Path to SuperHot Geothermal Energy Development

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ABSTRACT

To seriously address climate change, the world needs to massively shift away from carbon intensive energy sources that drive the global economy. Electricity and transportation comprise nearly 70% of global carbon emissions. Electrifying transportation and decarbonizing electricity production can effectively zero-out carbon emissions from these sectors, but it will require replacing the installed 4 TW of fossil fueled electric production and meeting a 50% increase in carbon-free future demand by mid-century. This is a significant challenge, requiring sources of energy that can be rapidly scaled all over the world at power densities consistent with urban demand, low environmental footprints and affordable. With all great challenges, come opportunity and the repowering to a carbon-free energy economy will create new engines of economic growth. Geothermal energy, the heat from the earth, is one of the most promising and under accessed sources for meeting the TW global demand for clean power; however current geothermal energy provides only a small source of global electricity The heat held between 3-10 km of crustal rock is one million times greater than modern global primary energy use, but the current geothermal industry only scratches at the surfaces of this resource. Breakthrough technologies will capture deeper heat at energy densities that will disrupt the renewable energy landscape. Very high temperatures can provide low-cost, carbon-free sources of electricity anywhere, minimizing need for transmission and related infrastructure required for other renewables and with very low environmental footprints. This advanced form of geothermal energy is referred to as Superhot Rock (SHR) geothermal. Because of the very high energy density, developing the technology to use SHR can not only expand world-wide access to zero carbon emission energy, but can also provide affordable, locally sourced and secure resource for electricity production everywhere. SHR will require advancements in subsurface technology, similar to the breakthroughs and massive scale-up of the unconventional oil and gas resource development in the US over the past two decades. The oil and gas and geothermal industries should partner to develop the needed technology and demonstrate the viability of this resource and open up entirely new business opportunities leveraging the oil and gas industry's scale and resources toward extraction of heat instead of carbon globally. This paper lays out the

technology needs to achieve SHR, current efforts toward developing and demonstrating the resource around the world and a path forward to realizing SHR's scale and opportunity.

1. Introduction

Scalable, low-cost, locally sourced, carbon-free electricity to meet rising global demand can be uniquely achieved with Superhot Rock Geothermal (SHR) resources. The objective of SHR is to mine heat from deep hot dry rock where temperatures are in excess of supercritical water conditions, >375C and 22Mpa. To be able to access this resource ubiquitously, requires the ability to repeatably and cost effectively drill to depths greater than 10km to access the heat and engineer reservoirs in the impermeable rock to provide the heat exchange surface area to mine the heat. At these conditions, a single well could yield up to 10x the energy per well compared to conventional geothermal or natural gas wells. Within a 1 km2 area, a 3-well system comprised of one injector and two producers could yield between 80-100 MW/km2. This is a power density that is orders of magnitude higher than other renewables like solar and wind and approaching the power density of fossil fuels. It is anticipated that at the target depths, induced seismicity concerns are ameliorated because of the damping effect of the high temperature plastic rock. The high-power density, small environmental footprint, and potentially low seismic risk makes SHR an ideal electricity source to place within the urban boundary reducing the need for expensive transmission infrastructure. Because we know hot rock is available everywhere in the earth's crust, if the heat can be accessed economically through advancements in drilling and reservoirs, SHR can be located anywhere. In order to meet the climate challenge, we need to prove the technology and business case to scale SHR globally with the objective of a low power cost of < $0.02/kWh and the ability to deploy a TW per decade. These are very ambitious goals, but the magnitude of the challenge requires audacious ideas. However, there are some nearer term steps along the way that can prove the viability and business case for supercritical geothermal resources and allow a path for parallel development of the advanced technologies needed to meet our goal. It begins with the existing Supercritical hydrothermal resources, those that occur naturally and have been developed in many places in the world and moves to magmatic resources, where high temperatures can be reached at depths where conventional technology can be used to drill and create reservoirs using novel Engineered Geothermal System (EGS) methods to demonstrate the first SHR resource for electricity production. These incremental developments exploiting both supercritical hydrothermal and higher temperature EGS at shallower depths can pave the path to the development of the ubiquitous SHR system at 10km and beyond with step-change advancements in drilling, well completion and reservoir development.

Supercritical hydrothermal resources have been developed in a number of areas around the world with magma close to the surface and natural permeability. Despite the fact that the geothermal fluids in these very high temperature resources can make drilling and completing the wells and operating the plants at these projects a real challenge, the high energy density in areas like the Salton Sea in California, the Reykjanes Peninsula in Iceland, Larderello in Italy and the Taupo volcanic field in New Zealand make these fields very economical . Resources like these where supercritical fluids are found in naturally faulted and fractured rock near the surface are rare, so in order to make this important resource accessible to a wide area of the globe, we need to develop technology that will help us drill and complete wells to deep depths 10-20 km and create an artificial 'heat exchanger' in hard rock to mine the heat. Until we get to that point, there are shallower, accessible high temperature resources we can drill using currently available drilling and EGS stimulation technology to engineer a reservoir, mine heat with water and run it through efficient and conventional supercritical steam cycle technology to produce electricity.

In the Western US, there are a few places with enormous capacity for SHR development at shallow depths (<5km) where 20 GW of power can be developed, these include The Geyers and Coso, Mt. Shasta, Mt. Lassen, Medicine Lake and the Long Valley Caldera in California, Newberry, Mt. Hood, Mt. Jefferson and the Three Sisters in Oregon, and Mt. Baker, Mt. St. Helens, Mt. Rainier and Glacier Peak in Washington. While many of these areas are protected by national parks or monuments, the heat under them may be accessible from nearby through directional drilling technology. Within 5-7 years, with appropriate investment, it is possible that these resources can be brought online using conventional technologies with some advancements and enhancements in high temperature well completion and reservoir development. Investment in the first plant to demonstrate the ability to produce the resource and generation power is likely a public/private partnership which will be accompanied by research and testing to find the best methods for development. However, over multiple plants, costs should drop to enable producing power at an LCOE equivalent to \$0.03-\$0.04/kWh to be competitive with US power costs for baseload carbon free electricity sources by 2025. To enable widely scalable geothermal all over the world, we need both technology advancements and cost reductions to approach < \$0.02/kWh.

