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Committee, Subcommittee on Energy

Hearing Entitled
“Water and Geothermal Power: Unearthing the Next Wave of Energy Innovation”

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Good Afternoon--Chairman Lamb, Ranking Member Weber and distinguished Members of the Subcommittee, my name is Joseph Moore from the University of Utah’s Energy and Geoscience Institute. I am honored to appear before you today to discuss Project FORGE, an innovative geothermal energy research project funded by the Department of Energy in the state of Utah.

The thermal energy beneath our feet is enormous. Some of this energy reaches the surface naturally through hot springs like those found in Virginia, Arkansas, and Wyoming. But this is only a tiny fraction of the available energy. If we could capture even 2% of the thermal energy at depths between about 2 and 6 miles, we would have more than 2000 times the yearly amount of energy used in the US.

Natural geothermal systems require a source of heat, water to transfer the heat, and permeability to allow the water to carry the heat upward. These natural systems are found primarily in the western US. Hot water produced at temperatures of 250°F or above can be used to produce electricity. Although we can drill deep enough to reach temperatures of 250°F anywhere in the world, and inject water to transfer the heat, most areas don’t have sufficient natural permeability to circulate water at the depths we require. The oil and gas industries have demonstrated that permeability can be created or enhanced through hydraulic stimulation, but these techniques require modification because of the higher temperatures required to generate electricity and lower thermal value of geothermal fluids.

Attempts to create Enhanced Geothermal Systems (EGS) were initiated by the Los Alamos National Laboratory in the late 1970s at Fenton Hill, New Mexico. More than a dozen attempts followed worldwide. These projects utilized pressurized water to stimulate existing fractures and create new ones. While important lessons were learned, none of these attempts created commercial scale reservoirs capable of producing more than a couple of megawatts of electricity.

Rather than repeat the previous experiments, the DOE issued a Funding Opportunity Announcement (FOA) for building and operating an underground laboratory where new technologies for EGS reservoir creation and operation could be developed. Some of these technologies were successfully tested in April 2019 during the stimulation of well 58-32, a 7536 foot well drilled at the Utah Frontier Observatory for Research in Geothermal Energy (FORGE) site.

The Utah FORGE site was one of five locations in Utah, Idaho, Nevada, Oregon and California originally considered for the laboratory. The first phase of the project consisted of desktop studies. Based on these studies, the Fallon, Nevada and Milford, Utah sites were selected for further evaluation. A deep well was drilled at each of the two sites to demonstrate the reservoir met the required temperature, rock type, permeability, and stress criteria established by the DOE. In 2018, the site in south-central Utah was selected.

The granite reservoir rocks at the Utah site are representative of the geologic environment at many locations across the US. Thus, reservoir creation in Utah can provide a template for EGS development elsewhere. The site is located on state land in Utah's renewable energy corridor. This corridor contains three conventional geothermal plants, a windfarm, a solar field, and a biogas facility. There are no environmental or cultural constraints that would impact Utah FORGE activities. Water for testing is available at the site. The local groundwater cannot be used for agriculture or human consumption and the Utah FORGE project has secured sufficient water rights for testing and drilling. The local infrastructure is well developed and the site can be accessed year-round on public roads near, Milford, a community of 1400 located 10 miles away. The residents of Milford, the Beaver County commissioners, local landowners, and state and federal agencies have all enthusiastically supported the project. The Governor's Office of Energy Development, the Office of Economic Development, and the University of Utah have contributed significant funds to the project.

In FY2020, we will begin full deployment of the Utah FORGE laboratory. The centerpiece of the laboratory will be a pair of deep wells, one for injection and one for production. Additional infrastructure will consist of wells to monitor microseismic activity and produce groundwater, and facilities to support the research activities. The deep wells have an estimated cost of \$15 million each. The first deep well will be drilled in FY2020-2021; the second in 2022-2023. Once the two wells are drilled, water will be circulated between them to extract heat from the hot rocks. Currently, the project is scheduled to continue through 2024.

DOE has obligated nearly \$125 million to Utah FORGE for FY2020 to 2024. Fifty percent of the funds will be utilized for research; the remainder will be used for field operations and drilling. Definition of the research and development topics is the responsibility of an independent group of experts that includes members of the Fallon, Nevada FORGE team. The first set of competitive solicitations will be released in FY2020. Solicitations will then be released yearly throughout the project's life.

EGS reservoirs have the potential to provide low cost, secure, green electrical energy across the US. Research conducted under the Utah FORGE program will allow the scientific and engineering community opportunities to develop and test technologies outside of those used by commercial geothermal developers and the oil and gas industry. New stimulation and drilling technologies will, in turn, improve the productivity of conventional geothermal systems and high-temperature oil and gas plays. The cost of geothermal wells typically accounts for 50% of the total cost of a geothermal project. Stimulating existing wells and increasing production and injection rates can significantly reduce the overall cost of a geothermal project by reducing the number of wells that must be drilled.

The development of new technologies requires a fundamental understanding of the reservoir characteristics. These include temperature, rock type, principal stress orientations and magnitudes, the mechanical properties of the reservoir rock (e.g. rock strength), fracture orientations and distributions, sustainable heat extraction, the potential to induce microseismic events, and the level of seismic risk.

