PROCEEDINGS, 45th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2020
SGP-TR-216

Technology Needs for SuperHot EGS Development

Susan Petty, Trenton Cladouhos, Jill Watz and Geoffrey Garrison

4010 Stone Way N, Seattle, WA 98103

Susan.petty@cyrqenergy.com

Keywords: Enhanced Geothermal Systems, supercritical, SuperHot, ultra-high temperature, well completions, reservoir stimulation, reservoir management

1 ABSTRACT

Several countries around the world are investigating the development of very high temperature geothermal resources using Enhanced Geothermal Systems methods to extract this high energy density resource. Japan, Iceland, Mexico, Italy and New Zealand all have projects aimed at developing an EGS resource in rocks in the brittle-ductile transition zone with temperatures above 400°C. Wells have been drilled in Iceland, Italy and Mexico into rocks with greater than supercritical temperature. High enthalpy fluids mean better energy conversion efficiency to electricity. Very high temperatures make thermal energy storage more economic for flexible generation to meet demand. There are many areas around the world where temperatures >400°C can be reached within 5-6 km of the surface making drilling for this resource feasible today.

So where is the technology to exploit this resource today and what is needed to make SuperHot EGS development happen in the near term and to extend it to a wider area in the future? Near and long-term technology development needs are broken into three areas: Wellfield development, reservoir characterization and creation, and long-term resource management. Energy conversion technology improvements specific to the geothermal system will also be important.

While we can drill wells into very high temperature rock now, our methods rely on cooling the wellbore drastically as we drill. Our ability to control direction is limited and we don't have access to the kinds of Measurement While Drilling (MWD) and direction control systems that we have come to rely on for guiding and turning wells at more typical geothermal temperatures. Bits specifically for these very high temperature rocks are in development and in the meantime, we use conventional bits with cooling. Well completions including casing and cementing offer the most technical challenges. Cements are available for temperatures up to 350°C but not above that. Casing materials and connections as well as casing design are challenged above 350°C. Reservoir creation and reservoir management are perhaps the areas where the greatest technical improvements are needed. The behavior of rock in the brittle ductile transition and the long-term behavior of fluids reacting with rock at these temperatures is not well understood. Basic science and testing is needed to gather data and advance existing models to be able to predict behavior of rock during fracturing and reservoir operation. While we assume that thermal stress cracking will dominate the stimulation and reservoir creation process, it isn't clear whether tectonic differential stresses will play a role in fracturing or if fractures will remain open after creation. Reservoir management depends on rock/fluid interactions and since EGS involves injecting fluids from the surface not in equilibrium with the rock, it isn't clear how these fluids will evolve as the flow through the reservoir. Steam flood well completions and reservoir management may help to inform our technology development for superhot EGS. This paper will review the status of numerical modeling for fracturing, well life cycle analysis and geochemical rock/fluid behavior as well as the technology needed for near and long term development of superhot EGS.

1. INTRODUCTION – ENERGY DENSITY AND CAPITAL COST/LCOE FOR SUPERHOT EGS

MIT's 2006 study of the US geothermal potential found that extracting just 2% of the thermal energy stored 3 to 10 km below the surface could meet the US energy consumption for over 2000 years with minimal environmental impact. For a decade the industry, national labs, and the USDOE have pursued Enhanced Geothermal System (EGS) development in resources ≤225°C to adapt existing oil and gas technologies to these temperatures. What they found is that the costs of materials and extra drilling to create an EGS at 200°C prevent it from being a truly economic option given today's very low power prices.

Geothermal energy is renewable, has low or no CO2 emissions and is available 24/7. So why hasn't this energy source been more widely used? The most frequently given answer is the high capital cost of power. However, the most recent capital cost values are based on using organic Rankine cycle power plant technology on resources with temperatures between 125C and 200C. Energy density for these low temperatures is very low so that plant efficiencies are also quite low ranging from ~8%-15% net thermal efficiency (ηth). Even for higher temperatures where a steam turbine can be used, energy density of geothermal fluids is still low and ηth rarely exceeds 25%.