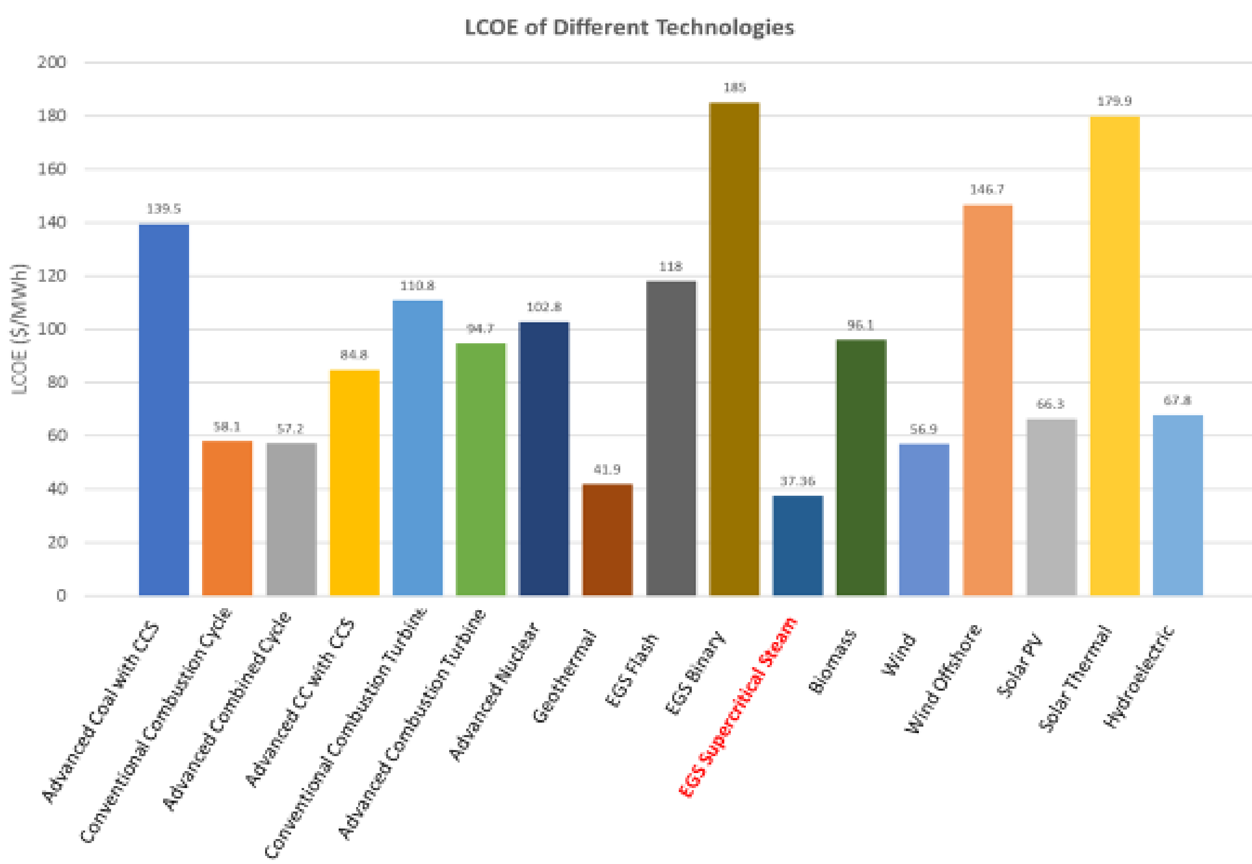

Figure 1: Costs are projections for 2025. SHR EGS is for nth of a kind plant using best available current technology.

Technology Development Needs for SuperHot EGS

We need to start with science that informs technology development, field demonstrations and eventually commercial deployments across four key areas:

- Resource Characterization
- Drilling and Well Completion
- Reservoir Creation and Management
- Energy Conversion

Table 1. Summary of science and technology development needs for achieve global SHR resources.

Technology	**SHR-Hydrothermal**	**SHR-HDR (SH-EGS <5km)**	**SHR-DHDR (deep>10km)**
Resource Characterization	Passive seismic surveys and active seismic studies using forward scatter MT, Gravity, Magnetic, InSAR and Geodetic surveys Field geology, geochemical analysis, and downhole stress analysis	Passive seismic surveys MT, Gravity, Magnetic, InSAR and Geodetic surveys Field geology, geochemical analysis, and downhole stress analysis	Passive seismic surveys Gravity, Magnetic, Geodetic surveys Field geology, geochemical analysis, and downhole stress analysis
Drilling Well Completion	Conventional Drilling High T materials for casing/cement/connections High T wireline monitoring and measurement tools/imaging	Conventional Drilling/some HT bit development High T materials for casing/cement/connections High T wireline monitoring and measurement tools/imaging	Advances in Drilling to enable fast, efficient drilling to depths >10km Novel approaches to well completion beyond conv casing/cement that can be incorporated with drilling
Reservoir Development	Utilizes existing permeability structures and supercritical water at depth May utilize thermal stimulation to enhance permeability Reservoir characterization tools such as tracers	Requires both mechanical isolation tools and thermally degradable diverters High temperature proppants and proppant emplacement methods Reservoir characterization tools such as tracers New stimulation methods and monitoring techniques	Requires mechanism to isolate production intervals, unclear if mechanical isolation will work at these depths High temperature proppants and proppant emplacement methods Reservoir characterization tools such as tracers New stimulation methods and monitoring techniques
Power Plant/Surface System	Conventional geothermal power plant technology/systems can be used, optimization needed around higher T fluids, brine management and reheat cycle, etc.	Conventional geothermal power plant technology/systems can be used, optimization needed around higher T fluids, brine management and reheat cycle, etc.	Conventional geothermal power plant technology and systems can be used; however, other power generations method may be better suited.

Pathway to SuperHot EGS

While the goal is world-wide economic SuperHot rock energy, the pathway to achieving that goal is through development of resources with very high temperatures at shallow depth. While of limited extent volcanic systems with magma bodies at depths of 6-9 km not only make immediate drillable targets but contain an enormous amount of thermal energy at each site. Most geothermal assessments of the Cascades volcanic system have looked at naturally occurring hydrothermal systems. While acknowledging the enormous amount of heat stored in and near the magma chambers under these volcanos (Table 2, the size of any accessible hydrothermal resources are small. How we access that energy and get it to the surface is the pathway to development we need to understand to develop economic SHR.

Table 2: Estimated electrical energy in selected varge volcanic systems in the U.S.

System Name	State	Estimated Electrical Energy (MWe)
Island Park Caldera	ID	158,378
Newberry Volcano	OR	1557
3-Creeks Butte Volcanic Area	OR	1104
Mt. McLaughlin Area	OR	14,078
Crater Lake Area	OR	36,241

While more than 25 geothermal wells have encountered temperatures ≥374 °C, and some supercritical fluids have been reached, only a few of these wells have been operated and none are used to operate a supercritical power cycle. Thermal cycling in supercritical temperature wells is also a major issue for sustaining production from naturally occurring supercritical fluids with geochemistry the next problem. Thermal cycling can stress the casing and damage cement resulting in loss of well integrity. Supercritical fluids in natural hydrothermal systems often contain large amounts of volcanic gases and dissolved solids that make them corrosive or form scale.

Cooling the very hot rock during drilling seems to improve rate of penetration, direction control is severely limited. There isn't the ability to monitor while drilling (MWD) that conventional drillers currently enjoy. Bit life can be drastically shortened in these harsh environments leading to more frequent tripping to change out bottomhole assemblies. Casing, and cementing are severely challenged above 350 °C.

All of the supercritical temperature wells drilled to date have been in hydrothermal fields with very high temperatures. If we want to move to SHR we will need to create or engineer a reservoir and find ways to manage that reservoir long term to extract the heat. The behavior of rock in the brittle–ductile transition and long–term behavior of fluid/rock interactions are poorly understood. Basic science and testing are needed to model behavior of reservoir fracturing and operation. Thermal stress failure is assumed to dominate reservoir stimulation, but it isn't clear how tectonic differential stresses will play a role or whether such fractures can even remain open.

It is now technically feasible to drill and complete wells at temperatures over 375 °C. However, scientific and technical development is needed to be able to stimulate, produce and operate SHR power projects. Reaching temperatures over 450 °C may involve drilling into the transition from brittle to ductile rock. Basic science research is needed to understand rock mechanics, tectonic stresses, and rock fluid interactions in the brittle-ductile transition zone. We not only need to understand how fractures propagate in very high temperature rocks of different compositions but also how those fractures will behave long term. Numerical simulators typically used for geothermal reservoir modeling do not currently include temperatures above the critical point of water. Very high temperature conditions need to be included in thermo-hydro-mechanical-chemical codes to allow us to model heat extraction, reservoir behavior and stimulation/fracturing.

SHR R&D Projects Around the World

So how do we get from today's technology in geothermal to developing SHR? The biggest stumbling block to development of any new technology is not the cost of development or the risk. The first of any new technology needs that believer who will back the first project and stay with the technology until it is accepted. This backing can come from government, from industry or from venture capital, but there is almost always a champion who believes things will improve if the goal is reached. SHR research projects around the world are testing the limits of current technologies.

Known Magmatic Superhot Geothermal Resources

There are several resources where temperatures above 374 °C have been encountered. In some cases, these high temperatures were specifically targeted and in other cases they were accidently discovered within active geothermal fields. Together, these locations represent a potential experimental testbed for research and development of SHR technologies.

