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Next-Generation Geothermal Technology Reaches Higher Temperatures

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ABSTRACT

Enhanced Geothermal Systems (EGS) and Advanced Geothermal Systems (AGS) represent the next frontier in geothermal energy, leveraging proven directional drilling technologies from the oil and gas sector to access heat in regions previously unreachable through conventional hydrothermal wells.

Accurate well placement, typically involving horizontal trajectories, is critical to the success of these unconventional systems. The oil and gas industry brings decades of expertise and mature directional drilling capabilities, instrumental in drilling next-generation geothermal wells. However, to make EGS and AGS economically viable at scale, wells must be drilled and completed at significantly higher temperatures, beyond the thermal limits of current oil and gas equipment.

Bridging this performance gap requires a step change in the thermal resilience of electronics in downhole equipment. To guide this transition, a technology roadmap will be shared to adapt directional drilling and measurement capabilities to meet the need for high temperature geothermal applications. Real-time sensing, measurement, control, actuation, and reliable downhole communication are essential, not only to improve precision and efficiency, but to ensure long-term access and maintenance of geothermal wellbores.

A key milestone in the roadmap is the deployment of a Measurement While Drilling (MWD) tool capable of operating at circulating temperatures up to 210°C. Future developments aim to push downhole electronic systems to withstand circulating temperatures even greater than 300°C, enabling access to superhot rock systems at 400°C with significantly higher energy potential. Advances in high temperature electronics and robust telemetry systems will be central to this evolution to reduce costs and enhance scalability of geothermal energy.

1 HIGH TEMPERATURE REQUIREMENTS

Directional drilling and real-time measurement technologies developed for the oil and gas industry are critical enablers of next-generation geothermal systems. Many of these tools, Measurement While Drilling (MWD), Logging While Drilling (LWD), Rotary Steerable Systems (RSS), completion technologies, and intervention tools have matured over decades of drilling experience, with the unconventional oil and gas industry in North America being potentially a very good analogue for next-generation geothermal (Clegg et al., 2024). Their functionality is directly transferable to geothermal applications, where precise well placement and formation characterization are essential for effective heat extraction.

However, oil and gas tools were designed primarily for reservoirs below 175-200°C. Next-generation geothermal systems, by contrast, have the ability to target reservoir temperatures of 250-400°C. This thermal gap represents a fundamental barrier to scaling geothermal energy beyond conventional hydrothermal fields.

The current generation of oil and gas MWD and RSS tools has “run out of steam” just below 200°C (Figure 1). Thermal degradation of electronics, elastomers, and sensors limits both tool longevity and data reliability. Extending performance into the 250–300°C range will require not incremental, but step change advancement in materials, thermal management, and high temperature technologies.

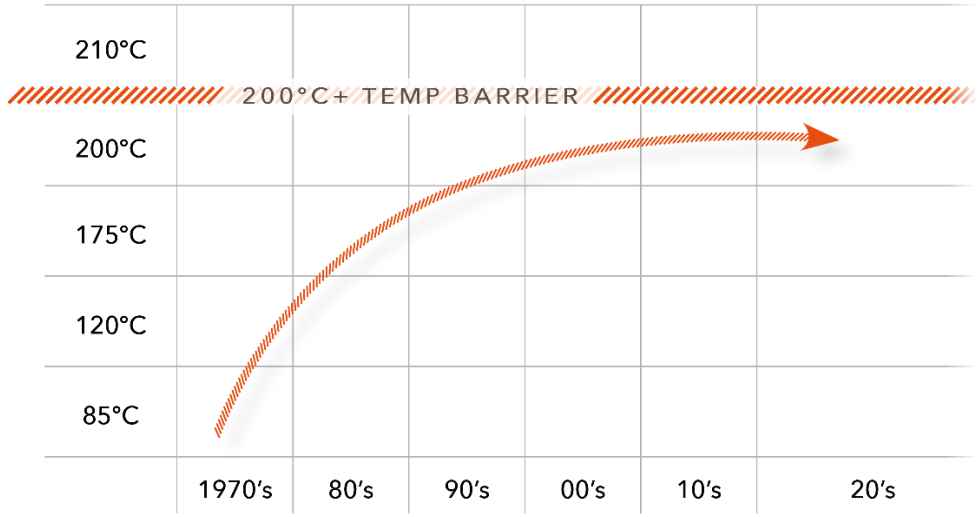


Figure 1: Evolution of temperature capability in oil and gas drilling equipment, showing plateau at ~200°C.

