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The EGS Collab Project: Mesoscale Rock Stimulations

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1. Introduction

The EGS Collab Project, sponsored by U.S. Department of Energy Geothermal Technologies Office, aims to increase the understanding needed to efficiently implement enhanced geothermal systems (EGS). EGS offer tremendous potential as an energy resource supporting the energy security of the United States with estimates exceeding 500 GWe for the western US surpassing the resource base hosted by conventional hydrothermal systems, to an order of magnitude more for the entire United States [1, 2]. To overcome one of the technical challenges for EGS – understanding reservoir creation – we are examining stimulation of crystalline rock, and created an underground test bed at the Sanford Underground Research Facility (SURF) in Lead, SD at a depth of approximately 1.5 km to examine hydraulic fracturing (Experiment 1) at the ~10-meter scale. We have collected high quality data during our stimulation and flow tests to allow comparison to numerical coupled process models in an effort to build confidence in the codes and modeling techniques used. We are currently building a second test bed at the 1.25 km depth aimed at investigating shear stimulation (Experiment 2). Here, we provide an overview of Experiment 1 and plans for Experiment 2.

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2. EGS Collab Experiment 1

Experiment 1 was performed on the 4850 (feet deep, ~1.5 km) level at SURF. SURF, located in the former Homestake gold mine, is operated by the South Dakota Science and Technology Authority and hosts a number of world-class physics experiments related to neutrinos and dark matter, as well as to geoscience research [3]. SURF has been reasonably well characterized , and provides infrastructure (e.g., ventilation, power, water and internet) and excellent staff dedicated to scientific research support, in addition to cost-effective proximal monitoring of a deep crystalline rock mass before, during, and after stimulation through multiple boreholes drilled from an underground tunnel.

Experiment 1 was intended to use hydraulic fracturing to establish a fracture network to connect an injection well and a production well. Six monitoring wells containing instrumentation surrounded the experiment. In total, we cored eight ~60 meter long subhorizontal boreholes. The injection and production boreholes were drilled in approximately the minimum principal stress direction based on prior characterizations in adjacent rock [5] so that hydraulic fractures would tend to propagate orthogonally to the injection well. Numerous techniques were used to characterize the testbed [6, 7]. Boreholes were characterized using optical and acoustic televiewers, full waveform sonic, electrical resistivity, natural gamma, and temperature/conductivity logs. The test block was further characterized using seismic tomography (compressional- and shear-) using grouted and mobile sources and sensors, electrical resistance tomography (ERT) for baseline and during flow, and extended hydrologic characterization including tracer tests. The detailed site characterization together with the array of installed monitoring systems and inversion methods help to constrain the coupled process models. During stimulation and flow, monitoring included 1) passive seismic; 2) continuous active source seismic monitoring (CASSM); 3) ERT in conjunction with dynamic electrical imaging using high contrast fluids; 4) acoustic emissions; 5) distributed fiber optic sensors to monitor seismicity (DAS), temperature (DTS), and strain (DSS) changes. During flow and stimulation tests fracture aperture strain monitoring was performed using the Step-rate Injection Method for Fracture In-situ Properties (SIMFIP) tool, continuous monitoring of pressure and flow conditions in the injection and production boreholes, tracer tests, and wavefield imaging and inversion. Laboratory measurements on selected core samples from the site provided fundamental physical rock properties needed to constrain the coupled process models, and provide specific information on rock behavior [8-11].

With the exception of very large data sets, all data collected and analyzed are stored on a data storage collaboration space (EGS Collab on OpenEI's Data Foundry) and made available to the public through DOE's Geothermal Data Repository (https://gdr.openei.org/egs_collab). An index of project presentations and publications is available at https://scholar.google.com/citations?hl=en&user=h-rd4hkAAAAJ.

Experiment 1 was entirely within the Poorman Formation, a metasedimentary rock consisting of sericite-carbonate-quartz phyllite (the dominant rock type), biotite-quartz-carbonate phyllite, and graphitic quartz-sericite phyllite [12]. Carbonate minerals consist of calcite, dolomite, and ankerite. The rock is highly deformed and contains carbonate, quartz veins/boudinage, pyrrhotite, minor pyrite, graphite, and chlorite. Optical and acoustic televiewer logs identified natural fractures crossing the boreholes and these were correlated with fractures mapped in the core samples and drift walls when possible. The adjacent kISMET boreholes, previously used for stress measurement, were utilized to measure temperature gradients away from the drift walls. To the extent possible, all characterization data are integrated into the geologic framework model of the Experiment 1 site [13]. Few fractures were encountered in the 300 m of core collected from the adjacent near-vertical wells at the kISMET site, so few fractures were expected in Experiment 1. We encountered many fractures however, and cores, core images, and borehole logging have been used to begin to understand the natural fractures in our test bed. Core segments from the test bed were sent to the National Energy Technology Laboratory