<u>The Geysers, USA</u>

Located north of San Francisco, California in the United States, The Geysers is the oldest operating geothermal field in the western hemisphere. Power production began in 1960 and continues to today. The field is a steam field and is famous for its high temperatures. The hottest well at the geysers is Prati–32, where 400 °C was encountered. The depth of this well was 2.4 km. A broad supercritical resource is believed to be underlying the geysers geothermal field. More exploration would be required to better define this resource (Stimac et al., 2017).

<u>Salton Sea, USA</u>

Located East of Los Angeles, California, The Salton Sea is large operating geothermal field. The first commissioned plant was in 1982 and since then 10 more power stations have been built. The resource is a well characterized dual phase system located in a region with significant faulting. The hottest well drilled there is IID–14 at 390 °C at a depth of 2.1 km. It is believed that there is a broad–based supercritical resource underlying the existing field (Stimac et al., 2017).

Puna, USA

The well with the hottest recorded temperature was in Hawaii at the Puna Geothermal Field, located on the big island of Hawaii. The first only power plant was constructed in 1989 and has produced power until 2018, when the plant was shut down due to an eruption. The hottest well at Puna is KS–13, which drilled into magma at 2.5 km. The inferred bottom hole temperature was 1050 °C (Bromley et al., 2020).

Coso, USA

Located near the China Lake Navy Base in southeastern region of California, the Coso Geothermal Field has been in operation since 1981. It is a steam dominated reservoir with a magmatic source of heat. While no wells have encountered temperatures of 374 °C or above, based off an abundance of well log data and geophysics, a supercritical resource has been inferred to underly the known reservoir at a depth of ~5 km (Stimac et al., 2017).

Kakkonda, Japan

In 1994, the Japanese government financed a well drilled to a depth of 3.7 km to learn more about the source of heat at the Iwate geothermal area. It was drilled at the Kakkonda geothermal power plant which has been in operation since 1978. The well target was a granitic pluton underlying the geothermal field. It successfully drilled to the target depth but did not encounter permeability. It reached a bottom hole temperature of 500 °C (Bromley et al., 2020).

Larderello, Italy

Larderello is the oldest operating geothermal field in the world and is located in Tuscany, west of Florence. The first power plant was built in 1913 and the field has been in continuous operation ever since. Starting in May 2015 the DESCRAMBLE project sought to drill into the source of the heat for the field. In 2017, Venelle-2 was drilled to a total measured depth of 2.9 km to target this heat source. A mechanical Kuster tool was able to record a temperature of ≥504 °C near the bottom of the well, but it is unknown whether this an equilibrated temperature. Fluid inclusion analysis predicts an equilibrated temperature of 507–514 °C. Venelle-2 had one recorded loss circulation zone at 2.7 km with a temperature of ≥400 °C and a leak-off pressure of 30 MPa. The well is currently suspended awaiting next steps (Bertani, 2018).

Iceland

Iceland has many potential supercritical geothermal resources accessible by today drilling technology. The Icelandic Deep Drilling Project (IDDP) has drilled into two of these resources with a plan to drill into a third. IDDP–1 was drilled in Krafla Geothermal Area, IDDP–2 was drilled in the Reykjanes Geothermal Area, and the third well is expected to be drilled in the Hengill Geothermal Area. There are 6 operating geothermal power plants in Iceland and robust infrastructure, making it one of the best places to test concepts on superhot geothermal systems. IDDP–1 was drilled to 2.1 km and produced steam at 450 °C and 14 MPa. IDDP–2 was drilled to 4.65 km and had an estimated equilibrated bottom hole temperature of 540 °C (Bromley et al., 2020).

Menengai, Kenya

Menengai Crater is volcanic crater in Kenya and is the site of a developing geothermal field. Three 35 MW powerplants are currently planned and many well have already been drilled. During the initial drilling phase, well MW–O1 had a measured static bottom hole temperature of ~390 °C and many of the wells drilled have temperatures over 300 °C. Modeling efforts have shown that there may be an influx of supercritical fluids from beneath the known field (Kipng'ok, 2014; Sullivan, 2015).

Los Humeros, Mexico

Located in the state of Puebla and east of Mexico City, Los Humeros is a volcanic based resource with an operating geothermal powerplant producing 94 MW of electricity. There are at least seven deep wells have estimated stabilized temperatures greater than >380 °C. Two well, H–26 and H–12, encountered young intrusions at depth (Dobson et al., 2017).

Superhot R&D Projects

Japan Beyond Brittle Project (JBBP)

The objective of the JBBP is to conduct engineering and scientific investigations into the extraction of geothermal power from beyond the brittle–ductile transition zone. Research is focused on rock mechanics, induced seismicity, exploration techniques, drilling and logging technologies. The aim of this research is to provide a foundation of knowledge for the development of superhot systems. Specifically, JBBP is targeting shallow magmatic based systems. JBBP has had some initial research successes with the discovery and characterization of "cloud fracture" formation. The team was able to recreate superhot reservoir conditions and subject representative core to different stimulation methods. It was found that thermal shock and overpressure caused reactivation of natural microfractures, which created a permeable connected network of small "cloud fractures" (Wantanabe, 2018).

Iceland Deep Drilling Project (IDDP)

IDDP is long term research project with the aim of drilling into three separate superhot resources. The first two wells, IDDP-1 and IDDP-2, have already been drilled and IDDP3-3 is currently being planned. The IDDP wells have been successful in accessing superhot resources but have encountered challenges when it comes to wellbore completion. IDDP-1 is located at the Krafla Geothermal Area in Iceland. It was drilled to 2.1 km and produced 450 °C at 14 MPa, but it had to be shut down because the significant corrosion and abrasion caused by the steam produced from the well. The expected generation of IDDP-1, if the well could withstand the harsh conditions, was 25-35 MW at a measured flow rate of 10-12 kg/s (Fridleifsson et al., 2014). IDDP-2 is located within the Reykjanes Geothermal Area. It was drilled in 2016-2017 to a depth of 4.65 km and had an estimated bottom hole temperature of 540 °C (Talinus and Neilsson, 2020). Coring revealed that the project had drilled into a sheeted dike complex of highly altered gabbro. Upon completion IDDP-2 underwent stimulation.

Hotter and Deeper Exploration Systems (HADES)

HADES is a research organization based out of Newland focused on fracture characterization, deep reservoir delineation and fluid interaction in superhot geothermal resources. Work is focused on deep geothermal resources in New Zealand. The program was born out of conference in 2011 and published research has been fairly diffuse since that time. The project is overseen by GNS Science, an earth science consulting firm based out of New Zealand.

Integrated Methods for Advanced Geothermal Exploration (IMAGE)

The IMAGE consortium was comprised the leading European geothermal research institutes and industry partners who performed testing and validation of the new methods at existing geothermal sites owned by the industry partners, both in high temperature magmatic and in basement/deep sedimentary systems. The project ran from 2013 to 2017 and focused on the process and properties of high temperature geothermal systems, new exploration techniques and integrating finding into operating projects. A book outlining the results of the project was published in 2017 (Wees, 2017). The work done for this project was comprehensive, project partners developed a catalog of rock properties at high temperatures and pressures, a world stress map was developed, new active seismic techniques were developed and tested, and many other areas were explored as well. Any future work on supercritical systems should reference the wok completed for this project.

Drilling in Deep, Supercritical Ambient of Continental Europe (DESCRAMBLE)

The focus of the DESCRAMBLE project, which ran from 2015 to 2018, was to develop and test new and innovative drilling technologies able to withstand the conditions of superhot resources. Much of the research and development went into the service of deepening a well found in the Larderello Geothermal Field in Italy. Venelle-2 was deepened from 2.2 km to 2.7 km in attempt to access the inferred supercritical resource underlying the known geothermal reservoir. The final depth was just short of the target, which was a seismic reflector found at ~3-4 km depth across the field called the K-horizon. However, recorded bottom hole temperature exceeded the expected temperature of 450 °C and drilling can therefore be considered a success. Based off fluid inclusion analysis, the expected equilibrated bottom hole temperature was determined to be between 507-514 °C. A mechanical Kuster tool recorded a maximum temperature of 504 °C (Bertani, 2018). This project pushed forward many innovative solutions for deep and high temperature drilling. This includes advances in drilling mud, mud cooling systems, drill bits, casing, cementing, logging tools, wellhead design and exploration techniques.