The key to making EGS competitive is to tap into heat resources that have an order of magnitude more energy potential than conventional systems. By drilling into very high temperature (superhot) rock, >450C, we can access an energy source that has a higher energy density than fossil fuels. (Figure 1)

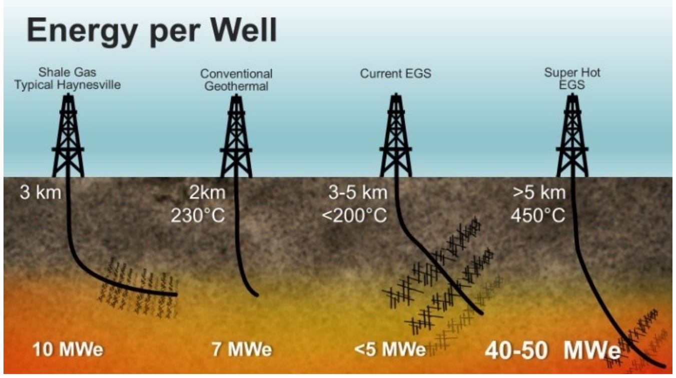

Figure 1 Comparison of Energy Per Well for Geothermal and Unconventional Gas

Water at 450°C has 4X the energy density of water at 200°C while the energy conversion efficiency is 2.5X that of an organic rankine cycle (ORC) using this temperature geothermal fluid. While the U.S. DOE is focused on Enhanced Geothermal Systems (EGS) at lower temperatures, the international geothermal community understands the economic value of producing supercritical fluid. The most geothermally savvy countries in the world, Iceland, Italy, Japan and New Zealand, are all currently pursuing SuperHot rock projects. These include the Iceland Deep Drilling Project (IDDP), the Japan Beyond Brittle Project, the DESCRAMBLE project at Larderello, Italy, the Hotter and Deeper (HADES) project in the Taupo Volcanic Zone of New Zealand and the GEMex joint EU-Mexico project, in Mexico.

The Iceland Deep Drilling Project (IDDP) focused initially on drilling into fractures containing supercritical fluids (Elders, 2010) IDDP-1 intersected magma with an estimated temperature of 1050°C. Supercritical fluids encountered in the well were found to be highly corrosive, damaging the casing and wellhead so that the well had to eventually be abandoned (Friðleifsson, 2015). IDDP-2 was drilled as an EGS well with the goal of stimulating rock at very high temperature. The well was completed on Jan. 25, 2017 at a depth of 4659 m, where an unequilibrated bottomhole temperature of 427°C was recorded together with a fluid pressure of 340 bars (www.iddp.is) (Dobson, 2017), well above the critical point for water.

The DESCRAMBLE project in Italy is an example of the successful completion of the hottest geothermal well drilled in the world to date. The well was completed in rock with temperature in excess of 500°C. Venelle-2 was completed in 2017 and test planning is now underway. The GeMex project is also ongoing with EU funding targeting temperatures above supercritical for water.

It's important to understand that the target that will access the most resource is very hot rock, not naturally occurring supercritical fluids. Several wells have intersected supercritical fluids, and some are now being produced. However, these natural supercritical temperature hydrothermal resources are very rare and problematic to find. The much larger resource is rock at temperatures above 450°C. This resource is found at depths less than 6 km near volcanic areas and in extensional tectonic settings like the Basin and Range in the western U.S. At these depths the basement rock is, for the most part, impermeable or very low permeability. To develop it for power generation will require fracturing rock to create a reservoir, i.e., engineering a geothermal system – EGS.

Current US efforts to develop SuperHot geothermal are way behind other nations which are led primarily by government funding in the EU, Iceland, Japan and China. It is imperative the US step-up its efforts to develop this resource as part of its future carbon-free energy portfolio and invest in the science and technology needed to enable commercial development. The US has a very large resource with temperatures at depth over the critical point (Figure 2).

