ID^2

1. Integrated Diagnostics to Interpret Doublet Heat Sweep Efficiency

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- Subcontractors and/or Participating Organizations: Resman; Neubrex Energy Services; University of Utah; Precise Downhole Solutions
- Project Start and End Date: April, 2024 – June, 2027

2. Project Objectives and Purpose

- The objectives of the ID2 project are to:
  - Characterize the effective heat exchange area of the Utah FORGE enhanced geothermal system;
  - Characterize the number and uniformity of fracture flowing pathways;
  - Integrate diagnostics and compute the heat sweep efficiency through numerical simulations.

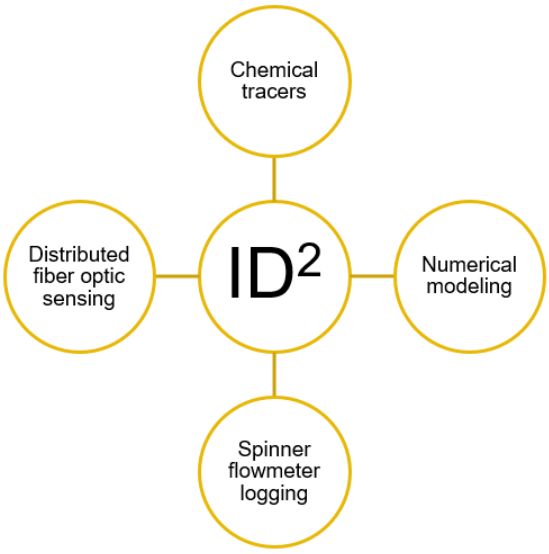


Figure 1. We use distributed fiber optic sensing and chemical tracer measurements to simulate the long-term heat sweep efficiency of the Utah FORGE EGS.

- The impact of the research on geothermal development includes:
  - Once developed and validated, our integrated tracer and fiber-optic diagnostic methods could help developers estimate effective heat-exchange area, assess completion performance, and identify opportunities for remediation. If the initial completion provides insufficient heat-exchange area, adding stages or restimulating existing stages may improve heat recovery and strengthen long-term project economics.
  - Chemical tracing and fiber optic thermal tracing methods we develop to estimate the uniformity of fracture flowing pathways can be used in lieu of expensive production logs, lowering operating expenses for EGS developers. Decisions can be justified to conduct remedial workovers to shut-off thief zones.
  - We transferred learnings from high-temperature fiber optic deployments in steam-assisted gravity drainage applications to geothermal.
  - We increased the number of conservative chemical tracers qualified for geothermal applications.
  - Simulations of long-term heat production performance will inform the economic feasibility of EGS developments.

3. Technical Barriers and Targets

- Our project addresses the following technical challenges

Table 1. Summary of technical challenges addressed by the project

Technical Barrier	*Significance*
Lack of reliable method to forecast thermal breakthrough in EGS projects	EGS projects have 15+ year timeframes; need assurance of stable produced fluid temperatures
Methods to determine fracture number, flow uniformity, surface area are unproven	These variables are primary inputs into models used to forecast thermal breakthrough
Insufficient number of chemical tracers qualified for geothermal applications	2-mile wells can have 50+ fracture stages; need as many unique tracers to characterize flow
Survivability of fiber optic cables in EGS wellbores	Distributed fiber optic sensing a key source of data to inform flow and fracture characteristics

- The following technical targets and status are summarized below:
  - Diagnose flow uniformity using distributed fiber optic sensing of thermal slugs – Completed
  - Determine the number of fracture flowing pathways using fiber optic strain/temperature sensing – Completed
  - Demonstrate reversibly adsorbing chemical tracer methods to estimate fracture surface area – In Progress
  - Forecast the heat sweep efficiency of the Utah FORGE EGS – In Progress

