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U.S. geothermal research examples aimed at lowering development risks and increasing value

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1. INTRODUCTION AND CONTEXT

Recent national focus on the value of increasing our supply of indigenous, renewable energy underscores the need for re-evaluating all alternatives, particularly those that are large and well-distributed nationally. To transition from current hydrocarbon-based energy system in the U.S., we will need to expand and diversify the portfolio of options we currently have. One such option that has been undervalued and often ignored completely in many national assessments is geothermal energy from both conventional hydrothermal resources and enhanced or engineered geothermal systems (EGS). Although geothermal energy is currently used for both electric and non-electric applications worldwide from conventional hydrothermal resources and in ground source heat pumps, most of the emphasis in the U.S. has been generating electricity. For example, a 2006 MIT-led study focused on the potential for EGS to provide 100,000 MWe of base-load electric generating capacity in the U.S. by 2050. Since that time, a Cornell-led study evaluated the potential for geothermal to meet more than 25 EJ per year demand in the U.S. for low temperature thermal energy for heating and other direct process applications (Tester, 2011 and Fox et al., 2011)

Examples of Research, Development and Demonstration (RD&D) activities in three areas important to geothermal deployment on a national scale are highlighted following the format of a summary or extended abstract. The areas are: 1. Resource Assessment, 2. Reservoir Technology, and 3. Utilization. The examples discussed in this document only provide a small sampling of a much more extensive U.S. geothermal research program. More information about the U.S. programs can be found on the U.S. Department of Energy (DOE) website under Geothermal Technology at

http://energy.gov/eere/geothermal/geothermal-energy-us-department-energy

Below we present a brief overview of specific examples of ongoing EGS research in the U.S. Details can be found in the references listed at the end of this document.

2. RESOURCE ASSESSMENT: ESTIMATING THE MAGNITUDE AND DISTRIBUTION OF THE U.S. RESOURCE.

2.1 Play Fairway Analysis of the Appalachian Basin

The oil and gas industry has addressed exploration and development complexities through use of a technique referred to as Play Fairway Analysis (PFA). The PFA technique assigns risk metrics that communicate the favorability of potential hydrocarbon bearing reservoirs in order to enable prudent allocation of exploration and development resources.

A U.S. Department of Energy funded project led by Cornell with collaborators at Southern Methodist University and West Virginia University used the PFA approach to evaluate the potential of utilizing geothermal energy in the Appalachian Basin. Even though all of the geothermal resources in the Appalachian Basin are low grade and not

economically feasible for electric power generation in current U.S. energy markets, the high population and high heating demand across New York, Pennsylvania, and West Virginia translate into economic and environmental advantages if geothermal direct-use heating replaces electricity-based heating and/or direct fossil fuel fired heating, which both have significant carbon footprints.

Four risk factors of concern for direct-use geothermal plays in the Appalachian Basinwere evaluated for portions of New York, Pennsylvania, and West Virginia. The risk factors were 1. thermal resource quality, 2. natural reservoir quality, 3. induced seismicity, and 4. utilization opportunities. This research project expanded upon and updates methodologies used in previous assessments of the potential for geothermal fields and utilization in the Appalachian Basin (Aguirre, et al. 2013, Reber, et al., 2014, and Stutz, et al., 2015). The project introduced novel approaches and metrics for quantification of geothermal reservoir productivity in sedimentary basins (see Jordan et al, 2015 for details). Based on these metrics, geothermal plays in the Appalachian Basin were identified as potentially viable for a variety of direct-use-heat applications. The methodologies developed in this project may be applied in other sedimentary basins as a foundation for low temperature (50-150°C), direct-use geothermal resource, risk, and uncertainty assessment. Through our identification of plays, this project revealed the potential for widespread assessment of low-temperature geothermal energy from sedimentary basins as an alternative to current heating sources that are unsustainable.

3. RESERVOIR TECHNOLOGY: DEVELOPING AND CHARACTERIZING EGS RESERVOIRS FOR ENERGY EXTRACTION, INCLUDING DRILLING, RESERVOIR DESIGN, STIMULATION, IMAGING AND HEAT PRODUCTION MODELING.