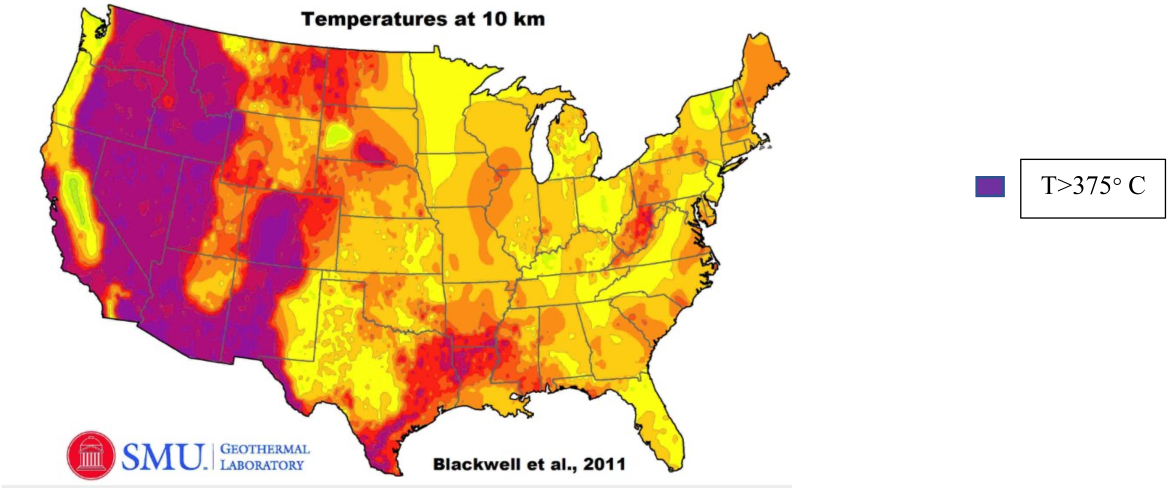

Figure 2 Temperatures at 10 km with areas greater than critical point for water in purple. (SMU, Blackwell et al, 2011)

While we can currently drill and complete wells at temperatures over 375°C, scientific and technical development is needed to be able to stimulate, produce and operate a supercritical power project long-term. Reaching SuperHot temperatures over 450°C may involve drilling into the transition from brittle to ductile rock. Basic science research for development of SuperHot EGS 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 include temperatures above the critical point of water, although LBNL is working on including this in TOUGH-2. Very high temperature conditions need to be included in thermo-hydro-mechanical-chemical (THMC) codes to allow us to model heat extraction, reservoir behavior and stimulation/fracturing.

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.

2 TECHNOLOGY NEEDS FOR SUPERHOT EGS SUCCESS

Many focus on drilling technology as the primary need for developing SuperHot geothermal resources. However, there can be no production of this rich energy source without creating a fracture network to extract the heat. The heat exchange area needed to economically produce superhot fluids is large and can't be created easily by drilling. Not only is a large surface area to volume ratio needed to create an adequate heat exchanger subsurface, but the hot fluids need to be moved from the rock into the wellbore at high rates with as little pressure drop as possible. Flow rates for economic superhot geothermal power production are less than what is needed at lower temperatures, but they are still far higher than flow rates for economic production of oil or natural gas. Until microhole drilling methods or some other strategy that can directly emplace a heat exchanger-like structure in the rock can be developed, creating a fracture network is the fastest path to successful superhot EGS. (Wang, 2009)

Technology development focus areas include:

- Resource characterization – surface and subsurface methods for understanding the superhot rock at depth and predicting its behavior
- Well Field Development in the Near and Long Term – Well drilling, cementing and completion technology. Advanced drilling methods for long term expansion of resource base
- Reservoir Development and Management – Creating and operating the EGS reservoir. Stimulation methods, reservoir management.
- Energy Conversion Technology – Supercritical cycles using geothermal fluids. Adding thermal energy storage for flexible generation.geoff

2.1 Resource Characterization

Designing a fracturing method for superhot rock, requires understanding the nature of the rocks and the stresses acting on them we will encounter at depth at the very high temperatures we plan to exploit. Characterizing the superhot resource from the surface is the first step in the process of evaluating the superhot potential.

Geophysical Methods - In order to understand how the signals from geophysical methods we have at our command behave in the superhot environment both field and laboratory experimentation and testing is needed. The ability to "see" deep into the earth using seismic and magnetotelluric data is a fast-developing technology. Seismic tomography from teleseismic data and from ambient noise may play a significant role in characterizing the superhot resource. Laboratory experimentation could be useful for developing these methods to point where field testing can be accomplished.

Remote sensing methods such as LiDAR can help to map fractures and faults on the surface. While the surface features may or may not translate to the deep subsurface, the tectonic forces that caused them can be used to model the stresses at depth. Refinement and calibration of stress models extending into the transition between brittle and plastic rocks is needed.

