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Development of Multi-Stage Fracturing System and Wellbore Tractor to Enable Zonal Isolation During Stimulation and Enhanced Geothermal System Operations in Horizontal Wellbores - First Year Progress

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Abstract

This paper describes first year's progress on the three-year DOE funded project for the development of tools for the construction of a subsurface heat exchanger for Enhanced Geothermal Systems (EGS) at the Utah-FORGE site using unique casing sleeves that are cemented in place in horizontal wells. The sleeves function both as a system for rapid and inexpensive multi-stage stimulations and then are used to perform conformance control functions at 225 °C. A tractor uses modular capabilities to allow various tools and sensor packages to be attached with standard connections for flow conformance control of the system.

The original hydraulic tractor concept using coiled tubing was replaced with an electric wireline design to improve operating costs by not requiring coiled tubing. A flask design for critical electronic components was identified as a solution to the 225 °C wellbore conditions, eliminating the need for circulation of water for cooling the electronics. This high temperature tractor was developed using an electric wireline design with a fluid survey capability to detect fluid injection and production and allow closing or opening of the sleeve for fluid movement. Modeling was performed for determining temperature impacts on the tools, the effectiveness of well stimulation (pressure transient analysis, tracer flowback and inter-well analysis, heat gathering and transport to the surface.

The 7-inch frac sleeves were tested using single-sized 5-¾-inch frac balls to simulate conditions of cemented sleeves run on 7-inch, 38 ppf casing to actuate for fracture stimulation at ambient and 225 °C geothermal conditions. The sleeve components were first tested in hydraulic test fixtures followed by surface flow loops and are being prepared for a test deployment in an extended reach geothermal test well at Utah FORGE. The high temperature. electric wireline wellbore tractor's specific mission critical components were tested to 225 °C for a 12-hour duty cycle, using flask heat protection for critical electrical components. Test results indicate that a simple cemented valve can be used for both multi-stage hydraulic fracturing and conformance control. The use of this valve with the electric wireline tractor will allow an economic subsurface heat exchanger to be constructed.

Two critical EGS well stimulation and operation technology gaps are addressed by these tools. First, development of multi-stage stimulation technology tools which do not have temperature limitations of the conventional "Plug and Perf" stimulation equipment. These tools are designed to be cemented in place. Second, EGS conformance control methods are demonstrated using a wireline tractor operable to 225 °C to detect fluid flow and close the same multi-stage stimulation sleeve. These tools allow an EGS system to be constructed to provide geothermal electric power.

Introduction

Enhanced Geothermal Systems (EGS) inject water into wells where water travels through the reservoir and harvests heat from the hot rock; then, the resulting hot water is produced to the surface. Unlike a hydrothermal system, where hot water and/or steam is produced from an existing reservoir, EGS targets areas of hot rock without sufficient reservoir rock to create a permeable reservoir. EGS systems create a reservoir and then inject fluid into this enhanced reservoir system to harvest heat. Horizontal wells offer the opportunity to create large, enhanced reservoir systems with large amounts of heat that can be harvested (Gringarten 1975). This paper updates the progress on a new innovative EGS system (Fleckenstein 2021), called GeoThermOPTIMAL (Figure 1). Multi-stage stimulation techniques in horizontal wells have been applied successfully to reduce costs in unconventional oil and gas wells and are now starting to be applied to geothermal wells, due to temperature and casing size limitations, which this paper addresses.

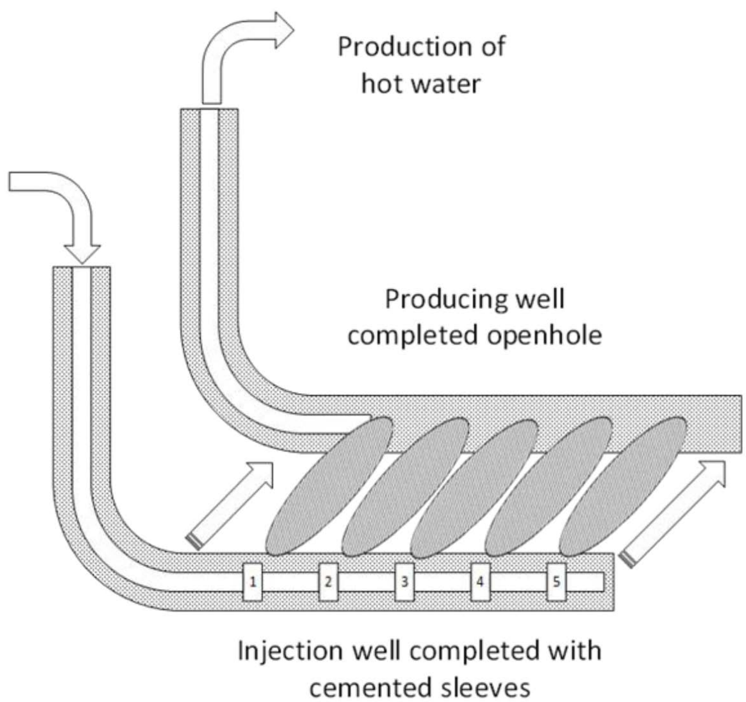


Figure 1—GeoThermOPTIMAL (Fleckenstein et al. 2021)

FORGE Wells Updates

Hydraulic fracturing of the first three stages was successfully completed in the deep deviated well 16A(78)-32. As discussed below, the modeling of this series of hydraulic fracturing stimulations allowed the characterization of the induced fractures and a more complete understanding of the formation. The well path that was drilled was analyzed to determine the wellbore tortuosity and make the necessary modifications to the proposed frac sleeve and tractor to navigate the doglegs that may be as great as 15 degrees/100' in the lateral section. A second well will serve as the production well of a two well doublet, and will mirror the existing injection well, which was drilled between October 2020 and February 2021. The new well is located on a rough parallel well path approximately 300 feet from the injection well.

Like the injection well, the upper part of the production well was drilled vertically through approximately 4,550 feet of sedimentary rock until it penetrated hard crystalline granite. At about 5,600 feet, the well was planned to be kicked off to build angle at a designed build gradient of 5-degrees for each 100 feet drilled until it reaches an inclination of 65 degrees from vertical. The total length, or measured depth of the well will be approximately 10,700 feet with the "toe" – or the end of the well – reaching a vertical depth of 8,265 feet. The temperature at this depth will be 225°C. This well was planned to be drilled with a rotary steerable assembly, an important test in a geothermal application to provide a smoother well path with acceptable penetration rates.

Enhanced Geothermal Systems (EGS) Recent Developments

Research and Development efforts have continued with multiple projects funded by the DOE as part of the Utah-FORGE project. Funding has been provided by the DOE EERE Geothermal Technologies Office to Utah FORGE and the University of Utah for Enhanced Geothermal System Concept Testing and Development at the Milford City, Utah Frontier Observatory for Research in Geothermal Energy (Utah FORGE) site. Summaries of these projects are located at Utah FORGE | Open Energy Information (openei.org). Notable results to date include improvements in well construction during drilling at the Utah FORGE site indicate that costs are dropping rapidly for drilling in granitoid rock, as the drilling rates have improved with the use of PDC bits optimized over the 3-well program. Instantaneous ROP increases of 400% have been observed and the record footage per bit improved 200% (Dupriestmic 2022).

Another FORGE project is enabling Fervo Energy to develop a commercial nearfield EGS project adjacent to the Blue Mountain geothermal field, in northern Nevada. The goal of the project is to provide production uplift to the Blue Mountain power facility, with a three-well drilling project, which included a Vertical Monitoring Well 73-22, a Horizontal Injection Well 34A-22, and a Horizontal Production Well 34-22, that were drilled and completed successfully in 2022 (Fercho 2023). Drilling results from Vertical Monitoring Well 73-22, targeted a location approximately at the midpoint of the laterals, confirmed the predicted temperatures. The temperature profiles of the horizontal wells were measured by both wireline logging and fiber optic sensing equipment. After the stimulation of the injection Well 34A-22, the production Well 34-22 was drilled through the stimulated reservoir volume. A variety of measurements in the production well suggest the presence of tensile fractures created during the injection well stimulation treatment, as well as the detection of proppant in the production well. Heat-in-place calculations were used to estimate the stimulated reservoir volume created from the stimulation treatment in injection well 34A-22. It is calculated that the volume is large enough to produce approximately 5 MW of electric power over a 10-year project life, consistent with the target for the dual horizontal well system.

Sage Geosystems (Wright 2023) has been testing a new hybrid EGS technology with a project at a former Shell oil well in Starr County, Texas. The project will test the company's HeatRoot technology. The project calls for drilling four laterals around 350 ft apart, then fracturing those from the top down to create connectivity that will act as a sort of chimney for heat for the deeper formations. Sage is measuring temperature, pressure, and flow rate of fluid in the well to simulate how electricity could be generated through the combined laterals vs. a single wellbore.

Multi-Stage Fracturing – Recent Developments

The initial concept of multi-stage hydraulic fracturing in the oil and gas industry is commonly associated with the DOE's Devonian shale program in the late 1980's (Yost et al. 1988). Application of multi-stage fracturing grew exponentially with the development of shale plays in the early 2000's to arrive at what is now commonly applied in current shale developments (Miskimins 2019). However, even with the lengthy history associated with this completion technique, advances continue in a variety of multi-stage treatment areas, especially in horizontal well applications. Some of these advancements are applicable in EGS systems, while others struggle in the high temperature environment.

Diagnostics, such as fiber optics and acoustic measurements, continue to shed light on hydraulic fracture growth highlighting both positive and negative consequences. Perforation cluster spacing in plug and perf (PNP) completions has continued to decrease to allow more fracture initiation points, and with this trend has come the use of extreme limited entry or XLE (Weddle et al. 2018). However, fiber has shown the potential for longitudinal fracture failures and significant tortuosity in cemented horizontal completions leading to issues initiating treatments, severe near wellbore tortuosity and communication between stages (Ferguson et al. 2018; Ugueto et al. 2019). The use of low frequency distributed acoustic sensing (LF-DAS) fiber systems has also been extremely beneficial in determining fracture growth and impending interception (i.e. "frac hits") between horizontal wellbores (Zhu and Jin 2021; Ugueto et al. 2022). These uses of fiber show potential for similar EGS applications in determining the locations and activation behaviors of fractures both as they initiate and as they interact between EGS well pairs.