DEEPEGS

Centered in Eurozone, this project seeks to deploy new technologies and techniques to further the development of engineered geothermal systems. The project started in 2015 and finished in 2019. The project focused on three projects: Reykjanes, Rion Limagne and Valence. Findings from the three projects were to be shared to improve the efficacy of geothermal stimulation of deep reservoirs. The project at Reykjanes involved the stimulation of IDDP-2 in 2017 and 2018. Of the three projects, Reykjanes was the only one exploring the stimulation of superhot resources. A multimodal stimulation approach was used in which the reservoir rock underwent thermally induced fracturing and hydroshearing through the use long-term over-pressured injection of water. Stimulation began in February 2017 and was paused late in July 2017 because of heat-up associated with the use of diverter materials. Stimulation resumed in early 2018 and was continued until the end of 2018. The flow test officially started in December 2019 and results are pending (SAGA REPORT, 2018; Peter–Borie et al., 2019; Friðleifsson et al., 2018; DEEPEGS, 2020).

GEOWELL

GEOWELL is a three-year project that began in 2016 and ended in 2019. The program addressed various aspects of new and enhanced technology for the design and operation of high–temperature geothermal wells. These include cement slurry design, casing material selection, coupling of casings, downhole temperature and strain measurements in real time using fiber optic technologies and novel methods for risk assessment. One of the more interesting results to come of the project was the fabrication of expandable couplings made for high temperature wells. These coupling should prove quite useful in the development of high temperature geothermal resources because they can potentially mitigate the damage caused by the thermal expansion of casing (Ragnarsson et al., 2018).

GEMEX

A partnership between European and Mexican institutions, the project began in 2016 and is expected end in 2020. The focus of the project is the exploration and development of two superhot resources located in Mexico. The first resource is located east of Mexico City at the Los Humeros Geothermal Field and the other resource is located at the Acoculco Geothermal Field. The project has generated many interesting results, especially in regard to exploration, modeling, and rock mechanic studies (GEMEX, 2020).

Newberry Geothermal Energy (NEWGEN)

NEWGEN is a collaborative effort lead by a team of researchers from Pacific Northwest National Laboratory, Oregon State University, and AltaRock Energy. The NEWGEN team includes experts in EGS research and development, commercial power generation, engineering and the hard sciences which will lead the project forward while maintaining educational outreach in both the local and scientific communities. The NEWGEN research site is located on the western flank of Newberry Volcano in central Oregon, the site of previous stimulation efforts. NEWGEN is actively seeking funding to pursue the superhot resource at Newberry using new and innovative technologies. It has the option to deepen two existing wells whose bottom hole temperatures are both above 300 °C.

Beyond basic science, there are some technology developments both short and long term that would make near term development of a supercritical EGS project possible and improve cost, risk, and outcome for the long term. Technology development for resource characterization, wellfield development, both near and long term, reservoir development and management and energy conversion are all needed for successful SuperHot EGS power generation. Need to delete, not included in paper.}

2. Technology Development Pathway to SHR

The first steps in developing SHR EGS technology will be to better understand the resource and its potential behavior under the various heat extraction scenarios as well as understanding the well construction materials and well designs. To do that we feel that there are four pieces that need to be put in place:

- High pressure high temperature laboratory that can handle large samples of ~1 m^3 in size
- Hydro-thermal-mechanical-chemical numerical modeling capabilities for a range of possible fluids circulating in the rock at temperatures >400°C
- High temperature well to test out SHR fracturing methods, instrumentation, drilling and well design technology.

To better understand the potential SHR resource, an updated resource assessment that encompasses temperature and depth information beyond the 10 km depth and 350°C limit of the Future of Geothermal Energy Study of 2007 is needed. This will not only help to make the case for developing SHR technology but will also provide technology needs goals for advanced drilling methods as well as heat extraction methods for getting the heat to the surface.

This paper explores the resource technology needs for SHR EGS. Power generation is an important part of development of this enormous resource, but this paper will not discuss it since supercritical power generation to use the high temperatures has been developed and is currently in use in both fossil fuel and nuclear power plants.

Near Term Drilling Technology

While we can drill wells into very high temperature rock now, well directional control, casing and cementing are a challenge for temperatures above 350°C. Installation of the well head, casing, cement, and liner is the largest challenge for the development of superhot resources. These components maintain wellbore stability, separate deep geothermal resources from shallow aquifer systems and help to ensure the safety of wellfield operations. If cement or casing fails it can lead to hole collapse, which often causes permanent damage to a well. Casing or cement failure can also cause blow outs, where over-pressured steam is leaked into an underground aquifer. Steam or brine leakage into a ground water system will reduce production and, in some cases, cause contamination of water resources. Leaks can also form at the wellhead if the system is not designed correctly. A leak at the surface is a severe safety hazard and can be difficult to fix. During the design of a well, engineers aim for each one of these components to last the projected life of the project, which is normally 20-30 years. With the extreme temperatures being produced from superhot resources, large thermal stresses will be imposed on the casing, cement, and wellhead. Thermal expansion of steel will cause the casing string to grow, and the expanding and contracting casing will impose large stress on the cement holding it in place. Superhot wells pose a significant engineering challenge, however, there are existing solutions and technologies on the horizon that promise to solve many of the known problems.

Directional Control - We can cool mud motors or use a bent sub and pendulum assembly to control well direction, we currently don't have high temperature Measurement While Drilling (MWD) equipment that will withstand high temperatures unless we can circulate cool fluids. The current method for direction drilling is to use logging while tripping to get directional information and then modify direction without the use of a mud motor after downhole temperatures exceed about 350°C. The need for high temperature instrumentation with power supplies stable at high temperatures is a key technology need for improving not only the performance but also the cost of SHR geothermal wells.

Casing and Cementing - The diameter of the producing interval of geothermal wells tends to be larger than oil and gas wells to allow for higher expected flow rates with less pressure drop. (Figure 2) This increases the cost of geothermal wells drilled to depths of up to 3 km for conventional geothermal projects up to 3 times the cost of oil and gas wells of the same depth. In the case of superhot resource, the cased sections of the well will extend deeper than conventional wells and will be completed with different casing material and cement but will still need to be larger diameter to minimize pressure drop. Designs for very high temperature need to be tested by modeling the potential thermal cycling. Materials also need to be tested at these temperatures to ensure that they will perform as needed to line the well, contain pressure and to maintain the long-term integrity of the wellbore. While we have materials that have been used in supercritical conventional geothermal wells, the longevity of these wells is reduced by the harsh environment. Understand the reasons for well degradation and failure at very high temperatures is very important for the long-term sustainability of the wellfield assets.

Casing connections are another technology need for SHR wells. We do have high temperature connections but there is currently no lab which can simulate the high temperature and pressure conditions we will encounter downhole with large enough samples to really predict performance.

Cements are currently available for temperatures up to 350°C. If cemented casing is needed at deeper depths research will be needed to develop it. Casing materials and designs for going beyond the yield point of metals have been tried in very high temperature thermal recovery wells drilled and operated for heavy oil. While these wells can be operated, their useful life is shortened by thermal cycling.

It is the open hole section of the well where new drill bits and drilling systems will be required. We can certainly drill these wells, and in fact see better rates of penetration as the temperature becomes very hot, probably due to thermal stress fracturing of the rock.

