Drilling for Superhot Geothermal Energy:

A Technology Gap Analysis

Authors: **Rebecca Pearce**, Cascade Institute and **Tony Pink**, Pink Granite Consulting

Full report: *Pearce, R. and T. Pink. 2024. Drilling for superhot geothermal energy: A technology gap analysis. Version 1.0. Clean Air Task Force and Cascade Institute.* *https://cascadeinstitute.org/technical-paper/drillingreport/*.

Summary

The research frontier of drilling and well construction for superhot rock (SHR) geothermal energy systems—*the production of renewable, baseload electricity by circulating water in deep (>5 km), hot (>374˚C) rock*—is steadily advancing. Recent achievements in polycrystalline diamond carbide (PDC) drill bit design, improved rates of penetration (ROP) into hard rock, and the development of insulated drill pipe show that deep drilling for SHR geothermal projects is on the not-distant horizon.

But several key technology gaps still stand in the way of deep drilling in hostile subsurface geological environments. Technology companies and laboratories must make rapid advances in specialized drilling rigs, bit technology, high-temperature downhole tools, and temperature management equipment. Currently, these drilling systems—and the amount of time required to access deep, hard rock formations—create significant project costs. To bring SHR geothermal to commercial viability, technology companies and laboratories must rapidly develop, test, and deploy new technologies.

This report reviews state-of-the-art deep geothermal drilling and well construction technologies, identifies existing technology gaps, and suggests strategies to overcome these gaps. Each technology is given a technology readiness level (TRL) between 1-9, from theoretical to commercially scalable.

Overall, we find that SHR geothermal wells can be drilled by deploying a combination of existing technologies and that the technological challenges to SHR drilling are surmountable. The economic challenges are a function of limited availability and testing of these drilling systems, both of which will decrease as the SHR geothermal industry expands. A first-order gap shared by these technologies is the lack of access to SHR conditions, both in-field and in controlled laboratory conditions. Without open-access experimental facilities and pilot sites, these technologies cannot undergo iterative improvements necessary to de-risk SHR drilling and propel the industry forward.

Big-picture technology gaps for SHR drilling and well construction

Technology companies and laboratories must overcome two "big-picture" technology gaps to make SHR drilling and well construction technically and economically viable:

1. Improve the ROP when drilling into crystalline basement rock.
2. Develop ultra-high-temperature electronic downhole tools and temperature management equipment.

Although SHR wells have been drilled in the past, their unprecedented temperatures, pressures, and depths present significant technical and financial challenges. Technology companies and laboratories must make rapid advances in specialized drilling rigs, bit technology, downhole sensors, and temperature management equipment to drill quicker and cheaper—the key hurdle for scaling up and de-risking SHR systems. Recent progress in improving ROP into hard rock and developing insulated drill pipe shows that the technoeconomic challenges of deep drilling for superhot geothermal are surmountable. However, further innovation, collaboration, laboratory experimentation, and field testing are crucial for drilling and constructing wells in superhot environments.

Table 1: Big-Picture Technology Gaps for SHR Drilling

Gap	Why	Current capability
Stronger, faster rock-destroying technology, including stronger drill bits.	To increase rate of penetration into crystalline basement rock.	Tools can penetrate crystalline rock, but too slowly to be economical in deep boreholes; high pressures up to 40 MPa and temperatures >375°C exceed the pressure-temperature capabilities of most drill bits.
Ultra-high-temperature downhole tools and temperature management equipment.	To access geothermal gradients sufficient for power generation (375°C to 450°C or more).	Most downhole drilling tools run at 175°C, with a few operating in the range of 200-225°C; some drill fluids can reach to 353°C.

Key findings

Rock-destroying technology

There are three categories of drilling technologies that are relevant for SHR geothermal: conventional rotary drilling, hybrid conventional drilling, and direct energy drilling.

Conventional rotary drilling

Conventional rotary drilling technologies (also called mechanical drilling), such as PDC, roller cones, and hybrid PDC/roller cone systems, are the most mature of the three categories. Most conventional geothermal and enhanced geothermal wells have been drilled with conventional rotary drill bits. These mature drilling technologies currently have the most potential for reaching deeper, hotter regimes—especially in the short term. TRL: 9.