Additionally, the variability of fracture initiation in PNP as compared to the cemented sleeve systems, such as the one that is the subject of this paper, could be determined with these diagnostic techniques. The first three stages treated in FORGE well 16A(78)-32 exhibited breakdown pressures that were significantly lower than expected. While encouraging from a treatment standpoint, this leads to questions as to why this behavior was observed and what impacts such might infer about transverse versus longitudinal fracture growth and near wellbore tortuous behavior (Barree and Miskimins 2015; Michael and Gupta 2021). Recent improvements in diagnosing PNP behaviors can be transitioned to also understanding similar or divergent behaviors in cemented sleeve systems, especially in deviated wells such as those being utilized in the FORGE project.

Multi-stage fracturing micro-seismic images as well as rate transient analysis (RTA) have revealed long relatively planar induced frac system with "frac hits" are common occurrences in offset laterals. (Morad and Angus 2019). The frac hits studied in multi-stage fracturing will be critical to the success of EGS due to the importance of and need for conductive connections between injection and production wells in a functioning EGS system. Devon Energy has developed a monitoring technology (Sealed Wellbore Pressure Monitoring, SWPM) to use the frac hits to identify fracture arrivals at offset wells, providing positive measurement of the frac length and connection between the two wellbores, a technique that has been used on at least 1,500 stages (Haustveit et al. 2020). SWPM usage has allowed the detection of frac hits and provides a data point to construct the morphology of the induced fracture.

Given the potential for cyclic and longer-term injection treatments in EGS wells, knowledge gained regarding injection point erosion in multi-stage horizontal wells could potentially shed light in EGS behaviors. The XLE perforating schemes noted above have led to renewed focus on perforation erosion, both from a diameter and discharge coefficient standpoint (Roberts et al. 2022). This work has led to the determination that the discharge coefficient changes in horizontal well orientations and with different exit geometries, such as cemented sleeve systems. Although the injection rates and pressures of EGS will likely be significantly less than those used in hydraulic fracturing treatments in oil and natural gas, the potential of erosion with multiple injections is present, and the knowledge being gained in this area will likely be useful in future applications of EGS.

GeoThermOPTIMAL EGS System Overview and Update

GeoThermOPTIMAL EGS System has been previously described (Fleckenstein 2021). This project uses "next generation" multi-purpose sleeves, called FracOPTIMAL sleeves, that are run with the casing into a horizontal or deviated wellbore and cemented in place, though the casing sleeves can be used with packers. Single sized, dissolvable balls that are near the casing drift diameter are used for zonal isolation between stages during multi-stage stimulation operations. The cement encapsulates the casing and the sleeves for annular isolation between frac stages, allowing thermal axial stresses associated with geothermal wells to be resisted by the cement sheath. During subsequent stages during the multistage stimulation, fluid could flow to the surface through the producing well. The flow from the injector to the producer could continue through the induced fracture, even after the fracture stage is complete, draining the stimulation fluid, and pressure that would be trapped in the previous stage(s), reducing the horizontal stress in the rock.

A tractor using modular capabilities to allow various tools and sensor packages to be attached with standard connections for flow conformance control of the system is being built and tested. The original hydraulic tractor concept using coiled tubing was replaced with an electric wireline tractor design to improve operating costs by not requiring coiled tubing. To address the challenging wellbore conditions reaching 225°C, a flask design was devised to protect the critical electronic components. This design eliminates the requirement for water circulation to cool the electronics, providing a practical solution. The high-temperature tractor was developed based on an electric wireline design that incorporates a fluid survey capability. This capability enables the detection of fluid injection and production, allowing for the precise opening or closing of the sleeve to achieve conformance control. It is contemplated that future tractor tools are expected to incorporate a feature that enables the installation of a choking capability in the sleeve to control fluid flow through the sleeve, regardless of the conductivity of the fracture. Modeling is being performed for understanding temperature impacts on the tools, the effectiveness of well stimulation and the effectiveness of the system as a whole.

The testing phase for 7-inch frac sleeves involves the utilization of 5-¾ inch frac balls of a single size. This approach aims to replicate the conditions experienced by cemented sleeves that are employed in 7-inch, 38 lb/ft casings. The purpose is to activate fracture stimulation under both ambient and geothermal conditions reaching 225°C. Initially, the sleeve components are subjected to testing in dedicated fixtures, followed by evaluations in surface flow loops. Subsequently, preparations are underway to deploy these sleeves in an extended reach geothermal test well at Utah FORGE. To ensure the suitability of the electric wireline high temperature wellbore tractor's mission-critical components, they have been tested up to a temperature of 225°C, employing flask heat protection for crucial electrical elements. The results from these tests indicate that a basic cemented valve can be employed for both multi-stage hydraulic fracturing and conformance control. By utilizing this valve in conjunction with the electric wireline tractor, it becomes feasible to economically construct a subsurface heat exchanger.

These tools effectively tackle two crucial technology gaps in enhanced geothermal systems (EGS) well stimulation and operation. Firstly, they overcome the temperature limitations associated with conventional "Plug and Perf" stimulation equipment by introducing multi-stage stimulation technology tools that are not bound by such constraints. Secondly, these tools are specifically designed to be cemented in place, offering improved reliability and stability. In addition, the tools demonstrate EGS conformance control methods by utilizing a wireline tractor that can operate up to 225°C. This wireline tractor enables the detection of fluid flow and subsequent closure of the multi-stage stimulation sleeve. By leveraging these advanced tools, it becomes possible to construct an EGS system capable of generating geothermal electric power.

After the multi-stage fracturing treatments are completed, the well would be ready for immediate injection operations. Sleeves can be closed to prevent short-circuiting of injection fluids through highly conductive fractures and improve the EGS thermal decline by providing the EGS operator the means to diagnose thermal injectivity into specific reservoir areas and divert injection fluid into areas of the reservoir that has remaining heat resources available. The optimization of the distribution of the injection fluid will improve the economics since the cost of the use of frac sleeves is similar to "Plug and Perf" systems, and the capital costs of the system such as well drilling, surface lines, power plant etc. are identical for both systems but with significant economic benefits of lower thermal declines and power generation compared to "Plug and Perf" systems.

Cemented Frac Sleeve Development and Testing – Update

Successful laboratory frac sleeve development testing was divided into major segments, seal drag testing and collet loading – each requiring focus and individual data collection prior to integration into the main assembly. The Collett Load Test Fixture and Seal Drag Test Fixture are shown below. Each set of data results is compiled from testing at multiple pressures and temperatures. The third segment of testing defines a System Integration Test (SIT) where the tractor (discussed hereinafter) shall motor in a test bed simulating an extended reach or horizontal well having three sleeves and will demonstrate the ability to successfully traverse sleeves in the test well as well as locate, engage, open and close the sleeves at a variety of pressures and temperatures.

When the laboratory testing is successfully completed at the Tejas Research & Engineering facility located in The Woodlands, TX, the project moves to field trial phase at the FORGE facility in Utah.

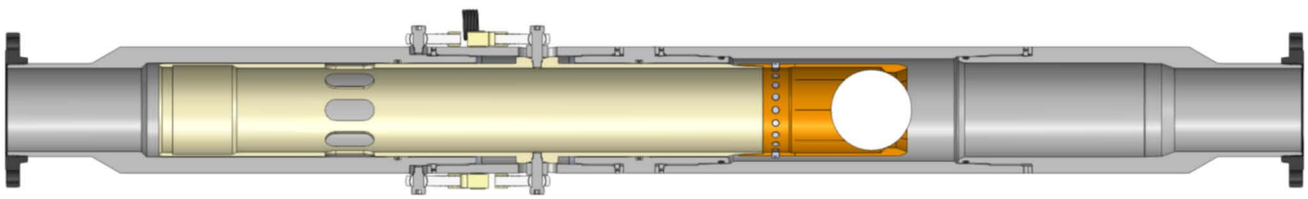


Figure 2—Collett Load Test Fixture

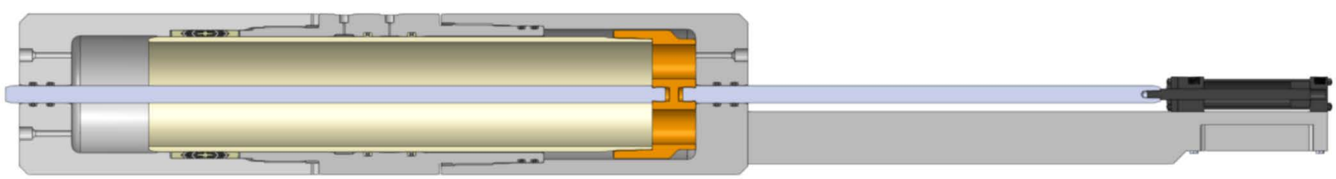


Figure 3—Seal Drag Test Fixture

The foregoing full scale prototype fixtures have been built and the qualifying criteria have been identified. The following are design parameters for the well completion and the sleeves being developed:

Design Specifications:

- Open Hole Diameter: 9.500″
- Casing size; 7″
- BHT 225 °C (437 °F)
- OD – 8.750″
- Minimum ID – 5.940″
- Radial Clearance = 0.375″
- Standard Frac Sleeve = 0.375″
- ID – 5.950″ +.010/-.000 (End Housings, 0.030″ Over ID)
- ID – 6.080″ +.010/-.000 (Internal Sleeves)
- ID Flow Area – 27.802 square inches. Downloaded from
- Ported Flow Area – 38.18 in2 (1.37X Factor)

- OAL – 146″ (just over 12')
- Adapted to receive a 5.75" Frac Ball

Flow Rate sleeve opening/closing logic review:

- High Flow Rate – Ball Trips Thru (Inner Sleeve cannot respond quickly, fluid metered response)
- Low Flow Rate – Metering system releases the Inner Sleeve for shifting (similar to a hydraulic jar – loses its fluid resistance at a particular stroke)
- Side door re-closeable with a tractor, in an Upper Inner Sleeve Profile
- Transitable by tractor – easy to roll through
- Inside diameter of the sleeve is larger than the drift ID of the casing
- Rapid, Hi-Flow Rate Ball passed through the Lower Tripping Collet – Damping in Play
- A slower Flow Rate Ball allows the Hydraulic Damping System and Power Spring to "Deactivate" allowing the Inner Sleeve to fully OPEN for stimulation operations
- The upper Shifting Profile is used to Pull the Sleeve CLOSED. Once almost closed, the Power Spring re-activates helping assist with closing the Sleeve
- Low Cement fouling areas – Simple, proven functionality

High Temperature Tractor Development and Testing – Update

A tractor is being built and tested with modular capabilities that will allow various tools and sensor packages to be attached using known HPHT standard connections for flow conformance control of the system. In order to enhance operating costs by eliminating the need for coiled tubing, the original hydraulic tractor concept has been substituted with an electric wireline tractor design. This transition offers improved cost efficiency. Moreover, the modularity of this system enables easy adaptation to coiled tubing if the need or specific application arises in the future. To address the challenges posed by wellbore conditions reaching 225°C, a flask design has been implemented for critical electronic components. This innovative flask design serves as a solution by eliminating the requirement for water circulation to cool the electronics. It ensures the proper functioning of the electronic components even in high-temperature environments. This high temperature tractor was developed using an electric wireline design with a fluid survey capability utilizing high resolution temperature and pressure measurements to detect fluid injection and production. The electromechanical section of the tractor will allow for the closing or opening of the sleeve for conformance control. It is contemplated that future tractor tools would include the capability to install a choking capability in the sleeve to control fluid flow through the sleeve, regardless of the conductivity of the fracture. Modeling is being performed for understanding the tractor system options to understand the temperature impacts on the tools, the effectiveness of well stimulation and the overall evaluation of the ESG operation in real time.

