a metal power section or, again, it could use a geared turbine.

Critical to the success of such a drilling system will be the temperature capability of the sensors and electronics used.

7. A NEW APPROACH TO TEMPERATURE RESILIENCE

Generally, the approach employed to date when attempting to make high temperature drilling and measurement tools has either been to find electronic components that will work at the ambient temperature via a process of screening and selection (Beckwith, 2013) or to try to shield the entire tool from temperature and cool it (Vedum *et al*, 2017 and Stefánsson *et al,* 2018*)*.

Despite many years of trying, the former approach does not appear to capable to get equipment to work reliably above an operating temperature of 200°C. One or two oil and gas manufacturers have managed to get close to 200°C, by using technologies including application specific integrated circuits (ASICs) or multi-chip modules (MCMs). Unfortunately, these approaches suffer from very high non-recurring engineering (NRE) charges, making them unsuitable for products like high temperature drilling tools which are made in low volumes.

A new approach builds on but also modifies these previous attempts. It uses discrete components either selected for or protected from the operating temperature. Discrete components are considered a more cost-effective way of building low volumes of tools. The new approach considers three key requirements:

- Protect the assembly from the external borehole temperature
- Protect components from themselves and efficiently and quickly remove the heat that the components generate internally
- Take the rejected heat from the components to a place where it will do no harm.

This new approach creates a system for mounting boards which allows heat to be removed and rejected quickly. As a first step, it replaces the rectangular printed circuit boards (PCBs) which are ubiquitous in oil and gas drilling and measurement tools, and replaces them with a circular board design. Further, instead of being placed parallel to the axis of the tool, the circular boards are placed normal to the drilling axis in a stack – or perhaps more accurately, in a series of stacks.

The small size of the board means that no component is very far from its edge, and the circular shape tends to promote heat flow, with resistance to radial flow reducing as a function of radial position. The function of the board, and the numerous special materials used in its construction, is to get heat away from vulnerable components as quickly as possible and to the board circumference.

Once at the circumference, the heat can be picked up by a stack of thermally conductive rings which act somewhat like a “thermal superhighway” to take heat away from the board. This “superhighway” could take heat to a pressure vessel which is in contact with drilling fluid flowing past the outside of the tool. This would allow the tool to take advantage of the cooling nature of the drilling fluid, which will almost certainly be at a lower temperature than the formation being drilled. It also allows operation in tandem with technologies like mud chillers and insulated or coated pipe, which can further reduce said temperature of the drilling fluid.

Alternatively, for higher temperature tools, especially as the operating temperature approaches 300°C, the “superhighway “could take heat into a variety of cooling options, which will not be described in this paper. The combination of circular boards and conductive rings lends itself very well to a modular architecture which allows different boards to be treated differently in terms of how they are cooled. By dividing the tool into a small number of stacks of boards, it becomes possible to have very small, compact chambers which can be maintained at different temperatures if necessary. In order for systems to remain cost effective, cooling must be used selectively. Previous projects described above have attempted to cool the whole assembly to the minimum capability of any individual component. This can work for short periods of time, however this approach can be very expensive and power hungry. An alternative approach is to build a series of small chambers and cool each to an appropriate temperature for the weakest component therein. This will avoid cooling a lot of components that do not need it and is much more efficient than maintaining the whole tool at a low temperature.

Figure 5 below shows an example of the new generation, high temperature circuit board.

