16A(78)-32 and 16B(78)-32 Stimulation and Circulate Wells Test

Final Report for FloTrac Nanoparticle Tracer Services (Geothermal Application)

RFP # UU182380810

Prepared for
The University of Utah

By
QuantumPro, Inc. HQ

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2. Project Overview

The Utah Frontier Observatory for Research in Geothermal Energy (FORGE) is a specialized underground field laboratory funded by the Department of Energy (DOE). Its purpose is to develop, test, and accelerate innovations in Enhanced Geothermal Systems (EGS) technologies promoting the global adoption of geothermal resources. The Utah FORGE focuses on developing, testing, and optimizing the methods necessary to create, maintain, and monitor enhanced geothermal systems. A key aspect of the EGS roadmap is achieving commercial flow rates in low permeability rocks at temperatures above 400°F, which is vital for meeting the DOE's goals of generating 90,000 MWe by 2050 at a cost of $45 per MW-hour.

The goal of the Utah FORGE project is to develop reliable and reproducible solutions that make geothermal energy accessible worldwide. Utah FORGE aims to facilitate advanced research, drilling, completion, and the testing of new technologies, enabling scientists to discover a replicable and commercial pathway to Enhanced Geothermal Systems (EGS). Beyond the site itself, the FORGE initiative encompasses comprehensive instrumentation, data collection, and a data dissemination component that captures and shares real-time data and activities occurring at FORGE.

The Utah FORGE site is situated on State land near major paved roads, graded dirt roads, an airport, and a railway line, ensuring year-round accessibility with minimal rain or snowfall. It is located 16 km (10 miles) from Milford, a small agricultural community with a population of approximately 1,400, and 50 km (31 miles) from the larger community of Beaver, Utah, which is adjacent to Interstate I-15. Beaver is a 3-hour drive, covering 320 km (200 miles) from Salt Lake City.

The field subsurface laboratory consists of a substantial volume of hot crystalline granite located between two deep, directionally drilled wells at approximately 8,000 feet below the surface. It is operated by a multidisciplinary team of engineers, experts, and scientists from the University of Utah, in collaboration with partner institutions that include universities, national laboratories, federally and state-funded organizations, and private industry.

The first deep deviated well, 16A(78)-32, was completed at the end of 2020, followed by the completion of the second deep deviated well, 16B(78)-32, in 2022. Additionally, a network of vertical wells (68-32, 78-32, 78-32B, and 56-32) was drilled and equipped primarily for deep seismic and environmental monitoring (Figure 1). Seismic activity has been tracked throughout the drilling, completion, and injection testing phases. All data collected during ongoing research at the site, along with that from R&D recipients, is publicly accessible and stored in the Geothermal Data Repository.

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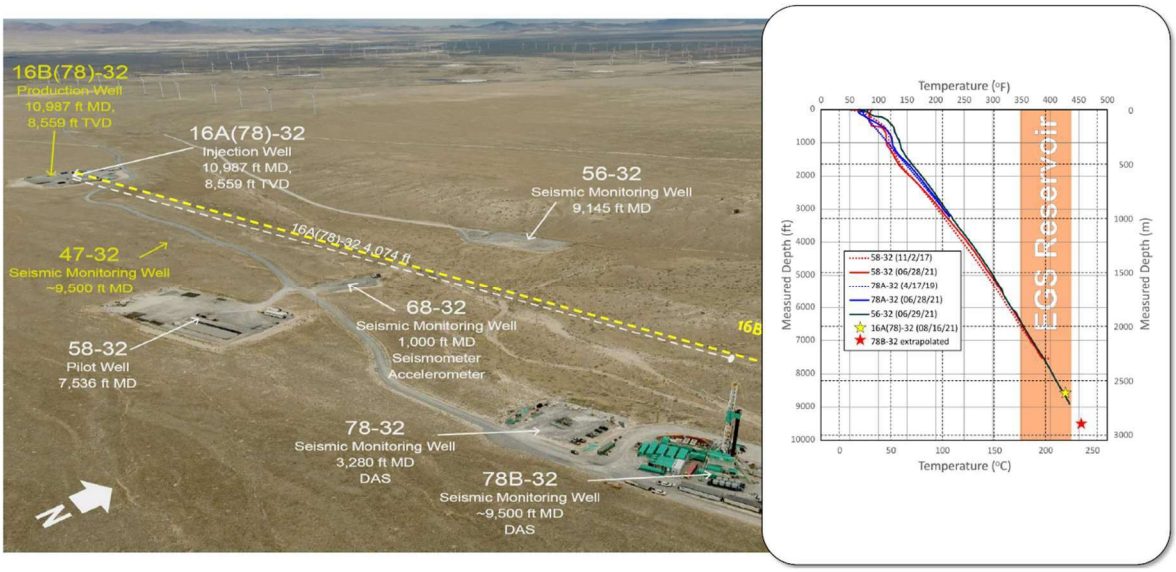

Figure 1: The Utah FORGE wells location and downhole temperature profile

The Utah FORGE project operates one injection well, 16A(78)-32, and one production well, 16B(78)-32, both of which underwent stimulation followed by a circulation test to assess their connectivity. Figure 2 is a schematic comparing the two wells. The stimulation process employed silica sand proppant, multiple cluster stages, frac plugs, slickwater, and viscosified fluid, achieving injection rates of up to 80 bbl/min (aka bpm) and a cumulative total proppant volume of up to 1,075,200 lb/stage. The initial stimulation at the toe of Well 16A(78)-32 occurred in April 2022. In March and April 2024, eight additional stages in Well 16A(78)-32 and four stages in Well 16B(78)-32 were effectively stimulated, followed by nine hours of circulation testing (Figure 3). The stimulation design for Well 16A(78)-32 included the injection of a unique nanoparticle tracer for each stage, enabling post-stimulation flow measurement and evaluation of circulation efficiency between the wells, which was successfully designed, executed, and assessed in August and September 2024.