The tractor system includes an up hole to downhole assembly that consist of the KSWC monocable cable head, a swivel joint, a CCL sub, a high-resolution temperature and pressure module, the electronics flask module, a pressure balance section for oil compensation, two to three tractor drive modules, a hydraulic pump module for tractor wheel actuation, sleeve latch, close actuation and the sleeve actuation module. The system also has roller centralizers in three to four locations on the assembly. The KSWC cable head has been tested to 500 °F operation and at a load of 5 amps and 1500 volts. In the current testing the temperature rise of the cable head was in the range of 30 to 40 degrees F. The swivel primary component rotary connector has been tested and qualified to 500 °F. The CCL is rated to and has been tested to 500 °F. Both the pressure and temperature sensor have been tested and qualified to 450 °F. All PC boards used are rated and certified to 350 °F operation. The flask assembly has been rated and qualified, with an expected duty cycle for 3 sleeve actuation using full power of four motor operation, to a time of internal flask temperature build to allow operation for a 12 hour round trip in the hole. All motors, solenoids, and pumps are rated and certified to 450 °F operation. All connectors utilized in this system have been load tested and qualified to 500 °F. The tractor assembly is shown in Figure 4.

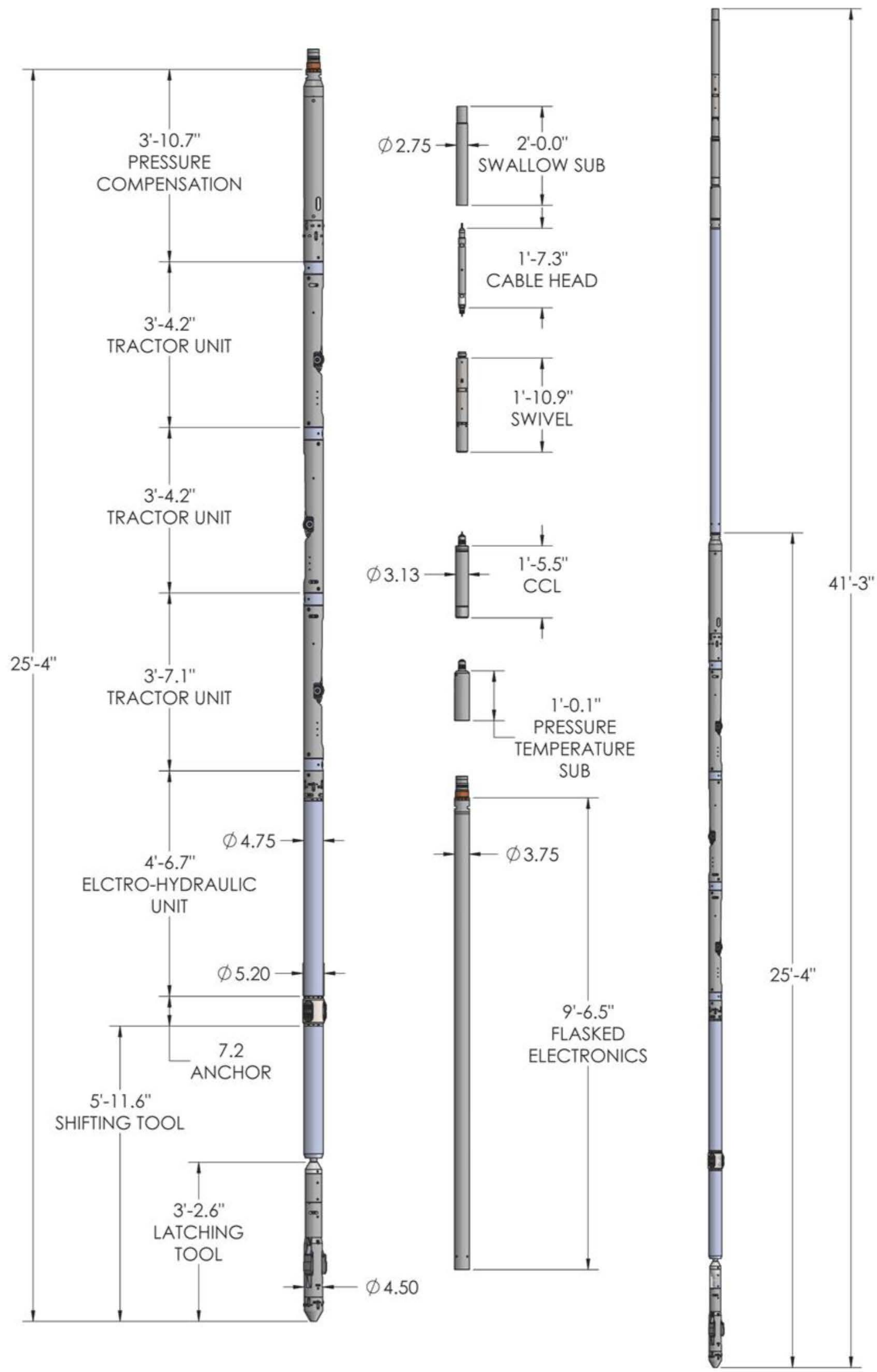


Figure 4—Tractor assembly tool drawing

Specification defined:

1. Casing diameter: 7 inch
2. Casing weight: 38 pound
3. Casing inner diameter: 5.920 inch
4. Sleeve minimum diameter: 5.375 inch
5. Tractor Tool String specifications:
    a. Surface operating Voltage 400-600Vdc
    b. Downhole operating Voltage: 300 Vdc
    c. Max Current: 6 Amps
    d. Tool outside diameter max: 5.20 inch (Anchor)
    e. Max tractoring speed: 30 feet per minute
    f. Tool string length: 41 feet
        i. Final length will be determined after qualification testing
    g. Max temperature: 450° F (232° C)
    h. Max pressure: 15,000 psi
    i. Max actuator pull force: 15 kip
        i. Final pull force will be determined in qualification testing
    j. Max linear actuator displacement: 19 inches
    k. Max anchoring casing ID: 6.184 inches
    l. Deployment method: Conventional wireline
        i. Minimum max working tension: 5500lb
        ii. Min conductor AWG rating 15
        iii. Max line & armor resistance at operating depth: 150Ω
    m. Communication protocol
        i. Surface to Downhole Telemetry: RS232 half duplex transmission
        ii. Downhole Electronics: UART & CAN 2.0

Modeling

Background

Utah FORGE is a dedicated underground field laboratory sponsored by the U.S. Department of Energy (DOE) for developing, testing, and accelerating breakthroughs technologies to extract thermal energy from hot dry rocks for generating electricity. In this spirit, in the last eighteen months, a team of graduate students in the PE Department at Colorado School of Mines have conducted research on deciphering the formation characteristics of the Utah FORGE using the enormous, highly credible, field measured data from the project that are available to the public. The following is a summary of this research in the time period: (1) experimental measurement of permeability and porosity on 1-1/2 by 2 inch core plugs both in unfractured and fractured FORGE core samples, (2) analytical and numerical modeling assessments of the injection pressures and subsequent pressure falloff data from hydraulic fracturing stages 1, 2, and 3 conducted in injection well 16A(78)-32, (3) assessment of flow between injection well 16A(78)-32 and the production well 16B(78)-32 (being drilled as of this writing), and (4) assessment of heat extraction capability of injection-production well pairs.

One of the keys to the success of Utah FORGE hydraulic fracturing field trials includes understanding the quality of the hydraulic fractures and the stimulated volume associated with them, the average width and surface area of the hydraulic fractures. For instance, a narrow hydraulic fracture leads to ‘a large flow velocity’ which may be detrimental to lasting heat extraction quality. Similarly, short well spacing would yield smaller fracture surface area that cannot provide much heat to the flowing fluid. However, the Utah FORGE project is a research project to obtain parameters needed for a commercial project; thus, its physical dimensions do not reflect a commercial project; however, these dimensions must be accounted for in the demonstration procedures to qualify new tools for further applications.

In quantifying the heat exchange capacity of the Utah FORGE project, the modeling is based on the premise that Utah FORGE field consists of very low permeability, low porosity, hot, dry rocks. While formation stimulation resulting from the hydraulic fracturing process is inevitable, such stimulation must not ‘short-circuit’ between the wells in the EGS system described above; otherwise, a rapid thermal decline will occur in the produced water, and very little heat will be delivered to the wellhead in the production well. The modeling must also attempt to quantify the heat transfer in the smaller experimental EGS system at FORGE to predict the operating temperatures that will be encountered, allowing modifications to be made in the field demonstration protocols and procedures.