4. Technical Approach

- The following methods were used to characterize the EGS system for heat sweep simulations:
  - Distributed fiber optic sensing
    - The permanent fibers we planned to use in the 16B failed
    - We brought on Precise DHS as a collaborator to install coiled-tubing deployed fiber
    - DAS/RFS-DSS/DTS for thermal slug flow profiling (producer flow uniformity) and number of fractures identification
  - Spinner injection logs for 16A near wellbore injector flow uniformity
  - Conservative (non-reactive) chemical tracers for inter-well flow volume
  - Retarding tracers for the fracture flow heat exchange area
    - Our original 5 reversibly sorbing candidate tracers did not pass qualification tests
    - We used a novel freshwater slug injection in our field test to analyze heat exchange area from cation exchange reaction modeling
  - Numerical modeling of tracer adsorption/desorption for heat exchange area and long-term heat sweep efficiency reservoir simulations

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

- Figure 2 provides a summary of the project timelines and tasks completed. Key milestones and their date of completion follow.

	Project Subtasks	Year 1	Year 2	Year 3
1.1	Lab experiments to characterize reversibly adsorbing tracers	✓		
1.2	Lab experiments to validate fiber-optic-based thermal slug tracer tracking	✓		
1.3	Lab experiments to qualify conservative chemical tracers	✓		
1.4	GNG #1: Demonstrate qualified chemical and thermal tracing methods	✓		
2.1	Develop and validate numerical models for tracer characterization		✓	
3.1	Submit reports and upload data to the GDR.	✓		
4.1	GNG #2 – Design and plan the field experiments for Utah FORGE approval.		✓	
5.1	RFS-DSS measurements for strain sensing of fracture locations		✓	
5.2	Conservative chemical tracer deployment in stimulation fluid		✓*	
5.3	Fiber-optic-based thermal slug tracking for production log on the 16B		✓	
5.4	Spinner flowmeter injection log		✓	
5.5	Conservative chemical tracer deployment in circulation fluid		✓	
5.6	Reversibly adsobring tracer deployment for heat exchange area		✓	
6.1	Calibrate the numerical model and predict the heat-sweep efficiency			O
6.2	Update heat-sweep efficiency predictions after repeated field experiments			O
7.1	Conduct a repeat field test			O
7.2	Repeat tracer experiments to estimate heat exchange area			O
7.3	Repeat RFS-DSS experiments to estimate the number of flowing fractures			O
7.4	Repeat fiber optic experiments to estimate the uniformity of flow			O

*Completed by the Utah FORGE team prior to start of the project

Figure 2. Project timeline

- Negotiated and executed the subaward agreement (May, 2024)
- Milestone 1.1.B - Design, fabricate and verify a flow reactor capable of obtaining a relative retardation factor using established tracer standards and a flow cell filled with drill cuttings from the FORGE site (May, 2025)
- Milestone 1.2.A - Instrument the lab scale flow loop and conduct thermal tracer experiments. Create and apply a finite difference model to extract flow velocities from thermal velocities measured in lab experiments (January, 2025)
- Go/No-Go Decision Point: Subtask 1.4 – Demonstrate qualified reversibly adsorbing and conservative chemical tracers for field deployment (March, 2025)
- Milestone 1.3.A - Source candidate chemical tracers. Design and complete lab qualification tests. (December, 2025). Note: we used cation tracers since none of the 5 organic reversibly sorbing tracer candidates were qualified.
- Go/No-Go Decision Point: Subtask 4.1 – Design and plan the field experiments for Utah FORGE approval. Prior to field deployment, the recipient will present the deployment plan and NEPA and/or other environmental approval(s) to Utah FORGE for approval, prior to mobilizing any equipment or service. We will provide a detailed plan for field activities and provide quotes and a budget (AFE) for Utah FORGE approval. (July, 2025)
- Milestone 5.1.B - Obtain DSS measurements and provide a summary report cataloging fracture flowing pathways informed by numerical simulations. (September, 2026)
- Milestone 5.2.A - Trace the stimulation fluid on wells 16A and 16B (Accomplished by RESMAN in March/April 2024).
- Milestone 5.4.A - Run the spinner flowmeter log on the injection well and characterize the injection profile (August 2025).
- Milestone 5.5.A - Design and execute the conservative and reversibly adsorbing tracer sweep program. Obtain samples of produced fluid during circulation tests (August 2025)
- Milestone 5.6.A - Obtain/install field equipment for a field tracer test. Trace circulation fluid and obtain at least 10 samples of produced water. (August 2025)