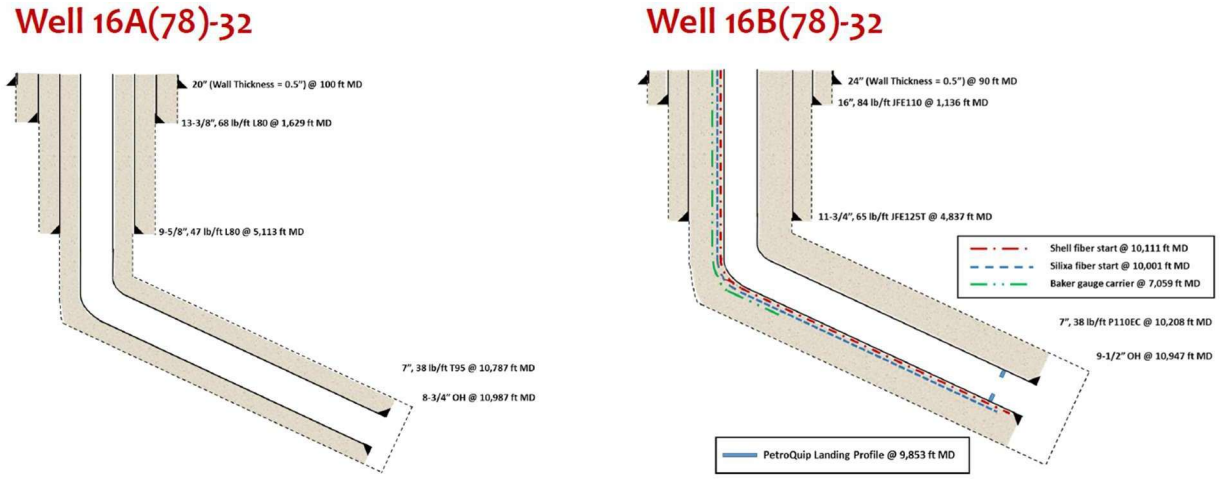

Figure 2: The Utah FORGE 16A(78)-32 and 16B(78)-32 well design

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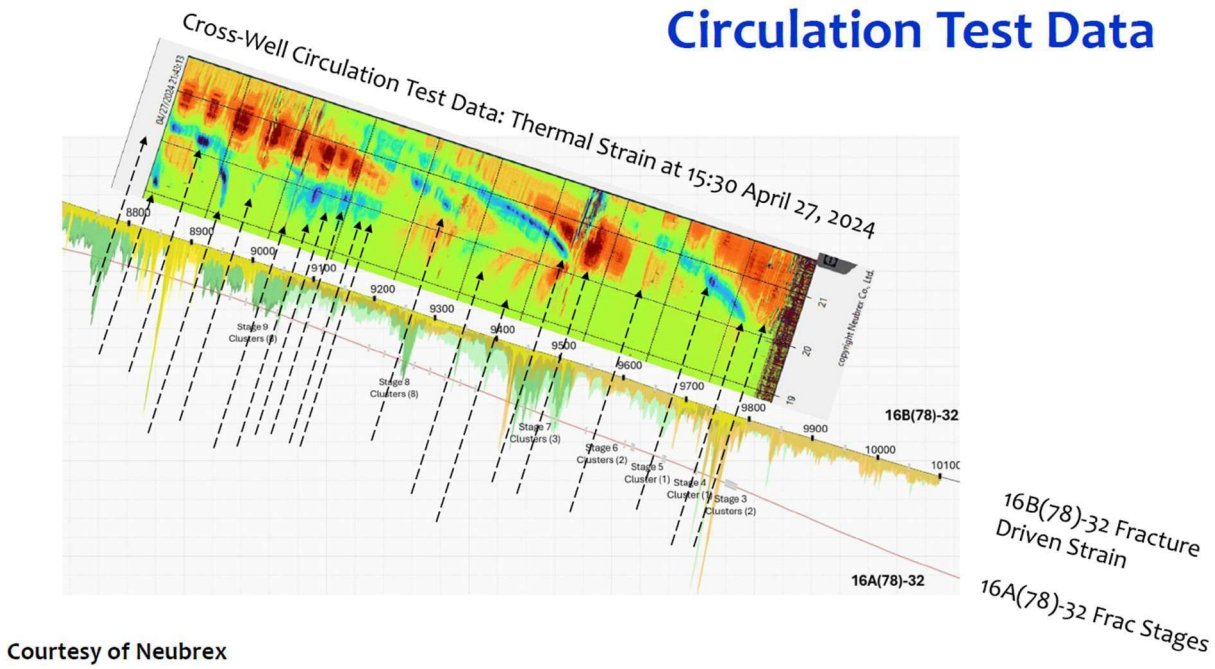

Figure 3: The Utah FORGE 16A(78)-32 and 16B(78)-32 circulation test data

3. FloTrac Tracers Design for Stimulation and Circulate Wells Test

QuantumPro, Inc. was awarded the nanoparticle tracer services for the Injection Well 16A(78-32) and the Production Well 16B(78)-32 as part of the geothermal stimulation tracer services for the Utah FORGE project.

FloTrac nanoparticle tracer technology provides advanced downhole deployment options and solutions. These nanoparticle tracers, paired with superior sampling techniques and high-resolution subatomic measurements, significantly reduces completion costs and enhances the efficiency of multistage hydraulic fracturing, stimulation, and injection operations.

[1] FloTrac is a trademark of QuantumPro, Inc.