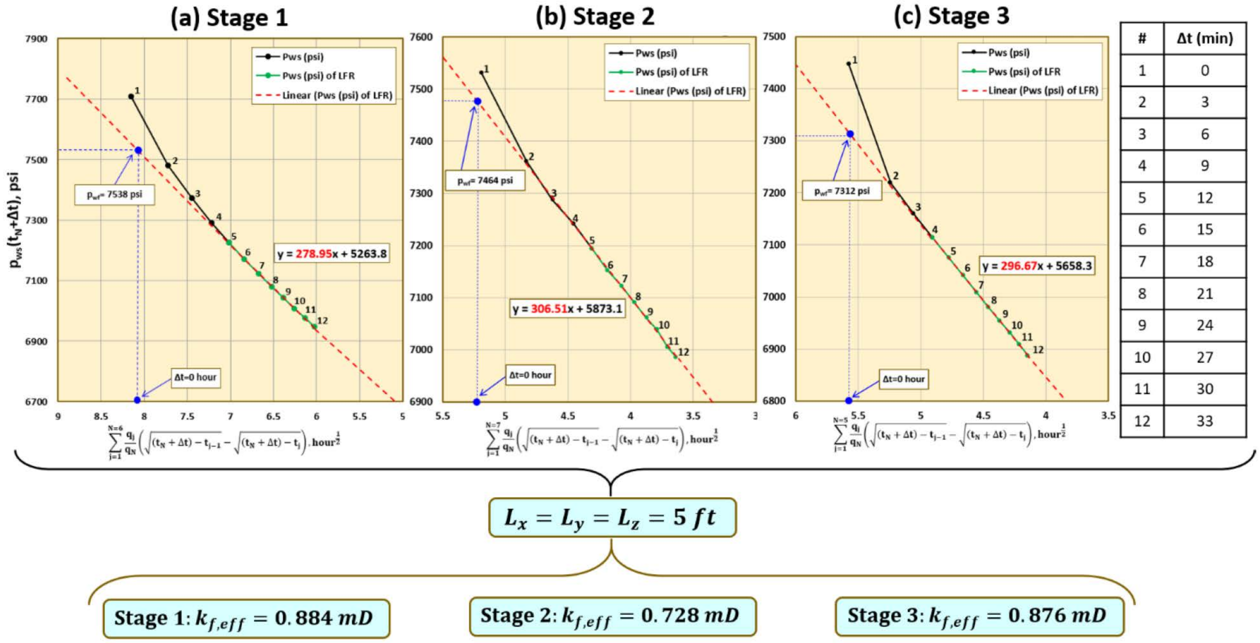
The current modeling efforts have focused on the following items:

- Quantifying the flow parameters of the dual-porosity environment in the stimulated volume associated with the Utah FORGE injection-production well pair.
- Quantifying the fluid leakage volume from hydraulic fractures to the surrounding rocks during heat extraction process.
- Quantifying the likelihood of Injection fluid short-circuiting.
- Calculating the heat extraction capacity of the well pairs as a function of number of hydraulic fracture stages.

Pressure Falloff Analysis of Stage 1, 2, and 3

Figure 5 presents the analysis of the pressure falloff from Stage 1, 2, and 3 of Utah FORGE for determining the effective permeability of the stimulated volume surrounding the hydraulic fractures. The analysis of the pressure falloff data is based on Eq. 1, while the associated data plots and the results are shown in Figure 5.

$$p_{wf}(t_N+\Delta t)=p_i-\underbrace{\frac{4.064\,q_N\mu}{\sqrt{k_{f,eff}}\,(h\,L_f)}\left(\frac{1}{(\phi c_t)_{f+m}\mu}\right)}_{Slope\ m}\left[\sum_{j=1}^{N}\frac{q_j}{q_N}\left(\sqrt{(t_N+\Delta t)-t_{j-1}}-\sqrt{t_N+\Delta t-t_j}\right)\right] \quad (1)$$



#	Δt (min)
1	0
2	3
3	6
4	9
5	12
6	15
7	18
8	21
9	24
10	27
11	30
12	33

Figure 5—Pressure falloff analysis of the shut-in bottomhole field pressure data (y-axis) versus convolution-based time functions (x-axis). Each straight-line section yielded the effective formation permeability, $k_{f,eff}$, of micro- and macro-fracture system surrounding the hydraulic fractures. In this analysis several matrix block sizes were used; however, a companion dual-porosity model indicated matrix cube size of 5×5×5 ft as the most likely representative size. The details of each stage are: (a) Stage 1 was pumped into the 200 ft long open-hole section (10,826-10,828 ft MD) section of the well with slickwater, (b) Stage 2 was pumped into a cased and perforated zone (10,560 – 10,580 ft MD) section of the well with slickwater, and (c) Stage 3 was pumped into a cased and perforated zone (10,120 – 10,140 ft MD) section of the well with slickwater pad followed by a crosslinked CMHPG fluid with DEEPROP™ microproppant (mesh sizes of 40/70 Local/White and 40/140 Sand) at concentrations of 0.5 to 0.75 pounds of proppant per gallon of slickwater.

Laboratory Characterization of FORGE Core Plugs and Outcrop Granite Plugs

Figure 6 shows the core plugs used to determine the fracture characteristics of a stimulated matrix rock for use as a guide in field scale numerical modeling.

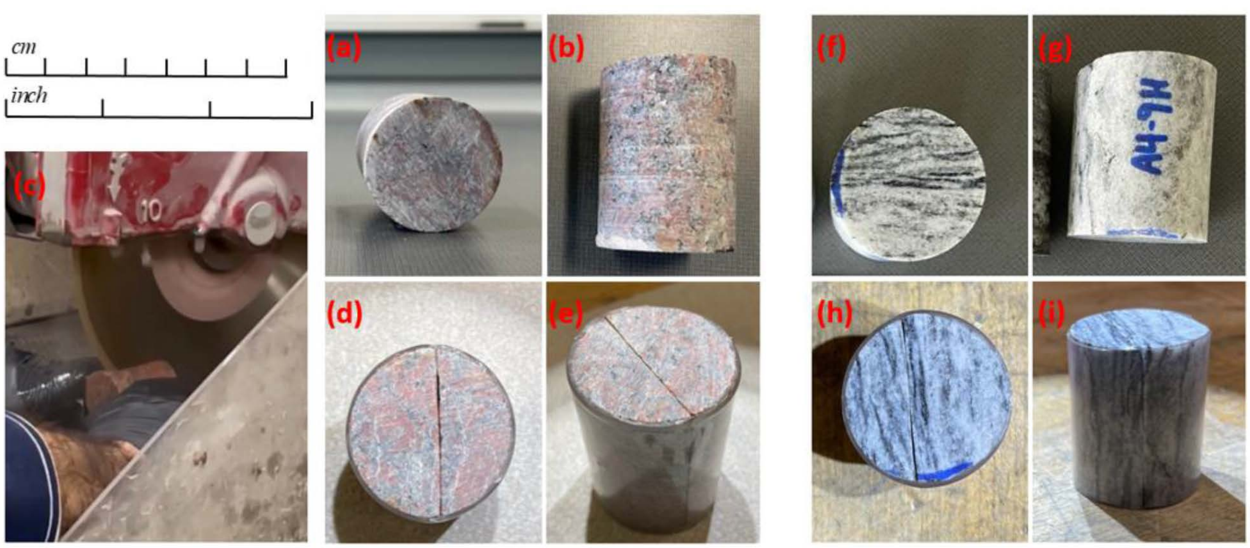
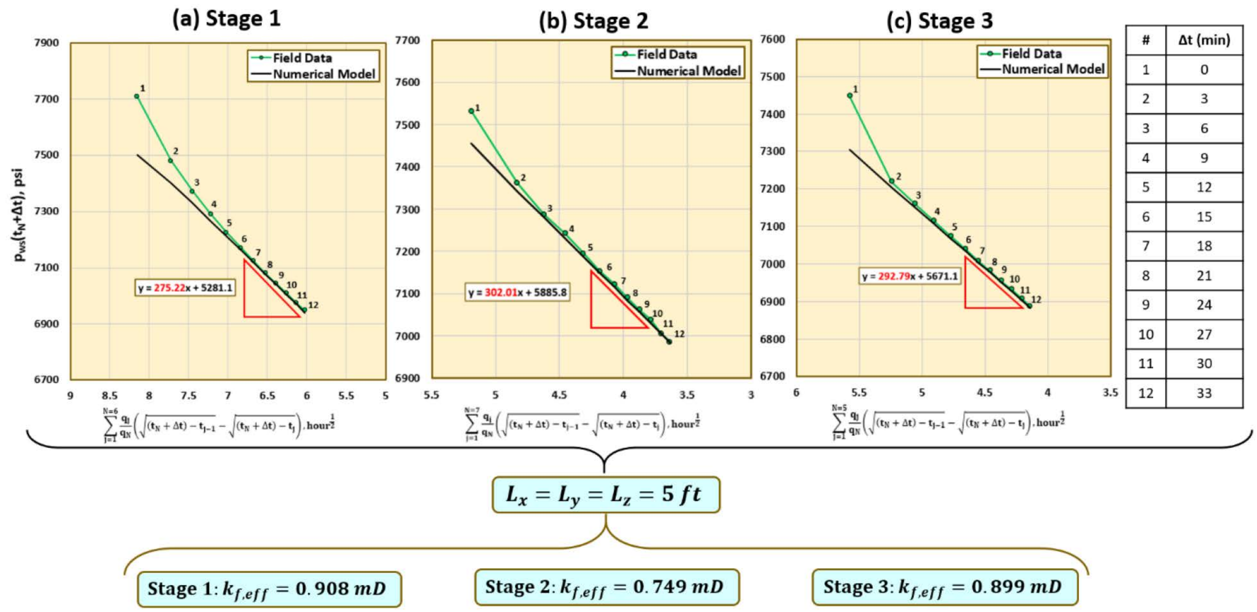


Figure 6—Granite core sample (designated Granite Core 1, GC1): (a) top view and (b) side view prior to the fracturing (these images are consistent with the scale on the left); (c) cutting core into halves with a saw to create a fracture; (d) top view and (e) side view of the fractured core while wrapped with PVC tape to keep core intact. FORGE horizontal core A4-9H: (f) top view and (g) side view prior to fracturing (these images are consistent with the scale on the left); (h) top view and (i) side view of the fractured core (after being cut into halves with a saw, similar to Part c) while wrapped with PVC tape to keep core intact.

Dual-Porosity Numerical Modeling to Validate Pressure Falloff Analyses

Figure 7 presents the numerical modeling results which clearly validate the analytical solution pressure falloff analysis of the FORGE data.



#	Δt (min)
1	0
2	3
3	6
4	9
5	12
6	15
7	18
8	21
9	24
10	27
11	30
12	33

Figure 7—Numerical modeling of the pressure falloff in black and field pressure falloff in green (y-axis) versus convolution-based time functions (x-axis). The effective stimulated permeability of natural fractures ($k_{f,eff}$) used in the numerical model is included below each plot. The numerical model is a 1D dual-porosity with matrix block size of 5×5×5 ft (Parts: a-c). The effective permeability ($k_{f,eff}$) obtained from each analytical pressure falloff test and the associated fracture porosity, and fluid properties were the key input data into the numerical model.

