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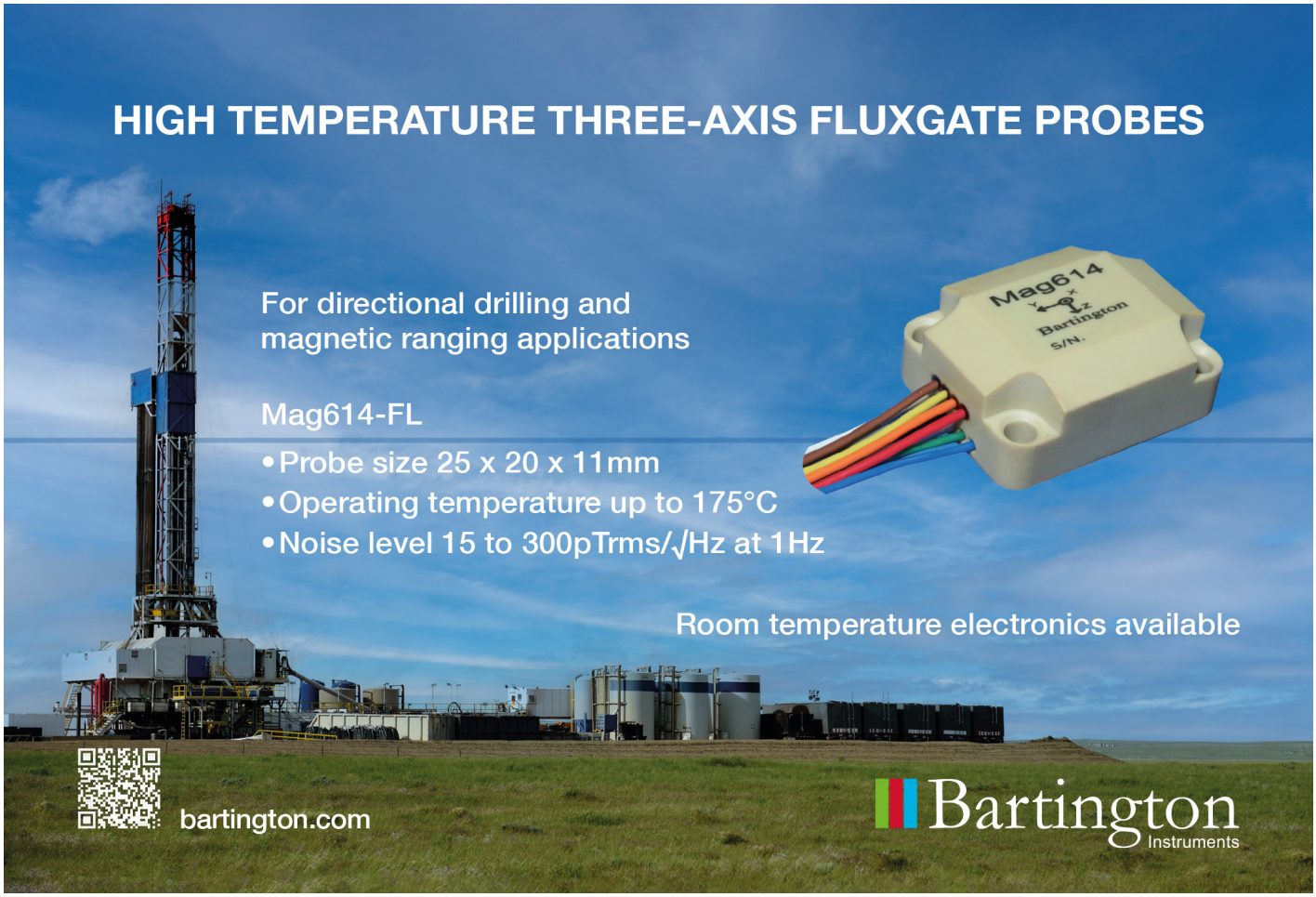
Nanoparticle tracer technology drives innovation in enhanced geothermal systems' efficiency, improves economics

The U.S. Department of Energy (DOE) established the Frontier Observatory for Research in Geothermal Energy (FORGE) to optimize Enhanced Geothermal Systems (EGS). Using cutting-edge techniques, including ultra-high-resolution, ultra-high-temperature nanoparticle tracers, FORGE researchers analyze complex fracture network flow behavior and improve EGS performance for enhanced economy and efficiency.