2 VALUE OF HIGH TEMPERATURE

According to Clean Air Task Force, just 1% of the world's superhot rock geothermal could generate 63 terawatts of clean firm power, eight times more energy than the rest of the world's electricity put together (2025).

Higher reservoir temperatures directly increase energy output and thermodynamic efficiency, lowering both the cost per megawatt-hour and overall Levelized Cost of Energy (LCOE). As temperature rises, each well delivers more power, enabling fewer wells to deliver greater output. Superhot rock could achieve competitive costs at scale, potentially as low as $20-35 per megawatt-hour (CATF, 2025).

If we can target reservoir temperatures at 250°C, this will reduce the LCOE by ~45%. Be reaching reservoir temperatures of 300°C, LCOE is reduced by 65%. Above 374°C we reach superhot rock, where the reduction in LCOE becomes exponential. This reveals very powerful economic value that could be realized by drilling deeper and hotter wells. Figure 2 outlines these LCOE reductions observed using the United States Department of Energy Geothermal Electricity Technology Evaluation Model (GETEM)(2025).

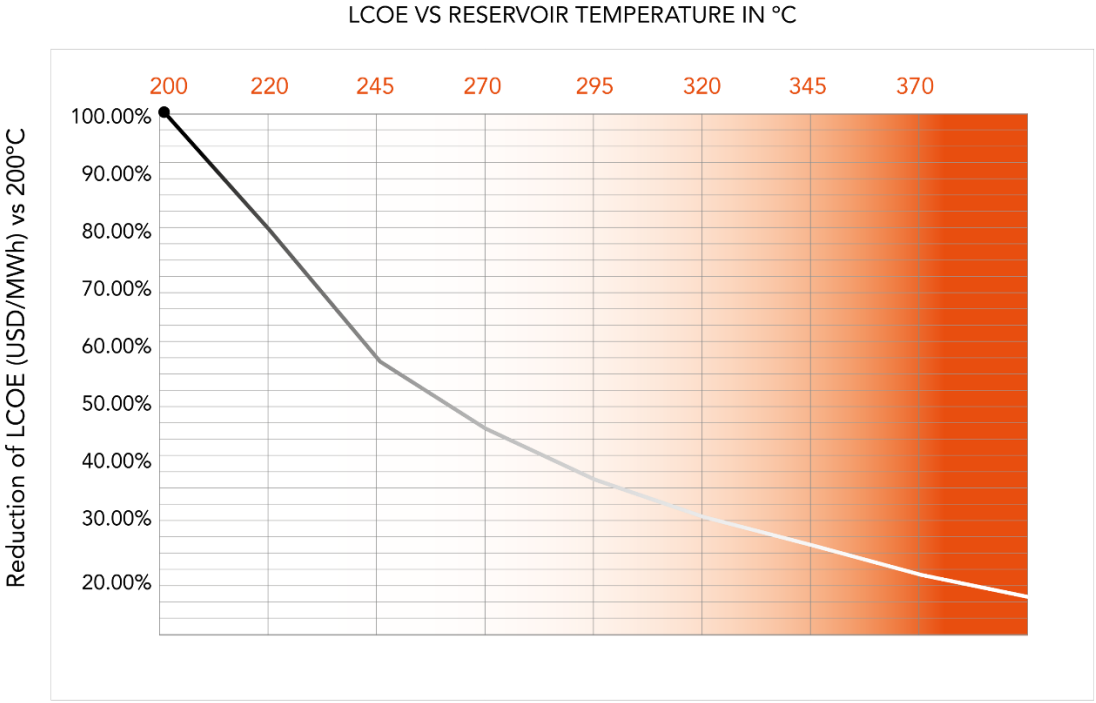


Figure 2: Reduction in levelized cost of energy vs. reservoir temperature (°C).

3 NEED FOR HIGH TEMPERATURE DOWNHOLE EQUIPMENT

The deployment of any technology tends to follow what is known as an "S-curve", whereby the rate of technological improvement during the heyday of any technology is fairly rapid, but, as it matures, improvement naturally and asymptotically approaches a limit which means that ever increasing amounts of effort are required to get closer to said limit, and it eventually becomes uneconomic to do so. Figure 1, above, shows such an asymptotic limit at 200°C. This phenomenon is described expertly by Clayton Christensen in his book "The Innovator's Dilemma" (1997). In the same book, he describes how successor technologies eventually replace technologies whose asymptotic limit has been reached. Figure 3, below, shows how the emergence of a successor technology will allow us to break the 200°C barrier. It looks exactly like the disruptive technology S-curve described in Christensen's book (1997). The development of high temperature electronics and sensors has been critical in providing a step change to break this 200°C temperature barrier.

