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Assessing Industry Challenges for High-Temperature Subsurface Instrumentation

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ABSTRACT

The advancement of hydrothermal plants and enhanced geothermal systems is significantly dependent on the accurate characterization of various parameters, such as pressure, temperature, fluid chemistry, fracture mapping, feed zone flow rate, casing scale and corrosion, rock strain, and cement/rock integrity. These measurements are taken during and after the development of geothermal wells using specialized high-temperature subsurface instrumentation, which must withstand harsh well conditions, including high temperatures, elevated pressures, corrosive fluids, and considerable depths.

Sandia National Laboratories has identified several challenges related to high-temperature subsurface instrumentation. To thoroughly understand these challenges, Sandia conducted interviews with various experts from the geothermal industry, including original equipment manufacturers and service providers involved in well evaluation, who possess firsthand experience in assessing the geothermal subsurface.

To support the rigorous advancement of geothermal energy production as a global renewable resource, we have pinpointed four priority areas for research and development: embedded electronic systems, sensing technologies, communications, and energy storage solutions. Addressing the existing technology gap necessitates a strategic prioritization of research and development efforts. By concentrating on these critical areas, we can create more robust and reliable tools that will improve the efficiency and effectiveness of geothermal energy extraction. Ultimately, these advancements will facilitate the broader adoption of geothermal energy as a sustainable and dependable power source.

1. INTRODUCTION

The operation of geothermal power plants relies on geothermal wells, which require substantial investments in drilling, stimulation, and ongoing maintenance. These investments are critical not only for the initial setup but also for ensuring the long-term viability and productivity of the wells. As the demand for renewable energy sources increases, the efficiency and reliability of geothermal systems become paramount, making the optimization of well performance a top priority.

Over the years, high-temperature (HT) instrumentation tools have been developed to evaluate the condition of these wells and their fracture networks, ensuring the effective management of investments and optimal heat production, e.g. Kruszewski and Wittig (2018) and Kurata (1992). These tools are typically equipped with advanced electronics and sensors that collect data, which can either be stored within the tool or transmitted to the surface for real-time monitoring of well characteristics. By providing continuous feedback on well conditions, these instruments help operators make informed decisions that can enhance production and reduce operational risks.

To ensure reliable operation in the harsh geothermal environment, these instruments must be designed to withstand extreme conditions, including high temperatures (ranging from 200 °C to 320 °C and potentially higher), high pressures ($\geq$ 3,000 psi), significant depths (5,000 to $\geq$ 10,000 feet), and challenging fluid conditions (with varying pH levels). The ability of instrumentation to operate effectively under these conditions is crucial for the success of geothermal energy initiatives. The engineering of these tools requires innovative materials and designs that can endure such stresses without compromising functionality.

A comprehensive understanding of a well's condition and production potential necessitates a multitude of measurements, including pressure, temperature, fluid chemistry, fracture mapping, feed zone flow rate, casing scale and corrosion, rock strain, and cement/rock integrity. Each of these parameters provides critical insights into the well's performance and longevity, enabling operators to optimize production and ensure safe operations. Furthermore, the integration of data from these various measurements can lead to a more holistic view of well dynamics, allowing for predictive maintenance and improved resource management strategies.

In light of the challenges posed by these conditions and the diverse range of measurements needed, a survey was conducted with geothermal industry experts who are well-versed in the issues surrounding HT instrumentation tools and their data capture capabilities. The insights gained from this survey will drive the essential development of new technologies, providing effective and economical methods for measuring system parameters. By identifying the specific needs and pain points of industry professionals, this research aims to inform the design and functionality of future instrumentation tools, ensuring they meet the evolving demands of geothermal operations.

As the demand for geothermal energy continues to grow, the advancement and deployment of robust HT instrumentation tools will become increasingly crucial. These tools not only enhance the monitoring and maintenance of geothermal wells but also improve the overall efficiency and sustainability of geothermal energy production. The successful implementation of these technologies can lead to reduced operational costs and increased energy output, further solidifying geothermal energy's role in the renewable energy landscape. By investing in cutting-edge technologies and innovative solutions, the geothermal industry can strengthen its position as a key player in the global renewable energy landscape. The information collected from industry experts has been compiled and summarized in the following sections, providing a foundation for future advancements in geothermal instrumentation.