The importance of microseismic monitoring and seismic risk mitigation cannot be overemphasized. Because reservoir creation results in a release of energy, microseismic events are a natural consequence of stimulation. Events with magnitudes greater than 2-3 can be felt and have led to public outcries in Europe.

A unique feature of the Utah FORGE site is the opportunity to work on microseismic monitoring and hazard mitigation while simultaneously developing the permeability required for commercial EGS development. To mitigate issues related to microseismicity, a network of surface and downhole seismometers is being deployed at the Utah FORGE site and a Seismic Hazard Mitigation Plan has been developed.

Operational funds for the project will total approximately \$62.5 million for the remainder of the project. Close to two-thirds of these funds will be used for infrastructure development. This includes drilling, reservoir creation, and deployment of the microseismic monitoring network. Once the two deep wells are drilled, long term circulation testing will be required to confirm the universal application of the newly developed EGS technologies and to demonstrate the commercial viability of EGS resources.

We anticipate completing the second well in Q1 FY2023, as noted above, and decommissioning the site by Q4 FY2024. The completion of the second well will mark the full realization of the Utah FORGE laboratory and initiation of full-scale reservoir development. Significant testing, and demonstrating commerciality of EGS, will occur in the following 18 months. At end of these 18 months, Utah FORGE is required to plug and abandon the wells and bring the drill pads back to their original grade.

The Utah FORGE site is a unique publicly owned and operated laboratory and an essential stepping stone to commercial EGS development. Maintenance of the site beyond FY2024 will provide a facility where new technologies can be tested at low cost in an ideal EGS environment. No alternative facilities currently exist in the US. We strongly urge the Committee members to continue their support of the Utah FORGE project and EGS development in the US.

Thank you again for the opportunity to testify on Project FORGE. I am happy to answer any questions you may have.

Next-generation Energy

Enhanced Geothermal Systems (EGS) represent an enormous source of energy for the USA. The resource potential of EGS is much greater than the energy needs of our country.

Natural geothermal systems consist of a heat source, permeable pathways (fractures or permeable aquifers), and a fluid to transport the heat.

Enhanced Geothermal System reservoirs are hot, dry rocks that lack the natural permeability required to generate energy pathways.

Temperatures sufficient for electric generation can be found at drillable depths throughout the country. For EGS cold water is injected into hot rocks to transfer the heat to the surface to create electricity.

Geothermal Systems

Conventional



- Natural open fractures
- Water circulates in hot rocks
- Producing systems in the USA are restricted to the western USA and Hawaii

Enhanced



- Dry, hot rocks
- Hydroshear the sealed fractures to create permeability
- Can be developed across the USA

EGS Benefits the U.S.A.

- ✓ Energy Security
- ✓ Enormous Resource Potential
- ✓ Environmentally Friendly
- ✓ Sustainable for Generations
- ✓ Cost-Effective
- ✓ Low-Risk and High-Reward
- ✓ No or Low Emissions
- ✓ No Potable Water Required