6. Technical Accomplishments

- We installed an instrumented coiled tubing string in the 16B containing 1 multimode fiber for DTS, 2 single-mode fibers for DSS and DAS, and a bottomhole pressure and temperature gauge[1] (**Figure 3**). One of the single-mode fibers was an experimental test to enhance strain transfer to the fiber optic cable. This fiber failed shortly after installation in the middle of the well, likely due to thermal expansion of the silicone strain transfer gel. Despite this setback, the other instruments provided valuable data on the geothermal gradient, microseismic events, flow distribution and number of fractures contributing to flow in the well.

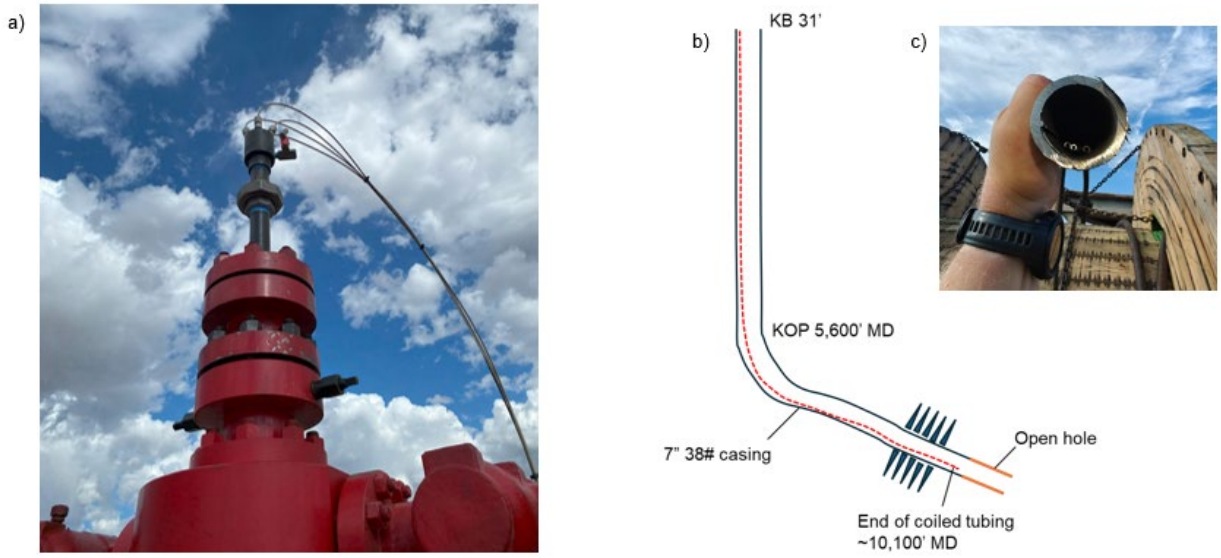


Figure 3. a) Photograph of 16B wellhead with instrumented coiled tubing (ICT) string installed, b) wellbore diagram depicting coiled tubing landing depth, c) photograph of cross-section of ICT and ¼" capillary tubes containing the fiber optic sensors