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QuantumPro, Inc. offers a portfolio of 220 unique FloTrac ultra-high-resolution and ultra-high-temperature nanoparticle tracers designed for high-resolution, granular, cost-effective, and non-intrusive flow mapping. With particle sizes ranging from 0.1 to 1 µm and a density of 0.92 to 1.17 SG, the tracers exhibit exceptional suspension properties in both oil and water. They can withstand reservoir temperatures of up to 2,000°F (1,093°C), significantly exceeding the stability of traditional chemical, liquid, and radioactive tracers (Figure 4). Additionally, these tracers are non-radioactive, non-hazardous, inert, and compatible with both oil and water streams.

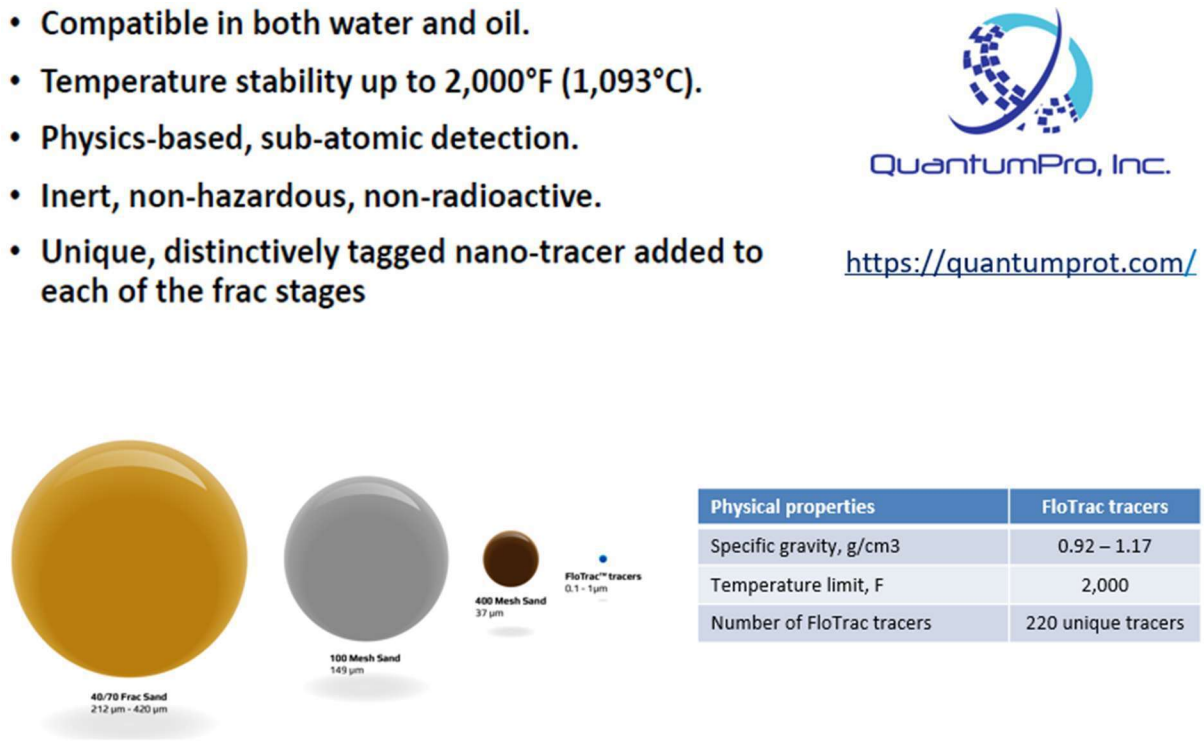

Figure 4: FloTrac ultra-high-resolution and ultra-high-temperature nanoparticle tracers

Developed from cost-effective materials, the 220 distinctively tagged, non-radioactive, and non-hazardous tracers in the FloTrac toolbox are formulated with the highest degree of subatomic detection accuracy and resolution, enabling exceptional recovery rates and flow mapping capabilities. FloTrac nanoparticle tracers are easy to deploy and do not require any surface or downhole modifications, in contrast to microseismic, fiber-optic, and other invasive, high-cost production diagnostic technologies.

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Prior to deployment, every FloTrac nanoparticle tracer is put through rigorous lab testing and validation processes to ensure optimal downhole performance and flow efficiency. That stringent protocol extends to the field where FloTrac tracers are deployed by highly experienced field specialists, using a precise automated dosage system with real-time injection video monitoring. The injection process is recorded and streamed live into the Cloud for real-time quality assurance and quality control (QAQC).

With their exceptional temperature stability, FloTrac signals offer diagnostic insights that help optimize injection rates, identify efficient cross-well communication, and improve the extraction of heat for generating a clean and reliable power supply.

A range of advanced tracer deployment methods and solutions enable discrete flow mapping, flow assurance, and production allocation for each stage or interval or perforation using nanoparticle tracers. This suite includes innovative technologies such as OmniTrac™ universal wellbore tracer technology, PerfTrac™ perforation flow efficiency tracer technology, and SoluTrac™[2] dissolvable inserts. These downhole tracers can be tailored to specific well completion designs, deployment complexities, reservoir flow mapping conditions, and field development goals.

3.1 Deployment, Equipment Setup, and Field Operations

QuantumPro, Inc. onsite tracer equipment includes:

- One high performance digital overhead stirrer mixer
- One high-precision adjustable dosing flow pump

The stirrer mixer is designed to ensure quality FloTrac nanoparticle tracer is fully mixed in the suspension fluid in each jar prior to injection onsite. The mixer has a quiet brushless motor, does not require any maintenance, and is rated to an input voltage of 110 volts. It has a large capacity and heavy-duty industrial specification that is designed for field use and applications.

The mixer is smooth and easy to use, and the unique cantilevered design can prevent liquid from entering the machine. It has a maximum speed of up to 2,000 rpm and a maximum torque at the stirring shaft of 1,850 gcm. The dimensions and photo of the overhead stirrer mixer are provided in Figure 5 and Figure 6.