(NETL) for X-ray computed tomography and measurements of magnetic susceptibility, gamma density, compressional (P-) wave velocity, Ca/Si, Ca/Al, Si/Al, and Fe/S ratios, and the abundance of light elements, Ca, and Si. In addition, cores have been sent out to researchers at a number of institutions to examine rock properties and behavior, and native biota.

Stimulations and Flow Tests

Summaries of stimulations, long and short-term flow tests, and tracer tests have been presented [6, 7, 14-16]. Notches were scribed at locations along the injection well to encourage perpendicular fracturing. The stimulations were planned to occur in 3 steps. The initial stimulation was designed such that it might create a 1.5 m radius penny-shaped fracture prior to being shut in for the night. The second step would extend the fracture to 5 m radius followed by being shut in for the night, and the third step would extend the fracture to the production borehole approximately 10 m away. Four stimulation tests and short- and long-term ambient temperature and chilled water flow tests have been performed, resulting in many rich data sets and many thorough analyses (see references in [6]).

First Stimulation

The first stimulation was performed at the 142’ Notch (142 feet from the collar of the injection well). The packer interval (approximately 65 inches including the SIMFIP tool) encompassed a large apparently healed natural fracture. Pressurizing at the 142’ Notch led to unexpected results including water flow returning past the packer up the borehole and a higher-than-expected fracture initiation pressure. Our analysis indicates that a hydraulic fracture was created, probably intersecting the observed natural fracture. A total of twelve liters of water were injected in this test. As shear stimulation was not intended in this test and the results indicated that we might be pumping into the natural fracture; therefore, the stimulation packer set was moved downhole to the 164’ Notch.

Second Stimulation

The stimulation at the 164’ Notch was carried out in steps over three days with shut-in periods between each step. The three steps resulted in water being produced at the production well at approximately the expected location. In addition to intersecting the production well, this stimulation intersected a monitoring well (located between the injection and production boreholes). This finding was indicated by seismic sensors, a temperature increase measured by the DTS in the monitoring well, and eventually water leaking out from the top of the grouted well.

Third Stimulation

The third stimulation was conducted at the 128’ Notch, attempting to avoid a fracture that connects a monitoring well and the production well, while still connecting the injection and production wells. In this test, flow bypassed the top injection packer through fractures, and resulted in a hydraulic fracture connecting to a monitoring well, but not the production well.

Fourth Stimulation

After a medium-term set of hydraulic characterization tests was conducted at the 164’ Notch, a second stimulation experiment was completed at the 142’ Notch by carefully placing the packer over regions of concern to avoid flow entering the fracture. We used high flow rates and pressures, and extended at least one hydraulic fracture to additional monitoring wells and the production well. Microseismic event locations at stimulations at both the 164 ft and 142 ft notches consistently indicate that the fracture extended toward the drift, as was predicted by earlier modeling of fracture growth under the stress gradient created by thermal cooling of the rock by the drift.

Flow tests

Long-term ambient temperature and chilled water flow tests were performed for about 10 months. In these tests, water was introduced at the 164' Notch interval, typically at 0.4 L/m. This rate, although lower than desired, did not result in additional microseismicity, indicating that the stimulated system was stable. During the first part of the flow test (~ 1 month), ambient temperature "mine" water was injected into the system. Following that, chilled mine water injection was initiated. Volumetric recovery of the injected water increased over the duration of the test reaching near full recovery from combined collection points, not all in the production well. In spite of reaching high volumetric recovery, tracer and microbial analyses indicate that the recovered water has differences from the injected water, indicating perhaps that the injected water is displacing and mixing with native water in the system, or the water is altered in different manners along different flow paths.

Pump and chiller failures occurred over the course of 10 months, providing additional experiment stimuli and responses. With the exception of changing injection fluid temperature, the injection pressure (in excess of the minimum principal stress) always increased over time. When a failure occurred, even a very short failure (on the order of a minute) and pumping restarted, the new injection pressure was always significantly lower than the previous injection pressure even though the rate was the same. This finding may be explained by chemical, biological, poroelastic effects, or a combination of them. When going from ambient temperature injection to chilled temperature injection, the injection pressure initially declined for a time prior to increasing, providing another example of thermoelastic system behavior.