TALGAT SHOKANOV, JOHN OLIVER and **QUAN GUO,** QuantumPro, Inc.; **JOHN MCLENNAN,** University of Utah; and **KEVIN ENGLAND,** E-K Petro Consulting LLC

Expanding the role of geothermal in the U.S. energy mix. Geothermal energy is experiencing a surge in both interest and investment, driven by its baseload power capabilities, abundance, and environmental benefits. This renewed focus is particularly relevant, given the immense energy demands of A.I.-powered data centers. These data centers—currently consuming 3–4% of total U.S. energy—are projected to account for a staggering 11–12% of total demand by 2030 (McKinsey & Company, 2024), making the search for reliable and sustainable energy solutions critical.



Several major tech companies are leading the charge in geothermal adoption. Google—already utilizing a geothermal plant in Nevada through a partnership with Fervo Energy—is planning a second geothermal project with NV Energy. Meta is also embracing this technology by collaborating with Sage Systems on a groundbreaking geothermal project in Texas.

The Meta initiative is the first of its kind east of the Rockies, and it underscores the growing recognition of geothermal's potential to meet the renewable and overall energy needs of data centers. Both Google and Meta have explicitly cited the energy demands of their data centers and their commitment to decarbonization as key factors driving their investment in geothermal energy.

Despite its potential, geothermal energy currently contributes a mere 0.4% to U.S. utility-scale electricity generation (U.S. Energy Information Administration, n.d.), a contribution dwarfed by fossil fuels (60%), wind (10.2%) and solar (3.9%). However, the Department of Energy (DOE) has ambitious plans to expand geothermal's role, aiming for 90 GW of generating capacity by 2050—a more than 20-fold increase from 2024's installed capacity (DOE, 2024).

A key element of reaching the DOE goal is achieving a target cost of $45/MWh. Currently, Enhanced Geothermal System (EGS) costs range from $65/MWh to $100/MWh, based on publicly available power purchase agreement pricing (National Renewable Energy Laboratory, 2024). Therefore, driving down costs through technological innovation, scale and advancement is crucial for wider geothermal adoption and is recognized by the DOE as essential for achieving its capacity growth targets.

FORGE: LEADING THE WAY IN GEOTHERMAL INNOVATION AND COST REDUCTION

To further accelerate geothermal energy development, the DOE established a dedicated field laboratory, FORGE, in 2016, **Fig. 1.** Managed and operated by the University of Utah, the FORGE site in Milford Valley, Utah, is a dedicated laboratory, where scientists and engineers develop, test and accelerate breakthroughs in EGS technologies and methods. The work conducted at the FORGE site is recognized as crucial for advancing geothermal energy and unlocking the full potential of this clean and reliable energy source, to contribute to a more sustainable energy future. The DOE's commitment to geothermal research is evidenced by FORGE's October 2024 announcement of an additional $80 million in funding through 2028.