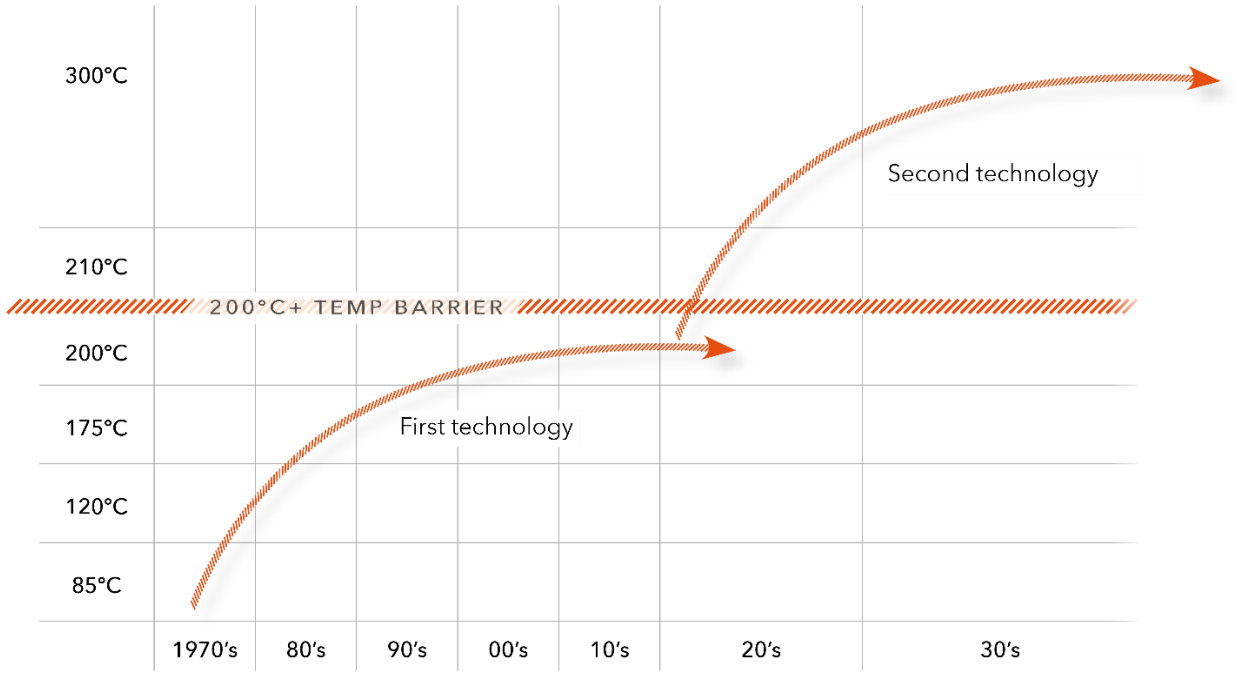


Figure 3: The evolution of temperature capability to enable next-generation geothermal drilling equipment.

The economic and operational benefits of high temperature downhole equipment are multifaceted. High temperature MWD systems can prevent frequent tool failures that force operators to halt drilling and pull the entire drill string out of the hole for costly repairs (rig trips). Additionally, they can minimize the time spent running back in hole after a trip to cool the well (staging time). Each stage adds cost, risk, and non-productive time. A single high temperature capable MWD system can eliminate these interruptions, significantly improving rate of penetration and project efficiency.

Developing high temperature directional drilling and measurement systems therefore has dual value: it reduces project costs today by improving reliability and reducing non-productive time from tool failures and staging the well, and it unlocks entirely new high-enthalpy resources as described in Section 2 above.

Reliability at temperature is another critical lever. Downhole electronics failure rates increase exponentially with temperature. Models developed by Svante Arrhenius can still be used to predict the impact of temperature on failure mechanisms. They translate into a rule of thumb that for every 10°C increased in temperature, reliability reduces by half. Conversely, every incremental improvement in thermal resilience yields exponential gains in tool longevity and reliability as shown in Figure 4. As shown, 210°C rated electronics provide a prolonged reliability at lower temperatures, up to a factor of 16 times increase in operating time when used in drilling circulating temperatures of 180°C. Improved reliability translates directly into lower overall well cost and fewer tool failures.

