

Tracer Huff-Puff Tests

1. 8-3617 Integrating Tracer Huff-Puff Tests and Geomechanical Analysis to Measure Evolution of the Fracture Network in EGS Reservoirs

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- Subcontractors and/or Participating Organizations: University of Oklahoma
- Project Start and End Date: 4/1/2024-6/30/2027

2. Project Objectives and Purpose

- A key economic predictor for EGS projects is the effective heat-exchange surface area created through stimulation. One approach to measuring this area is to perform injection/backflow (huff-puff) tracer experiments. Traditional single solute tracer tests result in non-unique predictions, however, primarily because the interrogation volume is unknown. By combining multiple tests (hydraulic, solute, reactive solute, thermal strain) we will provide a more unique estimation of heat-exchange area and, consequently, production life span.

3. Technical Barriers and Targets

- Although huff puff solute tracer tests have been used at geothermal reservoirs, there has not been a rigorous examination of the value of the testing. Neither has there been an evaluation of integration with other methods (hydraulic, thermal transport, reactive solutes etc.). Tests at analog sites have shown that combining hydraulic and tracer methods can constrain production life-time estimates.
- We revised our testing design and project management plan to account for updated condition of the FORGE reservoir and the available fiber optic sensing in 16B.
- The effectiveness of parameter estimation and life-time predictions as a function of incremental information will be evaluated using a THMC model developed by Oklahoma University.

4. Technical Approach

- We will overcome the limitations by integrating multiple methods of interrogation: (1) hydraulic, (2) solute tracer, (3) heat tracer, and (4) geomechanical strain
- Results will be used to calibrate a thermal-hydro-mechanical-chemical (THMC) model of the reservoir
- Cost-benefit analysis will estimate the relative value of each of the four methods
- The methodology developed here can be used for periodic monitoring of heat exchange area and predictions of thermal breakthrough through the lifetime of a geothermal reservoir.

5. Project Timeline (list milestones achieved and/or decision points)

Note that Utah FORGE has designated Year 1 to have 5 quarters.

- Task 0 – Project Management and Planning: **A revised project management plan and a revised budget were approved** based upon realigned project objectives.
- Task 1 – Forward Modeling: This task was accomplished in Year 1. **Milestone reports were submitted** documenting our progress.
- Task 2 – Design and Procurement: A revised deployment plan was approved based upon realigned project objectives. The revised plan resulted in tracer and fiber monitoring being outsourced to vendors in coordination with well-to-well tests conducted by TTU. **Milestone 2.1 was submitted** and our **Go/No-Go Decision #1 was passed** with approval from Utah FORGE. This Go/No-Go Decision #1 was based upon modeling conducted by Oklahoma University with collaboration from CSULB. It demonstrated that we could expect sufficient strain, temperature, and tracer response based upon simulations calibrated to FORGE data.

- Task 3 – Numerical Model Refinement: This task was completed the Q1 of 2026 (Q8).
- Task 4 - Conduct Experiments: This task was completed in Q3 of 2025 (Q6), including Milestone 4.1 and 4.2 reports. The **Go/No-Go Decision #2 was passed** in Q4 of 2025 (Q7). This Go/No-Go Decision #1 was based upon the quality of data collected at FORGE. It was deemed of sufficient quality to proceed with simulations and analysis.
- Task 5 - Modeling of Results: The milestone for Task 5.1 was completed this past quarter, but the entire task is currently not complete. Simulations have been made difficult by the complexity of the field data.
- Task 6 – Final Report: This task has not been initiated.