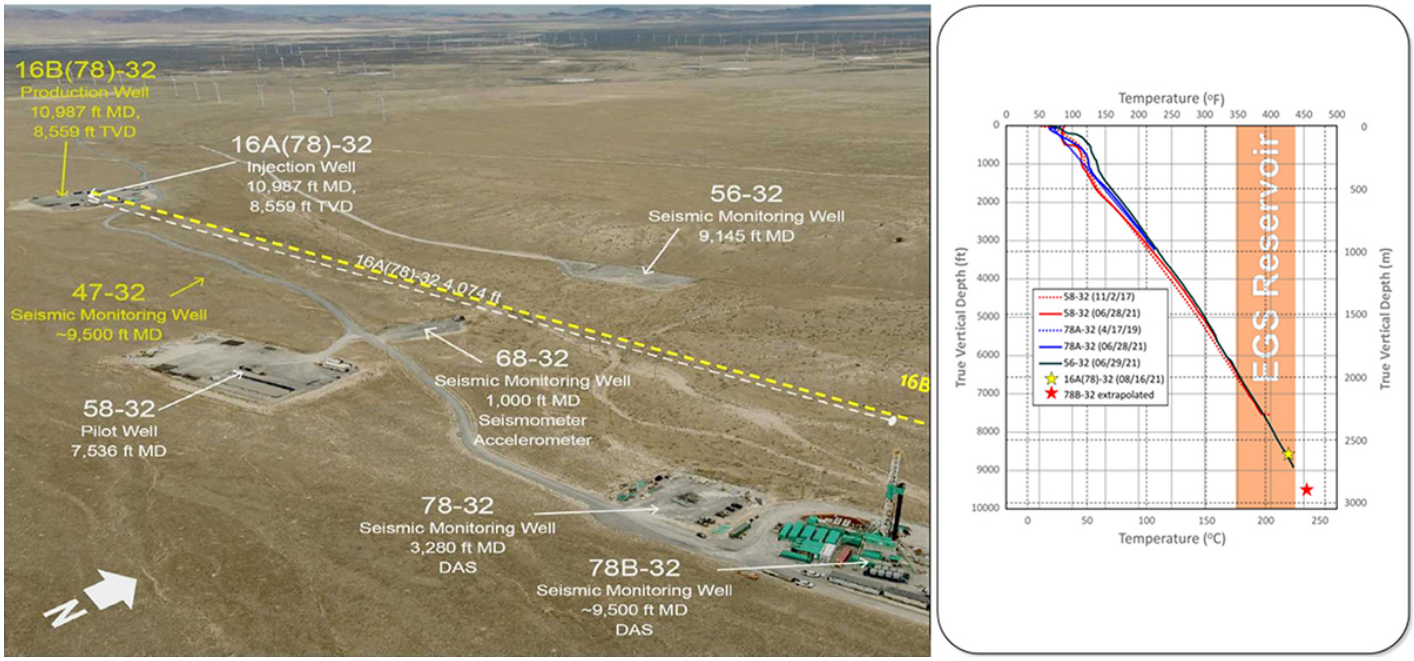


Fig. 1. A view of the Utah FORGE test site. Image: FORGE.

The FORGE EGS test site is configured with dual wells, comprised of an injection well, 16A(78)-32, and a producer well, 16B(78)-32, which are drilled 300 ft apart to a depth of approximately 8,500 feet TVD, each, **Fig. 2.** The injection well is stimulated via multi-stage hydraulic fracturing to create or enhance connection pathways to the adjacent production well. This fracturing process is crucial for establishing an effective Enhanced Geothermal System, as it allows for the circulation of water between the wells and the extraction of heat from the hot rock. Enhancing this connection pathway increases overall EGS efficiency, which is a focus area for improvements identified by FORGE researchers.