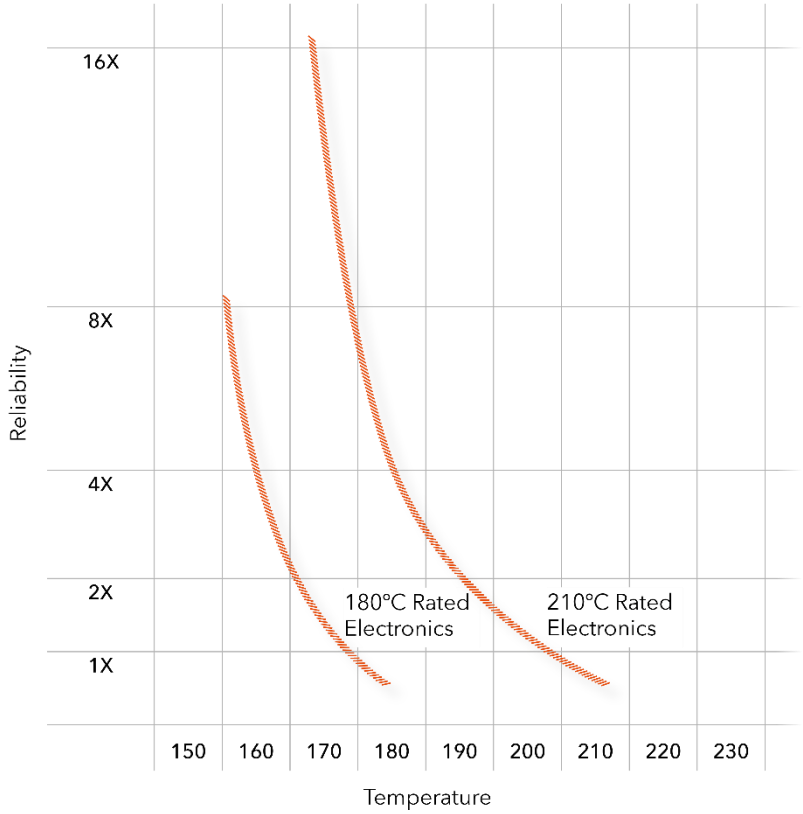


Figure 4: Incremental improvement in thermal resilience yields exponential gains in tool reliability and lifetime operation.

4 HOW EXISTING OIL AND GAS TOOLS ARE BUILT

Directional drilling systems are extensively used in the oil and gas industry (Ma et al., 2016), meaning that this technology is mature and well understood to make these approaches feasible. If we step back to the last century, when MWD tools were first introduced, the temperature ratings were driven by the rating of commercially available electronic components. In 1978, the first commercial MWD system was introduced with a temperature rating of 85°C. By 1996 a commercial MWD had been released with a temperature rating of 175°C, and others followed by 2001. So, in less than 20 years, the industry gained 90°C of capability and the ability to drill the majority of oil and gas reservoirs. Despite decades of refinement, these conventional approaches have reached their practical limit. Today, through progressive improvements in packaging, shielding, and derating strategies, components based on silicon electronics are only capable of reaching 200°C without severe degradation. This clearly explains the exponential limit shown in figure 1.

In a Journal of Petroleum Technology article written by Robin Beckwith in 2013, Baker Hughes' Robert Estes stated that 200°C is the new target: "high temperatures in the oil field seem to go in jumps of 25°C and these jumps may take 10 years". However, it's been more than 10 years since that article was written and we haven't seen a 25°C jump yet. This is because, as described by Christensen, technology development is not linear over time but reaches exponential limits. Effectively, progress seems to have stalled since the turn of the century. A few MWD systems have reached 200°C, but they are limited and come at a high cost.

Even the apparent temperature capability of the tools that the oil and gas industry has got used to using are not necessarily all that they seem. Research based on operations in a high temperature field in North America shows that while MWD failures show a correlation with temperature, they tend to occur a long way below the 175°C temperature rating of the tools.

It can be seen from figure 5 that MWD failures pick up between 120°C and 140°C. They appear to fall away above 140°C, but the reason for this is because the motors used to drill these wells, having significant elastomeric content, tend to fail in this range. These motor failures then mask MWD failures because the data plotted is based on the reason for pulling out of hole. Therefore, a rapid motor failure could hide an incipient MWD failure. This strongly suggests that the electronics used in existing MWD and RSS tools for oil and gas drilling are going to be difficult to apply to the higher temperatures required for next-generation geothermal.