[2] OmniTrac, PerfTrac, and SoluTrac are trademarks of QuantumPro, Inc.

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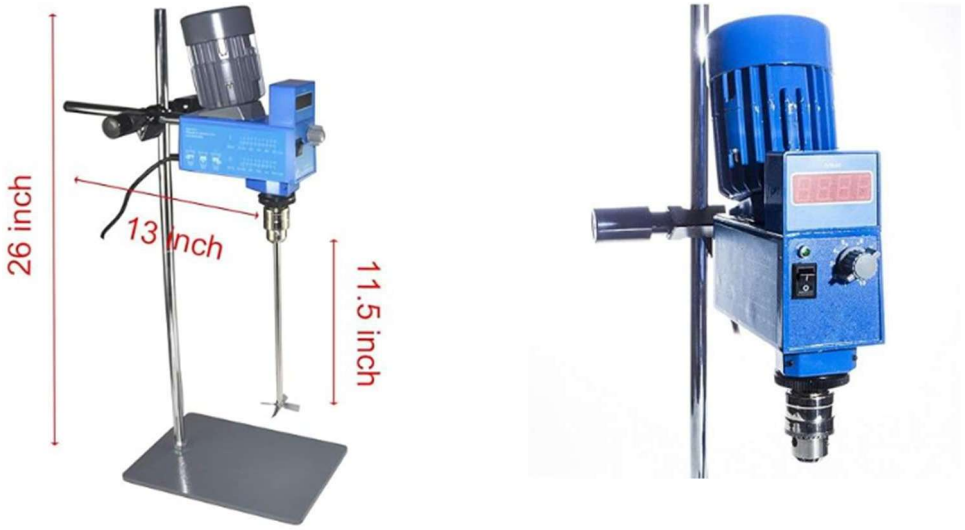

Figure 5: High-performance digital overhead stirrer mixer

The dosing injection pump enables direct injection of the FloTrac nanoparticle tracer into the fracturing-fluid blender tub from pre-mixed tracer jars (four 1-gallon jars per stage). The dosing pump provides a reliable tracer injection rate for each stage; the flow rate can be adjusted depending on the stage size, duration, and injection requirements.

The dosing injection pump includes ⅜-inch suction and discharge tubing and is quick and easy to install and use on the frac-blender floor. The dosing injection pump is designed and constructed using high-quality materials, ensuring long-lasting and durable use onsite.

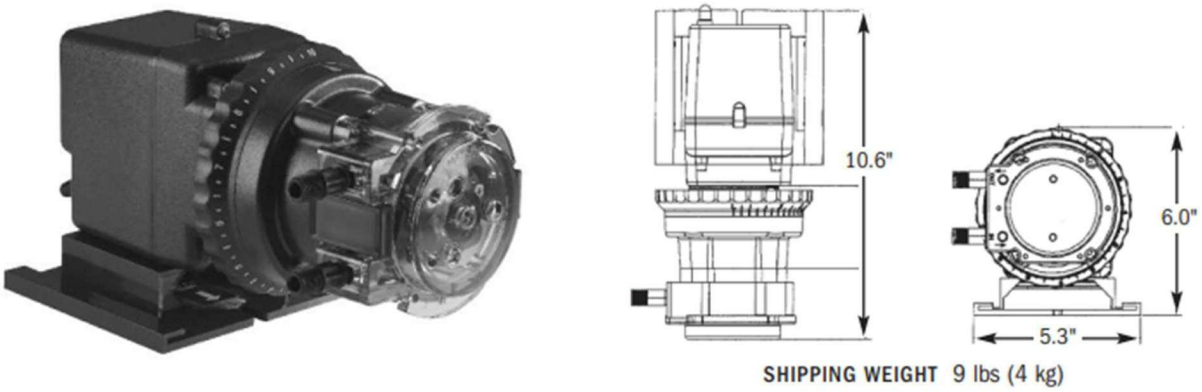

Figure 6: High-performance tracer dosing flow pump

All equipment and setup are compatible with common fracture equipment and approved by all fracturing vendors. The full equipment and FloTrac tracer's setup, tracer mixing and injection procedure, and actual photos on the fracturing-fluid blender are described in QuantumPro's Standard Operating Procedure (SOP) for tracer injection.

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A material safety data sheet (SDS) for the FloTrac nanoparticle tracer was provided to lab and field operations. During field operations, the FloTrac nanoparticle tracer was injected directly into the blender tub during sand addition and stopped a few seconds before the flush to avoid the tracer being located inside the wellbore at the end of each stage (Figure 7). In addition, no FloTrac nanoparticle tracer was injected during the pad to ensure good placement of the tracer inside the propant or conductive fracture.