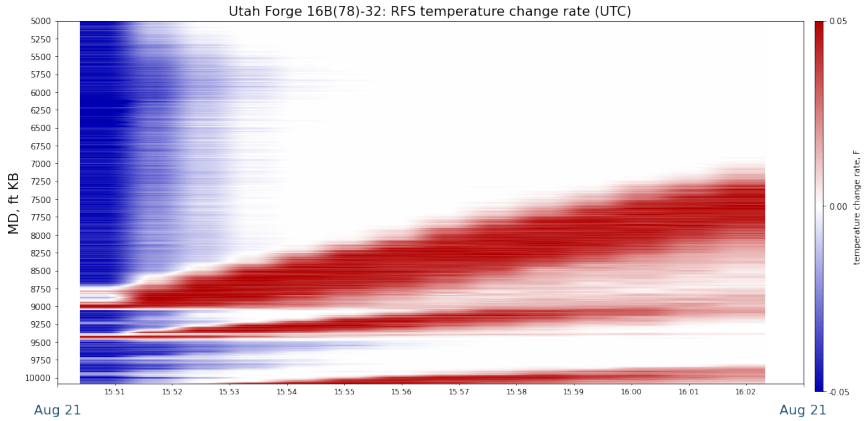


Figure 4. Waterfall plot from one of the thermal slugging events used to infer production allocation along the 16B during the circulation test.

[1] Leggett, S., Keough, D., Andriianov, A., Jurick, D. 2026. Deploying Coiled-Tubing Conveyed Fiber Optic Cables at the Utah FORGE Enhanced Geothermal System. Stanford Geothermal Workshop.

- We executed a week-long circulation test that included chemical tracer, fiber-optic sensing, bottomhole pressure/temperature, and spinner production log diagnostics[2]. Over 90,000 bbls of brackish water was injected at 10 BPM with a maximum production rate of ~6.5 BPM. Water losses to the formation decreased over the duration of the test and were still decreasing when the test was stopped. The inline production turbine meter upstream of the geothermal separator provided stable flow measurements in 2025. Steam and mineral scale production downstream of the geothermal separator was observed, causing questions of reliability in those flow measurements.

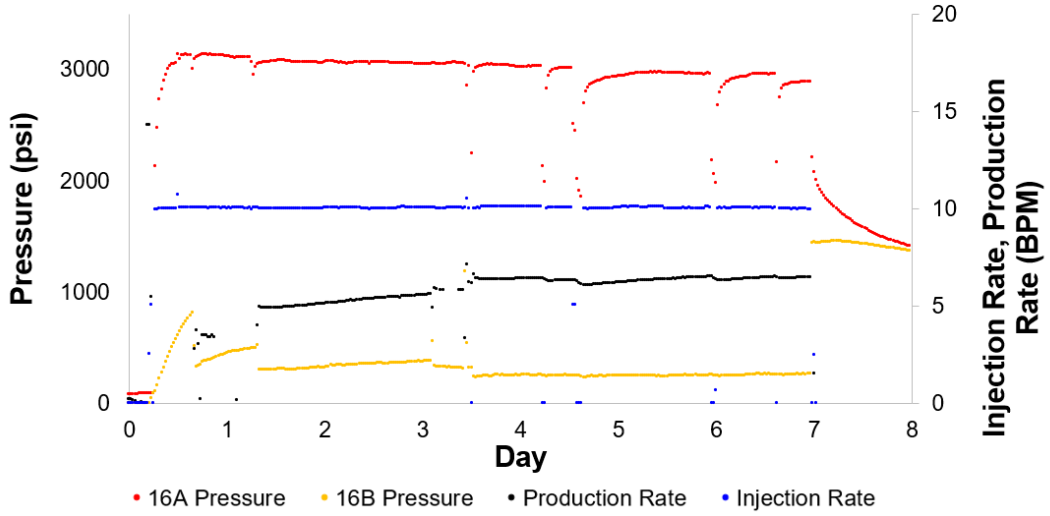


Figure 5. Surface pressure and production rate measurements for the 1-week circulation test.