2. ENHANCED GEOTHERMAL SYSTEM

To fully grasp the necessity for geothermal high-temperature (HT) instrumentation, it is crucial to first understand Enhanced Geothermal Systems (EGS), e.g. U.S. Department of Energy, and the pressing need for long-term measurements. EGS differs significantly from conventional hydrothermal geothermal systems, which rely on naturally occurring reservoirs of hot water and steam. In contrast, EGS involves artificially stimulating the subsurface to create or enhance fracture networks, allowing for the extraction of heat from dry or low-permeability rock formations. This engineered approach presents unique and formidable challenges due to the extreme conditions encountered deep underground. The high temperatures, often exceeding 300 °C, and pressures greater than 5,000 psi, combined with the corrosive nature of geothermal fluids, demand robust and resilient instrumentation capable of withstanding these harsh environments.

In light of these demanding conditions, a comprehensive suite of long-term measurements is essential for accurately evaluating an EGS, including pressure, temperature, fluid chemistry, fracture mapping, flow rates, and the integrity of casing and cement, as the well's condition evolves over time. High-temperature instrumentation is particularly crucial for evaluating EGS because it enables the accurate measurement of parameters that directly influence the efficiency and safety of geothermal operations. Without instrumentation capable of functioning at elevated temperatures, critical data regarding the thermal dynamics and fluid behavior within the reservoir would be unattainable, potentially leading to suboptimal performance and increased operational risks. High-resolution data is also vital for understanding the fracture network in the subsurface, as it allows operators to identify the size, orientation, and connectivity of fractures that influence fluid flow and heat transfer. Additionally, continuous monitoring of induced seismicity is vital, as the stress field and reservoir conditions are constantly changing due to the stimulation processes. This ongoing assessment helps ensure that operations remain safe and effective while optimizing the stimulation of the reservoir. Furthermore, to facilitate these continuous measurements, EGS will require the permanent emplacement of instrumentation within the subsurface, allowing for real-time data collection and monitoring over extended periods. The integration of high-temperature electronics and sensors capable of real-time data transmission is critical but poses significant challenges due to the extreme conditions. Given the extensive range of measurements required, the tools must be designed to operate in the subsurface for extended periods (greater than 24 hours) while being exposed to elevated temperatures. However, most commercially available instrumentation is limited by either operating time or temperature thresholds, which hampers their effectiveness in EGS applications.

Industry primarily utilizes vacuum flask instrumentation due to its cost-effectiveness, higher data rates, and superior data resolution from the sensors. This approach employs a pressure housing with a vacuum liner and reflector that slows down heat propagation to the electronics, thereby protecting low-temperature components from the well's heat for several hours—sufficient time to gather the necessary data for most measurements in a hydrothermal geothermal well. This method allows for the use of advanced components that are high-speed, high-resolution, low-noise, and equipped with non-volatile high-density memory, all at a lower cost compared to high-temperature alternatives. In contrast, commercially available high-temperature components are typically characterized by low speed, low resolution, high noise levels, limited memory, and higher costs. Additionally, the low demand for HT components can lead to their discontinuation, as it becomes economically unfeasible to continue production.

While vacuum flask instrumentation offers several advantages, they are not without significant limitations, particularly regarding their operational lifespan. This limitation highlights the urgent need for innovation in the field. To achieve the Geothermal Technologies Office (GTO)'s goal of significantly reducing the cost of EGS by 2035, the growth of EGS technology is essential, e.g. U.S. Department of Energy. Therefore, the development of novel long-term high-temperature instrumentation technology is imperative, as is the establishment and stability of human-made permeability. This means that subsurface instrumentation must be operable at elevated temperatures ranging from 200 to 320 °C, ensuring that the tools can effectively monitor and evaluate EGS systems over extended periods without compromising performance or reliability.

By tackling these critical challenges and advancing the technology, the geothermal industry can enhance the viability and efficiency of EGS, ultimately contributing to a more sustainable energy future.