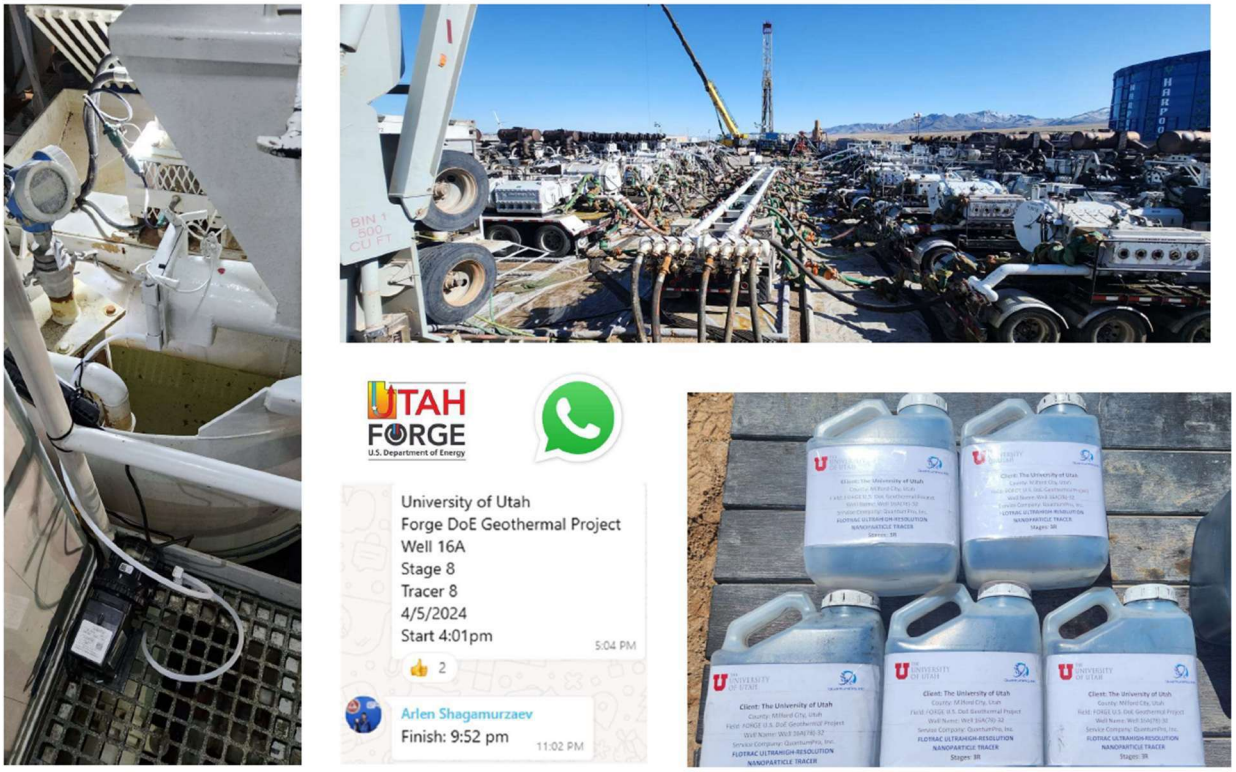

Figure 7: FloTrac nanoparticle tracer field injection, deployment, and reporting

3.2 Tracer Injection Schedule and Deployment Results

The Utah FORGE team requested unique FloTrac ultra-high-resolution nanoparticle tracers for each stage of the 16A(78)-32 well stimulation which was completed in April 2024. Eight FloTrac nanoparticle tracers were manufactured, one for each stage. Each FloTrac nanoparticle tracer has a unique composition and fingerprints and the tracers for this stimulation were designated by stage as: Stage #3R, Stage #4, Stage #5, Stage #6, Stage #7, Stage #8, Stage #9, and Stage #10.

During field fracturing operations and adjustments to the completion design, no proppant and tracer were injected during Stage #6 due to high pressure, and the tracer intended for this stage was instead injected in Stage #10. Additionally, in Stage #7 tracer was not pumped because adequate rate to safely inject proppant could not be achieved. Please refer to the final FloTrac nanoparticle tracer deployment report for the 16A(78)- 32 results which are summarized in Table 1.

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Table 1: FloTrac nanoparticle tracers deployment report with completion on 16A(78)-32

QuantumPro, Inc.

QuantumPro's FloTrac Ultrahigh-resolution Nanoparticle Tracers Deployment Report: Well 16A(78)-32

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: **4/3/2024**
Standby Days: **0**
Frac End Date: **4/6/2024**

Casing: **Surface**
Setting Depth MD: **1,629 ft**
Casing OD: **13-3/8 in**

Casing: **Intermadiate**
Setting Depth MD: **5,113 ft**
Casing OD: **9-5/8 in**

Casing: **Production**
Setting Depth MD: **10,987 ft**
Casing OD: **8-3/4 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	4/3/2024	11:03AM	1:45PM	Completed as per schedule
Well 16A(78)-32	Stage #4	FloTrac tracer #4	4/3/2024	6:58PM	8:50PM	Completed as per schedule
Well 16A(78)-32	Stage #5	FloTrac tracer #5	4/4/2024	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	4/5/2024	4:01PM	9:52pm	Completed as per schedule
Well 16A(78)-32	Stage #9	FloTrac tracer #9	4/6/2024	2:44am	7:04AM	Completed as per schedule
Well 16A(78)-32	Stage #10	FloTrac tracer #6	4/6/2024	9:32PM	11:06PM	Completed as per schedule

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Additionally, Utah FORGE requested assistance with the Extended Circulation Test and the manufacturing of 10 unique FloTrac nanoparticle tracers, which were injected into Well 16A(78)-32 and produced from Well 16B(78)-32. The deployment of FloTrac nanoparticle tracers was key in validating inter-well communication efficiency, arrival time, flow profile, and injection performance.

Following extensive technical discussions, Utah FORGE specified that the injection of FloTrac nanoparticle tracers during the Extended Circulation Test should commence once the injection rate stabilized at 10 bbl/min after the initial test (Table 2) shows the as-planned treatment schedule for the extended circulation test). This approach ensured a consistent addition of FloTrac nanoparticle tracers at a stable rate, resulting in a uniform concentration throughout the injection flow and providing more accurate flow mapping information.