Milestone Table											X Original Contractual Due Date G Active R&D O Adjusted Milestone Due Date ● Final (Completed) D Deliverable (Report required)
8-3617 CSULB PI: Becker											
	Budget Year	Year 2				Year 3					
	Actual Qtr.	Q3 25	Q4 25	Q1 26	Q2 26	Q3 26	Q4 26	Q1 27	Q2 27		
	Project Qtr.	Q6	Q7	Q8	Q9	Q10	Q10	Q10	Q10		
Task 3 – Numerical Model Refinement											
Sub Task 3.1 – THMC enhancement with tracers (OU)				●							
Sub Task 3.2 -SMART– THMC Benchmarking (OU)				●							
Task 4 – Conduct Experiments											
Sub Task 4.1 – Background monitoring and mobilization (CSULB)			●								
Milestone 4.1 Background temperature and strain results			●								
Sub Task 4.2 – SMART –Conduct 4Trace experiments (CSULB)			●								
Milestone 4.2 – SMART –Tracer experiments carried out			●								
Go/No-Go Decision #2: Sufficient data quality to proceed to thermal breakthrough and economic modeling (end of Q8): To proceed beyond this GNG2, we will need to demonstrate through analytic and numerical modeling that our data quality supports predictive modeling. The GNG will be based upon preliminary history matching (milestone 5.1) and uncertainty analysis (milestone 5.2). Advancement beyond this GNG2 does not necessarily require that all datatypes are completed successfully, only that sufficient data have been collected to proceed to modeling of thermal breakthrough for the reservoir and a cost/benefit analysis of the acquired datasets. GNG2 will be satisfied if any two of the four tracer criteria are satisfied, i.e. downhole pressure history peak to trough of 500 psi OR measured return tracer >100x detection limit OR thermal temperature change of 10C above injected temperature downhole OR 1 nanostrain response at DAS cable. This GNG2 is jointly owned by CSULB/OU and culminates in GNG Report#2.			X	●							
Task 5 – Modeling of Results											
Sub Task 5.1 – History match results (OU)			X				O				
Milestone 5.1 – SMART – History match of 4Trace results to extract surface area			X			●					
Sub Task 5.2 – Forward model thermal breakthrough (OU)				X			O				
Milestone 5.2 - Uncertainty analysis of inverted models				X			O				
Sub Task 5.3 – Cost/benefit analysis (OU)					X		O				
Milestone 5.3 - Cost benefit preliminary results					X		O				
Sub Task 5.4 – Workflow analysis						X					
Milestone 5.4 - Workflow report						X					
Task 6 – Final Report						X					

Figure 21. Tasks 3-5 for Year 2 and look ahead to Year 3.

6. Technical Accomplishments

Task 1 – Forward Modeling

- CSULB Design Modeling:** We developed COMSOL Multiphysics models to simulate coupled transport of water, geomechanical strain, heat, and non-reactive tracer. These simplified models are not intended to represent FORGE conditions but to answer questions regarding value of datasets (hydraulics, strain, temperature, tracer breakthrough) for determining effective heat transfer area. An example simulation is shown in Figure 43

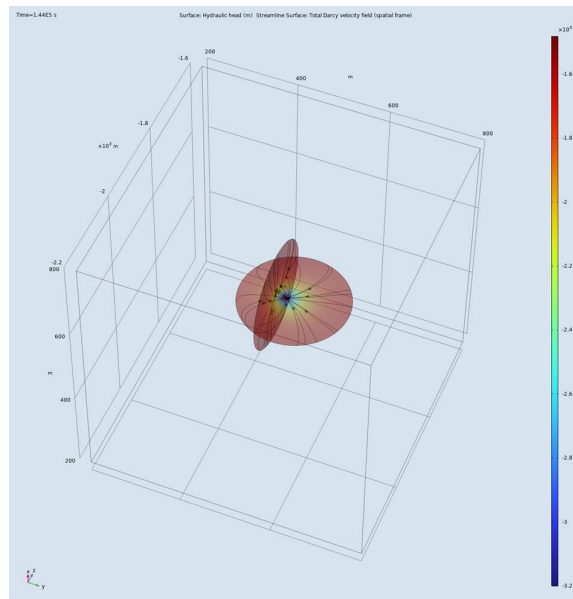


Figure 3. COMSOL Multiphysics simulation of head and streamlines in orthogonal fractures.

Oklahoma University Calibrated Modeling: Oklahoma University Calibrated Modeling: Oklahoma University is developing discrete fracture network models with heat and tracer transport based upon prior information from microseismic epicenters and geological modeling. These models will be calibrated to experimental data but have been used initially to design tests and demonstrate, numerically, that we can expect useful experimental results. The fracture network has been simplified by removing fractures that are hydraulic dead ends (Figure 5). Simulations of water temperature return and tracer concentration were used to design tracer test and anticipate fiber optic monitoring of fluid temperature (Figure 6). Figure 7. Shows the simulated strain rate recorded at the fiber in well 16B. As the fractures open and close, they impart extension and expansion on the fiber.