3. CHALLENGES IDENTIFIED

3.1 Technical Challenges for High-Temperature Subsurface Instrumentation

Given the increasing importance of Enhanced Geothermal Systems (EGS) and the Department of Energy's (DOE) goal to promote the advancement of EGS, Sandia organized a set of general questions for industry experts, including tool developers and service companies, to identify the challenges and needs observed for subsurface instrumentation. Recognizing the critical role that advanced instrumentation plays in the successful implementation of EGS, this initiative aims to gather insights that will inform future technological developments.

By engaging with experts in the field, Sandia seeks to ensure that the evolving demands of geothermal energy production are met with innovative solutions. The questions included:

1. What subsurface measurements do you wish you could perform that are currently unavailable?
2. Is there a need to conduct subsurface measurements at 250 °C, 300 °C, or higher?
3. Is there a need for long-term (greater than 24 hours) measurements at elevated temperatures?
4. What subsurface conditions create measurement challenges?
5. Is there a need for instrumentation that transmits data in real time?
6. How often do tools fail? What are the typical failure points?
7. Are there limited electronic component options when developing a tool?
8. What electronics are needed for future tools?
9. Are higher pressure/temperature data cables required?
10. Is there a need for HT cables with fiber optics?

The survey revealed a significant demand for equipment capable of operating at higher temperatures and/or for longer durations within the well, depending on the required measurements. This feedback underscores the necessity for advancements in geothermal instrumentation to meet the evolving needs of the industry. The ability to gather accurate and reliable data under these challenging conditions is essential for optimizing EGS performance and ensuring the safety and efficiency of geothermal operations. To facilitate the development of subsurface instrumentation that can withstand higher temperatures and longer operational durations, four primary focus areas have been identified: embedded electronic systems (EES), sensing technologies, local energy storage, and communications to the surface, as illustrated in Figure 1, e.g. Sandia National Laboratories. These focus areas will guide future research and development efforts, ensuring that the geothermal industry can effectively address the challenges posed by EGS and enhance the overall efficiency and reliability of geothermal energy production.

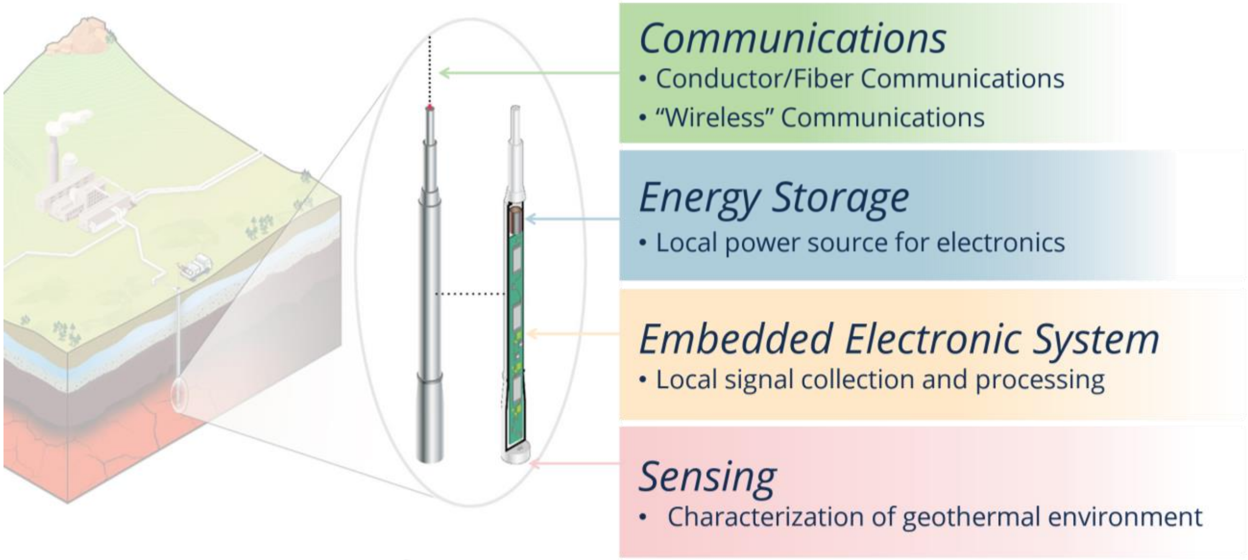

Figure 1: Illustration of Geothermal subsurface instrumentation emplaced in a multi-thousand foot well, e.g. Sandia National Laboratories.

