New Advances in High Temperature Electronics and Sensors for Geothermal Drilling

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ABSTRACT

Enhanced and Advanced Geothermal Systems (EGS and AGS) are new methods of creating geothermal installations that have already been demonstrated to potentially increase electric power production by a factor of greater than 10 when compared with more conventional methods. Some involve fracturing the rock between injector and producer wells, and some rely on drilling wells to convey closed loop fluid systems to take heat from the rock.

Compared with conventional hydrothermal wells, they are technically challenging to drill. In particular, very accurate well positioning, generally including horizontal wells, will be required. The oil and gas industry can already drill accurate directional wells and this capability to position the well 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 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 mean time between failure and/or service. Therefore, the industry needs a step change in its approach to the temperature capabilities of downhole equipment.

Keywords: EGS, AGS, unconventional, high temperature, electronics, cooling, MWD, RSS.

1. INTRODUCTION

Key challenges facing geothermal energy include the cost of drilling wells and the maximum temperature at which they can be drilled.

In a briefing to the European Parliament, Vittorio Prodi noted that "the main obstacle to the development of the geothermal sector in Europe remains the high cost of drilling, which represents two thirds of the costs of a geothermal plant" [1]. And Farina et al reported in 2023 that "high enthalpy scenarios, for temperatures higher than 170°C, present many challenges for most of the current drilling and completion technologies" [2].

This needs to be considered in the context of the leverage that can be achieved by drilling higher temperature reservoirs.

Hephae Energy Technology has used the US Department of Energy Geothermal Electricity Technology Evaluation Model (GETEM) [3] to calculate the leverage of temperature over the economics of geothermal wells, and the results are significant.

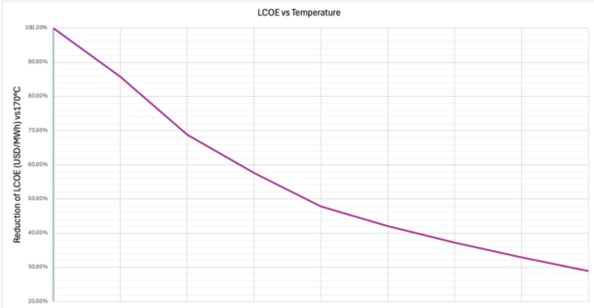

Fig 1: LCOE as a function of reservoir temperature.

Increasing reservoir temperature from 170°C to 210°C improve LCOE by approximately 25%, and increasing further to 250°C improves LCOE by approximately 45%.

To further emphasise the opportunity that would be opened up by solving these dual problems, the United States Department of Energy's "Earthshot" published a set of pathways to the "Enhanced Geothermal Shot", which included: drilling at four times current speed; reducing well construction cost by 60%; and enabling access to 50% more hot rock [4].

The oil and gas industry already has proved its ability to drill much more efficiently and with less use of resources, by tripling the amount of footage drilled per rig in the last two decades [5], [6].

Now, unconventional geothermal operators are planning to drill wells that look like unconventional oil and gas wells, with long deviated or horizontal sections that are precisely controlled. For example, Eavor is drilling a set of deviated AGS wells in Bavaria that intersect each other at the very end of the well in order to create the required closed loop [7]. And Fervo is drilling EGS wells in Nevada and Utah, USA, are drilled precisely parallel to each other in order to optimise the hydraulically stimulated completion.

These pilot projects are being drilled with reservoir temperatures between 150°C and 200°C, but both would benefit from better economics if they could be drilled deeper and hotter.

1. CURRENT STATE OF DRILLING

The precision with which EGS and AGS wells will need to be drilled demands technologies familiar to drillers in oil and gas, namely measurement while drilling (MWD) and rotary steerable system (RSS) technologies. The MWD provides to the driller real-time measurements of inclination and azimuth in addition to some geologic information, and status information on things like downhole mechanics and dynamics. This allows the well path to be monitored and adjustments made as necessary to keep on track and to prevent equipment damage. The RSS can be used to make directional adjustments in long tangent and horizontal sections. Both rely on complex sensors and electronic systems.