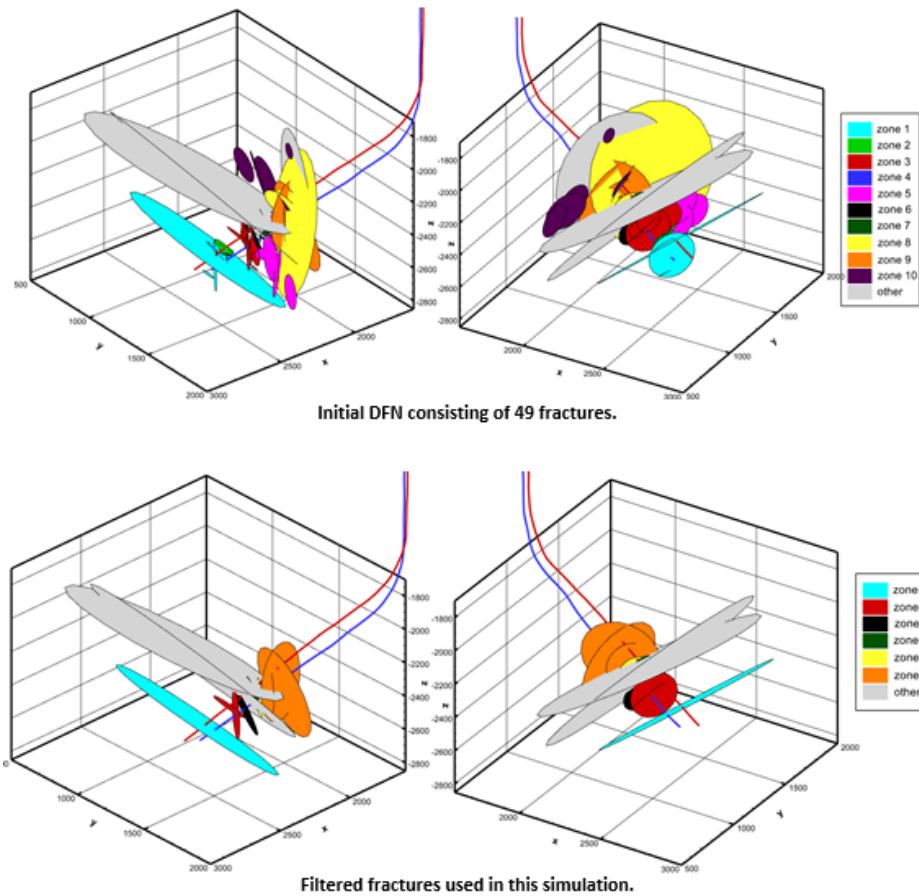


Figure 4. DFN geomechanical model used to design heat and tracer tests.

Task 2 – Design and Procurement

Due to field constraints and collaboration with the recirculation tests performed by Texas Tech, the project progressed from largely self-directed experiments to using multiple service providers to install coiled tubing, perform field pumping and chemical treatment, inject and analyze solute tracers, and monitor fiber optics. As a result, contracting was complicated and pushed the limits of the CSULB grants and contracts office. All contracting was completed in time for the field experiments, however.

Because we have transitioned to using an intervention coiled tubing deployment of fiber in 16B, we have concerns about recording strain in the formation using a fiber laying loosely in the coiled tubing. Formation strain due to fluid pressure must transfer through casing cement, casing, coiled tubing, capillary tubing, and finally fiber cable construction. We anticipate that strain transfer will be frequency dependent with higher frequencies transferred more efficiently due to momentum coupled friction. Our laboratory setup (Figure 5) uses ceramic piezoelectric stacks to induce strain in a pvc casing. Fiber is cemented outside and then laid inside the casing. All fiber is spliced into a single pathway so that DAS can record strain outside the casing and then inside using a variety of cable constructions. The piezoelectric actuators can vary strain in frequency between mHz and Hz. We do not attempt to replicate field conditions but seek to demonstrate the effective of frequency on strain transfer in frictionally coupled fiber.

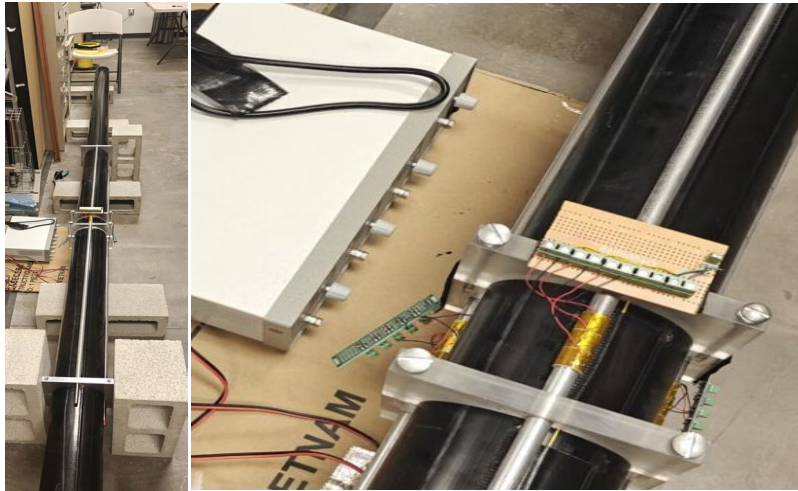


Figure 2. Laboratory stretcher monitored by a cemented fiber externally and loose fiber internally, to determine strain transfer with DAS.