Drilling Fluids - Conventional drilling fluids use biopolymers to increase viscosity and help form wall cake along the wellbore surface. Wall cake formed along the wall of the wellbore help prevent fluid loss to the formation. However, these conventional polymers are only effective at temperatures <149 °C. Synthetic polymers can be used for higher temperature environments, but these are only stable at temperatures <204°C. The DESCRAMBLE project in Larderello successfully used novel clay-based drilling fluids to drill the hot open section of there well. Specifically, they used an Ilmenite-based mud system called (Microdense^{TM}). A mud cooling system (MCS) was also required to maintain down hole temperatures and mud stability. This system was provided by Halliburton (Bertani 2018). The fluid used at the second Iceland Deep Drilling Project (IDDP-2) was a water-based system containing bentonite stabilized with a low molecular-weight copolymer. Filtration control and supplemental viscosity were obtained with variations of vinyl sulfonated copolymers (Chatterjee et al., 2014). This system required mud coolers as well. While these solutions exist today, research will improve the efficacy of drilling fluids at even higher temperatures. A typical drilling system has to account for chemistry of the well, the pressure of the formation, produced volatiles and other issues.

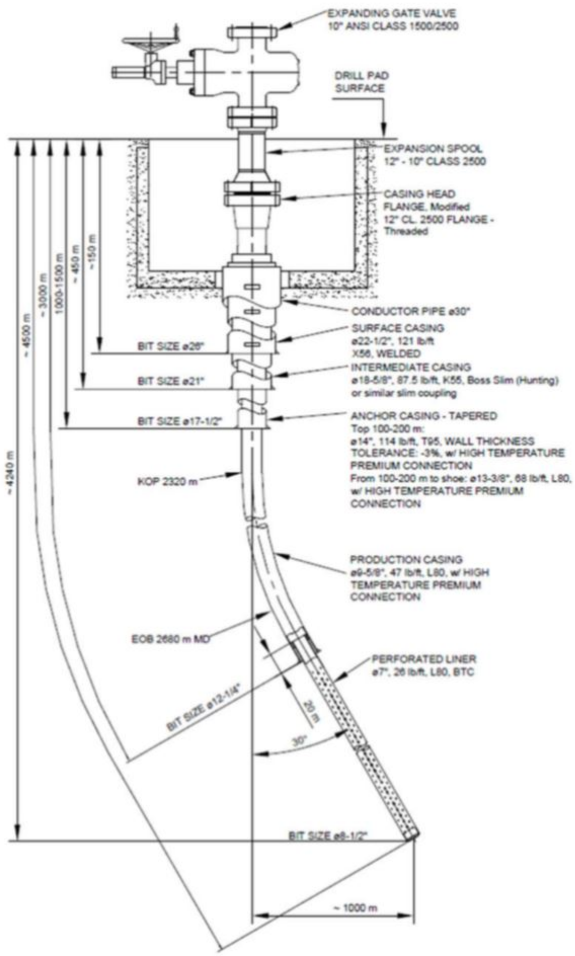

Figure 2: Well schematic of the IDDP-2 illustrating the larger diameter of most geothermal wells (Inganson, 2018).

Drilling Bits - Until recently there were few drill bits able to withstand the temperatures required for development of superhot resources. Traditionally, tricone bits have been used in a geothermal setting and are effective at conventional temperatures. However, the elastomer seals and bearing assemblies are only rated to 135 °C. While the upper part of the well can be drilled with these bits, even in hard crystalline rock, it is the open hole section of the well where new drill bits and drilling systems will be required.

Baker Hughes, a market leader in drill bit design, has overcome some of the short comings of traditional tricone bits during the development of its series of high temperature geothermal bits, which are rated up to 177 °C, 288 °C and 300 °C respectively (Stefasson, 2018). The key design element that allows for high temperature operations are upgrades to the metallurgy, bearing assembly and seals. These new bits were tested at IDDP-2 and were shown to be effective at high temperatures for long duration. The average ROP of the 8.5" bit rated to 300 °C was 4.2 m/hr and the ROP for the 8.5" bit rated to 288 °C was 3.4 m/hr. At DESCRAMBLE, a Full Stringer Poly Diamond Crystalline (PDC) bit manufactured by Smith called StingBlade™ was used. This bit was chosen because it was determined that it was better suited for the phyllite found at the target depth. Another bit that has shown promise is the Kymera bit, also provided by Baker Hughes, which combines the elements of a tricone and PDC bit. These have been used in Iceland and the Salton Sea and have shown to improve ROP and operate at high temperatures (Richard, 2018). There are different options currently available for rotary bits, and drillers must balance durability, temperature restrictions and speed when choosing the correct bit. Another option outside of rotary drilling are fluid hammers. Fluid hammers have a reciprocating head powered by the pressurized mud in the drill pipe. Drill bit heads for these systems tend to have a flat or slightly convex face with durable buttons impregnated in a matrix. Companies with developed fluid hammer technologies include Hanjin D&B, NOV, Wassara, and Strada. Fluid hammer technology has been shown to achieve faster ROPs than conventional rotary drilling in hard rock environments. However, the larger diameter upper sections of the well will likely require rotary drilling. This suggests that fluid hammer systems compatible with conventional drill rigs will reduce costs.

Long Term Technology Needs for Deep Superhot Drilling

To realize the future of accessing economic geothermal anywhere, we will need to reimagine drilling. As the hole becomes deeper, the drilling process becomes less efficient. This is because of increasing frictional forces between the drill pipe and the wellbore, larger energy requirements for the mud circulation system and greater energy requirements for lifting the drill string. As the hole becomes deeper the rock becomes harder and the temperature higher so we need more trips out of the to change worn bits and bottom hole assemblies. As the hole becomes deeper the well also becomes larger at the top in order to maintain a large enough hole size at the bottom to reduce pressure drop. So we need a drilling method that doesn't lose efficiency with depth, maintains hole diameter as much as possible over the length of the wellbore, has no need for bit or bottom hole assembly changes and can maintain directional control for very complex configurations.

While conventional drilling methods may be capable of reaching superhot magmatic systems at 5-7 km at competitive costs, drilling to 10-20 km will be a much larger challenge. In addition, modern drilling technology is not well suited for high temperature rock >450 °C. Many advanced drilling technologies focus on improving rate of penetration, but a bigger problem for long term well integrity and sustainability is the well design and construction that currently uses metal casing, casing connections and cement.

For deep superhot resources new drilling technologies and well designs are required. Unconventional drilling techniques which show promise include:

1. Projectiles
2. Thermal Spallation
3. Laser Drilling
4. Plasma Drilling
5. MMW Drilling
6. Chemical and Electro-chemical Dissolution Drilling

Projectiles - Projectile drilling uses conventional drilling technologies but incorporates the use of projectiles. A conventional BHA system is outfitted with a chamber that can fire projectile rounds at hypersonic speeds into the rock. A hole at the center of the drill bit allows the projectile to be shot through the bit. The projectile fractures and weakens the rock in front of the bit, increasing ROP and reducing wear and tear on the BHA, allowing for longer run times. This technology is being developed by HyperSciences Inc. and has been tested in the field. HyperSciences believes that the technology will increase ROP by 5-10x over conventional drilling methods (Russell, 2017). While this technology may increase ROP of conventional drilling methods, it still has the same temperature constraints as today's technology.

Thermal Spallation - Thermal spallation causes brittle failure by rapid heating of a rocks surface. The thermal spallation process was designed with hard rocks in mind. Hard rocks are characterized by low heat transmissivity, minerals with varying degrees of thermal expansivity and natural porosities and zones of weakness. When a high impulse of heat is applied to the rock, it causes internal stresses that lead to brittle failure or spall. One of the first technologies considered that used this process was flame jet drilling, which imposes a hot flame on to the rock face. This technology was first deployed successfully in the 1940s for the mining of taconite. Multiple iterations of this technology have been it has not been widely deployed for drilling purposes because this method does not work well in wet environments. Water limits the heat impulse into the rock and makes ignition of fuel difficult (Yadav, 2017). The modern iteration of this technology is hydrothermal spallation drilling. This technology was developed by Potter Drilling, which no longer appears operational. This method shoots supercritical water through a special nozzle onto the rock surface causing spallation. This drilling technology was tested both in the lab and in the field and was shown to work reasonably well. Tests showed that high ROPs of 6-16 m/hr could be achieved in granites. However, there are significant challenges facing this technology. These include, cutting transport, potential impacts of high-pressure environments and energy efficiency. Significant energy is required to heat water to the supercritical phase and the system needs to be carefully designed to ensure that the energy carried by the fluid is transferred efficiently to the rock. This is difficult when the well is filled with water (Wang, 2017).