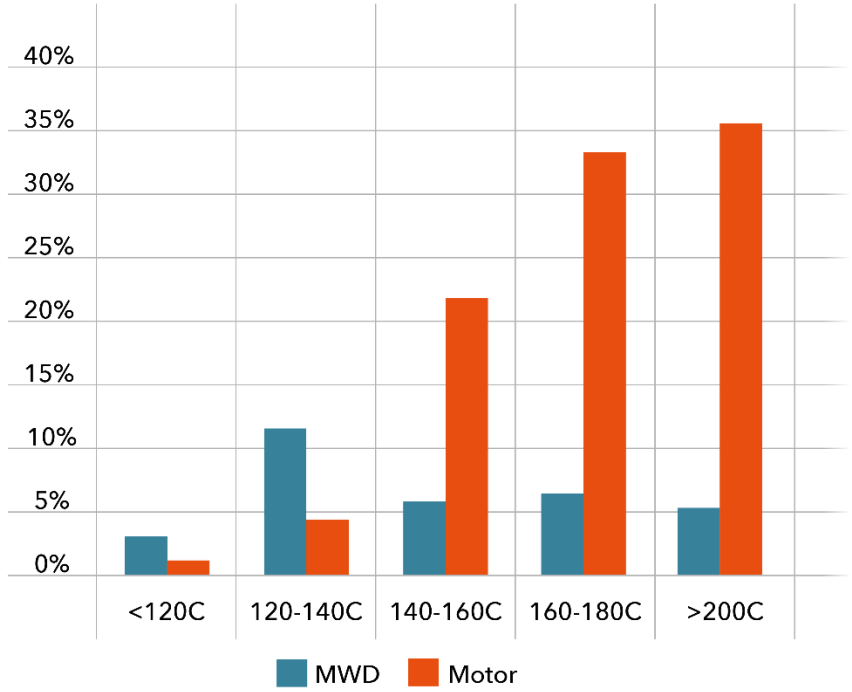


Figure 5: Probability of run terminating failure as a function of temperature.

Significant advancements in drilling technologies need to be achieved to significantly reduce drilling costs to enable cost-competitive geothermal systems implementation (Malek et al., 2022). Hence, it is obvious that developing cost-effective directional drilling equipment for high temperatures is necessary to scale up next-generation geothermal systems.

Modern MWD tools employ rectangular printed circuit boards stacked inside pressure housings, protected by heat sinks, gels, and insulation layers (Figure 6) (Kleawyothatis et al., 2018). Reliability gains were achieved mainly through improved thermal isolation and component screening, rather than fundamental advances in electronic materials. While they are effective for managing shock and vibration, they lack effectiveness in dissipating heat.



Figure 6: Traditional rectangular circuit board commonly used in downhole drilling equipment design.

5 HISTORIC ATTEMPTS AT HIGH TEMPERATURE TOOLS

Multiple research efforts have sought to extend tool survivability beyond 200°C, with limited success. DESCRAMBLE ("drilling in deep, super critical ambients of continental Europe") was a project funded by the European Union and managed by a research organisation in Oslo, Norway. It built a logging tool (figure 7) specified to 450°C (but only for eight hours operation), using components rated between 200°C and 300°C in addition to a dewar type heat shield (Vedum et al, 2017). It was tested in a 250°C geothermal well in Lardarello in Italy and yielded some useful insight into the behaviour of the electronic components we will need at high temperature.

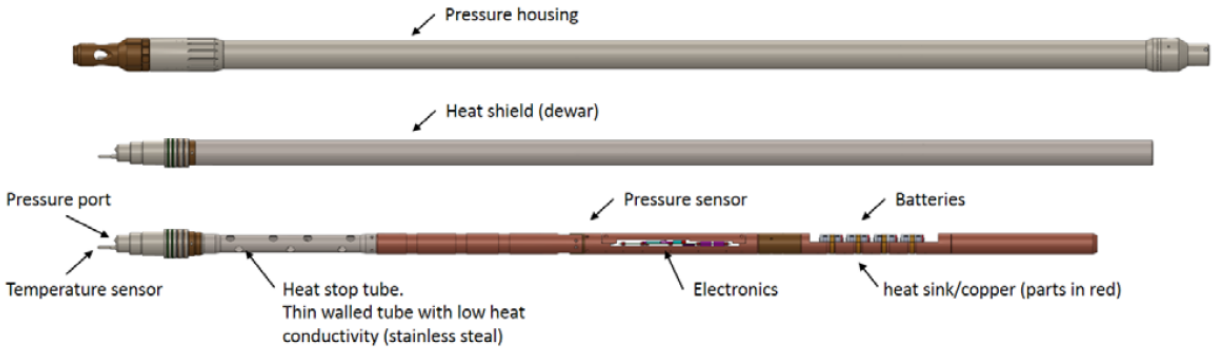


Figure 7: DESCRAMBLE logging tool (Vedum et al, 2017).