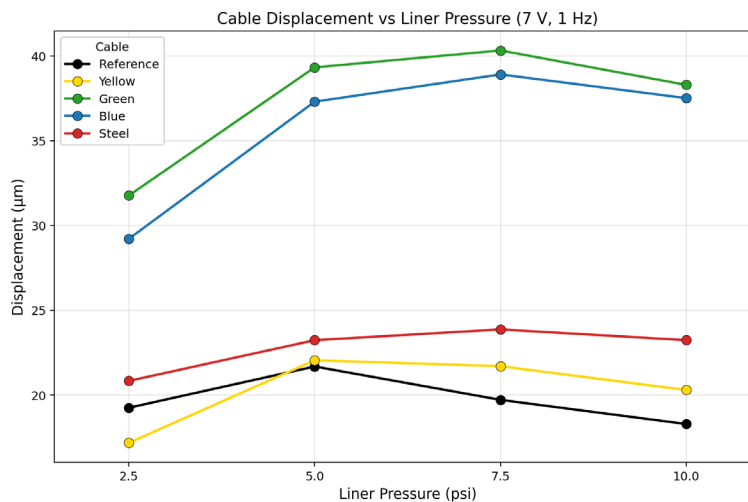


Figure 3. Preliminary results of laboratory stretcher experiments. Pressure was applied to an internal liner to press fiber against the model casing, representing gravity coupling in the real casing.

Task 3 – Numerical Model Refinement

The original proposal called for the use of reactive tracers, which were later deemed to be impractical given the high TDS of formation fluids. However, we proceeded to add capability of tracer reactivity to models for future use. CrunchFlow (Steefel and Lasaga, 1994) a reactive transport modeling framework capable of resolving coupled fluid flow and multicomponent fluid–rock interactions under dynamically varying injection and flowback conditions was used. The reservoir model is constructed using an equivalent permeability approach to represent a fracture network embedded within a low-permeability matrix.

Task 4 – Conduct Experiments

Huff-Puff field experiments were conducted successfully in well 16B. They were not as originally designed because the proposal was written before the behind-casing fiber failed. We proceeded to install coiled tubing with embedded fiber, in collaboration with Texas Tech, and carry out five injection/backflow experiments. The tests conducted and the specifics of the tests are provided in Table 1.

Table 1. Parameters of huff puff tests conducted at FORGE 16B

Start (local)	End (local)	CSULB Activity	Rate (bpm)	Inj/Ret Duration (min)	Inj Vol (bbl)	Ret Vol (bbl)	Chase Vol (bbl)	Tracer Mass (g)
8/26/25 13:38	8/26/25 17:01	Injection 1: Tracer 1	2.5	203	507		187	1000
8/26/25 17:01	8/26/25 21:20	Flowback 1	2.5	259		648		
8/27/25 9:20	8/27/25 13:58	Injection 2: Tracer 2	2.5	278	695		375	1000
8/27/25 13:58	8/27/25 20:06	Flowback 2	2.5	368		920		
8/28/25 6:12	8/28/25 6:17	Pulse 1: Inject	2.5	5	13			
8/28/25 6:19	8/28/25 6:24	Pulse 1: Flow	2.5	5		13		
8/28/25 6:25	8/28/25 6:35	Pulse 2: Inject	2.5	10	25			
8/28/25 6:36	8/28/25 6:46	Pulse 2: Flow	2.5	10		25		
8/28/25 6:46	8/28/25 7:01	Pulse 3: Inject	2.5	15	37			
8/28/25 7:01	8/28/25 7:15	Pulse 3: Flow	2.5	14		35		
8/28/25 7:17	8/28/25 13:10	Injection 3: Tracer 3	2.5	353	882		562	1000
8/28/25 13:10	8/28/25 21:12	Flowback 3	2.5	482		1205		
8/29/25 6:32	8/29/25 8:06	Injection 4: Tracer 4	5	94	470		150	1000
8/29/25 8:08	8/29/25 10:44	Flowback 4	5	156		780		
8/29/25 13:57	8/29/25 14:59	Injection 5: Tracer 5	7.5	63	470		150	1000
8/29/25 14:59	8/29/25 16:30	Flowback 5	7.5	90		677		

Figure 5 shows the temperature measured on the DTS during the experiments, which illustrates the timing and duration of the experiments. Relatively cool water can be seen to progress down the borehole during injection and then return upward during backflow. The velocity of these cool water slugs can be measured as isotherm slopes in the depth-time-temperature plots. These slopes were used to estimate flow in and out of individual stages.