3.1.1 Embedded Electronic Systems

The embedded electronic systems (EES) serve as the core of subsurface instrumentation tools, responsible for acquiring data from sensors and either transmitting it to the surface or storing it in local memory. EES are essential in all electronic-based subsurface instrumentation due to the significant depths at which these tools operate. At these depths, the low signal from the sensor cannot be transmitted directly to the surface without first being digitized and/or amplified. Key electronic components that are crucial include microcontrollers, high-resolution analog-to-digital converters (ADCs), non-volatile memory, and power regulation. While some integrated circuit (IC) solutions exist that are rated for 225 °C and can operate at 250 °C or even 300 °C, e.g. Ohme (2007), these components experience accelerated degradation when exposed to 300 °C, reducing their operational lifespan. According to the industry survey, service providers design their tools to ensure that the electronics can operate for a duration of two years without needing replacement, which is crucial for minimizing operating costs and underscores the importance of reliability and minimal maintenance.

Another disadvantage of existing high-temperature (HT) ICs is their lower performance compared to low-temperature electronics. For instance, HT ADCs typically offer 12-bit resolution and 100 kSps sample rates at 225-250 °C, e.g. Honeywell (2012) and Romanko (2009), or 16-bit resolution and 600 kSps at 210 °C, e.g. Watson (2015). In contrast, low-temperature ADCs can achieve 24-bit resolution and operate at sample rates of ≥1 MSps. Given that geothermal well operators require accurate data, higher resolution is highly valuable for effective decision-making and operational efficiency. Despite these drawbacks, the primary advantage of HT ICs is their ability to operate at elevated temperatures, allowing tools to function for extended periods, which is increasingly important for long-term measurements.

The study identified a significant need for EES rated to operate at 250 °C, 300 °C, 320 °C, and even 375 °C (supercritical geothermal) for longer than two years to meet economic requirements. In addition to higher temperature ratings, these components must also have high-performance specifications, such as microcontrollers operating at higher frequencies, ADCs with greater resolution, and larger electronic memory storage. Addressing these requirements will be essential for advancing the capabilities of subsurface instrumentation and ensuring the successful implementation of EGS technologies.

3.1.2 Sensing Measurements

To accurately characterize a geothermal well, a variety of sensing measurements are essential. These measurements play a vital role in evaluating the well's performance, ensuring its structural integrity, and optimizing the extraction of energy. The specific types of measurements required vary based on whether the assessments are for drilling, short-term, or long-term purposes, as well as the current condition of the well. Collecting precise data during these stages is crucial for informed decision-making and for maintaining the safety and efficiency of geothermal operations. The survey identified several key sensing measurements necessary for operation at temperatures of 250 °C or higher, including:

- Pressure
- Fluid chemistry
- High finger count caliper (a tool that mechanically measures the diameter of the well and surface buildup)
- Tool navigation/orientation
- Magnetic single/multi-shot (measures inclination)
- Fracture mapping
- Feed zone rate
- Scale
- Corrosion
- Cement/rock integrity

These measurements can be achieved using various types of sensors, such as:

- HT pressure transducers
- Solid-state chemical sensors
- Gyroscopes
- Magnetometers
- Accelerometers
- Piezo transducers
- Geophones
- Spinners
- Hydrophones

Devices will be exposed directly to the extreme heat, pressure, and harsh fluids present within the well, while others may not. As identified by industry experts, the most pressing needs for long-term measurements exceeding 250 °C include pressure monitoring, well integrity assessment, formation detection, and tool navigation. Although some technologies exist that can operate at elevated temperatures, it often lacks certain accessories or requirements. For instance, off-the-shelf pressure transducers can function above 300 °C, e.g. Emerson, but they do not have the essential embedded electronic systems (EES) to support these devices. Tool navigation during drilling relies on accelerometers, gyroscopes, and magnetometers; while accelerometers rated for over 300 °C, e.g. PCB Piezotronics, are available, the necessary EES to support them are still lacking.