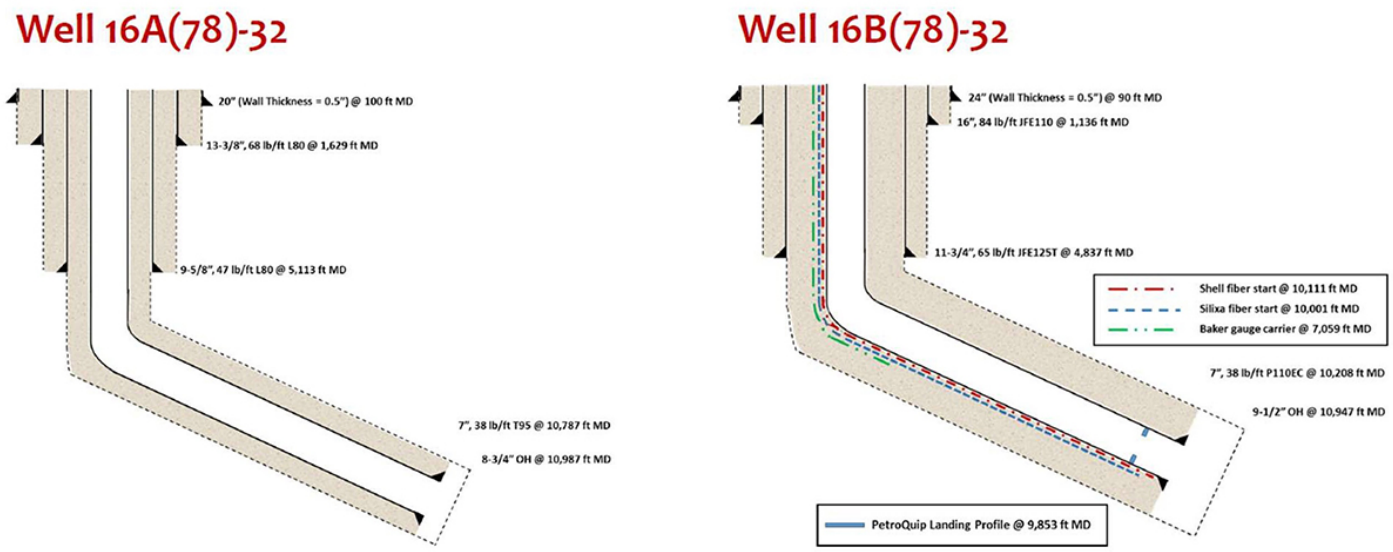


Fig. 2. The Utah FORGE "doublet" well design. Image: FORGE.

OPTIMIZING WELL STIMULATION FOR EFFICIENT GEOTHERMAL ENERGY PRODUCTION

Well stimulation is a major cost driver for EGS, second only to drilling. Reducing these costs is essential for wider EGS deployment and making geothermal a competitive clean energy source. The FORGE team is actively researching methods to make stimulation more efficient.

Effective EGS well stimulation requires creating or enhancing the fracture network between the injector and producing wells. Ideally, the injected water flows evenly through the fractures connecting to the producer, maximizing contact with the hot rock and producing higher-temperature water. This hotter fluid carries greater energy potential to the surface power plant, leading to increased electricity generation.

If fluid flow becomes concentrated in specific fractures, the overall heat exchange is less efficient. The water doesn't have sufficient contact time with the hot rock to reach optimal temperatures, reducing the system's energy output and economic viability. Conversely, some fractures may fail to contribute to fluid flow or have disproportionately low production, hindering the overall efficiency of the EGS system. Evenly distributed fluid flow maximizes this exchange, resulting in greater energy production and improved economics. In essence, the well doublet, fracture network and surrounding hot rock constitute a heat exchange system.

FORGE TEAM SEEKS NEW TECHNOLOGY TO MAP FRACTURE NETWORKS AND FLOW PATHWAYS

Understanding the complex network of fractures and flow pathways in Enhanced Geothermal Systems (EGS) wells is crucial for optimizing energy production. However, traditional methods often provide limited insight into the detailed flow dynamics within these fractured pathways. To address these challenges, the FORGE team sought new technology that could provide high-resolution, cost-effective mapping of fracture networks and fluid flow pathways.

The researchers at FORGE recognized the potential of FloTrac ultra-high-resolution, ultra-high-temperature nanoparticle tracers, developed by QuantumPro, Inc., for oil and gas applications. These inert, non-

hazardous and non-radioactive nanoparticle tracers were viewed as having the potential to deliver the detailed fractured network flow mapping capabilities needed for the FORGE EGS research.

After meeting with the FORGE team, and following extensive evaluation of the potential of the FloTrac nanoparticles for geothermal applications, QuantumPro, Inc., was awarded the nanoparticle tracer services contract for the FORGE project.

FLOTRAC ULTRA-HIGH-RESOLUTION NANOPARTICLE TRACERS, A GAME-CHANGER

FloTrac's ultra-high-resolution, ultra-high-temperature nanoparticle tracers allow for a deeper understanding of the fracture network compared to conventional methods, including downhole production logging tools (PLT), fiber-optics sensing, and many chemical tracers. The nanoparticle tracers also perform especially well in the challenging, high-temperature subsurface environments encountered in Enhanced Geothermal Systems (EGS), and they can withstand extreme temperatures up to 2,000°F (1,093°C) and pressures up to 10,000 psi.

With 220 uniquely tagged options, FloTrac tracers enable the mapping of fluid flow pathways with unprecedented resolution, permitting a far more extensive and detailed understanding of flow in complex fracture networks and fluid behavior within the geothermal reservoir.

Reactivity and enhanced environmental performance. Unlike some tracers, FloTrac tracers are chemically inert particles. This minimizes any potential negative impact on the environment and ensures accurate flow mapping. Additionally, FloTrac tracers are non-toxic and non-radioactive, addressing potential concerns associated with the use of chemical or radioactive tracers in sensitive environments.