A recent report published for the Clean Air Task Force [9] provides a very good description of the current state of drilling technology. It shows how existing electronics-based drilling tools are limited to temperatures between 175°C and 200°C. It also describes potential mitigating technologies including mud chillers (to reduce the temperature of the drilling mud before it enters the well so that any downhole tools are exposed to colder fluid) and coated or insulated drill pipe (to maintain that colder temperature for as long as possible as the fluid is pumped into the well). Unfortunately, neither of these techniques fully mitigate the situation because there are times when the drilling fluid is not circulated, and in this event any tools that happened to be downhole will be rapidly heated up. Accordingly, the Clean Air Task Force report proposes a hybrid solution whereby mitigating technologies are used alongside increasingly high temperature capable downhole tools in order to optimise the economics of the geothermal well.

2. FUTURE STATE – HIGH TEMPERATURE TOOLS

Hephae Energy Technology has set out to solve the problem of high temperature drilling tools by creating a new generation of downhole electronics combined with new ideas about how to keep them cool. The

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company is developing its electronics in Houston, Texas, USA – where there is a well-established ecosystem for high-quality and high-reliability electronics manufacture. It is developing its mechanical engineering and thermal modelling capabilities in Bilbao, Spain – an area not known for drilling technology. Solving the problem of thermal management presents a significant challenge and the company deliberately took on people who had not been exposed to previous attempts to solve it. To quote Edward De Bono: "sometimes the situation is only a problem because it is looked at in a certain way. Looked at in another way, the right course of action may be so obvious that the problem no longer exists" [10].

Keeping electronic components cool is not just a question of protecting them from the external environment. They have the capability to internally generate a substantial amount of heat, and therefore it is also necessary to protect them from themselves.

Therefore, the problem in question is how to get the heat from the die, in the centre of the electronic component, to a place where it can be safely disposed of – for example the drilling mud or a cooling system. The solution is complex. It necessarily includes design and packaging of printed circuit boards (PCBs), but it also must include consideration of how heat is transferred away from the board. Therefore, for high temperature tools, thermal design of the packaging in order to ensure flow of heat away from the boards and into a cooling medium is paramount. The oil and gas industry has done an excellent job over recent decades of packaging electronics in order to protect them from the shock and vibration environment typically seen while drilling wells. However, for higher temperature operation, packaging in this way is no longer enough. The need to avoid damage due to shock and vibration must be carefully balanced against the need for thermal management.

The solution selected, after careful consideration, by Hephae Energy Technology is the use of circular printed circuit boards, approximately 75 mm in diameter.

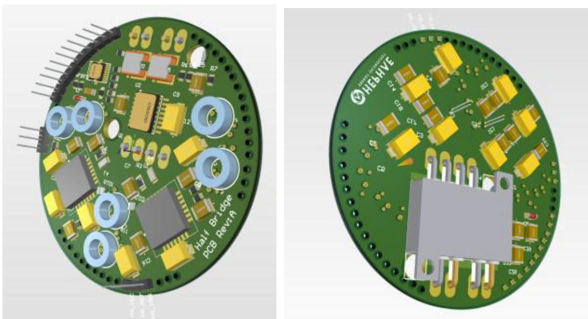

Fig 2: Circular printed circuit board assemblies.

The circular shape allows the most efficient use of surface area and volumetric space, and the thermally anisotropic characteristic of the printed circuit board assembly (PCBA), whereby the effective thermal resistance reduces as the radius increases, promotes radial transport of heat.

Modelling has shown that this arrangement can minimise the temperature difference between the die and a component at the centre of a board and a thermally conductive structure at the outside.