Rock mechanics - Watanabe, et. al., (2019) have shown through experimentation in the laboratory that a fine network of fractures can be created, largely along grain boundaries, in crystalline rock through hydraulic and thermal stimulation. Their sample size, a 10 cm cube, is limited by their equipment. Because the fractures they observe appear to follow grain boundaries the rock type is important. Having a sample large enough to test whether larger scale cross grain boundary fracturing can connect these smaller scale features will be important for follow on testing.

Rock fluid interactions - Naturally occurring supercritical geothermal fluids can be highly corrosive and also cause scale problems. The IDDP-1 well suffered from severe corrosion that eventually require the well be abandoned (Friðleifsson, 2015). The question is: Will surface water injected into the superhot rock have similar corrosion and scale problems as the wellfield matures over time? Rock-fluid interactions in EGS reservoirs have been modeled, but no system has been operated for a long enough period of time to history match the geochemistry at more conventional temperatures. Adding geochemistry at temperatures far above supercritical to the reservoir models we now rely on is an important technology development which may take laboratory work to complete.

Downhole logging-Once we have a well drilled into superhot rock we need logging tools to further investigate the stresses on the rock, image fractures, survey the angle and direction of the well, measure temperature, pressure and flow rate and other characteristics of the rock. Instrumentation using high temperature stable electronics including memory inside an insulating flask have been developed that can withstand very high temperatures for short periods of time. Design changes can increase the time these instruments can remain in the HT borehole. However, for extreme temperatures new concepts may be needed such as fiber optic sensors and cables hardened for very high temperatures. One of the difficulties with developing this technology is the lack of a market for the tools through service providers. Tools developed by government labs may not be able to meet the market through service providers and therefore may never get deployed. Tool testing in realistic superhot laboratory conditions is currently not possible leading to a need to test tools in actual wells.

Well Testing – Well testing methods that can determine fluid characteristics and better evaluate the results of fracturing and other stimulation methods need to be developed and proven with field testing. Progress on tracer methods that use reactive and non-reactive tracers have been developed but not extensively field proven for lower temperature EGS. Moving these methods to very high temperatures is a big step that will require developing and laboratory testing of high temperature stable nonreactive tracers as well as characterizing the reaction of tracers with rock at very high temperatures.

Most of these reservoir characterization technologies would benefit from testing in a laboratory capable of test large samples under realistic reservoir pressures including downhole instruments. The laboratory set up in Japan handles a 10 cm cube of rock, which is bigger than some test facilities can handle. However, we need to be aware of the representative elementary volume for different rock types with different grain/crystal sizes. There are laboratory facilities at national labs and universities that can test moderate size samples up to >300°C. It may be possible to adapt existing equipment for superhot conditions of over 500°C, but adapting existing equipment to handle very large samples, >1 m3 may be more challenging. Still, this would be a good first step toward advancing existing technology to the next level and improving our understanding of rock in the brittle/ductile transition zone.

Another area for technology development is in modeling the combined reservoir, power plant and financial aspects of a superhot project. The GETEM model developed by DOE to understand the impact of technology improvement on the cost of geothermal power is a good example of this type of model. Simplified resource heat extraction models can be coupled with models of the surface energy conversion to electricity and then to a financial model that uses the data to evaluate the economics of a superhot project. It's possible that GETEM could we extended to supercritical cycle temperatures and pressures or a new separate superhot EGS model could be developed.

2.2 Well Field Development in the Near and Long Term

Right now, we know how to drill and complete superhot geothermal wells. We can control the borehole direction and get basic data during drilling. However, there remain significant issues for constructing a well that will survive the thermal and pressure cycling during stimulation activities and long-term operations. An EGS well completed in superhot rock will see a thermal difference from top to bottom of over 400°C. During stimulation, cool water will be injected from the surface, cooling the open hole section, lined or unlined, and the lower section of the cemented casing down to surface temperatures. During production the wellbore will heat up to the very high producing temperatures and then cool off each time the well is shut in. The well design needs to survive this thermal cycling while holding the high pressures of these very hot fluids.