3.1 Hydrothermal Jet Drilling

Hydrothermal drilling is a non-contact drilling technology that has the potential to increase the rate of penetration and decrease drilling costs. The mechanism involves impingement of a heated fluid jet (>400ºC) onto the formation in the wellbore, where the high heat flux of the hydrothermal jet and the low thermal conductivity of the rock causes a steep temperature gradient and thermo-mechanical stress near the surface; the stress quickly leads to failure, a phenomenon known as thermal spallation. The momentum of the jet also provides mechanical and hydraulic enhancement to the drilling process, particularly to clear the spalls from drilling region exposing new rock surface to impinging jet. While open-air and hydrothermal flame jet drilling field trials and laboratory tests have demonstrated the attractiveness of the technology, further improvements may be possible. For instance, the process may be enhanced by joint application of chemically active solutions along with the hydrothermal jet to facilitate the dissolution of silica and weaken the structure of the rock. A fundamental study of chemical enhancement on Barre granite is being conducted in our laboratory at Cornell. The experiments will analyze a range of temperatures and pressures up to 550°C and 275 bar, as well as a variety of chemicals and concentrations. Rate of penetration and spall properties will be measured. In addition to this experimental work, a numerical modeling framework has been constructed to computationally represent the system. (Hillson, et al., 2014)

3.2 Thermal -Hydraulic Reservoir Modeling

Three aspects of EGS reservoir performance have recently been modeled by our group at Cornell: renewability of EGS resources, effects of variable fracture aperture, and effects of discrete fracture intersection within EGS reservoirs. To estimate how renewable EGS reservoirs might be, an analytical approach employing Green's function was used to model transient thermal conduction in an idealized reservoir containing a single rectangular fracture to evaluate heat transfer effects during alternating periods of extraction and recovery. Numerical simulations of a reservoir consisting of multiple parallel fractures using the TOUGH2 code agreed with the derived analytical solutions over a range of flow rates and interfracture spacings with only small deviation due to multidimensional effects. Thermal interactions between parallel fractures in crystalline rock spaced >50 m meters apart are negligible for production periods of 30 years, suggesting that the single fracture analytical model can be applied to multifracture reservoirs provided that the mass flow used is on a per fracture basis. Simulation results show that multifracture EGS reservoirs have a greater capacity to sustain high outlet temperatures, suggesting that conductively dominated EGS systems can be regarded as renewable over time scales of societal utilization systems (three to five times the heat extraction time) (Fox, et al. 2013).

In the second study, the effect of variable fracture aperture on the thermal hydraulic behavior of a discretely fractured model EGS reservoir was analyzed using a combined numerical and an analytical approach (Fox, et al. 2015). The third area of investigation (Fox et al, 2015) analytically and numerically examined how flow in a discretely

fracture network system with intersecting fractures influences thermal performance.

3.3 Chemically reactive tracers

An important subsurface characteristic of reservoirs used for groundwater remediation , oil and gas recovery, and geothermal energy production is the flow-wetted surface which describes the contact area between fluids flowing and the rock surface. For geothermal energy production, the flow-wetted surface area is of particular interest, because it strongly influences the thermal lifetime of the reservoir.

Based on heuristics verified by earlier computational modeling in our group [Fox et al., 2015] fracture aperture distribution has a strong influence on the available reservoir heat transfer surface area and will ultimately control thermal breakthrough. The goal of this study was to improve our understanding of the thermal hydraulic behavior of discretely fractured geothermal reservoirs. To achieve this objective, we conducted a geothermal analogue experiment in the field in which hot water was circulated through a well-characterized model geothermal reservoir initially at ambient temperature. As the reservoir is heated, a series of inert and thermally degrading tracer tests were conducted. In addition, predictions from computational models of tracer/thermal breakthrough are compared to experimental data to better understand how fracture volumes, mean apertures and aperture distributions influence thermal performance.