The DOE Geothermal Technologies Office (GTO) and UTAH Forge have been funding efforts to address these sensing challenges at elevated temperatures, e.g. Energy.gov (2024), which include:

- Formation fluid flow detection using high-temperature chloride sensors, e.g. Sauran (2024)
- Geothermal high-temperature geophones for fracture formation detection, e.g. Energy.gov (2024)

These initiatives aim to enhance the capabilities of geothermal sensing technologies, ultimately contributing to more efficient and reliable geothermal energy production. However, a broader array of sensors is necessary to effectively meet all data requirements in the subsurface. By tackling the challenges associated with high-temperature operations and developing advanced sensing devices, the geothermal industry can significantly improve its capacity to monitor well conditions, optimize energy extraction, and ensure the long-term sustainability of geothermal resources. Expanding the range of available sensors will enable operators to gather comprehensive data, facilitating informed decision-making and enhancing the overall performance of geothermal systems.

3.1.3 Energy Storage

In the realm of memory tools, energy storage solutions—such as batteries and high-density capacitors (including high-voltage capacitors and supercapacitors)—are essential for supplying continuous power to subsurface instrumentation that lacks a method for transferring power directly to the devices. These energy storage systems ensure that the instrumentation can operate effectively in the challenging conditions of geothermal environments, where reliable power sources are critical for data collection and monitoring. By utilizing advanced energy storage technologies, operators can enhance the functionality and longevity of memory tools, ultimately improving the efficiency of geothermal energy production. As of 2024, commercially available energy storage options are primarily limited to those designed for operation at temperatures below 200 °C. However, there is an increasing need for energy storage technologies that can reliably perform at temperatures of 250 °C and above. Feedback from the industry reveals that memory tools are primarily used to gather well data for post-processing once the tool has been retrieved from the well, e.g. Probe1, Kaldera, and ThermoChem. This method offers a significant cost advantage; employing slickline (high-strength cables lacking data communication capabilities) is considerably cheaper than using data cables, thus lowering operational expenses. However, the downside is that geothermal operators forfeit access to real-time data, which is essential for making timely decisions.

To address these challenges, further technological advancements in energy storage devices are needed to facilitate operation at temperatures above 200 °C. For instance, high-temperature ceramic capacitors and certain types of thermal energy storage systems, such as molten salt batteries, can operate effectively at elevated temperatures, providing potential solutions for energy storage in geothermal environments. Developing robust energy storage solutions that can withstand extreme conditions will not only enhance the functionality of memory tools but also improve overall operational efficiency in geothermal projects. As the demand for geothermal energy continues to rise, addressing these technological gaps will be crucial for maximizing resource utilization and ensuring the sustainability of geothermal energy production.

3.1.4 Communications

The survey underscored a significant demand for real-time data among customers. Access to real-time information enables prompt decision-making based on the dynamic performance of the well, particularly in identifying the connection zone between injection and production wells. The primary method for transmitting data from the instrumentation tool to the surface is through wireline cables, which typically contain one or more conductors and, in rare instances, fiber optics, e.g. Pastouret (2015), as illustrated in Figure 2. Since data is transmitted in real-time, local electronic memory is not necessary within the instrumentation. Additionally, these cables serve the dual purpose of powering the electronics, thereby eliminating the need for energy storage within the subsurface instrumentation.