Casing materials may need to resist corrosion as well as withstand thermal cycling. Casing connections either must hold pressure despite casing expansion and contraction, or the connections need to expand and contract themselves. Because the amount of casing growth and contraction can be severe with the range of temperatures possible in a thermal cycle in a superhot well, geothermal wells are normally cemented top to bottom behind each string. This reduces the amount of casing growth and contraction at the surface that needs to be taken up with an expansion spool but means that the cement is exposed to large radial stresses that will cause a brittle material to crack. (Petty, 2003)

Casing materials selection - Well casing design is typically based on the working stress the casing will see and maintaining the casing within the elastic limit. For a wellbore going from 20°C to 290°C the thermal stress would be 66 Mpa which would be beyond the elastic limit for K-55 or L-80. (Suryanarayana, 2018). Casing may also need to withstand highly corrosive very hot fluids, making material selection even more challenging. More data is needed on the behavior of casing materials, including clad casing and novel alloys, during thermal cycling, particularly at large differences in temperature. Alternative casing materials also need to be developed and tested. New methods for emplacing casing to allow for long lengths of cemented casing in high temperature rocks at deep depths will be needed in the long term to allow for designs with lower pressure drop. While some have proposed that forming a glass from the rocks that the well goes through will make a good casing substitute, a great deal of study is needed to see if this would be feasible. Even high strength ceramics with well-studied formulations are brittle and therefore not able to withstand the thermal cycling in a superhot well.

Casing connections – Casing connections are the primary weak point in any casing design, but particularly where extremes in temperature are involved. Connection designs are available for extreme thermal service, but most test facilities can only test the connection under the thermal stress condition and can’t mimic the pressure regime with cement that that the completed well would see. An unsupported casing connection will behave very differently under thermal cycling loads than one that is confined so testing with a thermal blanket that just heats the casing and connection can’t model the actual stresses on the connection. This ties in with the need for a superhot laboratory that can test large scale materials at high confining pressures.

Cement – The casing needs to adhere to the borehole wall to prevent migration of fluids outside the casing. Typical cements used in oil and gas wells for high-temperature oil wells silica-modified Portland-based cement formulations are not durable in hostile geothermal environments failing to provide good zonal isolation and metal casing corrosion-protection.

Directional control – The IDDP-2 well was directionally drilled using classic pendulum assembly methods. Mud motors have yet to advance to high enough temperatures to use in directional drilling superhot wells. Logging while drilling to get data to use in controlling the hole direction is also not possible for these very hot wells. However, cooling with drilling fluids can allow tools to be deployed through the drill string during tripping in or out of the well for making decisions during direction drilling. Downhole batteries that can withstand very high temperatures are key to measurement and logging while drilling. (MWD, LWD).

Drilling Optimization – By optimizing all aspects of drilling from rig selection, fuel use through casing design and drilling and completion practices, significant savings can be realized. Chevron reduced the cost of drilling at Gunung Salak to almost 1/3 of their original well cost through drilling optimization. (Prihutomo, 2010) Oil and gas operators have seen considerable savings using optimization software. However, not enough geothermal wells are drilled in a single wellfield in most cases to optimize drilling for a particular resource. For superhot EGS wells, conditions for different resources are not well know yet, so optimization would be theoretical and would have to be based on the geology of the upper part of the wellbore from areas with very high temperatures at depth. A study funded by the US DOE

Long-Term Advances in Wellfield Development - The first field trials of superhot EGS will be done at places where very high temperatures are close to the surface. While some superhot wells have been drilled through very hot hydrothermal reservoirs like the Geysers and Lardarello, this adds the complexity of completing the well through a permeable, very high temperature, possible corrosive zone that is likely under-pressured. Sites with low permeability through the entire length of the wellbore present the easiest to complete pathway to being able to test superhot EGS methods.

For the long-term expansion of superhot EGS, however, there is a need for development of advanced deep drilling technology to reach superhot temperatures at very deep depths up to 20 km. Several advanced drilling technologies have been proposed that would improve rate of penetration in very deep hard rock at high temperatures. Millimeter wave drilling (Oglesby, 2014) and plasma drilling (Kocis, 2017) propose to vaporize the rock, gasifying the wellbore walls as they go. Electro-chemical drilling (Beentjes, 2019), a recent innovation, holds promise. Other methods to increase rate of penetration in hard brittle rock at depth include laser drilling (Bajcsi, 2015) and thermal spallation drilling (Meier, 2015) have been put into practice.