Laser Drilling - Laser drilling uses high powered laser to either weaken, melt, or vaporize the rock. While there has been a lot research on using laser to drill exceedingly small diameter holes in a variety of materials, lasers have not been used widely to drill large diameter holes into hard rock. The key challenges facing the development of a laser drilling system are designing a field ready mobile high-power laser unit and fiber optic cable system capable of directing the high energy laser beam down the well and toward the bottom of the well without significant energy loss. The first company to successfully commercialize laser drilling is FORO Energy. Their key innovations were the development of a durable fiber optic cable capable of directing laser light to the bottom of the well with minimal energy loss, the development of an optical slip rig, which allows the fiber to be integrated with existing drilling technology and durable optical connectors. The current power capacity of the optical fiber and greater drilling system is insufficient to drill geothermal wells on its own and it is currently being used in conjunction with conventional drilling technology. The high power fiberoptic cable is run through a drill string and laser light is emitted from the drill bit. The laser heats the rock, causing spallation, which enhances the effectiveness of the rotary drill bit. Transferring cuttings to the surface is a remaining challenge for laser drilling. Researchers have found that the laser technology can precisely and efficiently cut metal casing, which has benefits for operators of oil and gas or geothermal wellfields (FORO, 2020; ARPA-E, 2016).

Plasma Drilling - Plasma drilling uses plasma ejected from a drilling tool to initiate spallation, melting or vaporization of rock at the cutting surface. Plasma is an ionic gas that is generated by either heating a neutral gas or subjecting it to a strong magnetic field. This technology has been commercialized by GA Drilling out of Slovakia. The device they have designed is called PLASMABIT and it has been tested in the laboratory and field-like conditions. The plasma reaches temperatures of 6000 °C, enabling it to melt or vaporize the rock depending on the presence of water and other factors. The device uses electric arc plasma that is discharged in a circular motion from the bit face. This circular motion creates a centrifugal force which expels melted and vaporized material around the bit and clears the cutting surface. In addition, this circular motion of the emitted plasma allows for more efficient drilling of larger diameter holes. The device has no moving parts and has been tested in high-pressure and high-temperature conditions. It can conceivably drill with long run times and at higher ROP's than conventional drilling technologies. Much like FORO, the first field test of this technology will focus on milling casing. This work is being done is coordination with the MOL Group, a Hungarian oil and gas company. Given that this technology does not rely on any conventional drilling technology and will melt or vaporize the rock, it has clear path forward to outperforming existing technologies in deep environments (Kocis, 2017; GA Drilling, 2020). The key unknown about this technology is drilling efficiency and the energy consumption required for to reach competitive ROPs.

Millimeter Wave Drilling - Millimeter wave (MMW) drilling technology uses electromagnetic waves in the 30 to 300 gigahertz (GHz) frequency range, with wavelength between 1-mm to 10mm, to melt or vaporize rock at the cutting surface. Millimeter waves are generated using a gyrotron, a class of high-power linear-beam vacuum tubes which generates millimeter-wave electromagnetic waves by the cyclotron resonance of electrons in a strong magnetic field. Gyrotrons were initially created as part of fusion energy research and are used to heat plasmas which are injected into magnetic confinement devices, such as a TORUS. A team at MIT headed by Dr. Paul Woskov began experimenting with using MMW to vaporize rock in 2012. Rocks generally have low reflectance and low thermal conductivities, which means that the energy of MMWs can be efficiently transferred to areas on a rocks surface where the beam is projected. The ability to efficiently transfer large amount of energy onto small areas of a rocks surface causes the rock to undergo melting and or vaporization. This process is incredibly efficient. Lasers can transfer ~20% of their energy onto the cutting surface on a rock, whereas MMWs able to transfer at least 50% (Ogelsby and Woskov, 2014; Araque, 2020).

Beginning in 2019, Quaise, Inc., in partnership with AltaRock Energy, started expanding MMW drilling research in order to commercialize this technology. To date, only laboratory tests of the technology have occurred, but the results are promising. The proposed drilling device will use a series of mirrors and waveguides to direct the MMW beam toward the cutting surface. Waveguides are internally ridged tubes which direct the MMW beam and minimize energy loss of beam as it travels toward its destination. A laboratory configuration of this device and one of the tested rock samples are shown in Figures 3-4. One can see from the rock sample that the walls of the drilled hole are vitrified, meaning that this process could potentially negate the need for lining the hole at depth. One of the challenges facing this technology is that it will not work in a water filled well. Therefore, this drilling technology, as currently designed, will be used once drillers already have reached deep and impermeable rock ~3-4 km. This technology as well as the plasma bit are best used for drilling from 3-4 km to target depths of 10-20 km, where rock is fairly impermeable.

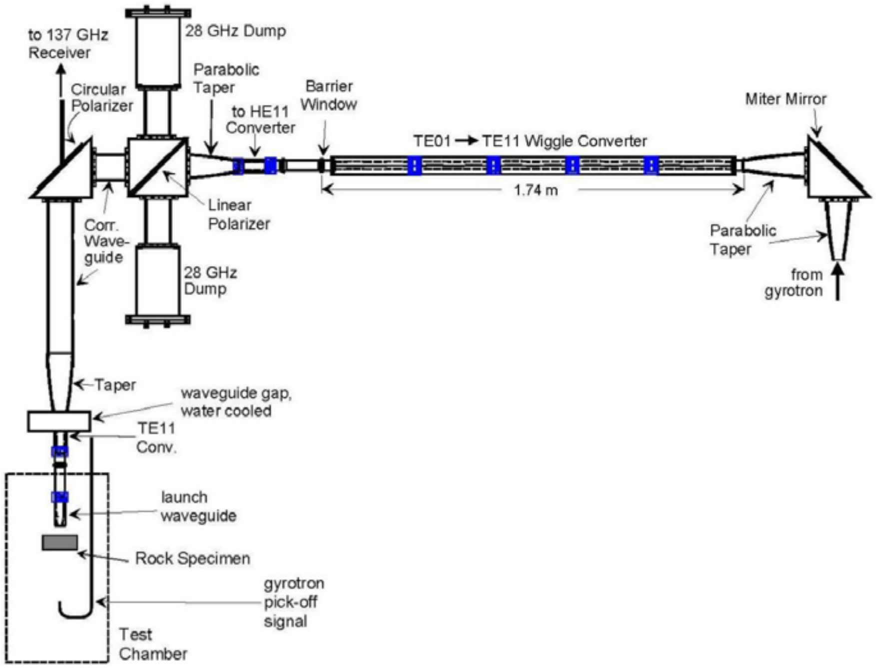

Figure 3: MMW drilling test apparatus – shows how a series of mirrors and wave guides are used to direct beam toward the rock sample.

Figure 4: Hole drilled by the MMW laboratory device (Oglesby and Waskov, 2014).