The PCBAs are mounted orthogonal to the axis of the tool in a stack which is surrounded by and contained by a set of metallic rings. Once heat has been conducted from a component to the edge of the circular PCB, it can be rapidly conducted through the metallic rings, either radially or axially, and into a cooling medium. This medium might be drilling mud flowing past the outside of the tool, or for higher temperatures it could include cooling methods embodied inside the tool itself. Either way, the architecture of the stack is the same.

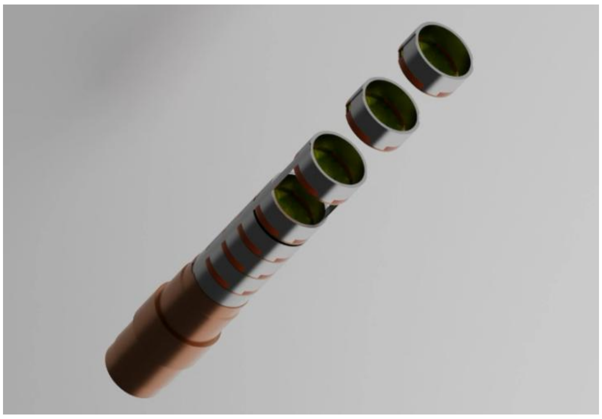

Fig 3: Exploded view of stack showing circular PCBAs and metallic rings.

As well as providing for optimum heat transfer, small, circular PCBAs are inherently very stiff, with a much higher resonant frequency than would be seen in a more conventional rectangular downhole PCBA. This additional stiffness will make them more suitable for the severe shock and vibration environment that they are likely to encounter in light of the dysfunctions present in drilling lateral wells.

3. PRACTICAL ISSUES – COMPONENT SELECTION AND TESTING

Initial attempts at component selection have identified many commercially available components that will operate at temperatures of at least 210°C. This matches the initial operating specification of the tool, which is good news in principle, provided that we remove heat from the components in the manner shown above and thereby minimise the difference between die temperature and cooling temperature.

Fig 4: Oven testing above 230°C.

However, a small number of components are not available for such extreme temperatures. In this case, it has been possible to repackage these and the repackaged versions have been thoroughly tested at high temperatures. So far, testing of components at temperatures between 220°C and 230°C has proved the physics. The components work reliably at these temperatures, indicating no major issues with capacitance or leakage currents. Further work will entail highly accelerated life testing (HALT) whereby assemblies are subjected to temperature, shock and vibration simultaneously. However, any problems identified during this phase testing will be soluble using known engineering techniques in terms of improving the support, mounting, or placement of components or PCBs.

4. CONCLUSIONS

Importing technologies from the oil and gas industry can significantly reduce the cost of drilling unconventional geothermal wells and allow the use of accurate directional drilling to optimise potential production.

The leverage of temperature is very significant, with a 25% reduction in LCOE available if reservoir temperatures can be increased by just 40°C.

However, at present the technologies used in the oil and gas industry are not capable of reliable operation above 200°C.

Although the temperature of drilling tools can be reached by the use of mitigating technologies like mud chillers and insulated pipe, none of these technologies will fully mitigate the situation because there are times when the drilling fluid is not circulated, and therefore the best solution for the industry will be a hybrid solution whereby mitigating technologies are used alongside increasingly high temperature capable downhole tools.

Developing high temperature electronics requires that the self-generated heat from electronic components is quickly and safely removed from the component into either or both of the drilling mud and a downhill cooling system. Thermal design of the packaging in order to ensure flow of heat away from the boards and into a cooling medium is paramount.

One approach is to use a circular printed circuit board to promote the radial transport of heat, and combine it with a terminally conductive structure to rapidly take heat away. This structure could comprise a set of metallic rings that constrain the circuit board.

The inherent stiffness and high resonant frequency of small circular boards will also be suitable for the severe shock and vibration environment that they are likely to encounter.

So far, heat testing of components has demonstrated reliable operation of all

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elements of the system between 220°C and 230°C.

Future work will entail highly accelerated life testing whereby assemblies are subjected to temperature, shock and vibration simultaneously.

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