However, rate of penetration is not the only issue with the cost of drilling very deep, very hot geothermal wells. The cost of casing and cementing can dominate deep hot wells. These very deep wells will need to be completed in a way that minimizes pressure drop so the traditional telescoped casing sizes will either need to be very large at the top of the well, dramatically increasing the wellcost. Case-as-you-go methods need to be developed that will allow the completion of a monobore, one casing size over the entire length of the well. (Oppelt, 2012) These may involve not only novel ways to emplace the casing, but novel materials that can be deployed as the well is drilled and withstand the heating and cooling cycles in the well. Materials with higher elastic modulii that can withstand large thermal cycles without exceeding the yield strength of the material need to be investigated for use in very deep, superhot well design.

2.3 Reservoir Development and Management

Creating a geothermal reservoir in superhot rock which may be in the brittle ductile transition zone has not yet been done and is key to enabling superhot EGS projects. Fracturing needs to be initiated and extended to develop a large enough surface area to volume to extract heat from the rock at economic rates. The reservoir needs to be able to heat up injected fluid as it passes through the created fractures without cooling the rock too quickly. The fractures need to stay open long enough for economic heat extraction, but shouldn’t develop preferential pathways that would create short circuits that cool the rock too fast. Restimulation methods may be needed to open up fracture pathways the close or close short circuiting pathways.

Stimulation methods that work to some extent in hard, brittle rock with lower temperatures may either work better or not at all in superhot rock. Thermal stimulation may be more effective at these very high temperatures but delivering cool water to the reservoir may not only be more difficult due to wellbore heating but may also stress the casing through thermal cycling. Long term injection of cool water is the method that has worked best in EGS reservoir stimulation so far. However, very large volumes of water are needed for this type of stimulation. Water can be cooled and recycled, but loss to the rock through chemical reaction may be a significant factor in water consumption. Alternative fracturing fluids such as compressed CO2 may be very useful in the stimulation of very hot rock. Hot wet CO2 can help to dissolve and etch the rock to preserve open fractures. Other chemical methods may also have high potential for improved stimulation outcomes in superhot rock.

Fracture initiation and zonal isolation – Fracture initiation has been one of the biggest challenges in developing EGS reservoirs at lower temperatures. In oil and gas, zones for stimulation are isolated allowing enough pressure to be put on a particular section of rock to initiate fracturing. These are hydraulic fractures and, in oil and gas, need to be propped open after they are created. In conventional geothermal stimulation isolating a zone to apply pressure is difficult due to large wellbore diameters and completion of most wells with perforated liners where isolation behind the liner is not possible. New methods being developed to isolate zones behind the liner in geothermal wells may possibly be advanced to work in superhot temperatures, but this well take significant materials research. In many EGS stimulations fractures are kept open by self-propping due to differential stresses which is a good thing because proppants mostly dissolve in high temperature fluids. Development of very high temperature proppants may be necessary in superhot rock that is plastic beyond the cooled fracture area.

Rock/fluid interactions - While no one has created an EGS reservoir in superhot rock as yet, there are some natural supercritical geothermal systems operating in Iceland, Hawaii and other areas. The long-term reservoir behavior observed in these systems can be observed for clues to how an engineered system will behavior. Will solids precipitate in the created fractures? Will the rock dissolve and create short circuits? How can scaling and corrosion of surface equipment be managed and what effect will this have on the reservoir long term? All of these questions need answers, preferably before the first superhot system is put in place.

Reservoir simulators - Numerical modeling of such systems is needed to help better understand how the reservoir will behave long term. Existing geothermal reservoir modeling software will need to be modified to include superhot temperatures and rock properties in order for the modeling of superhot systems to proceed. Adding supercritical and superhot temperatures and equations of state for water and CO2 to existing geothermal models is underway. (Finsterle, 2014) However, the ability to model fracturing, both thermal and hydraulic, in superhot rock that may be in the transition zone between the brittle and ductile state will require further research into rock behavior in this zone. Use of large scale fracturing tests in the laboratory mimicking superhot conditions to validate models would help to reduce risk in field testing.

Tracer testing – Tracer testing is an invaluable tool in the management of geothermal reservoirs. Adapting existing high temperature tracers, both nonreactive and reactive for superhot conditions may not be possible and needs to be the subject of technology development. Ongoing efforts to develop methods to use tracers to characterize created fractures and determine surface area to volume ratios could be a tool to observe the changes in the reservoir with time. More work will need to be done on both tracers and the behavior in the superhot rock/fluid system in order for this to be possible.