Extended sampling and analysis. FloTrac nanoparticle tracers do not dissolve after deployment, allowing for extended sampling and analysis. This enables long-term monitoring of fluid flow and reservoir behavior, providing valuable insights for optimizing EGS operations.

Overall, FloTrac nanoparticle tracers represent a significant advancement in geothermal reservoir flow mapping, offering superior resolution, thermal stability, environmental performance, and longevity compared to some conventional methods. This innovative one-of-a-kind technology is proving crucial for gaining a deeper understanding of fractured flow networks to drive stimulation efficiency and unlock the full potential of EGS. With the selection of FloTrac nanoparticle tracers for the FORGE research project, tracer deployment and sampling analysis commenced.

FLOTRAC TRACER DEPLOYMENT

FloTrac nanoparticle tracers were first deployed during stimulation treatments in the FORGE well 16A(78)-32, which was completed and stimulated in April 2024. QuantumPro, Inc., used a precise automated dosage system, comprised of a digital overhead stirrer mixer and a precise dosing pump to inject nanoparticle tracers into the well. Real-time injection monitoring was enabled via Starlink satellite internet, high-resolution onsite cameras and a monitoring system. This monitoring ensured accurate and controlled delivery of the tracers and stringent quality assurance and quality control (QAQC).

Eight unique FloTrac nanoparticle tracers were manufactured, one for each of the eight stages identified for testing. During field fracturing operations, no proppant and tracer were injected during Stage #6, due to high fracturing pressure, and the tracer intended for this stage was instead injected in Stage #10. In Stage #7, tracer was not pumped, due to not achieving the injection rate required for safely injecting proppant, identified in the FloTrac ultra-high resolution nanoparticle tracer report, **Table 1.**

Table 1. FloTrac nanoparticle tracers' deployment report.

Client:	The University of Utah
Business Unit:	Well 16A(78)-32
Completion Manager:	Kevin England Completion Manager kwengland@comcast.net
Company Supt.:	Leroy Swearingen Leroy-S@mpdconsultinginc.com 701.770.3057
Frac Company:	Calfrac
Frac Engineer:	Ryan Elliott
Email:	Relliott@calfrac.com

Well Name:	Well 16A(78)-32
Field:	FORGE
Job ID:	STIM2
County, State:	Beaver, Utah
Stage Count:	8
Pump Rate:	50, 35, 80-100 BPM
Fluid Type:	Slickwater, XL CMHPG
Proppant Types:	100 Mesh & 40/70 mesh
Frac Start Date:	4/3/24
Standby Days:	0
Frac End Date:	4/6/24

Casing:	Surface
Setting Depth MD:	1,629 ft
Casing OD:	13 ⅜ in
Casing:	Intermadiate
Setting Depth MD:	5,113 ft
Casing OD:	9 ⅝ in
Casing:	Production
Setting Depth MD:	10,987 ft
Casing OD:	8 ¾ in

Well Name	Stage Number	FloTrac nanoparticle tracer ID	Deployment Date	Deployment Start Time	Deployment Stop Time	Deployment Comment
Well 16A(78)-32	Stage #3R	FloTrac tracer #3R	4/3/24	11:03AM	1:45PM	Completed as per schedule
Well 16A(78)-32	Stage #4	FloTrac tracer #4	4/3/24	6:58PM	8:50PM	Completed as per schedule
Well 16A(78)-32	Stage #5	FloTrac tracer #5	4/4/24	1:37AM	3:09AM	Completed as per schedule
Well 16A(78)-32	Stage #6	FloTrac tracer #6				No tracer injected due to high preasure (tracer injected on Stage #10)
Well 16A(78)-32	Stage #7	FloTrac tracer #7				No tracer injected due to high preasure
Well 16A(78)-32	Stage #8	FloTrac tracer #8	4/5/24	4:01PM	9:52PM	Completed as per schedule
Well 16A(78)-32	Stage #9	FloTrac tracer #9	4/6/24	2:44AM	7:04AM	Completed as per schedule
Well 16A(78)-32	Stage #10	FloTrac tracer #6	4/6/24	9:32PM	11:06PM	Completed as per schedule

SAMPLING AND ANALYSIS

QuantumPro, Inc., next conducted nanoparticle tracer sampling and analysis for the FORGE project. Sampling occurred during two periods:

- Well 16A(78)-32 Flowback (April 7-27, 2024): Seventeen samples were collected, with each sample consisting of one gallon of flowback fluid. Sample details, including date, time, well information and temperature, were recorded.
- Well 16B(78)-32 Extended Circulation Test (Aug. 9-31, 2024): Sixty-six samples were collected, once again consisting of one gallon of fluid each, **Table 2.**

All samples from both periods were transported to QuantumPro's subatomic analytical laboratory in Houston for analysis. The analysis focused on detecting the presence and concentration of the injected FloTrac nanoparticle tracers.

Table 2. Stage-by-stage FloTrac nanoparticle tracer recovery in ppb for 16B(78)-32 during extended circulation test.

		8/9/24	8/9/24	8/9/24		8/12/24	8/12/24		8/30/24	8/31/24
		5:26 PM	7:26 PM	9:35 PM		11:30 AM	5:31 PM		5:29 PM	5:28 PM
Well 16A(78)-32	FloTrac tracer #	Water (ppb)	Water (ppb)	Water (ppb)		Water (ppb)	Water (ppb)		Water (ppb)	Water (ppb)
Stage #3R	FloTrac tracer #3R	2.00	1.40	1.10	...	2.60	2.10	...	0.04	0.05
Stage #4	FloTrac tracer #4	3.70	4.10	0.00		0.00	1.38		0.00	0.74
Stage #5	FloTrac tracer #5	0.00	0.00	0.00		0.00	0.99		0.00	0.29
Stage #8	FloTrac tracer #8	2.00	1.60	3.80		0.33	0.29		0.40	0.80
Stage #9	FloTrac tracer #9	0.00	0.00	0.00		0.37	0.99		0.23	0.27
Stage #10	FloTrac tracer #10	6.40	11.00	0.00		0.00	0.12		0.00	0.00

Cumulative tracer recovery amount from each traced stage measurement from Aug. 9–31, 2024, and the percentage of production flow of each stage relative to the entire 16B(78)-32 well, based on the cumulative tracer recovery was tabulated, **Table 3.** Stages #1, #2 and #3 were pumped in April 2022. Stage #3R, pumped in April 2024, was a "re-frac" of those three stages, with proppant added.

Table 3. Multi-stage fracturing of injector Well 16A(78)-32 and tracer flow mapping results from producer Well 16B(78)-32.

Stage #	Tracer #	# of Clusters	Fluid Name	Fluid vol. (bbl)	100-Mesh sand (lb)	40/70-Mesh sand (lb)	Tracer rec. (g)	Flow contr. (%)
1	...	OH	Slickwater	4,261	0	0	...	...
2	...	1	Slickwater	2,785	0	0	...	...
3	...	1	X-link gel	3,016	...	0	...	...
3R	3R	2+OH	Slickwater	10,319	136,260	199,300	63.62	37.8
4	4	1	Slickwater	5,263	54,920	72,700	23.01	13.7
5	5	1	X-link gel	4,537	55,680	81,200	11.00	6.5
6	...	1	Slickwater	...	...	...	...	...
7	...	3	X-link gel	12,596	0	0	...	...
8	8	8	X-link gel	35,295	439,500	642,000	32.39	19.2
9	9	8	Slickwater	27,237	445,260	285,372	29.02	17.2
10	10	1	Slickwater	4,550	54,000	79,800	9.37	5.6

UNDERSTANDING FLOW PATHWAYS AND FRACTURE NETWORK CONNECTIVITY

The FloTrac nanoparticle tracer data illuminated the complex flow paths of the injected water within the fractured rock formation. This helped visualize how the water moved between the injection and production wells, revealing the connectivity of the fracture network.

For example, the primary flow pathways from Injector Well 16A(78)-32 to Producer Well 16B(78)-32 were through fractures associated with stages #3R, #8 and #9. Combined, these stages facilitated

approximately 75% of the injected water flow. This imbalance indicates that specific pathways are more developed, leading to suboptimal heat extraction across the wells.

By tracking tracer production, QuantumPro, Inc., could map the interconnectedness of the fractures, crucial for understanding how effectively the injected water is contacting the hot rock and carrying heat to the production well. The tracer data provided a dynamic picture of the reservoir's response to stimulation and circulation. This included insights into flowrates, residence times and potential areas of flow restriction or preferential pathways.