Table 2: Initial injection test design during Circulate Wells test on 16A(78)-32

Step	Rate (bpm)	Volume (bbl)	Cumulative Volume (bbl)	Incremental Time (day)	Cumulative Time (day)	Well 16B(78)-32 Status
1	0	0	0	0	0	Shut-In
2	2.5	3,600	3,600	1.0	1.0	Shut-In
3	0	0	3,600	0.33	1.33	Shut-In
4	2.5	1,200	4,800	0.33	1.67	Open
5	5	3,600	8,400	0.5	2.17	Open
6	7.5	7,200	15,600	0.67	2.84	Open
7	10	391,104	406,704	27.16	30.00	Open
8	0	0	406,704	TBD	TBD	Shut-In

The injection of FloTrac nanoparticle tracers commenced on Day #4 of the Extended Circulation Test. We defined Day #4 as the day when a stable rate of 10 bbl/min was achieved. Following the operational pumping schedule, this injection process continued for 27 days, with FloTrac nanoparticle tracer injections occurring every other day to space the tracer injection. The final

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FloTrac nanoparticle Tracer #11 was injected on the last day of the Extended Circulation Test to capture the flow at the end of the circulation period (tail section). For further details and the injection schedule, please refer to Figure 8.

- **Day 1-3:** Injection test – no nano tracer to be injected during injection test. Tracer crew will wait and focus on sampling work.
- **Day 4:** Inject nano tracer #1 – 4 one-gallon jars per tracer. Injection rate: 1 gallon per hour, total of 4 hours.
- **Day 6:** Inject nano tracer #2 – 4 one-gallon jars per tracer. Injection rate: 1 gallon per hour, total of 4 hours.
- **Day 8:** Inject nano tracer #3 – 4 one-gallon jars per tracer. Injection rate: 1 gallon per hour, total of 4 hours.
- **Day 10:** Inject nano tracer #4 – 4 one-gallon jars per tracer. Injection rate: 1 gallon per hour, total of 4 hours.
- **Day 12:** Inject nano tracer #5 – 4 one-gallon jars per tracer. Injection rate: 1 gallon per hour, total of 4 hours.
- **Day 15:** Inject nano tracer #6 – 4 one-gallon jars per tracer. Injection rate: 1 gallon per hour, total of 4 hours.
- **Day 17:** Inject nano tracer #7 – 4 one-gallon jars per tracer. Injection rate: 1 gallon per hour, total of 4 hours.
- **Day 19:** Inject nano tracer #8 – 4 one-gallon jars per tracer. Injection rate: 1 gallon per hour, total of 4 hours.
- **Day 21:** Inject nano tracer #9 – 4 one-gallon jars per tracer. Injection rate: 1 gallon per hour, total of 4 hours.
- **Day 23:** Inject nano tracer #10 – 4 one-gallon jars per tracer. Injection rate: 1 gallon per hour, total of 4 hours.
- **Day 27:** Inject nano tracer #11 – 4 one-gallon jars per tracer. Injection rate: 1 gallon per hour, total of 4 hours.

Figure 8: FloTrac nanoparticle tracer injection schedule during the Circulate Wells Test

Due to the lack of fracturing-fluid blender equipment availability for the Circulate Wells Test, all FloTrac nanoparticle tracers were injected using the Liquid Additive System (LAS) unit, which was set up specifically for this purpose. The tracer technician managed the water supply to the tote tank during the injection which fed to the LAS unit, while the Liberty Oilfield Services (LOS) crew oversaw the LAS unit and its pumping into the 16A(78)-32 well.

All FloTrac nanoparticle tracer injections were completed as scheduled from August 11 through August 30, 2024. This completion as scheduled was attributed to excellent field execution by the tracer crew and proactive communication with the Utah FORGE team and LOS fracturing crew, ensuring efficient LAS operations and tracer injection. For the final FloTrac nanoparticle tracer deployment or injection report conducted during the Circulate Wells Test phase of the Utah FORGE project (Table 3).

Table 3: FloTrac nanoparticle tracers deployment report during the Circulate Wells Test on 16A(78)-32

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QuantumPro, Inc.

QuantumPro's FloTrac Ultrahigh-resolution Nanoparticle Tracers Deployment Report: Well 16A(78)-32

Client: **The University of Utah**
Business Unit: **Well 16A(78)-32**
Completion Manager: **Kevin England**
Completion Manager
kwengland@comcast.net
281.731.7816

Company Supt.: **Leroy Swearingen**
leroy-s@mpdconsultinginc.com
701.770.3057

Frac Company: **Liberty Oilfield Services**
Frac manager **Brandon Kremer**
Email: **720.390.1186**

Well Name: **Well 16A(78)-32**
Field: **Milford City**
API Number: **DOE FORGE R&D**
County, State: **Milford City, Utah**

Stage Count: **10**
Pump Rate: **10 BPM**
Fluid Type: **Water**
Proppant Types: **N/A**
Frac Start Date: **8/8/2024**
Standby Days: **5**
Frac End Date: **8/30/2024**

Casing: **Surface**
Setting Depth MD: **1,629 ft**
Casing OD: **13-3/8 in**

Casing: **Intermadiate**
Setting Depth MD: **5,113 ft**
Casing OD: **9-5/8 in**

Casing: **Production**
Setting Depth MD: **10,987 ft**
Casing OD: **7 in**

Well Name	FloTrac nanoparticle tracer ID	Deployment Date	Deployment Start Time	Deployment Stop Time	Deployment Comment
Well 16A(78)-32	FloTrac tracer #1	8/11/2024	7:25 AM	11:28 AM	Completed as per schedule
Well 16A(78)-32	FloTrac tracer #2	8/13/2024	7:00 AM	11:00 AM	Completed as per schedule
Well 16A(78)-32	FloTrac tracer #3	8/15/2024	7:00 AM	11:00 AM	Completed as per schedule
Well 16A(78)-32	FloTrac tracer #4	8/17/2024	7:00 AM	11:00 AM	Completed as per schedule
Well 16A(78)-32	FloTrac tracer #5	8/19/2024	6:00 AM	10:00 AM	Completed as per schedule
Well 16A(78)-32	FloTrac tracer #6	8/22/2024	7:00 AM	11:00 AM	Completed as per schedule
Well 16A(78)-32	FloTrac tracer #7	8/24/2024	7:00 AM	11:00 AM	Completed as per schedule
Well 16A(78)-33	FloTrac tracer #8	8/26/2024	7:00 AM	11:00 AM	Completed as per schedule
Well 16A(78)-34	FloTrac tracer #9	8/28/2024	7:00 AM	11:00 AM	Completed as per schedule
Well 16A(78)-35	FloTrac tracer #10	8/30/2024	7:00 AM	11:00AM	Completed as per schedule

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3.3 Sampling Schedule and Sampling Work

Sampling consisted of two periods: the first was sampling from April 7 to April 27, 2024 from well 16A(78)-32 during the flowback of the well; the second was sampling from August 9 to August 31, 2024 from well 16B(32)-32 during the Extended Circulation Test. QuantumPro's Standard Operating Procedure (SOP) for the sampling process was shared with the Utah FORGE team. All sampling was conducted by well-trained field personnel under a strict QA/QC process.