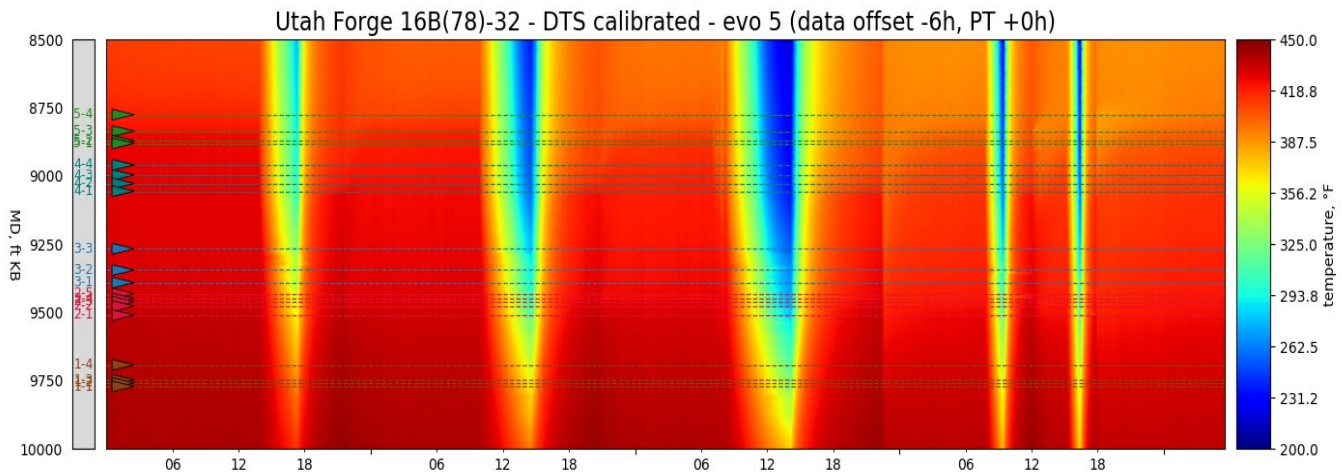


Figure 4. DTS measured temperature during the huff-puff experiments conducted at FORGE in 2025. Time is given in local time of day.

Figure 6. Shows the analysis of isotherms to produced flow profiles from Test 1. Note that the location of flow points can be seen as breaks in the isotherm slope and that those locations are not the same during injection and production. The magnitude of flow changes also between injection and production. This indicates the flow structure is not reversible, which significantly complicates the interpretation of testing. However, because no traditional flow surveys (e.g. spinner logs) were conducted this is the best reference we have for flow profile.