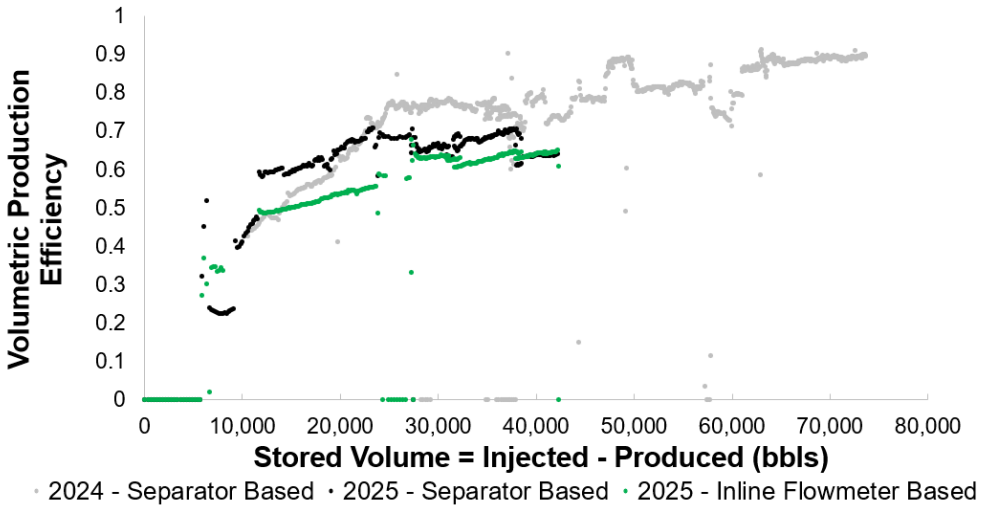


Figure 6. Volumetric production efficiency during the August 2025 1-week circulation test compared to the 2024 test. The inline flowmeter measurements are interpreted to be more reliable than the turbine meters downstream of the geothermal separator.

[2] Leggett, S., Morias de Almeida, C., Nakamoto, R., Nwubueze, Q. Seo, H., Jurick, D. Giri, P. Yaw Oforio, D. Yuan, Q. Abdellatif, M. 2026. Integrated Diagnostics for Interpreting the Efficiency of the Utah FORGE EGS. Stanford Geothermal Workshop

- During the 1-week circulation test, we executed a negative tracer test by co-injecting a conservative geothermal tracer with a 3,000 bbl freshwater slug[3]. This was followed by an additional conservative tracer test in the second half of the circulation test. Results from residence time distribution analyses of the 2025 conservative tracer test compare with August 2024 results as shown in the following table, indicating an average swept pore volume of 15,439 bbls, and an average modal or peak volume of 4,721 bbls. Analysis of the negative tracer test is still forthcoming.

Table 2. Comparison of Residence Time Distribution Analysis of Conservative Tracer Sweeps.

	August 2024	August 2025 – Pulse 1	August 2025 – Pulse 2	Average
Pore Volume (bbl)	14,870	16,008	6,320*	15,439*
Modal Volume (bbl)	4,570	5,202	4,390	4,721

**Pore Volume average only considers August 2024 and August 2025 – Pulse 1 . The circulation test ended before adequate samples could be obtained to fully characterize the tail of the tracer production curve, and thus the pore volume, in Pulse 2.*

- Validation of a new fiber optic thermal slug tracking interpretation method at the lab scale, and execution at the Utah FORGE site aided in determining the uniformity of fracture flowing pathways[4]. In combination with spinner PLT measurements, we found that the 16B production profile remained relatively stable between August 2024 and August 2025 circulation tests, with two-thirds of the flow from Stages 4 and 5 (**Figure 7**). No flow contribution is attributed to Stages 1 and 3; the remaining one-third comes from Stage 2 and the open hole section. Interestingly, the injection profile changed substantially from 2024 to 2025, with a shift to nearly 50% of injected fluid exiting the well at Stage 10 (**Figure 8**).
- Using locally cool spots from distributed temperature sensing measurements, we estimate that there are eight inflow locations in the cased section of the 16B where fiber optic measurements are available (**Figure 9**). These inflow locations align closely with perforated intervals and cross-well frac hits during stimulations. From this, we can hypothesize the existence of eight flowing fracture pathways between the 16A and 16B wellbores over the cased section. In addition, we infer from the fiber-optic based production logs that there is at least one flowing fracture pathway connected to the open hole section.