2D Numerical Modeling of Injected Water Loss to Hot Dry Rocks Surrounding the Three Hydraulic Fractures

Figure 8 shows the grid system used in evaluating the injected water loss from each hydraulic fracture stage to the surrounding hot dry rocks. The gird system is a highly fine grid arrangement near the hydraulic fracture walls. Figures 9 and 10 show water saturation distribution after 2 years of injection in the rock matrix and the stimulated natural fractures. By examining the results, we conclude that water loss (and water short-circuiting) is about 0.5 % of the total injected water.

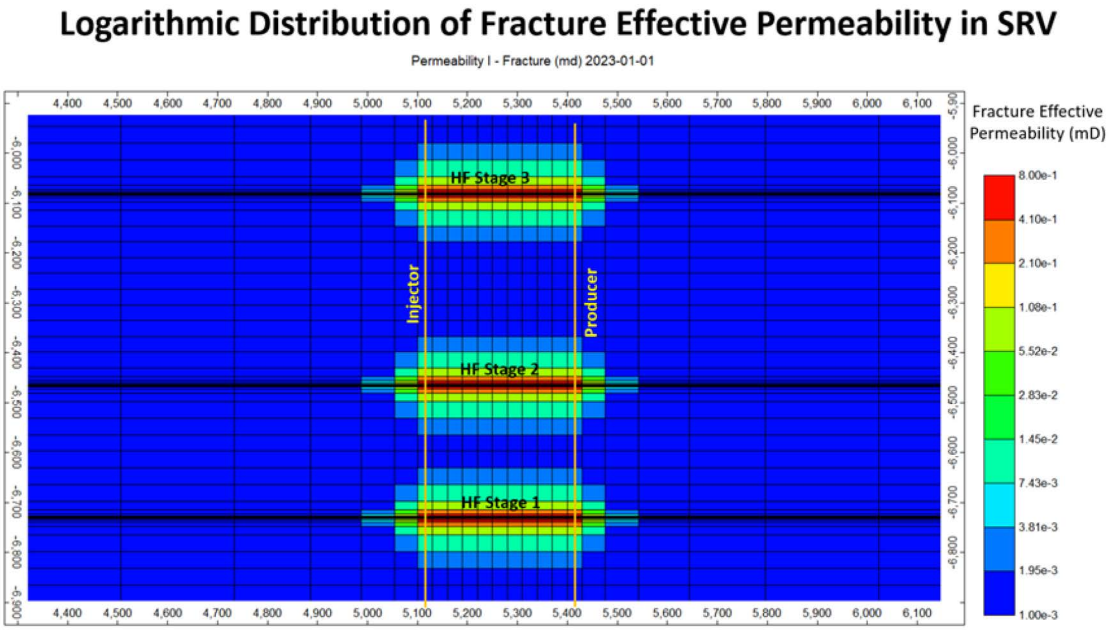


Figure 8—The grid system and fracture effective permeability used in evaluating the injected water loss from each hydraulic fracture stage to the surrounding hot dry rocks. The gird system is a highly fine grid near the hydraulic fracture walls.

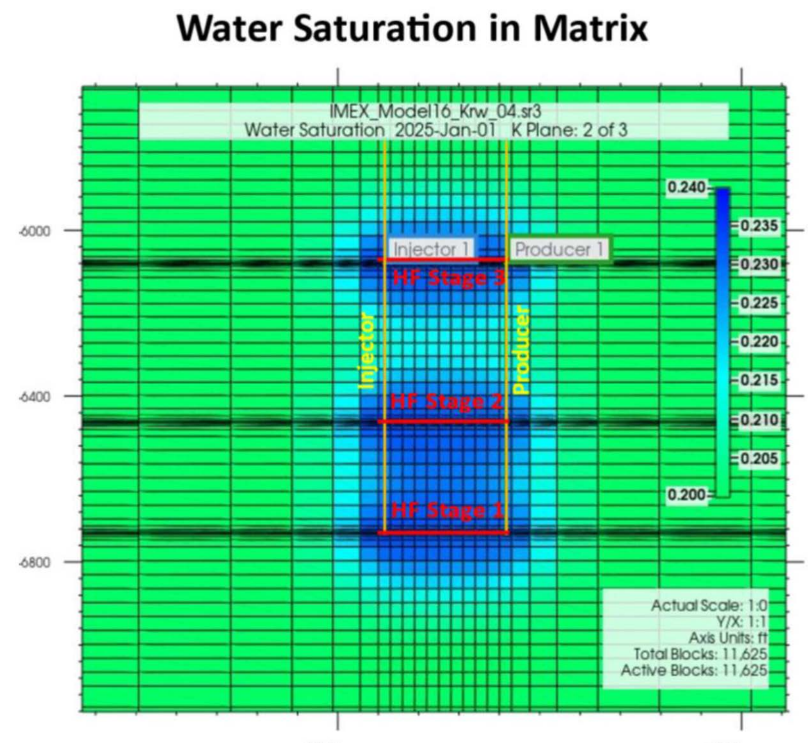


Figure 9—Water saturation distribution in the rock matrix after 2 years of water injection.

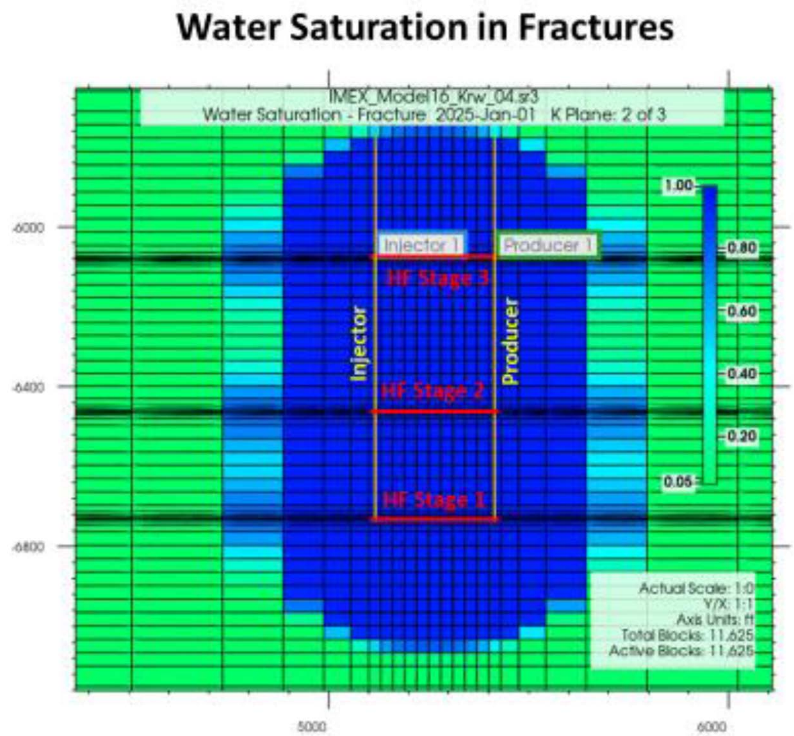


Figure 10—Water saturation distribution in the natural fractures after 2 years of water injection.

Heat Extraction from Fractured Hot Dry Rock

The following mathematical model (Gringarten et al., 1975) with its analytical solution, is of great value in getting a qualitative idea of heat extraction from fractured hot dry rocks without the need to resort to complex numerical models. The analytical model assumptions are: (1) the system includes an **infinite number of parallel vertical fractures** of uniform aperture; (2) fractures are uniformly spaced and drain heat from blocks of homogeneous, isotropic, and impermeable rock; and (3) cold water enters at the bottom of each fracture.

Gringarten et al. model assumptions are: (1) products of density and heat capacity for water and formation are constant; (2) thermal conductivity of the water and formation are constant; (3) water temperature is uniform in any vertical cross-section of the fracture and is equal to formation temperature at the fracture-rock interface; and (4) all heat transfer is by horizontal conduction in the in the rock and by a 1D convection of water along fracture (for Gringarten et al. the fracture-flow direction is the vertical direction). The heat transfer equations in the x-z domain (z the vertical coordinate and parallel to the fracture vertical face, x the horizontal coordinate perpendicular to fracture face) are:

Heat balance within each hydraulic fracture—advection-conduction heat flow without leakoff:

$$-\rho_w c_w u_{w,f} \frac{\partial T_{w,f}}{\partial z} - \left[-\left(\frac{K_R}{w_f/2} \right) \frac{\partial T_R}{\partial x} \bigg|_{w_f/2} \right] = \rho_w c_w \frac{\partial T_{w,f}}{\partial t} \quad (2)$$

Heat balance in the rock surrounding hydraulic fracture:

$$\frac{\partial}{\partial x} K_R \frac{\partial T_R}{\partial x} = \rho_R c_R \frac{\partial T_R}{\partial t} \quad (3)$$

No heat flow in the rock halfway between two hydraulic fractures:

$$\frac{\partial T_R}{\partial x} \bigg|_{x=L_x/2} = 0 \quad (4)$$

Inlet velocity boundary condition

$$u_{z,w,hf}\Big|_{x=0} = q_{inj}/\left(w_{hf}h\right) \text{ where } w_{hf} \equiv 2b \tag{5}$$

Solution Method

The above model (Eq. 2 – 5 and the associate schematic, Figure 11) is known as a 'bilinear model' and can be solved using Laplace Transform and Laplace Transform Numerical Inversion.

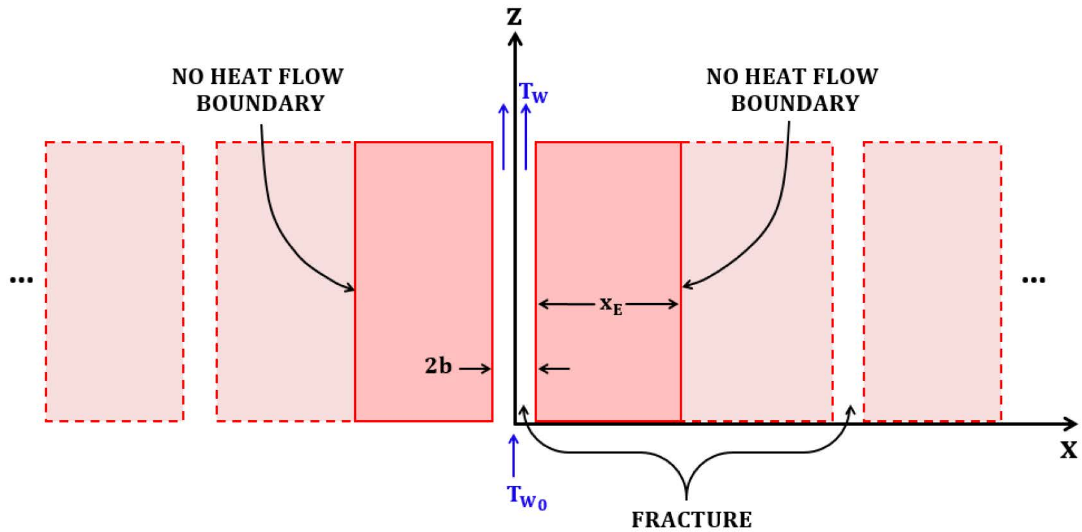


Figure 11—Gringarten et al. bilinear model for fractured hot dry rock.