Individual conventional drill bits can be specialized for extreme temperatures, interbedded formations, or extended bit life; however, no single bit features all these specifications. Combining these features may be the most efficient way to accelerate conventional drilling for SHR applications. To propel this technological frontier forward, we need to develop creative approaches to incentivize collaboration between major drilling firms while also protecting intellectual property and ensuring the profitability of firms.

The other major gap for conventional drilling is the lack of accessibility to supercritical conditions. There are no known laboratories capable of testing these drilling technologies at >374°C and testing in-field with these conditions is expensive and high-risk. Following extensive experimentation in a controlled laboratory setting, high-temperature, SHR-rated drill bits should be deployed in active SHR or EGS projects (e.g., Stn-1, IDDP, Japan Beyond-Brittle Project, Utah FORGE) for further optimization of deep, hot rock drilling.

Hybrid conventional drilling

Hybrid conventional techniques (also called nonconventional mechanical drilling) combine conventional drill bits with waterjet, percussion, or particle impact drill bits. Hybrid conventional techniques specifically target the brittle state of basement crystalline rocks (unlike conventional techniques, which were developed for soft rock formations). Hybrid conventional systems may offer competitive ROP and bit longevity relative to conventional drill bits; however, these systems are at a lower TRL for SHR conditions. TRL: 5-7 (5 for waterjet and particle drilling ; 7 for percussive).

One percussive drilling technique called air hammer drilling may not perform efficiently at great depths due to well instability and loss of force to the drill bit, while mud hammer drilling may incur substantial water loss if operating in porous or fractured media. Waterjet drilling is most effective when combined with another drilling system. It increases overall ROP and enables a lower frequency of tripping to surface. The reduction of downhole stresses is one of waterjet drilling's biggest advantages. However, the technology requires more validation. Surface systems need to be evaluated to ensure consistency with significantly increased flowrates at long distances through the drill string.

There are currently two main players in particle drilling: Particle Drilling and Canopus. Particle Drilling's technology is market-ready but requires further engineering, bench testing, modelling, and in-field operations to improve performance. Testing at the Utah FORGE site or at a similar open-access, hard-rock experimental site could accelerate the development of the technology. Canopus is pushing towards market readiness in 2024 but must perform a full-scale drilling test with a vertical-mounted conventional rig. Its tests thus far have been in soft rock and so it must validate its ROP improvements in hard igneous rock. Canopus must also address signal attenuation issues with further engineering and testing in deep hard rock and formations with high conductivity.

Direct energy drilling

Startups working on direct energy drilling technologies (plasma and millimeter wave) are targeting depths greater than 15 km, which makes it an important technology to consider for regions where superhot temperatures are only found at those depths. However, direct energy drilling has the lowest technological maturity right now as the techniques are still novel. Direct energy drilling uses plasma or millimeter-wave energy to weaken or vaporize rock. Advantages include minimal downhole equipment, few complications from high temperatures and pressures, and significantly less trip time than rotary or hybrid conventional techniques. Another advantage is the possibility that direct energy drilling would not fail in ultra-deep, high-pressure, high-temperature conditions where rock may exhibit more ductile behavior. TRL: 2-4 (2-3 for millimeter wave; 3-4 for plasma).

For direct energy drilling of hard rock formations (especially granite), the breakdown of the rock formation plays just as critical a role as the technology used to remove the material. The variance within different granite formations plays a significant role in the amount of energy consumed by the drill system and the amount of material removed during each pulse. In plasma drilling, researchers have identified a significant relationship between the pore size and the amount of total energy consumed during the operation, with implications for ROP and the total required energy to complete the borehole. Similarly, the rate of evaporation for MMW depends on the mineral content of the rock formation, which may lead to non-uniform removal of material with implications for ROP and performance. While controlled experimentation improves the understanding of these behaviors, larger-scale experimentation is necessary.

Another key factor in the success of plasma drilling is the drilling fluid. Most geological-based laboratory tests use water as the dielectric fluid within the system, but engineers need to better understand how to maintain clean drilling fluid downhole in field conditions.

The primary technology gaps for MMW drilling for SHR include:

- acquisition of a high-powered (>1 MW) MMW beam to conduct scale-up experiments;
- access to laboratory facilities with SHR conditions to conduct necessary experimentation;
- modelling analysis of heterogeneous absorptive properties in rock and the impacts on well shape and ROP;
- ruggedization of the gyrotron apparatus for in-field conditions and operability by drilling personnel, and adaptations of conventional rig systems for MMW compatibility; and
- engineering of waveguide deployment and removal, and methods to cope with: downhole bends or tortuosity, and expansion/contraction of the waveguide under different temperatures and pressures.