[3] Heshmat, M., Leggett, S., Yuan, Q. 2026. Analytical Modeling of Tracer Pulse Tests with Significant Background Concentration at the Utah FORGE Geothermal Site. *Geothermics.* 142. https://doi.org/10.1016/j.geothermics.2026.103817

[4] Nakamoto, R., Leggett, S. 2026. Analytical Model for Thermal Slug Tracking in Enhanced Geothermal Systems. *Geothermics.* Vol. 136. https://doi.org/10.1016/j.geothermics.2026.103680

Stage	Perforated interval [ft]		PLT 2024		Thermal slug 2024	Thermal slug 2025
5	8774	8778	trace	25.9%	61.3%	65.8%
	8834	8838	10.8%			
	8870	8874	2.6%			
	8879	8883	12.3%			
4	8958	8962	11.4%	37.8%		
	8995	8999	6.3%			
	9026	9030	11.9%			
	9054	9058	8.2%			
3	Below 9240		36.3%		0%	0%
2					32.1%	21.6%
1					0%	0%
OH					6.6%	12.6%

Figure 7. 16B production allocation by stage for three independent measurements across August 2024 and August 2025 circulation tests.

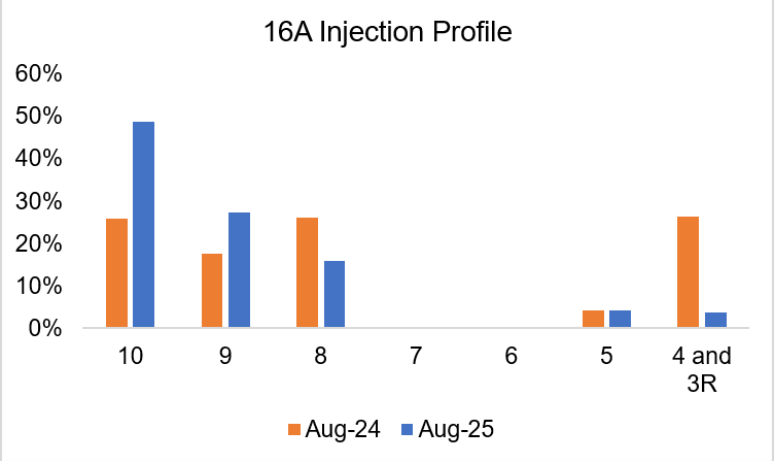


Figure 8. 16A Comparison of injection allocations from spinner logs from August 2024 and August 2025.