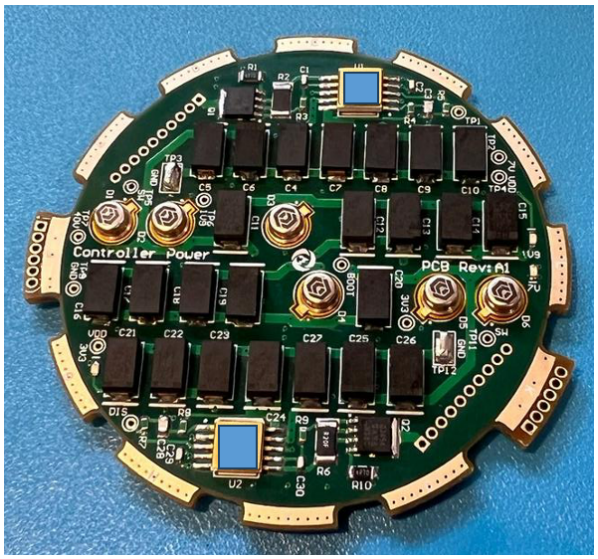
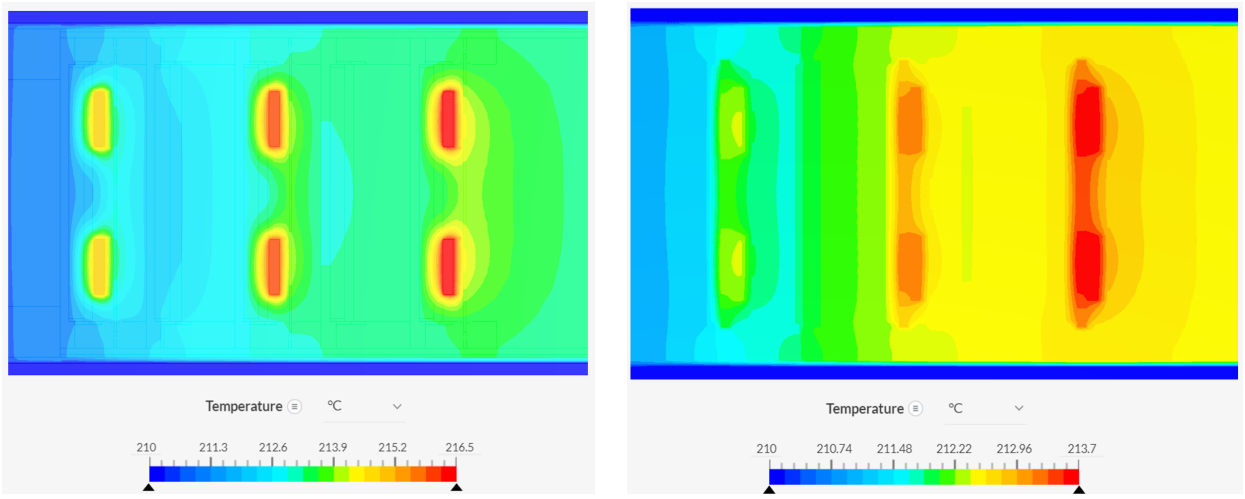


Figure 5: New generation circular PCB.

Figure 6 shows one element of the axial stack of PCBs.

Figure 6: One element of axial PCB stack.

Based on the design of multiple stacks as depicted in Figure 6, thermal modelling has been used to optimize the combination of geometric design and materials selection. As can be appreciated from Figure 7, this modelling has shown that it is possible to keep the temperature of components of the board in a multi-stack assembly within 3.7°C or less of the surrounding environment in an optimized PCB assembly and within 6.5ºC or less of the surrounding environment in a conventional PCB assembly.



(a) **(b)**

Figure 7: Thermal modelling of a multi-stack using (a) conventional and (b) optimized PCBs.

8. TEST RESULTS

Initial testing has focused on proving "the physics" for a 210°C drilling tool – that is, heat testing components and boards temperatures between 220°C and 230°C for extended periods to make sure that there are no fundamental issues that will prevent components from working – such as leakage or capacitance issues. This testing has proved successful, with components, prototype boards and downhole ready boards heat soaked at these high temperatures for over 500 hours.

Further work will require highly accelerated life testing (HALT) which combines temperature with shock and vibration to fully replicate the downhole conditions that components and boards will see. However, solving problems that might emerge at this stage is simply an engineering challenge. It does not challenge the physics in the way that initial heat testing has already done.

9. CONCLUSIONS

Unconventional geothermal systems (EGS and AGS) bring exciting new possibilities to the geothermal industry and will allow it to scale globally.

They can leverage techniques including directional and horizontal drilling developed for oil and gas and perfected in the unconventional shale boom in the last 15 years.

Those technologies have demonstrated remarkable cost savings in unconventional shale wells that should be directly transferable to geothermal drilling. But the technologies used in oil and gas do not usually work above 175°C and never above 200°C. In fact, it appears that systems tend to have reliability problems someway below their claimed temperature specification capability.

Temperature has a very strong leverage on the economics of unconventional geothermal systems, with modelled LCOE being very strongly dependent on formation temperature.

A high temperature directional drilling system is being developed which avoids the use of elastomers and incorporates new ways of protecting electronics and sensors from temperature. Instead of using long, rectangular PCBs, the new system will use circular PCBs mounted in stacks where the boards are orthogonal to the drilling axis.

This allows three key requirements for temperature management in high-temperature tools to be addressed

- Protect the assembly from the external borehole temperature
- Protect components from themselves and efficiently and quickly remove the heat that the components generate internally
- Take the rejected heat from the components to a place where it will do no harm.

Cooling may be required for operation at high temperatures, but it is not necessary to cool the entire tool – only those components that need it.

Initial test results are very encouraging, and have already shown that a 210°C tool is feasible, with much higher temperature capabilities to follow.

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