3. Numerical Modeling in Support of Experimental Designs and Understanding of Experimental Observations

Numerical modeling plays two vital roles for the EGS Collab project; providing guidance to the design of the experiments, and understanding of experimental observations. In each of these roles multiple simulation teams, computer codes, and modeling approaches were applied to specific problems, and simulation results were openly shared and discussed in weekly teleconferences yielding collaborative modeling outcomes. SURF offers scientists and engineers a unique opportunity in the EGS field of research to work at meso-scale, under near in-situ stresses, with proximity to the testbed rock, and slightly elevated temperatures. The counter to these positives is that the testbed is bounded by the mine drift, thus limiting the possible extent of the fracture network, but more subtly influencing the temperature profile and stress state within the testbed. During the design stages of Experiment 1, numerical modeling was used to forecast seismic magnitudes during stimulation, forecast the hydraulic fracture propagation trajectory under a thermally altered stress state, forecast whether the circulation experiments could be completed without extending the fracture network, estimate the temperature profile surrounding the drift, and determine whether the production borehole could serve to halt the extension of a hydraulic fracture, initiated at the injection borehole. Secondary design considerations addressed via numerical modeling were whether notching the injection borehole would avoid the formation of axial fracturing during fracture initiation, and what time period would be required to observe a temperature drop in the production borehole with the injection of chilled water in the injection borehole. The Experiment 1 testbed was anticipated to be homogeneous with respect to rock properties and relatively void of natural fractures, and the monitoring boreholes, which were grout filled, were anticipated to be passive observation features. In reality the testbed contained secondary folded bedding planes that yielded heterogeneity in rock properties, dividing the upper and lower portions, a number of hydraulically active natural fractures with near-vertical dip, and the hydraulic fracture intersected the monitoring boreholes, making them conduits for fluid flow. Numerical modeling helped to resolve questions concerning these unanticipated features of the testbed, but also to provide understanding of experimental observations, such as increases in temperature measurements where hydraulic fractures had intersected the monitoring boreholes, and the seemly discontinuity between relatively rapid breakthrough times for tracers and slow thermal breakthrough times. There remain three experimental observations that represent continued numerical modeling challenges: 1) increase in flow resistance with the injection of un-chilled water, 2) generally increasing flow resistance over the course of the long-term chilled-water injection test, and 3) sharp decreases in flow resistance with halts in chilled-water injection.

4. EGS Collab Experiment 2

The EGS Collab project is currently designing Experiment 2 to examine hydroshearing at a depth of about 1.25 km at SURF. We intend to surround our injection well with 4 production/ monitoring wells, in addition to two additional pairs of monitoring wells surrounding the test bed. The rock target here is an amphibolite, having a number of mostly healed fracture sets. Drilling is expected to start in late 2020.

5. Concluding remarks

The observations in Experiment 1 identified several important coupled effects, some of which are still under analysis. These include the following:

- Coupled Thermo-Mechanical: The injectivity of the injection well is highly sensitive to changes in injection water temperature. These effects are rapid (within minutes) and are thought to mainly affect the local transmissivity of the stimulated fracture near the injection well.
- Coupled Hydro-Mechanical: The long term (10-month) injections show a steady rise of almost 20% in the injection pressure, which is currently attributed to poroelastic effects but is still undergoing analysis.
- Coupled Hydro-Thermal: A major goal of the experiments is understanding the effective area of heat transfer in an EGS system. This is a major concern for EGS development. The lack of a thermal breakthough during cold-water injections into warmer rock over the ten-months of injection is consistent with a significant portion of the fracture is available for heat transfer, and there is not evidence of extreme short circuiting. Chemical tracers, however, show rapid breakthrough.

The EGS Collab project has performed a number of stimulations and flow tests in a well-characterized test bed. These tests have generated large amounts of high-quality data that are for the most part available to all. A number of interesting phenomena were observed and quantified, and geophysical techniques were able to validate each other. Many modeling studies have used the data both for understanding processes, but also in improving modeling approaches for fracturing and flow in fractures (see references in [6]). Construction of Experiment 2 is underway, and we expect to have an operational system and test bed in 2021. As with Experiment 1, we intend to disseminate data as quickly as possible for use by all.

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