Production flow contribution from each stage also varied over time. For example, the production flow contribution from Stage #3R was much higher over the second week than the first or the third week of the extended circulation test. This variation underlines the dynamic and evolving nature of inter-well flow pathways and production flow contribution from each stage.

Understanding the flow paths and fracture network connectivity allows for more targeted and effective stimulation strategies in future EGS development. Knowledge of the reservoir and created fractures behavior, coupled with continuous and granular stage-level flow mapping, enables better management of fluid flow and heat extraction, leading to increased efficiency of geothermal assets and longevity of geothermal power production.

SLICKWATER OUTPERFORMED X-LINK GEL IN PROMOTING FLOW CONNECTIVITY

Another interesting finding is that Stage #4 (slickwater) contributed 14%, compared with 7% for Stage #5 (X-link gel), indicating that the choice of fracturing fluid significantly affects inter-well connectivity, injection efficiency and inter-well communication. A comparison of Stage #8 (X-link gel) and Stage #9 (slickwater) supports the same conclusion, considering that more than twice the amount of 40/70 frac sand was pumped in the Stage #8 treatment than in Stage #9, while the production flow contributions from both stages were almost the same. This initial result may change over time and could suggest a connection between stages #4 and #3R but not for Stage #5, which is consistent with flowback tracer monitoring.

ENABLING DATA-DRIVEN DECISION-MAKING

The data collected from the FloTrac nanoparticle tracer deployments provided valuable insights into reservoir flow behavior, allowing FORGE researchers to make data-driven decisions about future well completion designs, stimulation strategies and well operations. The granular, stage-level production data, acquired with the nanoparticle tracers, can also validate and refine 3D numerical models used in EGS projects, improving the ability to predict reservoir flow performance and optimize energy production. The tracer data, combined with other monitoring data (temperature, pressure, etc.), also provide insights into the long-term performance and heat extraction potential of the geothermal reservoir.

By providing cost-effective, continuous, high-resolution and stage-specific flow mapping, real-time monitoring capabilities and data-driven insights, we improve our understanding of EGS reservoirs and enable optimized energy production. As EGS technology continues to advance, nanoparticle tracers are likely to play an increasingly critical role in unlocking the full potential of geothermal energy.

With this greater understanding, the geothermal industry can enhance the effectiveness and sustainability of EGS wells and stimulation designs, making this valuable, renewable energy source more accessible and economically viable. Based on the results of the FloTrac ultra-high-resolution nanoparticle tracer application, the FORGE research team has asked to continue collaboration with QuantumPro, Inc. The nanoparticle tracers deliver tremendous opportunities to better understand discrete fluid flow, fracture network complexities and flow performance and overall geothermal reservoir characteristics. **WO**

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QUAN GUO is a geomechanics advisor at QuantumPro, Inc. He was with M-I SWACO and later SLB from 2003 to 2022. Before M-I SWACO, he was with Advantek from 2000–2003 and TerraTek from 1992–2000. His experience includes perforating and hydraulic fracturing lab testing and modeling, drilling fluids and wellbore strengthening, cuttings and produced water re-injection. He holds 13 patents and has authored over 80 technical papers. He holds a bachelor's degree in mathematics and mechanics from Lanzhou University, a master's degree in engineering mechanics from Huazhong University of Science and Technology in China, and a doctorate in mechanical engineering from Northwestern University in Evanston, Ill.

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KEVIN ENGLAND is the sole proprietor of E-K Petro Consulting, LLC. He has over 40 years of experience in the oil and gas industry, 34 of which were spent with SLB, beginning with Dowell Schlumberger, where he gained extensive laboratory, field, operations, technical and management experience. He worked on projects with a variety of challenges worldwide in more than 50 countries until retirement in 2018. He is currently a consultant for the energy industry and has worked on projects for oil and gas well construction, completion, stimulation and production optimization, as well as carbon capture and storage (CCS) and geothermal projects. He holds a bachelor's degree in petroleum engineering from the University of Tulsa and a master's degree in Petroleum Engineering Reservoir Management from Ecole Nationale Supérieure du Pétrole et des Moteurs in France.

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