Instrumentation – Flow is one of the most difficult things to measure particularly in the very hot, possibly corrosive superhot geothermal environments. Downhole flow can be a very useful indicator for production management in the geothermal reservoir and is particularly difficult to measure. Tools used for flow measurement in geothermal wells most often have rotating elements – spinners. Keeping these rotating parts operating in very high velocity, very high temperature and possible corrosive wells is a challenge. There are several methods for measuring flow that don’t require moving parts: ultrasonic, magnetic and dye tracer methods are used on the surface to measure high temperature geothermal flows in pipes. High temperature electronics can be insulated from the well fluids to enable downhole sensors to measure temperature, pressure and flow. However, we currently don’t have high temperature electric cables that will allow for surface readout of these sensors. Other instrumentation that is currently very useful in geothermal wells, but which is not hardened for extreme temperatures is fiber optic distributed pressure temperature and acoustic measurement. A single optical fiber can monitor all three of these properties downhole but currently available systems have issues with hydrogen darkening which limit their use. Work on fiber optic systems is underway due to the needs of the nuclear and aeronautical industries. Long cables for deep well deployment are also an issue that will need to be addressed.

2.4 Energy Conversion Technology

Using the superhot fluid at the surface can rely on existing supercritical cycle turbines. However, geothermal fluids will be different from the very clean water in coal fired boilers or nuclear plants. Either use of heat exchangers to deliver supercritical fluids to the turbine without impurities, materials selection or treatment will be needed to maintain turbines for economic maintenance schedules. Supercritical cycles have reheat systems to keep fluids from dropping below supercritical temperatures as they pass through the turbine. There will need to be decisions made on how the produced geothermal fluids will be used to provide this reheat.

Thermal energy storage can be coupled readily with superhot geothermal. The produced fluids may be hot enough to charge the thermal energy storage system during low electricity demand times. Then the stored thermal energy can be used to supply the reheat to the system allowing all the produced geothermal fluids to be used in the turbine inlet to boost output during peak demand periods. Thermal energy can be stored for long time periods and discharged over long durations adding value to the superhot EGS project.

3 CONCLUSIONS

While superhot EGS may provide a future resource that is both economic and can meet the demands of utilities trying to achieve high fractions of energy from renewables, technology development is needed to enable commercialization. We can drill and complete superhot wells now. However, there are challenges for well design, stimulation and long-term reservoir management of a superhot EGS reservoir that require technology development. A high temperature laboratory that can test large samples or components at the very high temperatures and pressures found in a superhot EGS system downhole, will further the development of commercial superhot projects. Reservoir creation methods, drilling approaches for very deep systems, casing and cementing materials and methods are important technology needs for superhot success. High temperature instrumentation for reservoir characterization and reservoir management also need to be developed.

The Frontier Observatory for Research in Geothermal Energy (FORGE) concept could be extended to superhot EGS technology development. At FORGE a consortium of university, national laboratory and commercial entities join forces to manage technology development for EGS at temperatures between 175°C and 225°C. A similar concept would work well for superhot EGS. There are several potential sites in the US where very hot, low permeability rock can be reached at depths of 6 km or less. The Newberry volcano site currently working with the NEWGEN consortium is has high potential as a field laboratory for superhot EGS experimentation and testing. At Newberry, NEWGEN (Pacific Northwest National Laboratory, Oregon State University, Stanford University, Equinor and AltaRock) has curated a huge data set plus two wells drilled to very high temperatures. One well could be readily extended in depth to reach temperatures over 450°C for the purpose of getting data on the rock characteristics in the brittle ductile transition zone and performing fracturing experiments.