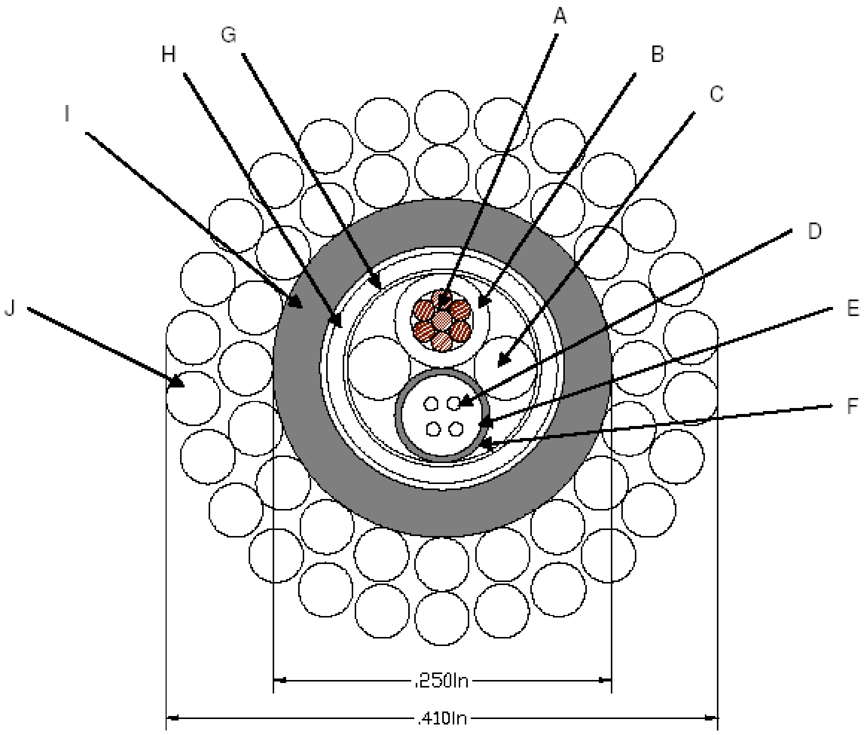

Figure 2: Prysmian illustration for high temperature cable with conductors and optical fiber, e.g. Pastouret (2015).

The industry commonly utilizes cables insulated with polytetrafluoroethylene (PTFE) due to its ability to operate at temperatures around 260 °C. However, PTFE transitions to a liquid state when exposed to temperatures exceeding this threshold, making it unsuitable for wells operating at higher temperatures. Moreover, these cables are encased in a wire rope to enhance their mechanical strength, which is essential for supporting the weight of the tool, which can weigh greater than 100 lbs. Unfortunately, this design compromises the ability to create a proper seal at the cable head (the junction between the cable and the subsurface instrumentation).

The presence of a leak path between the cable head and the cable necessitates the use of high-temperature (HT) grease to fill the cable head. Regrettably, this grease tends to dissolve over time when exposed to harsh high-temperature geothermal fluids, limiting the long-term operational viability of the cable. While this method may be effective for short-term measurements, it is inadequate for long-term monitoring. Consequently, there is a critical need for high-temperature cables that can endure temperatures above 300 °C and provide a direct seal with the tool, ensuring reliable performance for extended measurement periods.

Figure 3: Interior of cable head used to transition from the cable to the tool is filled with grease to temporarily prevent fluid contacting the electrical conductors.

3.1.5 Optical Measurement

An innovative alternative to electrical and electronic sensing (EES), power, and communication systems is the implementation of optical fiber technology. This subsurface instrumentation employs an optical fiber that extends from the surface to the tool, allowing light to propagate and interact with a sensor embedded within the system. The sensor then transmits modified light signals back to the surface for analysis. Optical-based hardware has gained recognition as a promising technology due to its proven capability to operate effectively at high temperatures. Optical sensing is particularly adept at measuring pressure, temperature, and acoustic signals, e.g. Haldorsen (2024).

One of the key benefits of optical sensing is its ability to operate without the need for traditional electronic components. This optical approach provides several advantages: it eliminates the need for energy storage and electronic components within the instrumentation, and it can significantly enhance data resolution and sensitivity compared to current high-temperature electronics. Moreover, the electronics required for data interpretation are situated at the surface, benefiting from the extremely low attenuation of optical fibers. This low attenuation allows for the transmission of data over long distances without significant loss of signal quality, making optical fibers particularly suitable for deep geothermal applications.

Communications through optical fibers involve the use of light signals to convey information. When light is transmitted through the fiber, it can carry a vast amount of data at high speeds, enabling real-time monitoring of well conditions. The ability to modulate the light signals allows for the transmission of multiple data streams simultaneously, which is essential for capturing various measurements from different sensors. Additionally, optical fibers are immune to electromagnetic interference, which can be a significant issue in environments with high electrical noise, such as those found in geothermal wells.

Historically, a major challenge for optical systems has been hydrogen darkening, a phenomenon in which hydrogen present in the well interacts with the doping in the optical fiber, resulting in substantial signal attenuation, e.g. Huang (2019). However, advancements in fiber technology have been made to enable operation above 300 °C while resisting hydrogen darkening, e.g. AFL Global and Jacobsen (2018).