Our Model

The heat transfer equations in the x-y domain (x the horizontal coordinate parallel to the fracture face, and y the horizontal coordinate perpendicular to fracture face) are:

Heat balance within each hydraulic fracture—advection-conduction heat flow without leak off

$$-\underbrace{\left(\rho_w c_w u_{x,w,hf}\frac{\partial T_{w,hf}}{\partial x}\right)}_{Heat\ Advection\ in\ HF} - \underbrace{\left[-\left(\frac{K_{R,y}}{w_{hf}/2}\right)\frac{\partial T_R}{\partial y}\Big|_{y=w_{hf}/2}\right]}_{Conduction\ of\ Heat\ at\ the\ Fracture\text{-}Matrix\ Interface} = \underbrace{\rho_w c_w \frac{\partial T_{w,hf}}{\partial t}}_{Rate\ of\ Heat\ Accumulatio\ in\ the\ Fracture} \tag{6}$$

Heat balance in the rock surrounding hydraulic fracture:

$$\underbrace{\frac{\partial}{\partial x}K_{R,x}\frac{\partial T_R}{\partial x} + \frac{\partial}{\partial y}K_{R,y}\frac{\partial T_R}{\partial y}}_{Heat\ conduction\ in\ the\ rock\ matrix\ surrounding\ fracture} = \underbrace{\rho_R c_R \frac{\partial T_R}{\partial t}}_{Rate\ of\ heat\ accumulation\ in\ the\ rock\ matrix} \tag{7}$$

No heat flow in the rock between two hydraulic fractures:

$$\frac{\partial T_R}{\partial y}\Big|_{y=L_y/2} = 0 \tag{8}$$

Inlet velocity boundary condition:

$$u_{x,w,hf}\Big|_{x=0} = q_{inj}/\left(w_{hf}h\right) \tag{9}$$

Solution Method

Time Implicit Finite Difference Method in a 2D Grid (Figure 12)

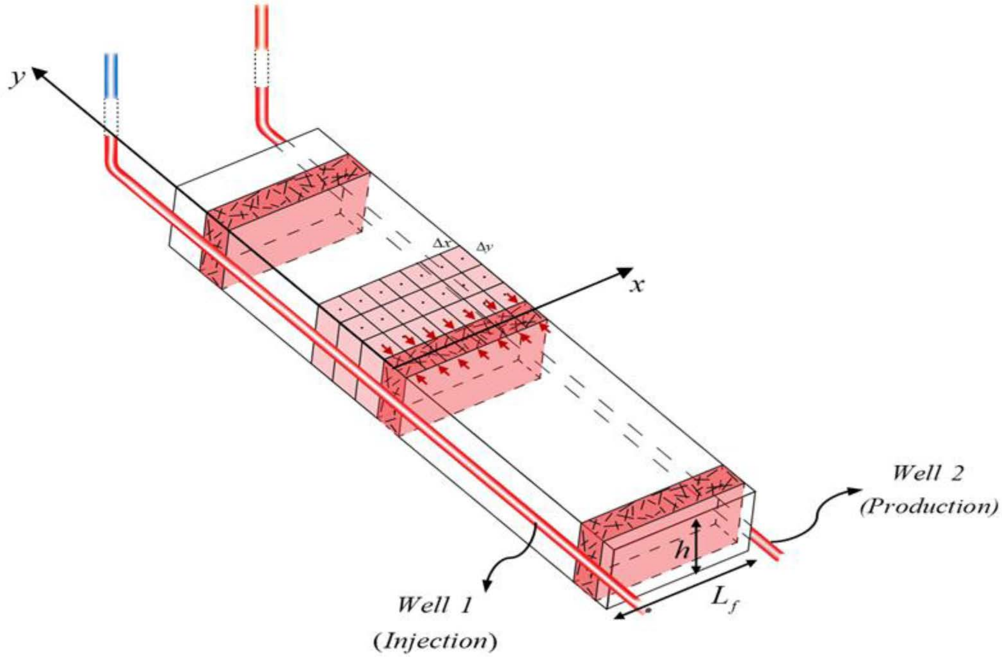


Figure 12—Numerical grid system used in the numerical solution of Utah FORGE injection-production well heat extraction system (Eq. 6 - 9) within the FORGE formation.

Example Case

Utah FORGE

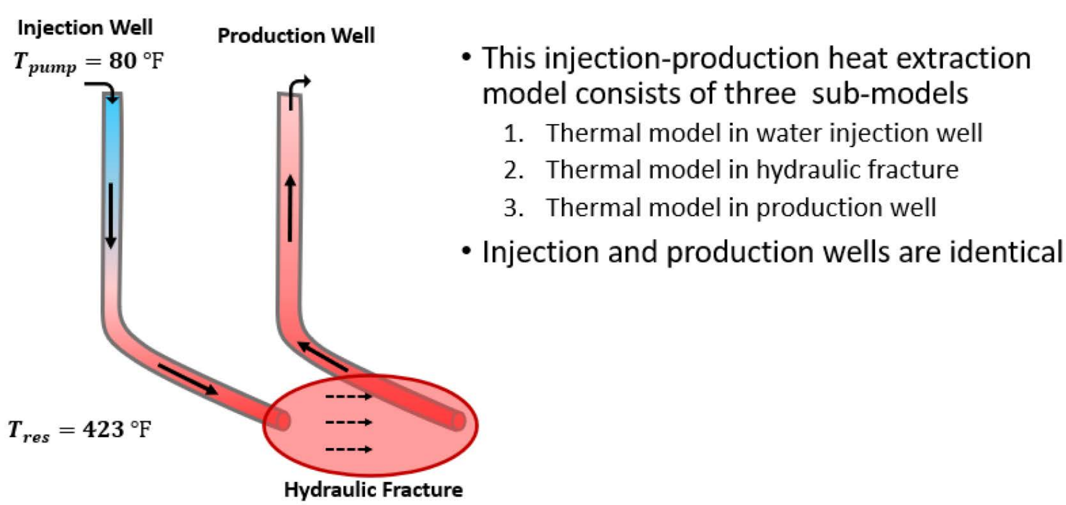


Figure 13—FORGE injection-production heat extraction model. The injected water becomes somewhat warmer in the injection well as a function of injection rate and well configuration before entering the hydraulic fracture. The injection water that enters the hydraulic fracture becomes warmer within the hydraulic fracture depending on the advective flow velocity of water in the fracture. Typically, the advective velocity of the water entering the fracture should be smaller than one length of the fracture per day. The fracture-heated water enters the production well and would lose some heat to the surrounding formation through the casing and cement sheath in the production well.

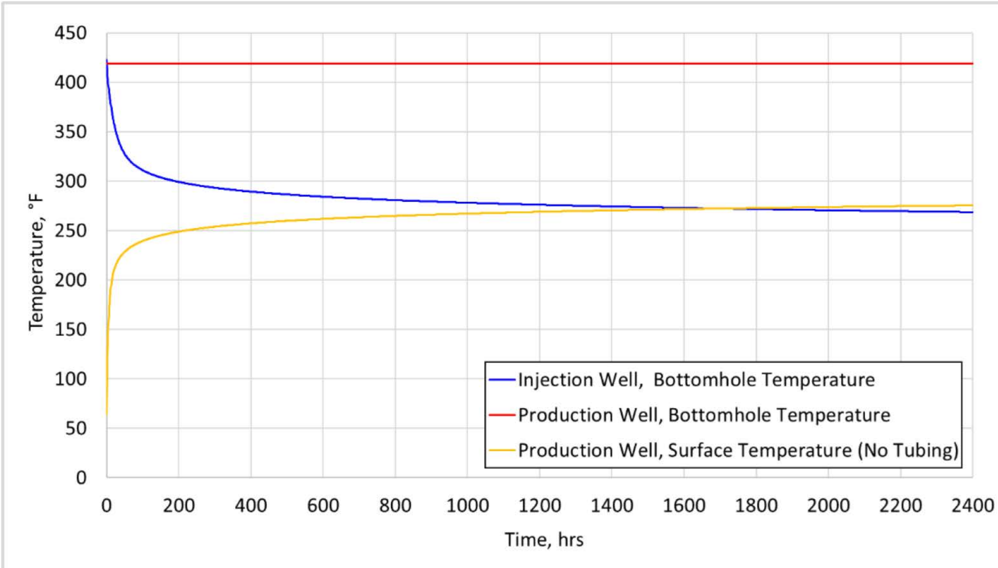


Figure 14—Temperature versus time at the hydraulic fracture entrance (blue), hydraulic fracture exit (red), and at the production well surface (yellow) for an injection rate of 1200 barrels/day. The temperature profiles were generated by a numerical wellbore model and a fracture heat-exchange model is described in the text. It is assumed that the water is injected at 80 °F into a 7-inch casing with an inside diameter of 5.92 inches. The water remains single-phase liquid without flashing inside the production well casing.

Stress Shadow

The input data and calculated stress changes resulting from Stage 3 hydraulic fracture propagation are summarized in Figure 15 (a), (b), (c), and (d). According to McClure (2023) "high-resolution microseismic observations show that the stimulation formed a planar region perpendicular to the minimum principal stress, suggesting that a planar fracture model is appropriate for describing the stimulation, and microseismic observations constrain the size, direction, and aspect ratio of such fractures. Also, the microseismic data from Utah FORGE Stage 3 suggests a mostly circular crack with slightly upward propagation." Our independent fracture analysis assumptions are in line with McClure's analysis as reflected in Figure 15 (a).