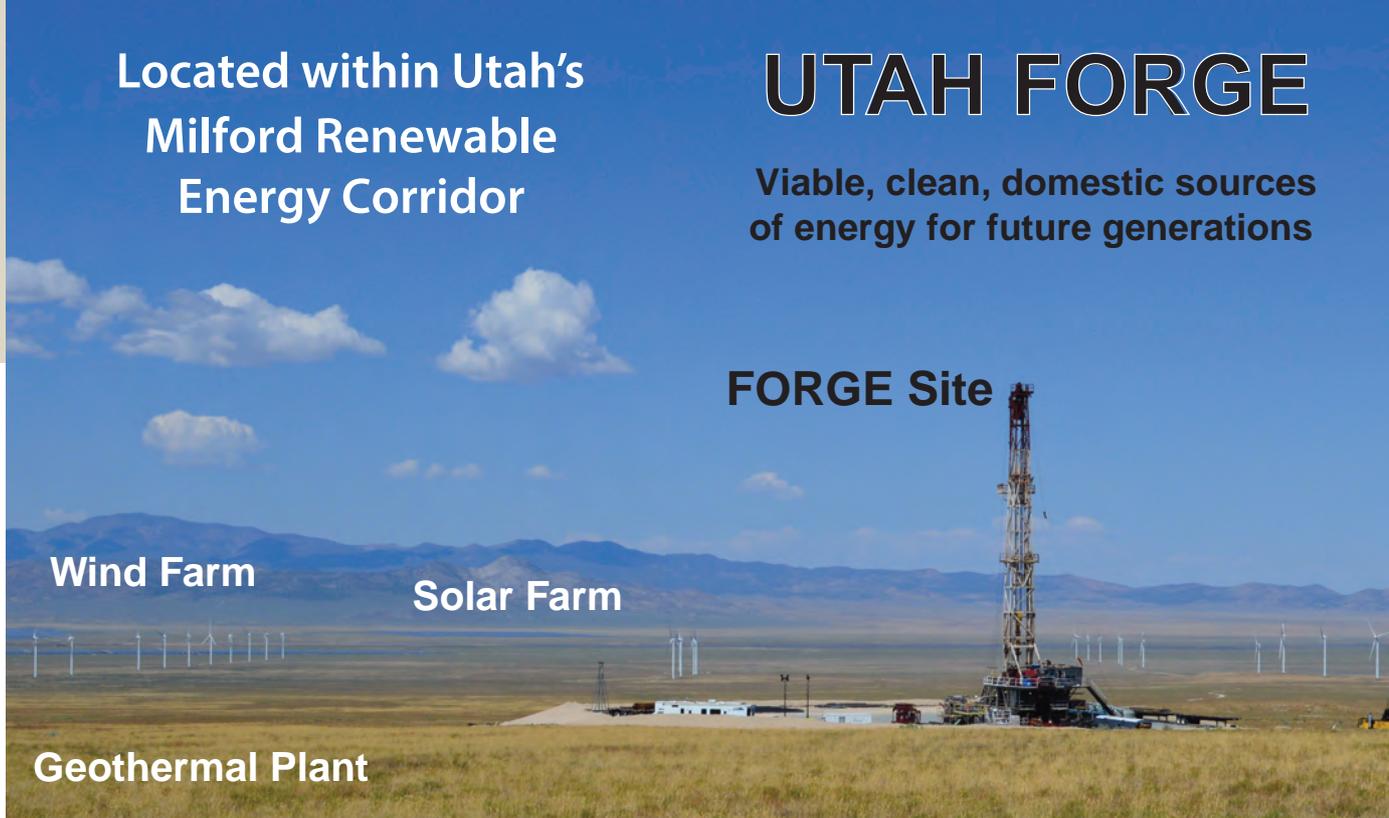


Located within Utah's Milford Renewable Energy Corridor

UTAH FORGE

Viable, clean, domestic sources of energy for future generations

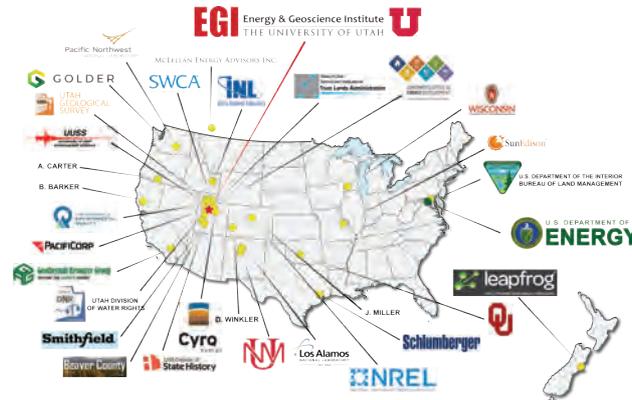
FORGE Site



Wind Farm

Solar Farm

Geothermal Plant



Frontier Observatory for Research in Geothermal Energy

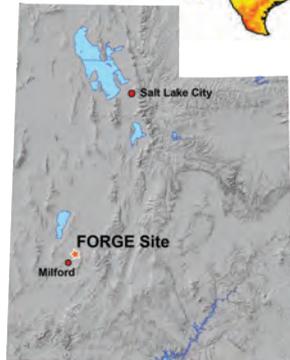
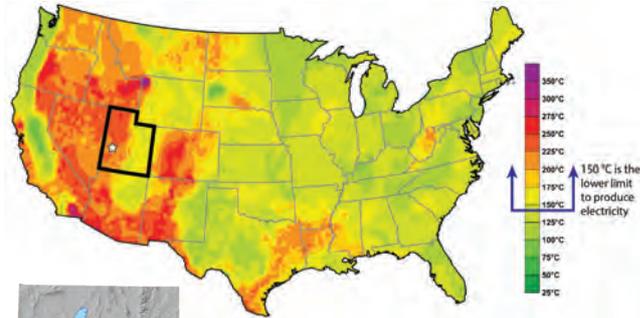
www.UtahFORGE.com

What is FORGE?

Frontier Observatory for Research in Geothermal Energy

Utah FORGE is a dedicated underground field laboratory sponsored by DOE for developing, testing, and accelerating breakthroughs in Enhanced Geothermal System (EGS) technologies to advance the uptake of geothermal resources around the world.

Subsurface Temperature Map at 20,000 ft



The basement rocks forming the reservoir are hot and impermeable, and they are representative of potential EGS sites across the USA. The findings and achievements at Utah FORGE will be the critical stepping stones to widespread development of geothermal energy and renewable power generation.