High-temperature downhole tools and temperature management equipment

An SHR drilling system must deliver a working fluid to the bottom of a well to cool the drill string and the electronic components of the borehole assembly (e.g., drill bits, logging tools) below the maximum temperature of the tool or component with the lowest temperature specification. SHR systems will encounter temperatures greater than 375°C.

There are two temperature management options: cool the well and rock or increase the temperature threshold of downhole tools. If drillers choose to cool the well and rock, then well temperatures need to be maintained during the entire energy production process. Models suggest that the drill string, the downhole tools, the annulus (the space between the borehole wall and the casing), and the rock can be cooled down below 175°C with a combination of technologies, but the process is slow. Currently, most downhole drilling tools—instruments and devices used in the wellbore to perform operations, gather data, and manage the drilling process—run at 175°C, with a few operating in the range of 200-225°C.

The most promising option is to combine cooling techniques and increase the temperature threshold of downhole tools. Temperature management options include:

- Apply low-heat coefficient coatings to conventional drill pipes. TRL: 6.
- Use insulated drill pipe (IPD) that's externally coated, internally coated, or vacuum sealed. TRL: 7.
- Use high-temperature drilling fluids (water-based additives with reasonable deformation characteristics). TRL: 8-9 for low-angle holes; 4-5 for higher-angle or horizontal wells.
- Use supercritical CO_2 (sCO_2) as a drilling fluid. TRL: 3.
- Apply mud coolers to lower the surface mud temperature. TRL: 9.

Technology companies must continue to improve high-temperature-resistant electronics with non-organic materials (such as all-metal seals) and develop high-temperature-resistant capsules for electronics. Further research into "one run" tools that are deployed once before expiring from high temperatures may provide a cost-effective (but potentially wasteful) alternative to engineering SHR-capable tools or deploying temperature management equipment in combination with existing high-temperature tools.

Currently available IDP technology can be used to manage the temperature of a 400°C SHR well below 175°C while drilling. However, the biggest challenges facing IDP are cost and weight. Operators should look for the lowest-cost, highest-value combination of coated pipe, IDP, and high-temperature downhole tools. If the IDP drill string is too heavy, higher-temperature-rated tools could be used and/or surface mud coolers could be added to the system. Cost is also the biggest challenge for titanium drill pipe.

Water, at the correct fluid velocity, is sufficient to clean the borehole if developers maintain the borehole inclination below 20 degrees. Above 20 degrees inclination, further research is needed in high-temperature additives, especially if operators begin drilling horizontal SHR wells. Another promising option is to use sCO_2 as a drilling fluid. All the components of a sCO_2 system exist, but the complete system needs to be engineered and fully integrated into a package that includes all the mechanical hardware, a control system, a model, and trained experts to run it—and then that package must be tested in the field. With the right level of investment, this package could be realistically developed and tested in 2-3 years.

Continued research into low heat coefficient coatings and the potential use of nanoparticles and other insulative materials is needed to further lower the conductivity of drill pipe. This research should be carried out through collaborations between national labs and commercial test partners. The low heat coefficient coatings may also be considered for insulative purposes on other tubulars in the wellbore.

Conclusion

SHR geothermal systems have the potential to provide long-term, scalable, renewable baseload power. Unlocking this potential requires significant innovation in drilling and well construction technologies to improve ROP and develop high-temperature downhole tools and temperature management equipment.

Currently, rock-destroying equipment, high-temperature downhole tools, and temperature management equipment share three overarching challenges:

1. Lack of access to SHR in controlled, laboratory settings,
2. Lack of access to SHR in in-field settings, and
3. Lack of incentives for collaboration between major drilling firms.

Collaboration between the public and private research community can help overcome these overarching challenges by first identifying all facilities around the world capable of SHR experimentation (e.g., Utah FORGE, IDDP), then creating the necessary incentives for greater cooperation between major drilling companies and research groups, and finally ramping up experimentation and R&D in SHR conditions.

Across all well-construction technology domains, one theme is clear: the technology to complete superhot or ultradeep geothermal boreholes and wells exists—but we must reduce the overall cost and time on task to drill a deep, superhot geothermal well. With continued support and development, the future of geothermal energy is extraordinarily bright.