4 REFERENCES

Bajcsi, P., Bozso, T., Bozso, R., Czinkota, I., Kovacs, B., Toth, T., Schubert, F., Szanyi, J.: Geothermal Well Completion Technology Using High Power Laser Device, Proceedings World Geothermal Congress 2015 Melbourne, Australia, 19-25 (April 2015)

Beentjes, I., Bender, J.T., Hawkins, A.J., Tester, J. : Chemical Dissolution Drilling of Barre Granite Using a Sodium Hydroxide Enhanced Supercritical Water Jet, Rock Mechanics and Rock Engineering, (August 2019)

Brikowski, T.: Modeling Supercritical Systems With Tough2: The *EOS1sc* Equation of State Module and a Basin and Range Example, URL: http://www.utdallas.edu/~brikowi/Research/Geysers/GRC01/grc01_paper.doc,

Dobson, P., Asanuma, H., Huenges, E., Poletto, F., Reinsch, T., Sanjuan, B.: Supercritical Geothermal Systems - A Review of Past Studies and Ongoing Research Activities, *Proceedings*, 41st Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 13-15, 2017 SGP-TR-212

Elders, W., and Friðleifsson, O.: Enhancement of The Science Program of the Iceland Deep Drilling Project (IDDP): A Study of Supercritical Geothermal Resources, *Proceedings World Geothermal Congress 2010, Bali, Indonesia*, 25-29 April 2010

Finsterle, S., Sonnenthal, E. L., Spycher, N.: Advances In Subsurface Modeling Using The TOUGH Suite Of Simulators, *Computers & Geosciences* Volume 65, (April, 2014)

Friðleifsson, G, Pálsson, B., Albertsson,A., Stefánsson, B., Gunnlaugsson, E., Ketilsson, J., Gíslason, Þ.: IDDP-1 Drilled Into Magma – World's First Magma-EGS System Created, *Proceedings World Geothermal Congress 2015 Melbourne, Australia*, 19-25 April 2015

Meier, T., Brkic, D., Schuler, M. J., Kant, M., von Rohr, R: The Potential of Hydrothermal Flames to Induce Spallation in Gneiss, Proceedings World Geothermal Congress 2015 Melbourne, Australia, 19-25 April 2015

Kocis, I., Kristofic, T., Gebura, M., Horvath, G., Gajdos, M., Stofanik, V.: Novel Deep Drilling Technology based on Electric Plasma Developed in Slovakia, 32nd URSI GASS, Montreal, 19-26 (August 2017)

Oglesby, K., Woskov, P., Einstein, H., Livesay, B.: Deep Geothermal Drilling Using Millimeter Wave Technology, *DE-EE0005504 Final Report,* Impact Technologies LLC Massachusetts Institute of Technology (December 2014)

Petty, S., Gastineau, J., Bour, D., Ravi, K.: Life Cycle Modeling Of Wellbore Cement Systems Used For Enhanced Geothermal System Development, *Proceedings*, Twenty-Eighth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 27-29, 2003 SGP-TR-173.

Prihutomo, M. J., Arianto, S.: Drilling Performance Improvements of Salak Geothermal Field, Indonesia 2006 – 2008, *Proceedings* World Geothermal Congress 2010 Bali, Indonesia, 25-29 (April 2010)

Schultz, A., Bonneville, A., Petty, S., Sørlie, C.: Toward Drilling the Perfect Geothermal Well: An International Research Coordination Network for Geothermal Drilling Optimization Supported by Deep Machine Learning and Cloud Based Data Aggregation, DE-FOA-0001880, U.S. DOE: Office of Energy Efficiency and Renewable Energy, 2019.

Sudarmadi, E., S. J., A., Bramantyo, E. A.: Modelling Production from Supercritical Geothermal Reservoirs, Proceedings the 34th New Zealand Geothermal Workshop, (November, 2012).

Suryanarayana, P. and Krishnamurthy, R.: Post-Yield Tubular Design and Material Selection Considerations for Improved Geothermal Well Integrity, *Proceedings*, 43rd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 12-14, (2018) SGP-TR-213.

Suryanarayana, P. and Krishnamurthy, R.: Strain-Based and Low Cycle Fatigue Methods to Design Geothermal Well Tubulars, *Power Plays: Geothermal Energy in Oil and Gas Fields Conference,* SMU, (April 25-26, 2016).

Wang, Z.: Modeling Study of a Single-Well Enhanced Geothermal System (EGS), Master's Thesis, Stanford University, 2009.

Watanabe, N., Sakaguchi, K., Goto, R., Takahiro Miura, T., Yamane, K., Takuya Ishibashi[2], Chen, Y., Komai, T., Tsuchiya, N.: Cloud-Fracture Networks As a Means of Accessing Superhot Geothermal Energy, www.nature.com/scientificreports, Published online: 30 January 2019.