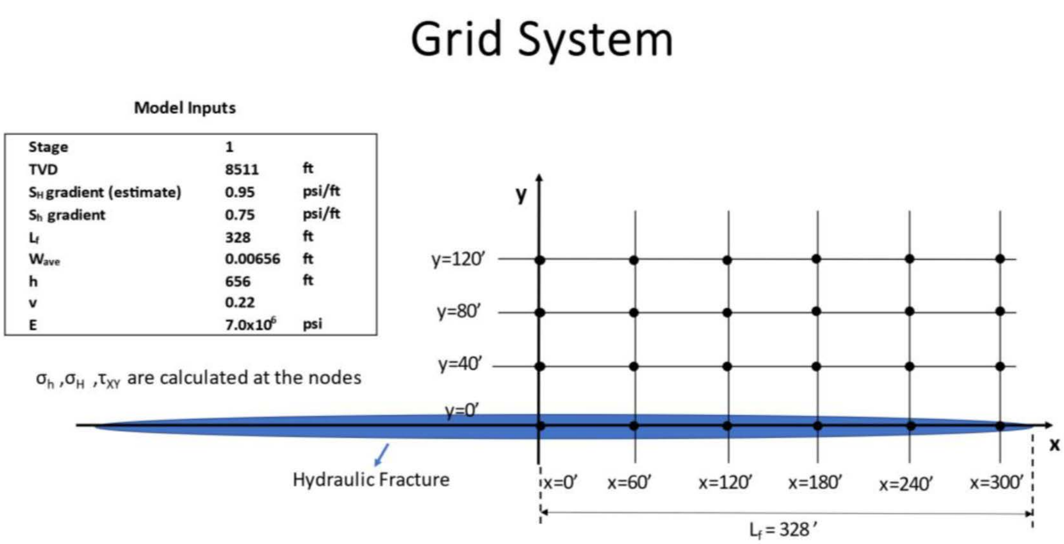


Figure 15 (a)—x-y view of a hydraulic fracture representing the Utah FORGE system and comutation grid system. Model input data are listed in a box on the figure face (upper left).

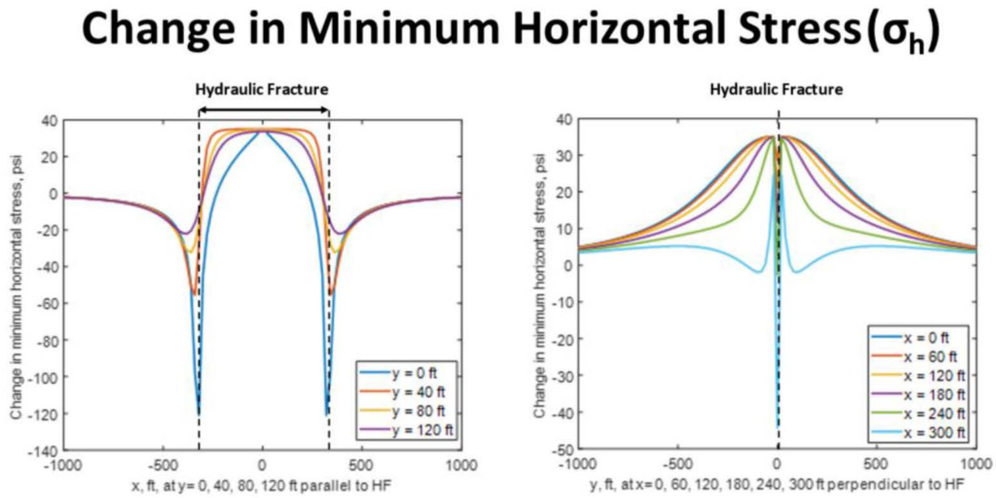


Figure 15 (b)—Changes in the minimum horizontal stress σ_h indicating that stress shadow magnitude is small.

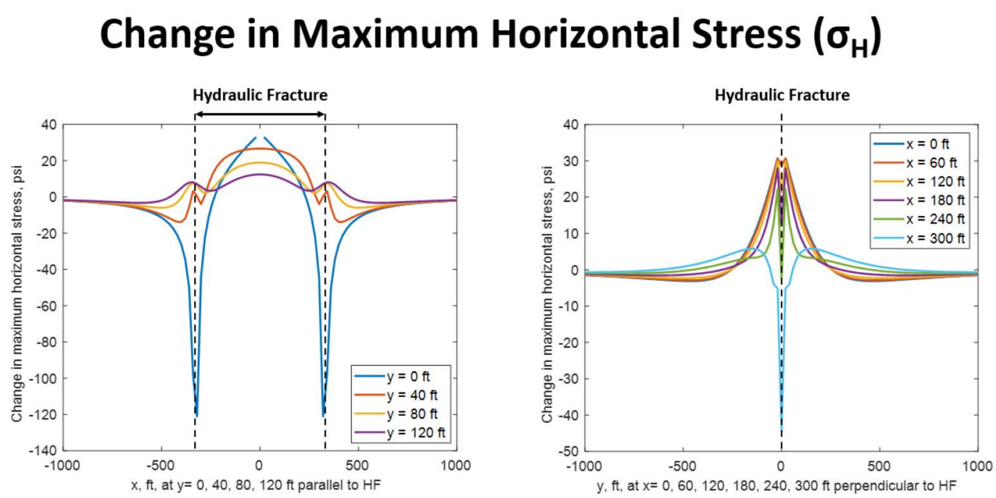


Figure 15 (c)—Changes in the maximum horizontal stress σ_h indicating that stress shadow effect is small.

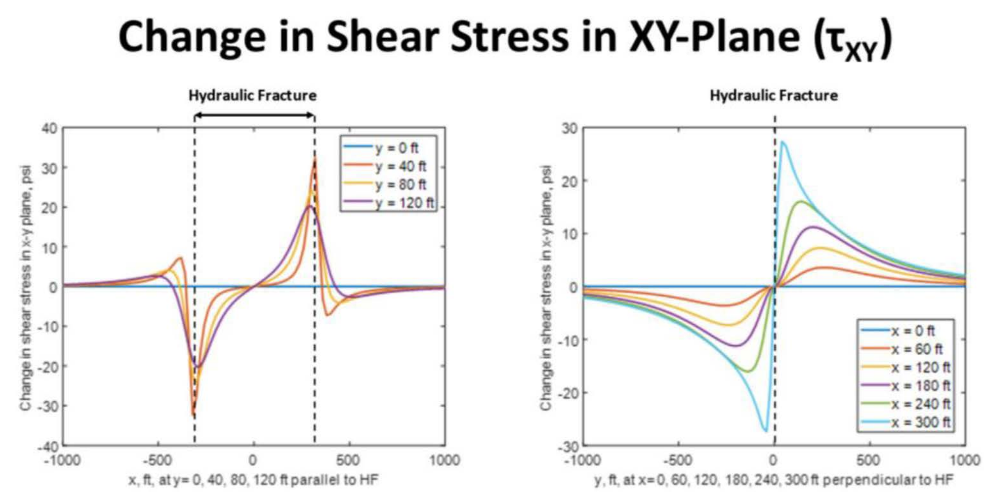


Figure 15 (d)—Changes in the shear stress τ_{xy} indicating a small shear stress effect in the vicinity of the fracture tips.

Potential Improvement in Heat Extraction

Figure 16 is the schematic of a potential three-well (one injector and two producers) FORGE thermal energy recovery system. With this well configuration, (1) heat will be extracted from both wings of the hydraulic fractures with twice the surface area, (2) the advective flow velocity could be smaller than in the two-well system; thus, increasing the residence time for injected fluid to extract heat, and (3) the three-well system will reduce total cost by having one injector feeding two producers instead of two injectors feeding two producers.

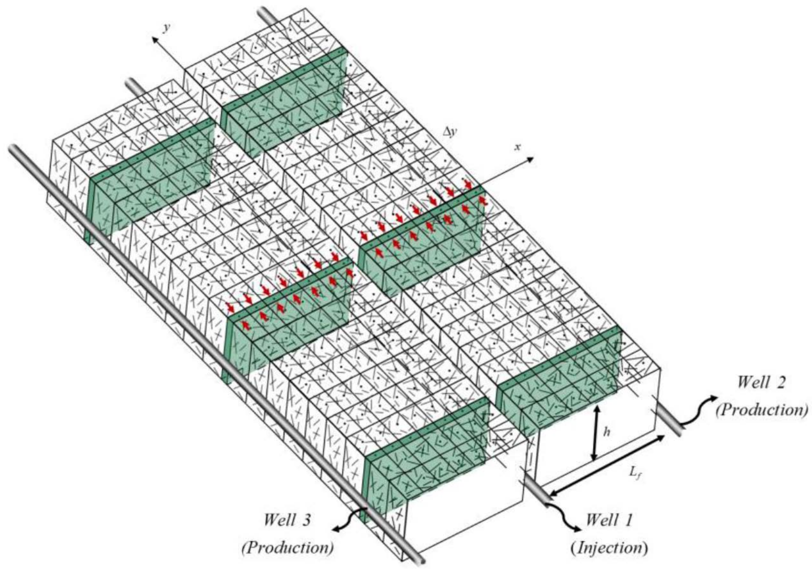


Figure 16—Schematic of a potential three-well FORGE thermal energy recovery system for improving heat extraction.

Modeling Conclusions:

1. Our research focused on deciphering the formation characteristics of the Utah FORGE using the enormous, and highly credible field measured data from the Utah FORGE project that is available to the public. We believe the analysi of such data has provided a clear vision and knowledge for future commercial field projects in the EGS hot, dry rock environment.
2. We have presented analytical and numerical analyses of the pressure falloff data of FORGE injection well 16(A)78-32 HF Stages 1, 2, and 3. The analyses clearly indicate the presence of highly conductive micro- and macro-fractures associated within the three hydraulic fracture stages. Furthermore, the effective permeability of the stages are very similar.
3. We used outcrop granite and FORGE granitioid core samples to obtain key flow properties (permeability and porosity) of micro-fractured rocks associated with the downhole environment.
4. We used the laboratory measured properties of outcrop granite and FORGE granitoid rock samples in the analyses of the shut-in pressure tests to infer information about the stimulated FORGE environment.
5. The fracture permeability values, calculated from pressure falloff analysis and numerical modeling, are dependent on the stimulated micro- and macro-fracture spacings, thus, the matrix block dimensions, which we consider a statistical measure of the fracture spacings of conductive fractures. From the analyses of field data, via analytical and numerical modeling, we conclude that the intrinsic stimulated fracture permeabilities are on the order of 10^3 to 10^4 mD.
6. The FORGE hydraulic fractures have small width and small surface areas for an in situ, commercial heat exchanger. For instance, injection 1200 B/D of water in each single hydraulic fracture in Utah

FORGE would result in an average flow velocity of 1560 ft/day. This velocity is recognized as too fast for the well spacing of 330 feet for a commercial system but allows for the rapid detection of temperature changes and tracers for technology evaluation. In the 1975 example case by Gringarten et al., the flow velocity was 820 ft/day for inlet-to-outlet spacing of 3280 feet. From this analysis we conclude that for a commercial EGS, a large number of hydraulic fracture stages per well will be required.