Utah FORGE Project focus:

- Heat transfer & fluid flow networks in crystalline rock
- High temperature tools for borehole and reservoir imaging
- Seismic monitoring and induced seismicity
- Stimulation & isolation technologies
- In situ stress management & monitoring
- Water-rock interaction
- Numerical simulations of fracture development & fluid flow
- Best practices for EGS development
- Improved public awareness & confidence of geothermal technologies
- Educational opportunities at all levels
- Management & prediction of induced seismicity

UTAH FORGE Site Characteristics

Reservoir attributes

- Temperature greater than 175 °C (~350 °F)
- At a depth of 2 km (~6500 ft)
- Reservoir formation in crystalline rocks (granite)

Environmental considerations

- Free of protected flora and fauna
- No identified risks to groundwater

Water rights and use

- No competition with human or agricultural water use or access
- Extensive supply of nonpotable water available
- Only nonpotable water will be used for EGS development

Seismic considerations

- Monitoring by University of Utah seismic stations since 1981
- Low risk of local and regional seismicity

Infrastructure

- Within the Utah Renewable Energy Corridor
- Adjacent to major highways, secondary roads, railroads, and airport

Access for scientists

- Resident and visiting scientists will have 24/7 access
- Supportive federal, state, and private landowners
- No high security or sensitive operations exist on the Milford site

Data

- Area has been subject of intense investigation and drilling by scientists, students, and geothermal companies since mid 1970s

The UTAH FORGE Laboratory

The field laboratory comprises a large volume of hot (175-225°C) crystalline granite between two deep directionally drilled wells at around 8000 feet depth below the surface. On site facilities include water, power, offices, broadband internet, which will be required for drilling,



stimulation, and injection -production activities. The facility is managed by a multi-disciplinary team of engineers and scientists led by the University of Utah, with expertise in geosciences, drilling, rock mechanics, reservoir engineering, environmental monitoring, outreach and communications.

www.UtahFORGE.com
www.facebook.com/forg Utah



Outreach Program

The outreach program is responsible for maintaining and improving the already strong community support from the residents, businesses and government agencies that are based in and around Milford and in Beaver County. Regular updates of activities, announcements, and events are available on our website and social media.

Multiple videos highlighting the project were produced in collaboration with the **Governor's Office of Energy Development**. The videos are available on our website.

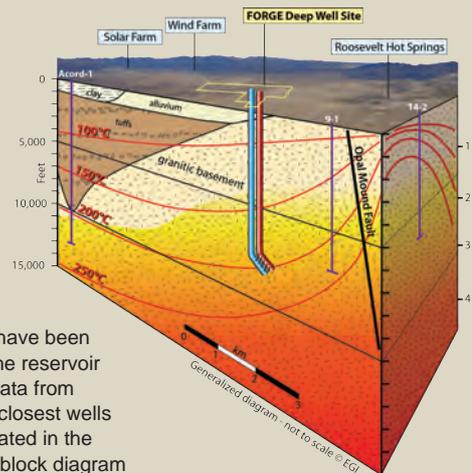
- Video 1 'Energy Success Stories: Discovering Utah's Geothermal Potential'
- Video 2 'FORGING' New Geothermal Technologies - Part One'
- Video 3 'FORGE: Exploring Utah's Potential for Enhanced Geothermal Systems - Part Two'
- Video 4: 'Unearthing the Utah FORGE Site's Data'
- Video 5: 'FORGEing into the Future'

Utah FORGE team members have 250+ years of Geothermal Experience and Expertise

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Milford FORGE Utah Site



Many wells have been drilled into the reservoir formation. Data from three of the closest wells are incorporated in the generalized block diagram

Geothermal Energy - Challenges for EGS Development: An Editorial Perspective

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Joseph Moore, Energy & Geoscience Institute, University of Utah,
Richard Allis, Utah Geological Survey

Introduction

The attractiveness of geothermal energy is manifest. For centuries, humans have been exploiting indirect uses ranging from heating to cultivation to aquaculture. More recently, hydrothermal geothermal operations have generated electricity. The viability of hydrothermal power generation has improved with organic Rankine cycle technology that affords somewhat lower temperature working fluid. Electricity generation is feasible at ~200°C while direct use can use temperatures less than 150°C.

Drilling for hydrothermal systems has confirmed that there is a vastly greater volume of relatively tight, hot rock compared to naturally fractured rock. If there is a way to extract this heat, the potential for geothermal could be at least an order of magnitude larger than what is developed for power today. For the last half century, the aim has been to extend the geographic and geologic reach of geothermal energy sources to scenarios where heat is present but conductive fracture networks and in-situ fluid are missing. This started with the Hot Dry Rock (HDR) pilots at Fenton Hill, United States, Soultz sous Forêts, France and other programs. Commerciality has always been one step away. A reinvigoration of these same concepts of developing high temperature (>200°C) but non-conductive fractured reservoirs has been coined as Enhanced Geothermal Systems (EGS). The greater the temperature, the greater the efficiency at the surface for conversion to electricity. Conversely, with greater temperature, tool design and performance (seals, packers, motors ...) becomes more problematic. The premise is to drill injection and production wells, not always concurrently, and hydraulically connect these by reactivating and extending existing fractures or possibly by creating new fracture networks. The premier example of this is the U.S. Department of Energy's FORGE initiative. FORGE is an acronym for Frontier Observatory for Research in Geothermal Energy^{1,2,3}