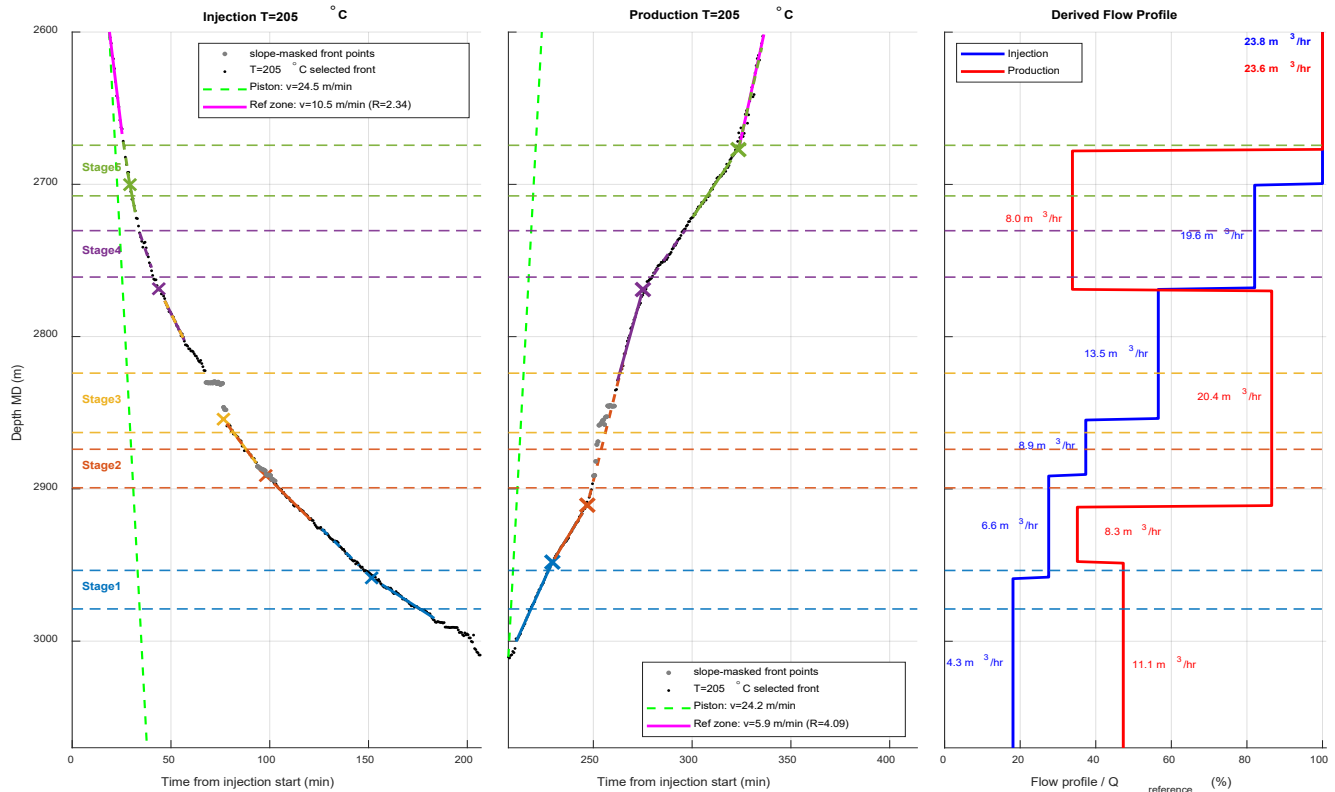


Figure 5. Isotherm slope estimation and the flow profile derived. The "X" marks show locations of strong inflow or outflow. Note that the location changes between injection and production as well as the magnitude of flow.

An objective of the project was to use strain to understand the permeability structure of the formation. However, strain was poorly measured by the fiber optic distributed sensing. Fiber can slip within the coiled tubing, which in turn can slip within the well casing. In addition, fiber strain measurements are equally sensitive to temperature and mechanical stretching. The variation in temperature during injection and production needs to be coupled from mechanical strain. We initially used DTS to accomplish this but the lower spatial and thermal resolution of DTS compared with DSS made this ineffective. We had better results using DAS temperature response to remove thermal signatures. An example of this exercise is shown in Figure 6. In the end, we were unable to see significant long term strain, although we were able to see strain rate signatures on DAS during our short pulse tests (Figure 7).

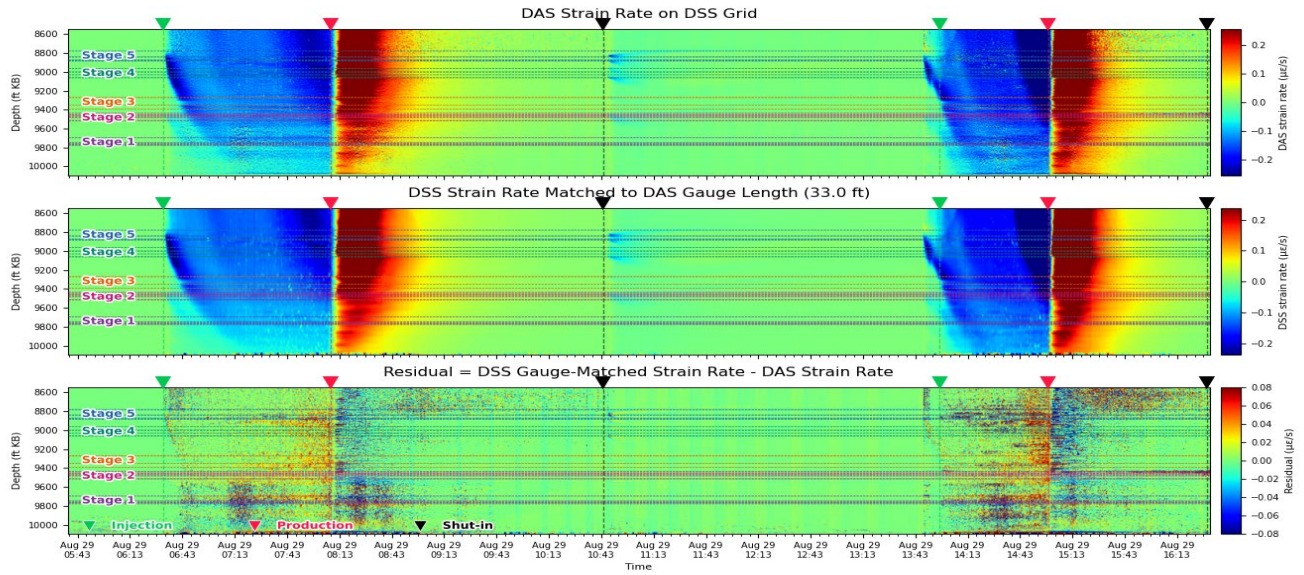


Figure 6. Separation of temperature and mechanical strain in FSDSS data.