Chemical Dissolution Methods

Chemical and electro-chemical milling has enabled the design and manufacture of incredibly complex metallic parts and components. Similar technology can be applied to the reduction of rock for drilling or to assist in mechanical drilling (Beentjes, 2019). Experimental studies have focused on evaluating the technical feasibility of chemically enhancing rock removal using supercritical hydrothermal jet drilling by increasing pH with additives. The combination of accelerated mineral dissolution due to the presence of hydroxide ions, high solution temperature increasing reaction rates, and thermal stresses resulted in high rates of rock removal Comparison with published empirical quartz dissolution rates at high pH suggests granite mass removal primarily resulted from weakening of the rock matrix as a result of the accelerated dissolution of quartz minerals. Experimentally determined heat flux and surface temperature measurements indicated that the rock comminution occurred below the empirically determined minimum levels for the onset of continuous thermal spallation resulting from impinging low-density flame jets or high energy heating.

Well Design and Completion

Installation of the well head, casing, cement, and liner is the largest challenge for the development of superhot resources. These components maintain wellbore stability, separate deep geothermal resources from shallow aquifer systems and help to ensure the safety of wellfield operations. If cement or casing fails it can lead to hole collapse, which often causes permanent damage to a well. Casing or cement failure can also cause blow outs, where over-pressured steam is leaked into an underground aquifer. Steam or brine leakage into a ground water system will reduce production and, in some cases, cause contamination. Leaks can also form at the wellhead if the system is not designed correctly. A leak at the surface is a severe safety hazard and can be difficult to fix. During the design of a well, engineers aim for each one of these components to last the projected life of the project, which is normally 20-30 years. With the extreme temperatures being produced from superhot resources, large thermal stresses will be imposed on the casing, cement, and wellhead. Thermal expansion of steel will cause the casing string to grow, and the expanding and contracting casing will impose large stress on the cement holding it in place. Furthermore, many conventional cements will lose their strength at superhot temperatures. New cements may need to be designed to develop these systems. Superhot wells pose a significant engineering challenge. There are existing solutions and technologies on the horizon that promise to solve many of the known problems.

The GEOWELL project conducted a broad analysis of potential candidate materials for casing used in supercritical wells with naturally occurring fluids. A suite of candidate alloys for high temperature casing were tested in the GEOWELL study (Thorbjornsson, 2016). Since it isn't clear how rocks and fluids circulated in the well for heat extraction will interact in an EGS well, these studies may not have the relevance to future SHR EGS systems. Design ideas for future SHR wells may include the concept of design beyond the yield strength of the material as is done for thermal recovery wells for heavy oil. Novel materials and methods of deploying them should also be examined. Casing connections are an important part of the well integrity system. One outcome of the GEOWELL project is the development of expandable casing couplings that can take up the thermal expansion and contraction inevitable in the operation of the very high

Cement - The most used cement for well completion is Portland cement, which is cheap, ubiquitous, and well suited for low temperature environments. However, in geothermal environments which are high temperature and can contain significant calcite, growth of calcite and amorphous silica within the cement matrix will weaken its effectiveness. Portland cement is also not thermally stable above 300 °C. Above this temperature the degradation of $Ca(OH)_2$ begins, causing an ongoing weakening of the cement (Lubloy, 2018). These challenges, combined with the stresses imposed on the cement by thermal cycling, make traditional formulations of Portland cement unsuitable for high temperature geothermal wells (Pyatina, 2019). Potential replacements for Portland cement are Phosphate based cements, Ca-Al-silicate cements, and Al-silicate (Pyatina, 2020). These are all thermally stable at superhot temperatures. Halliburton has developed a high temperature cementing solution, called Thermalock™, based on a phosphate-based cement. This cementing solution was used at Larderello and has so far been shown to effectively handle high temperature environments.

Additives can be used to increase fracture toughness, thermal shock resistance, strength recovery and other factors in cement systems. For example, milled carbon fibers can be added to cement to significantly improve fracture toughness while maintaining cement ductility during application (T. Sugama, 2006). The addition of zeolites and other minerals into cement slurries can be used to help cements to become self-healing in high temperature environments (Sugama and Pyatina, 2019). Fly-ash, which is a by-product of burning coal, can be used in cement to improve acid resistance and decrease permeability. The effect of additives on the characteristics of cement are complex and controlled by multiple factors. For a better understanding of the complex relationship between additives and different cement formulations one should refer to the work conducted by Brookhaven National Labs under the direction of Dr. Toshifumi Sugama.

Additives preventing the formation of free water within the slurry are also important for ensuring a complete cement job along the entire length of emplacement (H. Hole, 2008). Different parts of the cement slurry will be exposed to high temperatures for different amounts of time, because of this, the concentration of retardant within the column of slurry should be staged, this will help to mitigate premature setting of the cement (Bour, 2020).

Significant research is needed to come up with cement formulations and emplacement methods for superhot geothermal wells which will require high fidelity temperature modeling of the wellbore plus extensive testing in the laboratory in conditions which simulate the expect downhole temperatures and pressures as well as thermal cycles.

SuperHot Rock Reservoir Creation

When we get to the depth where very high temperatures are available to us, we need to create a heat exchanger that overcomes the issues of low thermal conductivity of rock so that we can get the heat to the surface. Geothermal stimulation research has focused on creating permeable pathways between injection and production wells. Testing of fracturing in rock with temperatures over 300°C has successfully created complex fracture networks which appear to benefit from thermal stress fracturing as well as shear failure fracturing or hydroshearing. It remains to be seen whether these mechanisms will work in very hot rock that is reaching the brittle-ductile transition point. Laboratory testing in conditions that simulate what will be encountered in SHR reservoirs is definitely needed.

There is no consensus on the best way to create or enhance fractures at depth in very hot rock. This is partly because different environments require different stimulation solutions, but it is also because the mechanism of fracture creation for igneous and metamorphic rocks at depth is still not fully understood. This is especially true for rocks approaching temperatures where plastic deformation begins. Despite the need for additional research, an exploration of traditional geothermal stimulation techniques may still provide a path forward. Traditional EGS techniques have relied three modes of failure and these are likely applicable to superhot rocks as well.

1. Hydrofracturing or Open Mode Fracturing – This is where water pressure in the well is brought above the minimum horizontal stress of the reservoir and rocks fail in tension, causing a fracture to open aseismically and propagate perpendicular to the minimum horizontal stress.
2. Shear Failure or Hydroshearing – This mode of failure occurs when natural critically stressed fractures fail in shear. It occurs when pressure inside the wellbore is brought above the critical stress for the fracture.
3. Thermal Shock and Thermal Contraction – This mode of failure occurs when hot reservoir rock is exposed to cold water causing rapid cooling on the rocks surface which results in brittle failure. Cooling of the reservoir rock also causes thermal contraction of the rock volume promoting fracture creation and propagation.

As with stimulation at lower temperatures, multiple permeable pathways will need to be generated in the well to produce economic quantities of power. This will require some form of isolation, either mechanical isolation, HTHP packers, or isolation through use of a diverter material. In some cases, both techniques will be used together to generate the required number of fluid pathways. These stimulations will also need to consider the use of high temperature proppant. While the permeability of an injector can be maintained by ongoing cooling and over pressure within the well, permeability of production wells will likely not be maintained without the use of proppant. This is because fractures induced by thermal shock and open mode fracturing caused by high pressure are reversable.

When the production well heats up and pressure is reduced in the well, the fractures generated during stimulation may close without the emplacement of proppant. The proppants currently being used in oil and gas are usually comprised of sand with a high silica content. While this proppant has been effective in an oil and gas setting, it will not work for superhot resources. Testing shows that silica will dissolve at temperatures at temperatures above 374° C, silica will begin to dissolve quickly (Crundwell, 2020). New proppant materials which can handle high pressures and temperatures will need to be developed to maintain permeability over the life of the well. Many of the substances which look promising include metals or metal oxides, however these are dense materials and will be difficult to emplace. In the oil and gas context proppants are usually emplaced using gels or viscosifiers, which help to push out the sand into the fracture. These mechanisms cannot be used given the high temperature of the resource. Other emplacement methods will be needed. If possible, these methods should be designed to emplace denser proppant material.