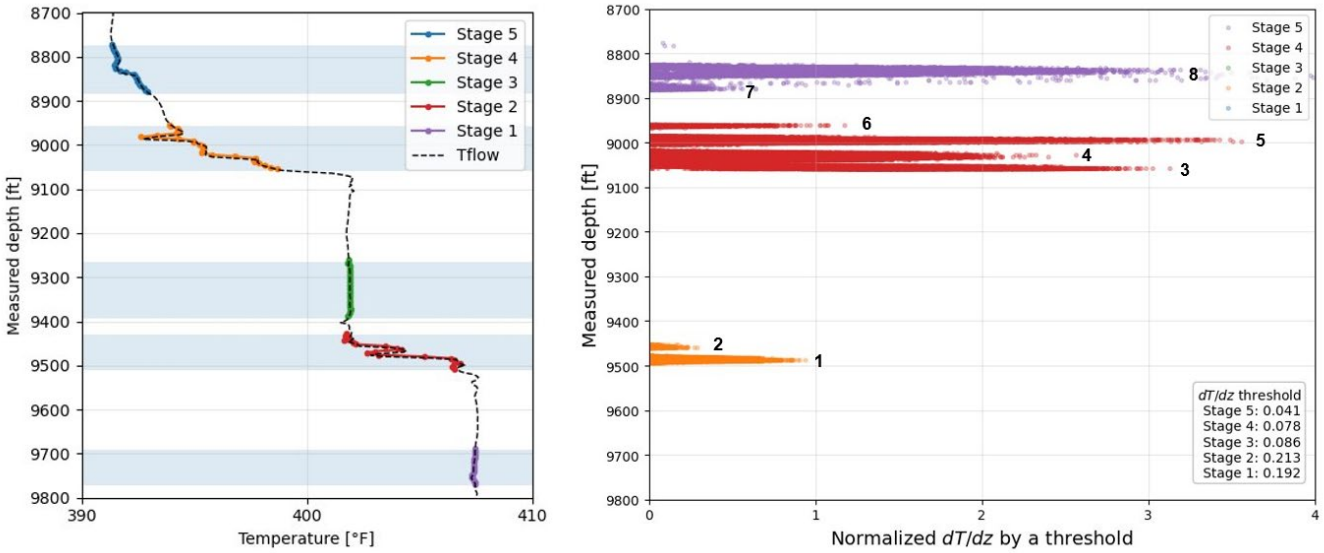


Figure 9. The DTS profile (left) shows localized cool spots, interpreted as inflow locations from fracture flowing pathways. By calculating the spatial gradient of temperature every 4-feet along the wellbore and normalizing by the anticipated cooling due to 1% flow contribution from that interval, clear inflow zones can be identified (right).

7. Challenges to Date

- Failure of permanent fiber in the 16B
  - We had planned to use permanent fibers previously installed in the 16B for our experiments.
  - We modified our budget to install a coiled tubing fiber optic string in the 16B.
  - We executed the installation and performed our experiment to meet our objectives.
- Lessons learned from the instrumented coiled tubing deployment
  - Digital depth record when RIH with coil was not obtained, had to rely on manual depth counter, limiting post-job analysis of friction and possible identification of sand in the wellbore
  - Compressed timeframe to construct and deploy experimental single mode fiber resulted in silicone gel only partially filling capillary tube. Fiber failed at or near gel-nitrogen interface, likely due to thermal expansions. Neubrex was still able to obtain DSS and DAS measurements by using Wavelength Division Multiplexing.
  - To conserve budget, we did not install a cell modem to transmit data from the bottomhole pressure and temperature gauges but relied on periodic data downloads from a micro-SD card. Unfortunately, we experienced data losses due to accidental memory wipes. We have since tied the sensors in to Utah FORGE's surface data acquisition system.
- Reassignment of responsibilities for reversibly adsorbing lab-scale chemical tracer qualification tests
  - We executed a budget revision for Texas Tech to assume responsibility for the lab-scale chemical tracer qualification experiments. The transfer delayed the experiments, but they were completed this year.
  - Challenges were encountered with access to water analysis equipment at TTU such as ICP-OES, ICP-MS. These were overcome by contracting a 3rd party lab to analyze tracer samples.
- Non-uniqueness of reversibly sorbing tracer analysis
  - Estimating the heat exchange area from reversibly sorbing tracers has proven difficult due to the non-uniqueness in fitting analytical models to the tracer return curve measurements. To supplement this method, we will consider other means of estimating the fracture surface area. Since the

conservative tracers provide an estimate of the fracture pore volume, we can estimate the heat exchange area from the average fracture width, estimated by other means (e.g. fracture models, fiber optic strain measurements, image logs).