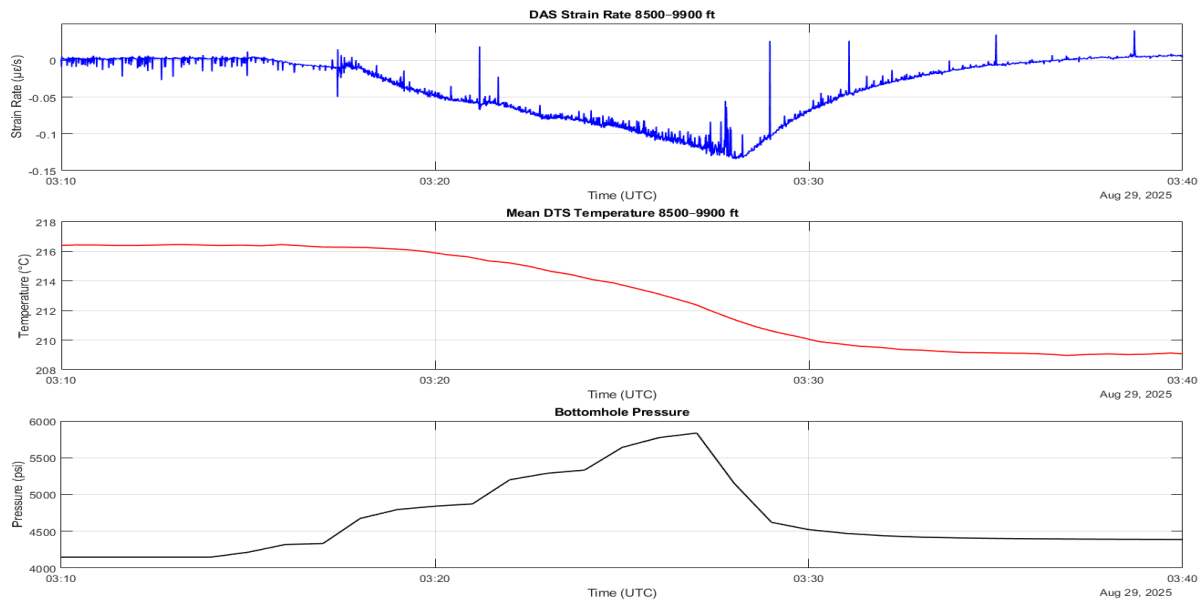


Figure 7. DAS response to pressure during short-term pulse testing.

Solute tracers injected and analyzed by Resman performed well. Recovery was excellent and produced quantitative breakthrough curves (Figure 9). We have begun some initial breakthrough analysis on these tests which will be better refined now that we have recovered flow profiles from the isotherm slope method. Tests were designed to compare different injection volumes and injection rates. The largest injection volume produced a significantly different breakthrough on return. This suggests that mixing may have occurred farther from the wellbore, but given the dynamic distribution of flow during the tests this conclusion is preliminary. Less variation was found with injection rate, although the largest rate showed a less dispersed breakthrough suggesting that fracture aperture opening with greater pressure may changed flow paths.

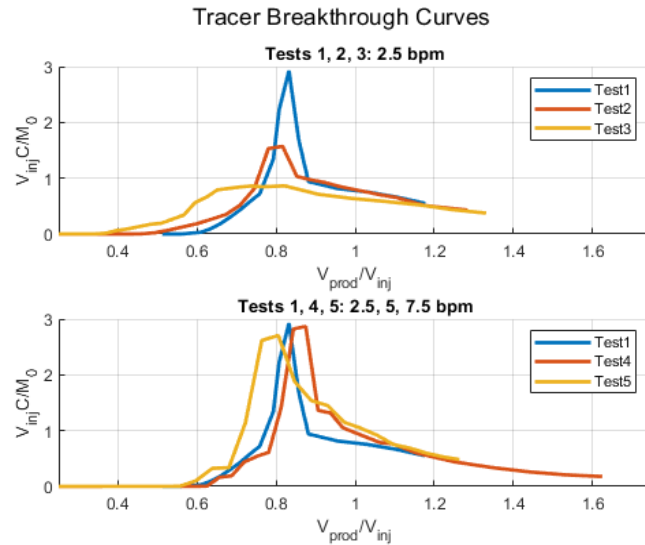


Figure 8. Breakthrough curves from solute tracers injected in 16B huff puff tests.

Task 5 – Modeling of Results

This task is currently underway. In order to simulate this multi-stage huff-puff test, an updated DFN (2025 V1) derived from FMI logs, Micro seismic data and hydraulic fracturing were used. To save computational cost not all fractures were used in the simulation. A total of 7 fractures were filtered from the initial DFN based on their connectivity with the two wells and to match the MD range of filed recorded DTS signature. Isolated fractures that were not connected to either well, fractures connected to only one well, and fractures located outside the DTS recording zones were excluded from the simulation.