Despite its benefits, optical technology is limited to specific types of measurements, including temperature, pressure, interferometry, spectroscopy, profilometry, and acoustic measurements. Importantly, not all optical sensing techniques have been validated for use in well environments. Additionally, the requirement for a continuous optical fiber imposes limitations for drilling applications, as the drill string must rotate, rendering optical fibers impractical. Similarly, the optical approach is incompatible with slickline instrumentation (memory tools). Given these constraints, EES remains essential for comprehensive data acquisition. Nonetheless, optical methods offer an excellent alternative for collecting high-resolution data in subsurface environments, contingent upon the specific measurement requirements and the means of capturing the data.

4. ADDITIONAL INFORMATION

Within and beyond the scope of this study, several noteworthy pieces of information have been identified that merit inclusion in this paper.

4.1 Conveyance

Advanced Logic Technology (ALT) and Sandia National Laboratories have developed a televiewer capable of performing well integrity analyses at temperatures up to 300 °C for durations of up to 12 hours, e.g. Advanced Logic Technology. This innovative tool is currently available for evaluating geothermal wells. Sandia has collaborated with multiple geothermal operators, including Fervo Energy, Utah Forge, Cyrq Energy, Quaise Energy, Ormat Technologies, and Enel Green Power, to utilize this tool for well measurements. However, a significant challenge has been the tool's limited conveyance capabilities. Most modern geothermal wells are deviated beyond 20 degrees to optimize energy production, which exceeds the operational limits of conventional wireline tools. In such deviated wells, effective conveyance is essential for evaluating the entire length of the well. The televiewer, designed to be lowered by wireline using gravity, becomes stuck when the well deviation exceeds 20 degrees. This multi-year effort to assist the industry in conducting well integrity evaluations has highlighted the critical need for tools that not only operate at high temperatures, high pressures, and in corrosive environments, but also possess robust conveyance capabilities.

4.2 Cooling the Well for Low-Temperature Subsurface Instrumentation

Sandia has engaged in discussions with customers regarding high-temperature subsurface instrumentation and the need for effective evaluation of a well. During these discussions, it was noted that measurements could be performed when the well is cooled, thereby eliminating the need for high-temperature instrumentation. Cooling the well can be achieved by injecting fluids, which is a viable solution for various measurements. However, this method is limited by the duration for which measurements can be conducted. In applications requiring multi-day measurements in a producing well, the temperature will eventually rise again, rendering long-term measurements impractical. Additionally, chilling the well can alter its characteristics and should not be performed during well production, as the thermal stresses induced during the cooling process may potentially damage the cement bond to the casing or the host rock.

This information underscores the importance of developing advanced tools and methodologies that can effectively address the challenges associated with geothermal well integrity evaluations and subsurface measurements.

5 CONCLUSIONS

To guide ongoing research efforts, we are actively working to identify critical and urgent challenges associated with geothermal subsurface instrumentation. This study underscores the increasing demand for long-term high temperature instrumentation to effectively evaluate Enhanced Geothermal Systems wells. Four primary categories require further technological advancements to address this need: embedded electronic systems, sensing technologies, energy storage solutions, and communications infrastructure. The timely realization of EGS is heavily reliant on progress in these areas.

To initiate the development of long-term high temperature instrumentation, we recommend prioritizing the advancement of integrated circuits utilizing silicon carbide (SiC) technology, as these components are fundamental to every electronic subsurface instrumentation system. SiC technology features a wide bandgap, high thermal conductivity, and a low thermal expansion coefficient, allowing it to withstand higher temperatures compared to traditional silicon-based components. These attributes make SiC particularly suitable for the demanding conditions of geothermal applications, where reliability and performance at elevated temperatures are critical for effective data acquisition and system functionality.

In addition to the technical challenges, there are significant concerns regarding the continuous supply of the identified hardware. While several high-temperature technologies have emerged in the market, most have not met the necessary demand to ensure a sustainable supply, resulting in their discontinuation. Therefore, effective long-term solutions to the challenges outlined in this paper are essential for mitigating risks faced by HT subsurface instrumentation tool developers and service providers, as well as for ensuring the overall success of geothermal power plants.

Addressing these challenges will not only enhance the viability of geothermal energy as a sustainable resource but also contribute to the broader goals of energy security and environmental sustainability. By fostering innovation and collaboration within the industry, stakeholders can work together to develop the necessary technologies that will support the growth and efficiency of geothermal energy production in the future.

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