8. Conclusion and Plans for the Future

- Conclusions to date:
  - The diagnostics provided by the instrumented coiled tubing string provided valuable data to characterize the Utah FORGE EGS. Survivability of strongly coupled fiber optic cables remains a challenge in EGS environments. Coiled tubing deployments offer an alternative deployment approach for fiber optic cables in EGS wellbores.
  - The Utah FORGE EGS demonstrated a relatively stable inter-well, tracer-contacted, pore volume between 2024 and 2025 circulation tests of ~15,400 bbls. Losses to the formation remain significant, with comparisons between 2024 and 2025 tests obscured by reliability questions of the flowmeters downstream of the geothermal separators.
  - Production along the 16B is not uniform. Stage intervals 1 and 3 do not appear to contribute to production, where stages 4 and 5 appear to contribute significantly based on thermal-slug based production logging.
  - There are eight unique inflow intervals that contributed to flow between the 16A and the cased section of the 16B during August 2025 circulation. There is also at least one inflow interval connected to the open hole section of 16B. From this, the existence of at least 9 unique flowing fracture pathways is hypothesized, although their independence in the reservoir is uncertain.
- Future plans:
  - Task 6. Next steps include integrating the diagnostic measurements to create a model of the fracture flowing pathways for long-term heat production and heat-sweep efficiency forecasting. These efforts are underway.
  - Task 7. An additional field deployment is being contemplated, either overlapping with or after the Utah FORGE 2026 extended circulation test. Specifics need to be confirmed with the Utah FORGE leadership team, but objectives may include replacing failed fiber in the coiled tubing string or conducting new tracer tests.

9. Geothermal Data Repository

- Tracerco High Temperature Tracer Thermal Stability Testing - https://gdr.openei.org/submissions/1729
- Fiber Optic Thermal Slug Experiments - https://gdr.openei.org/submissions/1728
- 2024 Annual Workshop Presentation - https://gdr.openei.org/submissions/1651

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

- Peer-reviewed journal publications:
  - Nakamoto, R., Leggett, S. 2026. Analytical Model for Thermal Slug Tracking in Enhanced Geothermal Systems. *Geothermics.* Vol. 136. https://doi.org/10.1016/j.geothermics.2026.103680
  - Heshmat, M., Leggett, S., Yuan, Q. 2026. Analytical Modeling of Tracer Pulse Tests with Significant Background Concentration at the Utah FORGE Geothermal Site. *Geothermics.* 142. https://doi.org/10.1016/j.geothermics.2026.103817
  - Nakamoto, R. Leggett, S. 2025. Development of a Transient Wellbore Heat Transfer Model Validated with Distributed Temperature Sensing Data. Sensors. Vol. 25, Iss. 21. https://doi.org/10.3390/s25216583
- Conference papers:
  - Nakamoto, R., Leggett, S. 2026. Numerical and Analytical Approaches to Production Logging in EGS Using Fiber-Optic Thermal Slug Tracking. 60th US Rock Mechanics Geomechanics Symposium. June 21-24, 2026. Tucson, AZ.

- Heshmat, M., Leggett, S. 2026. Analytical Modeling of a Negative Sorbing Tracer Pulse Test with Significant Background Concentration at the Utah FORGE Geothermal Site. 60th US Rock Mechanics / Geomechanics Symposium. June 21-24, 2026. Tucson, AZ.
- Leggett, S., Keough, D., Andriianov, A., Jurick, D. 2026. Deploying Coiled-Tubing Conveyed Fiber Optic Cables at the Utah FORGE Enhanced Geothermal System. Stanford Geothermal Workshop. https://pangea.stanford.edu/ERE/db/IGAstandard/record_detail.php?id=38328
- Leggett, S., Morias de Almeida, C., Nakamoto, R., Nwubueze, Q. Seo, H., Jurick, D. Giri, P. Yaw Oforio, D. Yuan, Q. Abdellatif, M. 2026. Integrated Diagnostics for Interpreting the Efficiency of the Utah FORGE EGS. Stanford Geothermal Workshop. https://pangea.stanford.edu/ERE/db/IGAstandard/record_detail.php?id=38329
- Nwabueze, Q. Leggett, S. 2025. Application of Strain Transfer Model for Fracture Conductivity Modeling and Monitoring of Enhanced Geothermal Systems. Stanford Geothermal Workshop 2025. https://pangea.stanford.edu/ERE/db/IGAstandard/record_detail.php?id=38081
- Rose, P. Abdellatif, M. Yuan, Q. Leggett, S. The Use of Reversibly Sorbing Tracers for Characterizing Reservoir Fracture Surface Area in Engineered Geothermal Systems. Stanford Geothermal Workshop 2025. https://pangea.stanford.edu/ERE/db/IGAstandard/record_detail.php?id=38107