Conclusion

The first year made substantial progress on the three-year DOE funded project for the development of tools for the construction of a subsurface heat exchanger for Enhanced Geothermal Systems (EGS) at the Utah-FORGE site using unique casing sleeves that are cemented in place in horizontal wells:

1. The original hydraulic tractor concept using coiled tubing was replaced with an electric wireline design to improve operating costs by not requiring coiled tubing. The flask assembly has been rated and qualified, with an expected duty cycle for 3 sleeve actuation using full power of four motor operation, to a time of internal flask temperature build to allow operation for a 12 hour round trip in the hole. This allows a much less expensive system for detecting and performing flow conformance operations in the wells without the need for cooling fluid to be pumped past the tractor, sleeve actuation and sensor packages.
2. The 7-inch frac sleeves are being tested to simulate conditions of cemented sleeves to actuate for fracture stimulation at ambient and 225 °C geothermal conditions. The sleeve components were first tested in hydraulic test fixtures followed by surface flow loops. The balls were caught or passed with repeatable results under a variety of operating conditions. The sleeve seal components are being tested rigorously with a variety of seals to identify the optimal seal system, with testing ongoing at 8500 psi and temperatures up-to 225 °C. Results have justified the component testing prior to full prototype testing, permitting the isolation of the high-risk components for individual testing.
3. The project is still on schedule for a field demonstration test in 2024 at the FORGE site in Utah, to provide a means of multi-stage hydraulic fracturing and conformance control of an EGS project.

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Nomenclature

α = Biot coefficient
α_f = Biot coefficient for fracture medium
α_m = Biot coefficient for matrix medium
$\alpha_{T,fl}$ = Fluid thermal expansion coefficient,° K^{-1}
γ = Fluid gradient, Pa/m

ε_v = Volume strain
η = Hydraulic diffusivity, m^2/s
κ = Thermal diffusivity, m^2/s
λ = Fluid mobility, 1/Pa.s
λ = Lame parameter, Pa
μ = Viscosity, Pa.s
ρ = Density, Kg/m^3
τ = Fracture-matrix pressure transfer function, s^{-1}
τ_c = Fracture-matrix tracer transfer function, s^{-1}
τ_m = Tortuosity of matrix pores
ϕ_f = Fracture porosity
ϕ_m = Matrix porosity
c = Fluid compressibility, Pa^{-1}
c_f = Tracer concentration in fracture medium, mole or weight fraction
c_m = Tracer concentration in matrix medium, mole or weight fraction
C_L = Seepage coefficient, $m/s^{1/2}$
D = Depth, m
$D_{f,eff}$ = Effective dispersion coefficient in the fracture, m^2/s
$D_{m,eff}$ = Effective dispersion coefficient in the matrix, m^2/s
G = Shear modulus, Pa
k = Permeability, m^2
k_f = Fracture permeability, m^2
$k_{f,eff}$ = Effective fracture permeability, m^2
k_m = Matrix permeability, m^2
K_{dfb} = Bulk ***drained*** modulus of matrix blocks containing fractures, Pa
K_{dm} = Bulk ***drained*** modulus of ***matrix blocks*** without fractures, Pa
K_{sm} = Bulk modulus of ***solid minerals*** in the porous medium, Pa
K_{fl} = Bulk modulus of fluids in the pores, Pa
L_f = Hydraulic fracture half length, m
M_f = Biot modulus for fracture medium, Pa
M_n = Biot modulus for matrix medium, Pa
λ = Lame parameter, Pa
p_f = Fracture pressure, Pa
p_m = Matrix pressure, Pa
r = Radial coordinate, m
r_b = Well grid block radius, m
r_w = Well radius, m
s = Skin factor
t = Time, s
τ = Fracture-matrix pressure transfer function, s^{-1}
τ_c = Fracture-matrix tracer transfer function, s^{-1}
τ_m = Tortuosity of matrix pores
τ_f = Fracture temperature,° K
T_m = Matrix temperature,° K
$\vec{u}$ = Formation displacement vector, m
$\vec{u}$ = Formation interstitial velocity vector, m/s

$\vec{v}$ = Darcy velocity vector, m/s
x,y,z = Cartesian coordinates, m
w_f = Hydraulic fracture width, m

References

Augustine, C.: A methodology for calculating EGS electricity generation potential based on the Gringarten model for heat extraction from fractured rock, 2016, GRC Transactions, V **40**.

Barree, Robert D., and Jennifer L. Miskimins. "Calculation and Implications of Breakdown Pressures in Directional Wellbore Stimulation." Paper presented at the SPE Hydraulic Fracturing Technology Conference, Woodlands, Texas, USA, February 2015. doi: https://doi.org/10.2118/SPE-173356-MS.

Fleckenstein, W. W., Miskimins. J.L., Eustes, A.W., Kazemi, H., Hill, T., Mailand, J., Ortiz, S., and King, G., Development of Multi-Stage Fracturing System and Wellbore Tractor to Enable Zonal Isolation During Stimulation and EGS Operations in Horizontal Wellbores, The Geothermal Rising Conference 2021 (GRC), October 3-6, 2021, San Diego, California, USA. GRC Transactions, Vol. **45**, 2021

Fleckenstein et al: Development of multi-stage fracturing system and wellbore tractor to enable zonal isolation during stimulation and EGS operations in horizontal wellbores, SPE-210210-MS, October 2022.

Gorjian, M., Hendi, S., and Hawkes, C. D.: An Analytical Framework for Stress Shadow Analysis During Hydraulic Fracturing – Applied to the Bakken Formation, Saskatchewan, Canada, Solid Earth Discuss. [preprint], https://doi.org/10.5194/se-2021-1, 2021

Gringarten, A. C., Witherspoon, P. A. and Yuzo, O.: Theory of heat extraction from fractured hot dry rock, *Jour. Geophysics Res.*, 1975.

Haustveit, K., Elliott, B., Haffener, J., Ketter, C., O'Brien, J., Almasoodi, M., Deeg, W., Monitoring the pulse of a well through sealed wellbore pressure monitoring, a breakthrough diagnostic with a multi-basin case study. *Society of Petroleum Engineers*, 2020, doi:10.2118/199731-MS.

McClure, Mark: Calibration Parameters Required to Match the Utah FORGE 16A(78)-32 Stage 3 Stimulation with a Planar Fracturing Model. 2023. Proc. 48th Workshop on Geothermal Engineering, Stanford University, Feb. 6-8, 2023, SGP-TR-224.

Michael, Andreas, and Ipsita Gupta. "A Semianalytical Modeling Approach for Hydraulic Fracture Initiation and Orientation from Perforated Wells." *SPE Prod & Oper* **36** (2021): 501–515. doi: https://doi.org/10.2118/204480-PA.

Mindygaliyeva et al: Experimental Fracture Creation in Cores: Permeability and Porosity Measurements of the Fractured Cores and the Use of Such Measurements in Analysis of Pressure Falloff Tests Following Well Stimulation, 2023, ARMA 23-0551.

Miskimins, J. ed. 2019. Hydraulic Fracturing: Fundamentals and Advancements. Richardson, Texas, USA: Society of Petroleum Engineers.

Morad P., Angus, D., Modeling frac-hits using dynamic microseismicity constrained enhanced fractured regions, URTEC, 2019, Denver, CO. https://doi.org/10.15530/urtec-2019-258

Roberts, Glyn, Saha, Souvick, and Johanna Waldheim. "An Expanded Study of Proppant Distribution Trends from a Database of Eroded Perforation Images." Paper presented at the SPE *International Hydraulic Fracturing Technology Conference & Exhibition*, Muscat, Oman, January 2022. doi: https://doi.org/10.2118/205314-MS.

Ugueto, Gustavo, Huckabee, Paul, Wojtaszek, Magdalena, Daredia, Talib, and Alan Reynolds. "New Near-Wellbore Insights from Fiber Optics and Downhole Pressure Gauge Data." Paper presented at the SPE Hydraulic Fracturing Technology Conference and Exhibition, The Woodlands, Texas, USA, February 2019. doi: https://doi.org/10.2118/194371-MS.

Ugueto, Gustavo A., Haffener, Jackson, Mondal, Somnath, Satviski, Alexei A., Huckabee, Paul T., and Kyle Haustveit. "Spatial and Temporal Effects on Low Frequency DAS and Microseismic Implications on Hydraulic Fracture Geometry and Well Interactions." Paper presented at the SPE Hydraulic Fracturing Technology Conference and Exhibition, The Woodlands, Texas, USA, February 2022. doi: https://doi.org/10.2118/209180-MS.

Weddle, Paul, Griffin, Larry, and C. Mark Pearson. "Mining the Bakken II – Pushing the Envelope with Extreme Limited Entry Perforating." Paper presented at the SPE Hydraulic Fracturing Technology Conference and Exhibition, The Woodlands, Texas, USA, January 2018. doi: https://doi.org/10.2118/189880-MS.

Winkler, D., Swearingen, L., & McLennan, J. (2021). Utah FORGE: Well **16A**(78)-32: Summary of Drilling Activities. https://gdr.openei.org/submissions/1296.

Wright, B. (2023). "Geothermal Potential Runs Hot in Texas" *J Pet Technol* **75** (03): 30–35. Paper Number: SPE-0323-0030-JPT, Published: 01 March 2023, DOI: https://doi.org/10.2118/0323-0030-JPT

Xing, P., Wray, A., Arteaga, E.I.V., Finnila, A., Moore, J., Jones, C., Borchardt, E. and McLennan, J., 2022. In-situ stresses and fractures inferred from image logs at Utah FORGE.

Ye, Z., Fang, Y., Ghassemi, A. and McLennan, J., 2022, June. A Preliminary Wellbore In-Situ Stress Model for Utah FORGE. In *56th US Rock Mechanics/Geomechanics Symposium*.

Yost, A.B., Overby, W.K., Wilkins, D.A., and C.D. Locke. "Hydraulic Fracturing of a Horizontal Well in a Naturally Fractured Reservoir: Gas Study for Multiple Fracture Design." Paper presented at the SPE Gas Technology Symposium, Dallas, Texas, June 1988. doi: https://doi.org/10.2118/17759-MS.

Zhu, Xiaoyu, and Ge Jin. "Analysis of cross-well fracture hits in DJ Basin, Colorado using low-frequency DAS data." Paper presented at the SEG/AAPG/SEPM First International Meeting for Applied Geoscience & Energy, Denver, Colorado, USA and online, September 2021. doi: https://doi.org/10.1190/segam2021-3582658.1.