Independent confirmation of thermal drawdown requires production times of a year or more resulting in large economic implications in operating geothermal fields. To provide a more tractable approach we conducted experiments in a meso-scale (~100 m^2) model fractured reservoir in which rock temperature and flow paths could be verified through the use of additional sensors. The model reservoir, located at a field site in Altona, New York, has been the subject of numerous other studies in flow and heat transport in fractured bedrock systems.

The specific components of this study included: 1. selection of appropriate inert and thermally degrading tracers for field testing, 2. heating the reservoir by circulating hot water between an injection/production well pair, 3. conducting inert and thermally degrading tracer experiments during reservoir heating, 4. calibrating computational models to observed tracer response and comparing tracer estimated and observed heat exchange areas, and 5. comparing tracer-estimated temperatures and sweep efficiency to independently measured reservoir temperatures (using Fiber-Optic Distributed Temperature Sensing, FODTS) and flow (using Ground Penetrating Radar, GPR).

4. UTILIZATION: EVALUATING END USE OPTIONS AND PROJECTING COSTS FOR DISTRICT HEATING, ELECTRIC POWER AND CO-GENERATION.

4.1 Analysis of direct use potential

Given that a large portion of the United States' primary energy consumption goes into heating, cooling, and providing electricity to residential and commercial buildings, geothermal energy has significant potential to deliver and distribute both thermal and electrical energy on a community scale. Excluding a few exceptional cases in the U.S., the focus for development has been on producing electricity from high-grade hydrothermal systems located in various western U.S. states. By ignoring the potential to deliver thermal energy directly, a large portion of the U.S. geothermal resource is marginalized. In particular, lower grade, lower temperature hydrothermal and Enhanced Geothermal Systems (EGS) resources are more widespread and have sufficient temperatures (> 80ºC) that they are ideally suited for direct-use applications. By employing Geothermal District Heating (GDH) on a community scale, low grade hydrothermal and EGS in formations with poor permeability have the potential to supply a significant fraction of the thermal energy (temperatures < 125ºC) throughout the U.S., used for heating buildings, supplying hot water, and for lower temperature process heating. A key objective of our study is to characterize a number of important geothermal resource types ranging from conduction-dominated EGS to permeable sedimentary aquifers, as well as technical and economic factors that influence the levelized cost of delivering geothermal heat and/or electric power to a range of communities in the Eastern U.S. from lower grade resources (temperatures < 125ºC) (Reber, et al., 2014)

To demonstrate the level of deployment possible, we developed a regional model to evaluate the potential for GDH in the states of New York and Pennsylvania. The regional model incorporated several sub-components that were developed by the Cornell group. These included the GEOPHIRES software platform for estimating the levelized costs of electricity (LCOE) and heating (LCOH) from EGS (Beckers, et al., 2013 and 2014) and updated drilling costs (Lukawski, et al., 2014)

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A GDH network was simulated at each population center within the study region and the LCOH was estimated from GDH for each community. LCOHs were then compiled into a supply curve from which several conclusions were drawn (Reber, et al., 2014).

Our evaluation revealed that geothermal resources have the potential to supply cost-effective energy for space and water heating in several New York and Pennsylvania communities in the near future. To realize wider deployment in New York, anticipated increases in conventional fuel prices, and/or more aggressive renewable energy policies and incentives along with modest improvements in EGS technology are needed to enable GDH to compete with other heating alternatives. In addition, creative implementation strategies would also help overcome the cost barriers that exist today for geothermal by focusing initially on developing the infrastructure needed for district heating and combined heat and power systems at a community scale. These district energy systems could be designed to initially utilize conventional fuels and waste biomass feedstocks and later transition to using geothermal energy as their primary energy source. Later efforts in our group refined the use of the model and applied it to a larger region of the U.S. (Tester et al., 2015)

Another utilization example is the recovery of mineral co-products from geothermal brines. In current research at Cornell (Palsdottir, 2016) in collaboration with HS Orka and the Icelandic Geothermal Resource Park, we are investigating the potential of recovering lithium from geothermal brines using selective extraction using engineered compounds that are soluble in supercritical CO_2. The project involves designing and laboratory testing of specific crown ether compounds to establish their selectivity for lithium and evaluating their practicality for use in the field at a geothermal power plant on the Reykjanes Peninsula.

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