Since the wellbore was not explicitly modeled in this simulation, the injection temperature had to be specified at the bottomhole. To account for this, the injection temperature for each stage was assumed to be equal to the temperature measured by the DTS at the corresponding bottomhole location. At each time step, the DTS temperature data for each stage were obtained and averaged, and the resulting value was used as the injection fluid temperature for that stage. Figure 9 shows a comparison of the variation in average bottom hole temperature (BHT) at the injection points in 16B over five cycles between the field results and the simulation results. Based on the plot, the temperature near the injection points almost reaches the injected fluid temperature during the injection phases, and then returns to the reservoir temperature during the shut-in and flowback periods. We are currently working on modeling of stage-by-stage temperature return.

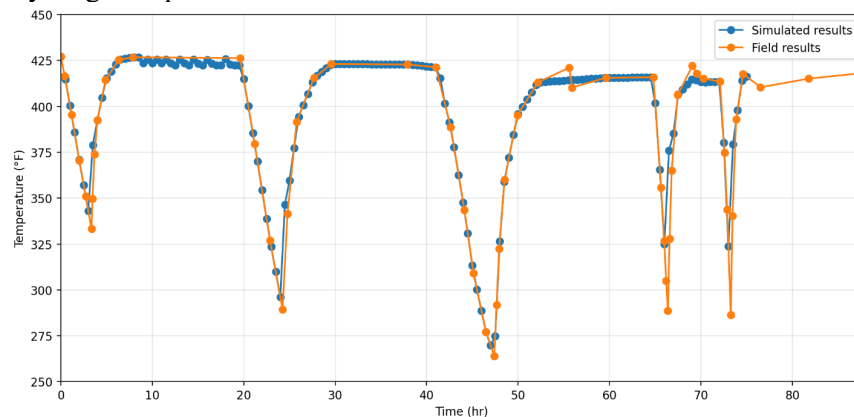


Figure 9. Average BHT at well 16B obtained in the field and from the simulation.

7. Challenges to Date

- After the original proposal was written, the last fiber behind casing failed in 16B. This made it impossible to carry out our primary proposal objectives.
- However, TTU was awarded a similar proposal to ours, involving fiber optic monitoring and tracer testing, but from well-to-well rather than huff puff configuration. This opened an opportunity to combine resources to install a coiled tubing fiber monitoring system which allowed us to carry out both of our proposed objectives. The project realignment required writing essentially new proposals and work plans, rebudgeting the both projects, designing new field deployments, and contracting vendors.
- Experiments were carried out successfully but we do not appear to have acquired usable strain data through the coiled tubing.
- Hydraulic structure changes between injection and withdrawal making some anticipated analysis methods infeasible.

8. Conclusion and Plans for the Future

- We have met our Go-No/Go decision points
- Tests were completed successfully and data are being interpreted.
- The complexity of the test behavior and the poor strain response are delaying some aspects and simulation of the data.
- A no-cost extension will allow us additional time to reevaluate the analysis and simulation and produce a recommended workflow for huff-puff testing.
- Our preliminary analysis is that if FORGE is taken as a typical example, huff-puff testing may be less useful than previous forward simulations suggested. Injection and withdrawal create different hydraulic signatures so that the tracers are not reciprocal.

9. Geothermal Data Repository

- We will submit a joint project GDR database between CSULB and Texas Tech. The data are ready for upload but have yet to create an archive for it. We will ask for guidance from FORGE before we proceed.

10. Publications and Presentations, Intellectual Property (IP), Licenses, etc.

- Becker, M. W., & Ifrene, G. (2026). *Flow profiling of a geothermal well using an isotherm-slope method applied to fiber-optic distributed temperature sensing data: An example from Utah FORGE EGS well 16B(78)-32*. Manuscript submitted to *Geothermics*; in review.
- Ifrene, G., Becker, M. W., Jurick, D., & Guzik, A. (2026). *Rayleigh-frequency-shift distributed strain sensing (RFS-DSS) of huff-puff tests conducted at Utah FORGE*. Submitted conference abstract.
- Ifrene, G., Becker, M. W., & Maloney, G. (2026). *Fiber-optic monitoring of a single-well huff-and-puff test at Utah FORGE*. ARMA Paper 26-0489, 60th U.S. Rock Mechanics/Geomechanics Symposium, Tucson, Arizona.
- Lee, S. H., Ghassemi, A., & Becker, M. (2026). *Numerical modeling of a huff-and-puff tracer test at Utah FORGE*. ARMA Paper 26-0499, 60th U.S. Rock Mechanics/Geomechanics Symposium, Tucson, Arizona.