For the flowback, the sampling took place on the flowback line, which was equipped with a dedicated sampling port, a liquid sample valve, and a cooling coil (Figure 9). The Utah FORGE field team provided daily flowback reports and supported the sampling work in the field.

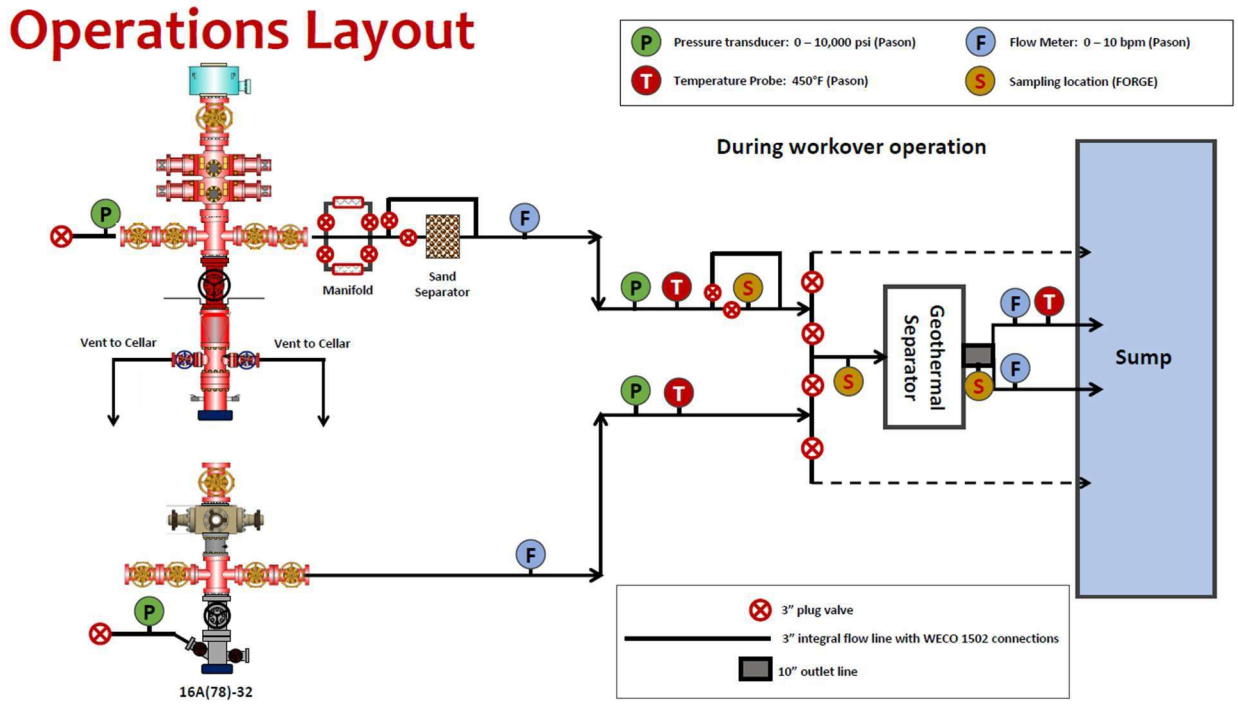

Figure 9: The Utah FORGE surface flowline schematics and sampling locations

Each day, one gallon of flowback fluid was collected. The sampling date, time, well information, and sample temperature were recorded on each sampling jar (Figure 10). Sampling by QuantumPro, Inc. took place from April 7 to April 27, 2024, resulting in a total of 17 samples collected post-completion from the 16A(78)-32 well. All samples were properly sealed and securely transported to QuantumPro, Inc.'s subatomic analytical laboratory in Houston for FloTrac nanoparticle tracer production analysis.

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Figure 10: 16A(78)-32 Well post-completion sampling process and sampling photos

As for the Extended Circulation Test, carried out subsequently in August and September 2024, a sampling schedule was developed and executed for Well 16B(78)-32 concurrently with FloTrac nanoparticle tracer injections at 16A(78)-32. The sampling schedule included the following design:

- **Day 1 and Day 2:**
  - Samples collected every 2 hours for 24 hours
- **Day 3 to Day 9:**
  - Samples collected every 6 hours for 24 hours
- **Day 10 to Day 20:**
  - Daily sampling for the remainder of the test

A total of 66 samples were collected during the Extended Circulation Test from August 9 to August 31, 2024. This sampling schedule and frequency were aligned with those of similar successful Circulate Wells Tests conducted by other geothermal operators. QuantumPro, Inc. provided high-temperature sampling jars, tools, and an experienced field technician for the sample collection.

Like the post-completion sampling work, the Utah FORGE team set up a dedicated sampling location, including a liquid sample valve and a cooling coil, on the 16B(78)-32 Well. Each sampling jar had the date, time, well information, and sample temperature recorded on it. All samples from the Extended Circulate Wells Test were promptly delivered to QuantumPro, Inc.'s subatomic analytical laboratory in Houston for FloTrac nanoparticle tracer production analysis.