Other initiatives explored cooling and phase-change thermal buffering, but these approaches added complexity, cost, and limited runtime. For example, in 2018 Stefánsson et al described a 300°C system which included a relatively standard, 175°C capable MWD that was put into a flask and kept cool using phase change materials. The requirement here was for 50 hours operation. There is no published record of the tool being used downhole, but the reference describes successful laboratory test results.

Focusing on the thermal load, there are two main heat sources that need to be considered: heat of the geothermal formation and heat generated by the electronics. While the first one requires some kind of heat shielding, the second one requires adequate cooling to avoid excessive electronics self-heating when used that could ultimately damage the electronics. Regarding the formation heat source, the drilling mud has been conventionally used to cool down the drilling equipment surroundings (Yan et al., 2014). During the last years, insulated drilling pipes have also been developed and successfully used to reduce the formation heat load into the drilling equipment (Figure 7) (Vetsak et al., 2024).

As for the electronic self-heating thermal load, thermal management technologies including vacuum flasks, heat sinks, phase change materials, or passive cooling systems to slow down external heat transfer while absorbing heat generated by electronics have been developed primarily for logging tools, which means that when used in isolation they will not be directly applicable to MWD as they are not designed for long exposures to high temperatures and harsh mechanical environments.

6 ROADMAP TO 400°C AND BEYOND

The pathway to 400°C and beyond involves integrating multiple step changes in technology to enable the development of deeper, hotter wells. The new approach for high temperature technology needs to consider 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 has 5 step change process to fully enable access to superhot rock at 400°C as shown in Figure 9.

1. Discrete components are selected for temperature resistance and repackaged where necessary as fit for purpose in building small quantities of tools. This broadly echoes the approach the oil and gas industry has taken over the years, but is insufficient to get past the 200°C barrier.
2. The addition of accelerated heat transfer ensures that heat can be removed and rejected quickly. The rectangular printed circuit boards (PCBs) which are ubiquitous in oil and gas drilling and measurement tools are replaced with a circular board design (Figure 8). Further, instead of being placed parallel to the axis of the tool, the circular boards are placed normal to the drilling axis in a series of stacks to ensure accelerated heat transfer. 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, allow heat to dissipate 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 (Figure 8). This “superhighway” can take heat to a pressure vessel which is in contact with drilling fluid flowing past the outside of the tool. This allows 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. Thus, the temperature capability of the electronic and sensor assemblies should be matched to the anticipated circulating temperature of the drilling fluid.

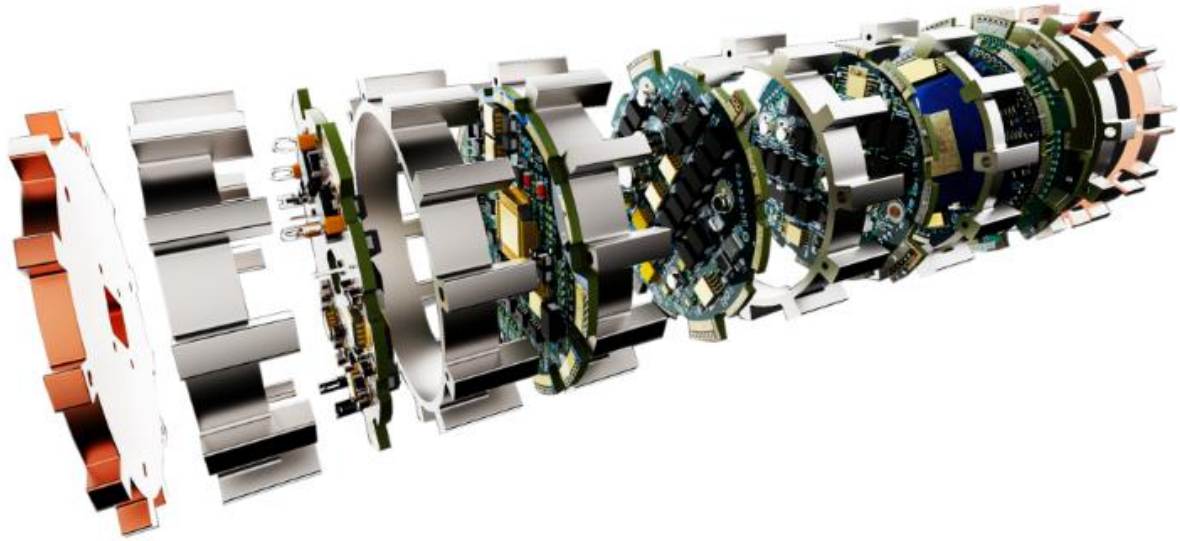


Figure 8: Accelerated heat transfer through stack of thermally conductive rings, dissipating heat from circuit boards.