The FORGE program is intended to provide an underground laboratory for developing and testing innovative tools and stimulation techniques for developing EGS reservoirs. This will provide a new opportunity to extend existing technologies developed for the oil and gas industry beyond current capabilities to successfully produce electricity from hot crystalline rocks. This is an opportunity to demonstrate technologies for application outside of hydrothermal plays and will provide funds for research to expand future energy availability. It will demonstrate suitability and safety of large-scale geothermal energy development to the public. This testing and research initiative is required because of ongoing challenges to commercially produce from enhanced geothermal settings. The challenges encompass exploration technologies and reservoir characterization, well construction (drilling, completion and stimulation) and reservoir management (heat management, diagnostics, induced seismicity ...). The challenges are discussed and research efforts for the entire subsurface community are indicated, allowing development of an exceptional energy opportunity. This research portfolio is building on the technical successes in the last five decades. Within the oil and gas sector drilling efficiencies have advanced rapidly in the last decade. Similar progress has been seen for solar panels and wind turbines. Geothermal has not necessarily kept pace. However, the development of new, cost-effective technologies in EGS has the potential to revolutionize geothermal power generation and make it an attractive, base-load option in future decades.

Challenges for Reservoir Characterization

This broadly encompasses research needs for exploration and then subsequently quantification and visualization of the potential reservoir and its surroundings, some of the same issues for other subsurface disciplines (see for example, Green, this issue).

What Have We Learned?

Although hydrothermal systems usually have some near-surface indicators (such as hot springs) or anomalous heat at depth, impermeable hot rock may be geophysically featureless – no surface geologic expression of thermal potential. In any case, delineation of reservoir temperature and fracturing potential is complicated. Gravity, magnetic, and magnetotelluric surveys may not have the resolution to circumvent the necessity for exploratory drilling. Specialists argue whether conventional seismic exploration will have the resolution to identify contributing fractures. Seismic reflection imagery of deep stratigraphic sequences has been crucial for identifying drilling targets in oil and gas reservoirs. However the seismic reflectivity of hot intrusive rocks has been poorly studied. Subseismic delineation of fracture systems, and forecasting of thermal characteristics remain pre-eminent considerations. This is not fundamentally different from unconventional hydrocarbon recovery. The geothermal explorationist is intent on defining the heat source, ensuring that the thermal reservoir is not substantially faulted and fractured, and ensuring that the heat is not convected elsewhere. In addition, most high temperature hydrothermal systems are also areas of high seismic activity – that is why natural seismicity monitoring can help delineate areas of faulting and fractures that are part of the natural fluid circulation at depth and targets for drilling. Again, outside of a hydrothermal system, could natural microseismicity (or nanoseismicity) be a useful indicator of small-scale fractures in the granite (host rocks) that then become targets for stimulation?

Just as with waterflood techniques for driving oil and gas towards production wells, the effectiveness of sweeping heat out of hot rock with injected cooler water requires a large surface area in the form of a fracture network or interconnected pores. Studies of power generation from hydrothermal systems show effective heat sweep efficiencies in the range of 15 – 25% after several decades of production. So far, EGS projects have shown heat sweep efficiencies of only a few percent because of few interconnected fractures. Typically, a 100 MWe geothermal power plant operating for 30 years requires a reservoir volume of 16 km³ if the heat sweep efficiency is 10%. This is a reservoir area of 4 km x 4 km with a production zone that is 1 km thick. These approximations assume 200°C production water, 75°C injection water, and 20% power conversion efficiency. Also, if heat is conducted through low permeability matrix between fractures, the characteristic thermal conduction thickness after 30 years of temperature change in the fracture is on the order of 50 m. This implies that nominally an EGS reservoir has to be fractured on a 50 to 100 m scale to sweep out a significant volume of heat over 30 years. These numbers define the challenges for EGS technology development to extract heat for the amortized life of a geothermal plant, or at least a significant fraction of that period. In addition, stimulation economics (ability to provide high enough treating pressures) may require pre-existing weaknesses in the reservoir. A multiplicity of subseismic natural fractures may be required for heat management and effective breakdown. On the other hand, major throughgoing fractures can be undesirable because of the potential for short circuiting where injection water moves from injector to producer with minimum exposure to the thermal reservoir. These larger systems are also undesirable if they contribute to induced seismicity triggered by direct fluid exposure or by reservoir adjustments due to thermal stress evolution.

What Are the Next Research Steps?

Previous EGS research projects have not been restricted by availability of heat. This suggests that with good exploration practices, thermally acceptable reservoirs can be identified. Beyond spatial definition of fractures, apertures, infill and mechanical properties are usually poorly characterized. Imaging logs delineate near surface fracture occurrence and can be significantly inaccurate for forecasting aperture. Very few techniques are available to constrain stochastic predictions of fracture length and effective conductivity. This is supported by observations in oil and gas scenarios where although hundreds to thousands of fractures may be recorded, production logging and distributed temperature surveys suggest very few are contributing to injectivity or productivity. The mechanical characteristics of native fractures is further unknown. Standard assumptions of a 30° friction angle may be unacceptable from the perspective of expenses related to casing integrity and surface horsepower during breakdown of high strength formations. While there are methods for inferring properties on a core scale (Figure 1 is an example), upscaling these is probably not adequately done. Methods based on RQD or GSI⁴ from civil and mining engineering disciplines can be usefully applied (Hoek and Diederichs, 2005;³ Liu et al., 1999⁶ ...) to comprehending and classifying hydrocarbon and geothermal reservoirs.