Another path forward may be to mine heat from only the wellbore. There are several potential configurations proposed that would :

1. Two wells, an injector and producer, which intersect at depth or a long reach series of wellbores that connect with the surface at each end.
2. A single well where heat mining fluid is injected and produced from the same well
3. Use of downhole heat exchangers that extract heat from the surrounding rock
4. Multiple small diameter wellbores connected to a central wellbore that can add surface area for heat exchange
5. Heat pipes using highly conductive materials to transfer heat to the surface

In all cases the heat flow into the system would be limited by the surface area of the wellbore, or wellbores, and thermal conductivity of the rock and the circulating fluid. Conductive heat transfer is the least efficient mechanism to transfer heat from one place to another and both rock and water have fairly low thermal conductivity. One way to increase the heat extraction from the subsurface would be to make wells as long or deep as needed for good heat exchange for as low a cost as possible. Another way which heat extraction could be improved is by increasing the thermal conductivity of reservoir rock near the wellbore. The conductivity of the near wellbore reservoir rock could be enhanced by creating many small fractures and filling them with water or another highly conductive material into the fractures. Still, convective heat transfer is so much more efficient at heat transfer that designing a system that uses both convection and conduction to move the heat out of

While wells intersecting at depth, multiple small diameter wellbores, long reach loop wells and downhole heat exchangers appear to be a potential path forward for SHR, there are significant technical challenges in drilling and completing these wells in very hot rock. Well intersection relies on advanced directional tools and most of these are not rated for the temperatures being considered. Baker Hughes has developed a high temperature directional system capable of drilling in temperature up to 300 °C, but it is unclear whether the system has enough precision to accomplish this task. High temperatures introduce considerable noise into the electronics governing these directional tools, reducing their precision and accuracy. Transmitting the data to the surface is a difficult task. Still, these are engineering challenges that can be solved if configurations can be designed that will extract sufficient heat from the rock to make them economical.

The proppants currently being used in oil and gas are often comprised of sand with a high silica content or high strength ceramics. The sand is typically sorted by different grain sizes, with different grain sizes having different uses depending on the nature of the lithology, brittleness of the rock and other factors. While this proppant has been effective in an oil and gas setting, it will not work for superhot resources. At temperatures from 150°C-350°C, silica will dissolve fairly quickly (Crundwell, 2020). Above 350°C silica solubility becomes lower and may significantly decrease at very high temperatures. Ceramic proppants not only breakdown at high temperatures but breakdown into clay minerals that may plug fractures. New proppant materials which can handle high pressures and temperatures will need to be developed to maintain permeability over the life of the well. Many of the substances which look promising include metals or metal oxides, or carbon in various forms. Form factors to reduce the density of metal proppants and the strength of carbon proppants will need to be developed. In the oil and gas context proppants are usually emplaced using gels or viscosifiers, which help to push out the sand into the fracture. These mechanisms cannot be used given the high temperature of the resource since organic polymers decompose into carbon particulates that reduce permeability. Other emplacement methods will be needed. One possibility is development of methods to emplace denser proppant material.

3. Conclusion - Impact of Technology Improvement on the Cost of Power

As actual development of SHR projects proceeds technology will improve incrementally. Leaps in technology will be driven by demand for renewable baseload power combined with innovation. Once technologies are implemented and accepted costs will come down as they have for wind and solar. With the technologies we see in progress now we can anticipate costs to improve exponentially until a limit it reached in technology improvement that only learning by doing will reduce costs further. As we improve technology, we make a larger and larger resource base accessible. AltaRock has conducted economic modeling for SHR EGS to examine the impact of technology improvement on the levelized cost of energy (LCOE). Work done by Alain Bonneville at PNNL has done a preliminary assessment of the depth to reach temperatures over 450°C around the world and AltaRock has worked with PNNL to make a preliminary assessment of the amount of recoverable energy in rock at these high temperatures (Figure 5). Figure 6 illustrates the impact of technology improvement not only on the LCOE of SHR energy but on the amount of resource that technology can access.

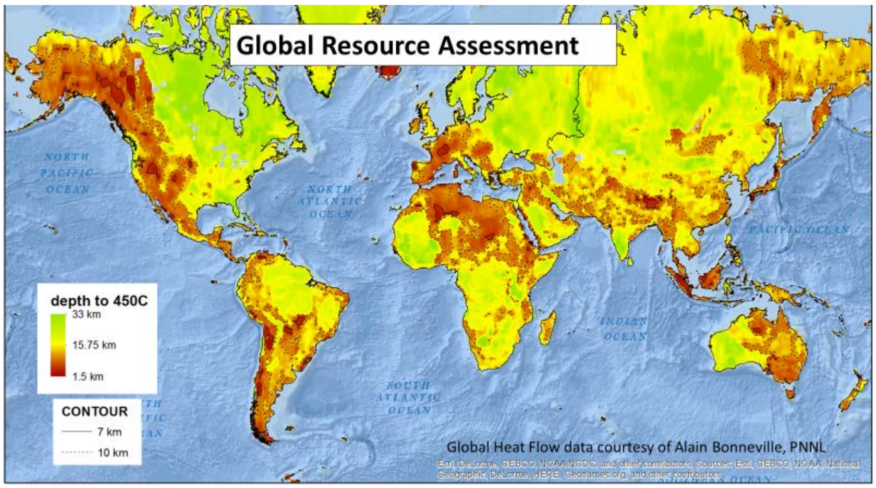

Figure 5: Global SuperHot Rock resource assessment showing depth to 450 °C.

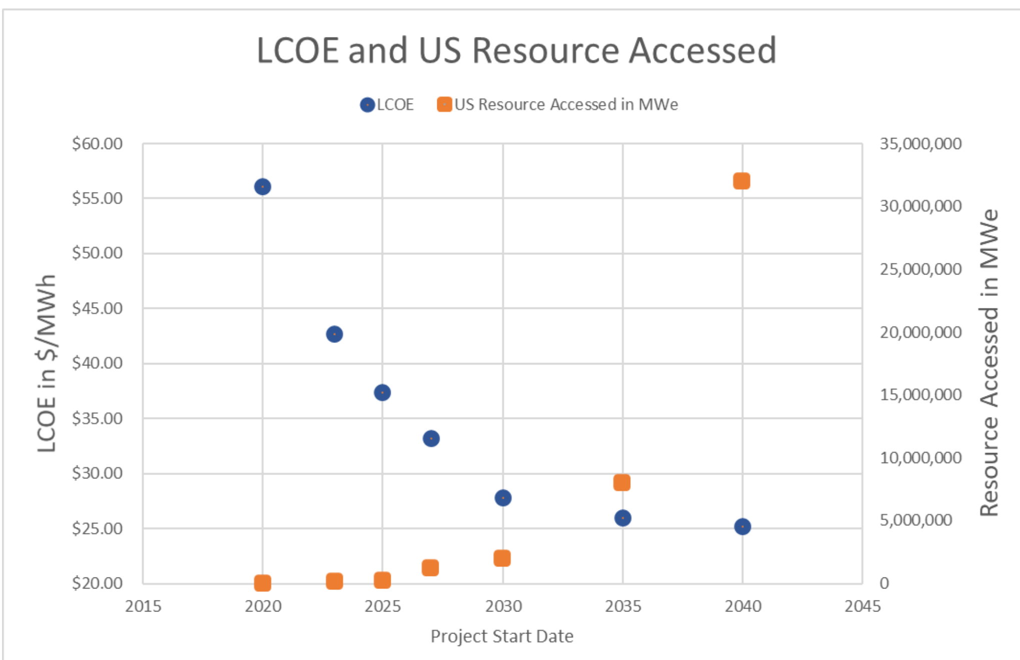

Figure 6: Impact of technology improvement on LCOE and on US SHR Resource accessed.

The extremely high energy density of this enormous resource is the reason to pursue and solve the engineering challenges of developing the resource commercially. By going hotter and deeper a carbon free resource that is sustainable and has low impact on the surface can be developed economically to replace fossil fuels.

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