3. In the event that a minority of the sensors and or electronic components in a device will not be reliable as the temperature increases further beyond 200°C, it is possible to add thermal shielding and selective cooling to them. For example, this could involve placing a small subset of a tool into a vacuum flask to protect it from the external environment, and then using modest solid state cooling devices, also located in the flask, to maintain the devices at an acceptable temperature. It's possible that this could be repeated at numerous locations, with different chambers maintained at different temperatures to keep each component in an environment which is comfortable for it.

4. The next critical step in the roadmap to 400°C is the development of high temperature integrated circuits (ICs) and sensor systems substrates. This is likely to involve a transition from silicon to silicon carbide (SiC) or silicon-on-insulator (SOI) integrated circuits, capable of intrinsic operation at ultra-high temperatures. Developments from organizations such as NASA Jet Propulsion Laboratory (JPL) have validated the feasibility of these platforms (NASA, 2024).

5. Combination of all of the above: accelerated heat transfer, cooling and shielding techniques, as well as high temperature IC's and sensor system substrates; will allow the industry to achieve circulating temperature even greater than 300°C that will enable access to superhot rock reservoir temperatures of 400°C.

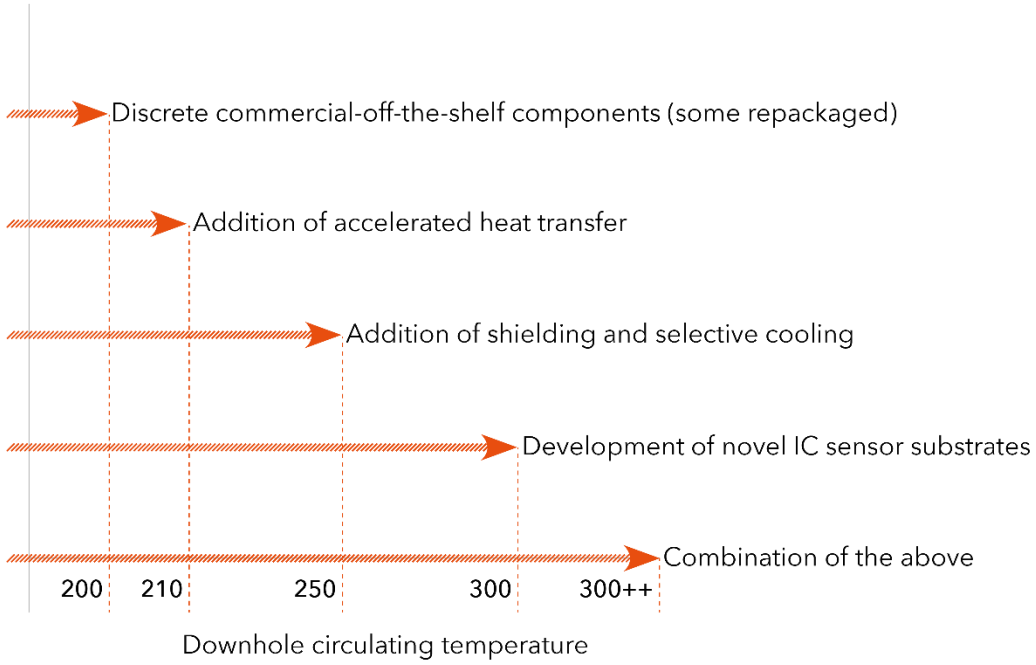


Figure 9: This new approach has a 5 step change process to fully enable access to superhot rock at 400°C.

7 PRODUCTS AND SOLUTIONS ROADMAP

There is a full suite of applications across the entire life cycle of geothermal, where high temperature electronics and sensors are of utmost importance to support drilling and completions, as well as operations and maintenance (Figure 10).