Improved deep penetrating logging and visualization methods can de-risk the potential for induced sensible seismicity by identifying fractures not intersecting the wellbore. With the natural fractures not always aligned with neo-stress directions, methods for determining the complete stress tensor are essential – a perpetual problem in deep subsurface energy recovery.

Controlled, carefully monitored experiments at a well characterized location would be valuable for improving our comprehension of the role and characteristics of natural discontinuities and their associated stress regimes.

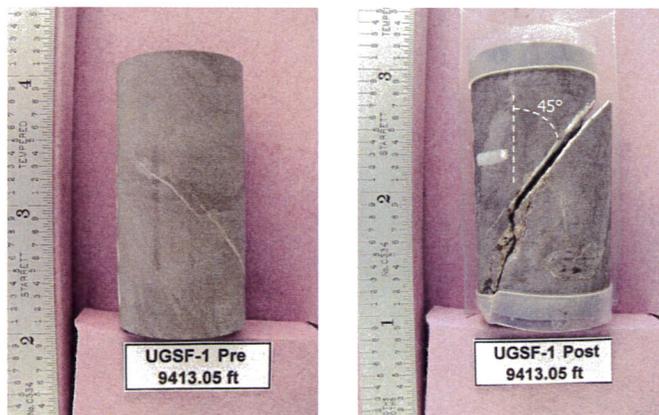


Figure 1. Standard rock mechanics testing, such as triaxial shear can help to delineate peak and residual shear resistance.

Challenges for Well Construction

Compared to hydrocarbons, the energy density for produced heated water requires large circulation rates⁷ and efficient, cost effective well construction in a difficult environment.

What Have We Learned?

Techno-economic restrictions mean there is a requirement for lower cost drilling in hard, hot rock, often at significant depth. The geothermal community is obliged to adopt cased and cemented completions with multiple access points. This will – at least for the near future – mandate

high angle or horizontal drilling. In the future, more temperature tolerant bits may relax this criterion. However, some steering capabilities will be essential to minimize surface footprint.

High temperature cementing of horizontal and extended reach wells will be challenging. Even when the well is cemented, effective completion and access to the formation through perforating at high temperature, reliable and easily or remotely manipulated sliding sleeves will be required.

To ensure adequate surface area for heat transfer, it is anticipated that there need to be multiple entry points along the length of a wellbore in the reservoir. Fracture networks are ideally activated from each of these access points. Oilfield technology should be adaptable (plug and perf). Even so, isolation technology to allow for discrete zonal stimulation faces some challenges in deep, high temperature, highly stressed environments. Finally, it will be necessary to reactivate or create a multitude of fractures from these access points, communicate these with one or more production wells and guarantee low term hydraulic and thermal conductivity. This will require hydraulic stimulation.

Legacy hydraulic fracturing for EGS, over the last forty years, has been an outstanding technical success. The monitoring and stimulation techniques foreshadowed current methods used for shale oil and gas recovery. Treatments (Brown and Duchane, 1999⁸) at Fenton Hill are reminiscent of those pumped today – high rate, high volume, and slickwater with CaCO₃ particulates for diversion or fluid loss control (Figure 3). This was an early demonstration of microseismic mapping. These treatments and treatments in the oilfield have helped identify the requirement of multiple existing fractures. Recently, work at the DOE Raft River Project (Bradford et al., 2015⁹) have suggested the effectiveness of hybrid stimulation protocols. This involves periodic, high rate stimulations accompanied by long term, low rate injection with accompanying thermal stimulation. Additional evaluation is important. Finally, the effectiveness of low rate injection and shearing with self-propping (so-called “hydroshearing”) continues to be advocated (Boyd, 2014¹⁰) – demonstration of its viability is important.

What Are the Next Research Steps?

One of the greatest uncertainties in developing an AFE¹¹ for an EGS well is drilling time and ROP (Rate of Penetration). Issues related to loss of circulation and well control, while critical considerations, can be addressed by modern methods, possibly including managed pressure drilling, MPD, where necessary. Important research is required to optimize bit mechanics. Some new developments are being evaluated, including hybrid bit technologies (Rickard et al., 2014¹²). Practitioners are concerned about torque and drag and tolerance of geosteering equipment at high temperature.

With a feverish development pace in oilfield applications, isolation technologies have dramatically improved. The value of these technologies in the geothermal sector is evident by assessing the proposed isolation methods from only a few years ago (Walters et al., 2012¹³). Horizontal completions and isolation protocols have developed substantially since then (for example, Packers Plus, 2016¹⁴). Regardless, the issues that need to be resolved – with funding and controlled experimentation include packer simplicity and reliability, component tolerance of temperature, and ability to withstand significant differential pressure (Figure 2). Deep, high temperature and highly stressed environments will continue to mandate research on isolation tools (Song et al., 2015¹⁵).