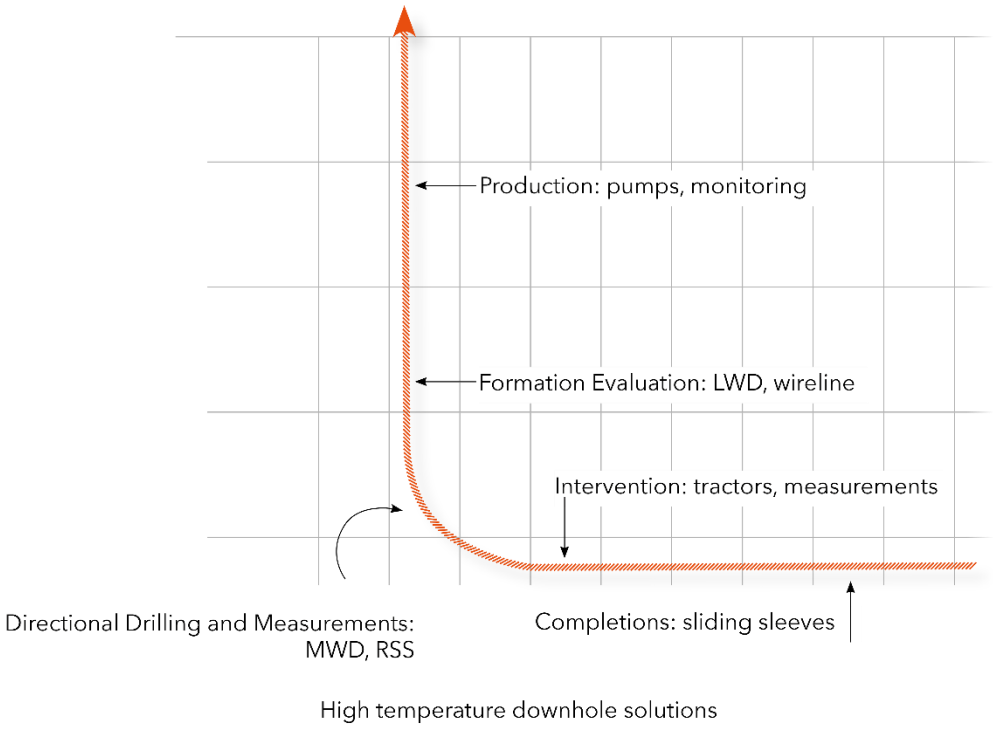


Figure 10: Full suite of applications for high temperature electronics and sensors to support drilling and completions, as well as operations and maintenance.

Applications requiring high temperature electronics and sensors include:

- Directional drilling systems: MWD and RSS tools for accurate well placement.
- Logging While Drilling (LWD) and Wireline (WL): sensors for formation evaluation and fracture characterization.
- Intelligent completions: sliding sleeves, flow and pressure control systems for zonal management.
- Production equipment: pumps, long-term monitoring systems for pressure, temperature, and flow.
- Intervention and maintenance: wireline tractors, data measurements, wellbore cleaning to optimize production and wellbore longevity.

These applications rely on temperature capable electronics and sensors for drilling systems, data measurements, control and actuation, steering and navigation, power conversion, and/or communication. Extending these capabilities will be foundational to the scalability of next-generation geothermal operations.

8 CONCLUSION

Next-generation geothermal systems offer a pathway to further unlock the Earth's largest untapped renewable energy resource. However, realizing its full potential depends fundamentally on the ability to operate reliably at temperatures far beyond the limits of existing oil and gas technology through the use of high temperature electronics and sensors.

As shown throughout this paper, the current plateau of 200°C in oil and gas drilling tools represents both a technical and economic ceiling for geothermal development. To scale geothermal energy to a globally significant level, this barrier must be surpassed. There is a full suite of applications across the entire life cycle of geothermal, where high temperature electronics and sensors are of utmost importance to support drilling and completions, as well as operations and maintenance. High temperature Measurement While Drilling, Logging While Drilling, and Rotary Steerable Systems are central to developing directional geothermal systems, providing the precision, reliability, and efficiency required for deep, high-enthalpy wells.

The pathway to 400°C and beyond involves integrating multiple step changes in technology to enable the development of deeper, hotter wells. A clear roadmap now exists to extend downhole equipment to circulating temperatures of 300°C and reservoir conditions approaching 400°C. This includes advances such as circular board architectures with accelerated heat transfer, selective cooling and shielding systems, and silicon carbide (SiC) or silicon-on-insulator (SOI) integrated circuits. Together, these technologies mark a milestone in history, bridging the gap between today's geothermal operations and tomorrow's superhot rock systems.

High temperature downhole tools will not only reduce drilling costs and non-productive time, but will also enable access to vastly greater geothermal resources. The resulting gains in thermodynamic efficiency and reductions in Levelized Cost of Energy (LCOE) have the potential to make geothermal one of the most competitive clean energy sources available.

By integrating proven oil and gas drilling expertise with next-generation high temperature technologies, the geothermal industry stands at the threshold of a new era, one where the world's most abundant heat source can be tapped reliably to economically to deliver clean, firm power at scale.

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