Figure 2. Regardless of the element type (inflatable for openhole or compression packer for casing), high differential pressure (pumping equipment is shown in the lower right) and temperature challenge reliability. Upper right is a failed inflatable packer. Lower left is tubing damaged as a result of energetic packer failure (refer to McLennan et al., 1986¹⁶).

Stimulation technologies range from moderate volume high rate, short-term, conventional stimulations, to low rate, relatively short term treatments at pressures below the minimum total principal stress (to induce shearing and self-propping) to extended injection periods, also at low rates to encourage thermal stress alteration and fracture modification, creation or evolution. There is likely a place for all of these depending on the specifics of the geologic regime.

Controlled, carefully monitored experiments at a well characterized location would be valuable for improving our comprehension of optimal treatment methodologies.



Figure 3. Part of a substantial frac fleet brought together for high rate, long term hydraulic fracturing at the Fenton Hill site in December 1983 (photograph by John McLennan).

Challenges for Reservoir Management

All the issues to this point are tractable with technology and field experimentation. The greatest uncertainty may be the overall economics and the ability to manage heat extraction for a long term payoff.

What Have We Learned?

Reservoir management requires modeling and forecasting of the fracture networks and reservoir performance (thermal depletion) over time. There has been a proliferation of coupled thermo-poro-mechanical-chemical numerical protocols in the last few decades. These offer important opportunities for simulating performance. Of course, these are all inhibited if reservoir characterization is inadequate. This is particularly true with current limited knowledge and mapping/measurement techniques for natural discontinuities and the in-situ stresses.

Adequate modeling, monitoring and diagnostics will allow an operator to identify deviation from ideality and possibly intervene. Preferred oilfield methods may be misleading because they don't reliably consider extensive fracture networks (many are ad hoc modifications of falloff behavior for a two-dimensional analytic fracture solution or are dual porosity approximations). Injection indices such as the Hall plot have limited value because they do not enable rapid diagnosis since fluctuations are intentionally inhibited. With additional and creative diagnostic tool development (analytical or numerical), specific manipulation of valves should be possible even in aggressive in situ environments (see for example, Abou-Sayed et al., 2002¹⁷). This is the key to reservoir management – simulation – measurement – injection/production manipulation.

What Are the Next Research Steps?

Numerical simulations either require more quantified data or should be nimble enough to carry out enough realizations to emphasize uncertainty and guide proactive intervention. New generations of diagnostics are desirable. Above all, few existing methods and simulations have been validated – this is an essential need, requiring field testing under controlled conditions.

Safe and sustainable operations are the primary criteria for successful reservoir development. In particular, validating codes for prediction of microseismicity and improving methods for actively and passively monitoring, evaluating and eventually predicting seismic activity is required. This implies processing low magnitude events for evaluating fractured surface area and predicting situations where more serious, sensible events may occur.

With safe operations, the next consideration is reservoir heat management. It is well established that adequate surface area needs to be created to minimize early thermal breakthrough. Ketilsson et al., 2012¹⁸ observed.

“By stimulating reservoir in a more uniform way or by creating multiple conductive fractures connecting injection and production wells, fluid movement becomes more uniform and involves reduced fluid velocities and less differential pressure.” (also, Podgorney, 2016¹⁹)

“This will also require wellbore completion that allows management of the flow at the multiple injection and production horizons. Flow localization is a function of the conductivity of pathways and injection rate-viscosity product.”

In order to develop and validate simulation methods and diagnostics and make real evaluations of thermal extraction, once again, *controlled, carefully monitored experiments at a well characterized location would be valuable for improving our comprehension of optimal diagnostics, simulations and intervention strategies.*

Summary

EGS offers exceptional promise for accessing the very large volumes of hot low permeability rock that are in high heat-flow areas of the globe. The challenge is to develop cost-effective technologies. The future FORGE laboratory and other field laboratories are essential to:

- provide technical vision to achieve infrastructure for EGS optimization and validation,
- provide controlled environments for developing comprehensive and meaningful research programs,
- apply technology from other disciplines (in particular oil and gas technology),
- to enfranchise learnings from fifty years of EGS evolution, and,
- optimize and validate simulation and diagnostic methods while validating economic potential in an unbiased fashion.

Acknowledgements

The authors gratefully acknowledge the financial assistance of the Department of Energy, under the FORGE Phase I and 2a awards for Enhanced Geothermal System Concept Testing and Development at the Milford City, Utah, Forge Site, DE-EE0007080.

Endnotes

¹ <http://energy.gov/eere/forge/forge-home>

² <http://www.forgeutah.com/>

³ Tester, J.W., et al. 2006. The Future of Geothermal Energy - Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century, November.

⁴ RQD is Rock Quality Designation and GSI is Geologic Strength Index

⁵ Hoek, E., and Diederichs, M.S. 2005. Empirical Estimation of Rock Mass Modulus, *Intl J. Rock Mech. Min, Sci*, 43, June.

⁶ Liu, J., Elsworth, D., and Brady, B.H. 1999. Linking Stress-Dependent Effective Porosity and Hydraulic Conductivity Fields to RMR, *Intl J. Rock Mech. Min, Sci.*, 36, 581-596.

⁷ 240°C water has an enthalpy of 1 MJ/kg whereas oil and gas have enthalpies 40 times this. In contrast to a high flow rate oil well (5,000 – 10,000 bbl/day) a good geothermal well (10 MWe potential) has a flow rate 50,000 bbl/day (100 L/s)

⁸ Brown, D. W., and Duchane, D. V. 1999. Scientific Progress on the Fenton Hill HDR Project Since 1983,” *Geothermics* 28(4/5) special issue: Hot Dry Rock/Hot Wet Rock Academic Review (Abé, H., Niitsuma, H., and Baria, R., eds.), pp. 591–601

⁹ Bradford, J., McLennan, J., Moore, J., Podgorney, R., and Tiwari, S. 2015. Hydraulic and Thermal Stimulation Program at Raft River Idaho, A DOE EGS, in *Transactions - Geothermal Resources Council*. (Vol. 39, pp. 261-268). Geothermal Resources Council.

¹⁰ Boyd, D. 2014. Hydroshearing for Geothermal Energy, Well Servicing, September/October.

¹¹ Authorization for Expenditures

¹² Rickard, W., Bailey, A., Pahler, M. and Cory, S. 2014. Kymera™ Hybrid Bit Technology Reduces Drilling Cost Proc., Thirty-ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, February 24 - 26, SGP-TR-202.

¹³ Walters, J., Thorhallsson, S., and Wood, E. 2012. Zonal Isolation for Geothermal Wells, International Partnership for Geothermal Technology, August.

¹⁴ <http://packersplus.com/systems-solutions/>

¹⁵ Song, Y., Lee, T.J., Jeon, J., Yoon, W.S. Background and Progress of the Korean EGS Pilot Project, Proc. World Geothermal Congress 2015, Melbourne , Australia , 19-25 April.

¹⁶ McLennan, J.D., Hasegawa, H.S., Roegiers, J.-C., and Jessop, A.M. 1986. Hydraulic fracturing experiment at the University of Regina Campus *Canadian Geotechnical Journal*, Volume 23, Issue 4, 548-555.

¹⁷ Abou-Sayed, A.S., Guo, Q., Wang, G., McLennan, J.D. and Zaki, K. 2002. Challenges for Monitoring and Verification of Drill Cuttings Reinjection Performance, SPE-78186-MS, SPE/ISRM Rock Mechanics Conference, 20-23 October, Irving, Texas

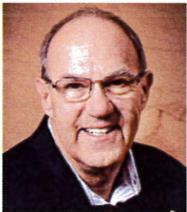
¹⁸ Jónas Ketilsson, J., Gunnarsson, G., Pálsson, H., Podgorney, R., Fairley, J., Ingebritsen, S., Driesner, T., Giroud, N., Baujard, C., Regenauer-Lieb, C. 2013, Geothermal Reservoir Modeling, Recommendations for Research and Development, International Partnership for Geothermal Technology, August.

¹⁹ Podgorney, R. 2016. Personal communication, presentation at 2016 GRC Workshop, Sacramento, CA.

Biographies



Since October 2009, **John McLennan** has been an Associate Professor in the Department of Chemical Engineering at the University of Utah. He has been a Senior Research Scientist at the Energy & Geoscience Institute and a Research Professor in the Department of Civil Engineering at the University of Utah, since January 2008. He received his Ph.D. in Civil Engineering from the University of Toronto, in 1980. He has thirty years of experience with petroleum service and technology companies. He worked nine years for Dowell Schlumberger in their Denver, Tulsa and Houston facilities, and later with TerraTek in Salt Lake City, Advantek International, in Houston, and ASRC Energy Services in Anchorage. He has worked on projects concerned with hydrocarbon recovery in a variety of reservoir environments, in domestic and international settings.



Dr. Joseph Moore received his Ph.D degree from the Pennsylvania State University in 1975. After graduation, he worked for the Anaconda Company as a uranium exploration geologist. He holds appointments at the University of Utah as a Research Professor in the Department of Civil and Environmental Engineering and as an Adjunct Professor in the Department of Geology and Geophysics. Since the mid 1970s, Dr. Moore has conducted research on the geology, hydrothermal alteration and geochemistry of geothermal systems throughout the world for the US Department of Energy, private geothermal companies, the U.N., and U.S AID. Dr. Moore currently serves as the Principal Investigator on US Department of Energy Grants focusing on the development of Enhanced Geothermal Systems.



Dr. Rick Allis has extensive geothermal experience, having previously worked on geothermal systems in the Basin and Range (UT and NV), Indonesia, and The Geysers (CA) while a Research Professor at EGI (University of Utah) between 1997 and 2000. Between 1977 and 1997 he worked for the New Zealand geoscience organizations, and was involved in many geothermal and oil and gas projects in New Zealand, Papua-New Guinea, Indonesia, Japan, and Vietnam. During this time he also spent 18 months as a visiting scientist at the Geology and Geophysics Department of the University of Utah on a Fulbright scholarship working on mostly on geothermal topics. He has a PhD from the University of Toronto, has been the Director and State Geologist of the Utah Geological Survey since 2000.