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4. Flowback and Extended Circulation Test Tracer Analysis and Interpretation

Section 4.1 considers tracer recovery results and their implications from the flowback of well 16A(78)-32 after its hydraulic fracturing treatment in April 2024. Sections 4.2 and 4.3 are on the tracer recovery results and their interpretations from the Extended Circulation Test carried out from August 9, 2024 to September 5, 2024.

4.1 Flowback Tracer Data Analysis and Fracture Network Diagnostics

Tracer data analysis reported here was from flowback samples collected from well 16A(78)-32 from April 7 to April 27, 2024.

After hydraulic fracture treatment from April 3 to April 6, the 16A(78)-32 well commenced flowback on April 7, 2024 while the frac plugs were being drilled out. The daily flowback samples were collected from April 7 to April 27, 2024. The concentrations of FloTrac nanoparticle tracer recovery in the flowback fluid samples were analyzed to provide stage-level flow and information on the fracture network created from the hydraulic fracturing stimulation. In the flowback data interpretation, it is important to note that the frac plugs could allow wellbore fluid flow because the balls were not necessarily seated in the frac plugs.

The frac plugs were drilled out at the following times:

- Frac Plug #6 – April 17th @ 17:15
- Frac Plug #5 – April 19th @ 09:45
- Frac Plug #4 – April 19th @ 21:30
- Frac Plug #3 – April 21st @ 16:50
- Frac Plug #2 – April 21st @ 20:30
- Frac Plug #1 – April 22nd @ 00:15

Table 4 presents the FloTrac nanoparticle tracer recovery concentrations per stage from collected water samples, expressed in parts per billion (ppb), for the tracers injected with the proppant during each fracturing stage of well 16A(78)-32.

Table 4: A granular stage-by-stage FloTrac nanoparticle tracer recovery in ppb for 16A(78)-32 during flowback

		Stage-by-stage Flow Profile Characterization (QuantumPro's FloTrac nanoparticles recovery in ppb)																
Well 16A	FloTrac tracer #	4/7/2024	4/8/2024	4/9/2024	4/10/2024	4/11/2024	4/12/2024	4/13/2024	4/14/2024	4/15/2024	4/16/2024	4/17/2024	4/18/2024	4/19/2024	4/20/2024	4/21/2024	4/22/2024	4/27/2024
		Water (ppb)	Water (ppb)	Water (ppb)	Water (ppb)	Water (ppb)	Water (ppb)	Water (ppb)	Water (ppb)	Water (ppb)	Water (ppb)	Water (ppb)	Water (ppb)	Water (ppb)	Water (ppb)	Water (ppb)	Water (ppb)	Water (ppb)
Stage #3R	FloTrac tracer #3R	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.31	1.09	1.04	1.23
Stage #4	FloTrac tracer #4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.43	1.46	1.59	1.37
Stage #5	FloTrac tracer #5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.09	2.56
Stage #6		No proppant pumped or no nano tracer injected at this Stage																
Stage #7		No proppant pumped or no nano tracer injected at this Stage																
Stage #8	FloTrac tracer #8	1.06	1.02	1.11	1.06	1.03	1.04	1.05	1.07	1.05	1.06	1.08	1.10	1.14	1.11	1.05	1.07	1.05
Stage #9	FloTrac tracer #9	0.00	0.00	1.15	1.20	1.17	1.48	0.27	0.54	1.12	0.00	0.00	1.15	1.32	2.56	2.65	2.29	2.09
Stage #10	FloTrac tracer #10	1.37	1.24	1.12	1.25	1.19	1.45	1.14	1.27	1.04	1.10	1.48	0.00	1.24	1.15	1.20	1.13	2.28

The observations and conclusions from the flowback tracer recovery results, as shown in Table 4, are summarized below:

1. **Stages #10, #9 and #8 were isolated from Stages #3R, #4 and #5**: From April 7 to 19, no flowback from Stages #3R, #4 and #5 was detected, indicating that Stages #10, #9 and #8 were isolated from Stages #3R, #4 and #5.

2. **All Stages open to flowback after frac plug #3 was drilled out**: Flowback from Stages #3R and #4 was detected on April 20, after frac plugs # 5 and #4 were drilled out on April

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19. However, no flowback from Stage #5 was detected until April 22 after frac plug #3 was drilled out on April 21, suggesting that frac plug #3 did not allow flowback from Stage #5 through the wellbore before it was drilled out.

3. **Connection Between Stage #10 and Stages #8**: There is a potential intersection of fractures between Stage #8 and Stage #10. After flowback from Stage #10 for two days, wellbore pressure above frac plug #6 was reduced and frac plug #6 allowed wellbore flow from Stage #9. Another possibility is that both frac plug #6 and plug #5 were open to wellbore flow. Stage #9 tracer in the near wellbore region was displaced by Stage #10 hydraulic fracturing treatment. This may be possible, but not likely. It is believed that Stage #10 and Stage #8 are connected by fractures created during hydraulic fracturing treatments. This explanation is supported by the Extended Circulation Test results to be presented later.
4. **Stage #5 not connected with Stage #4 or #3R**: Stage #5 does not appear to be connected with Stage #4 or #3R, as flowback from Stages #4 and #3R was detected two days before flowback from Stage #5 was detected. Flowback from Stage #5 was detected only after all frac plugs above Stage #5 were drilled.
5. **Connection of Stages #3R, #4 with Stages #8 and/or #7**: No flowback was detected from Stage #5 on April 20-21 while flowback was noted from Stages #4 and #3R. This suggests potential connections between the fractures of Stages #4 and #3R with those from Stage #8 and/or Stage #7. Again, it is possible that the connection could be through the wellbore if frac plugs #4, #3, #2 and #1 were all open for wellbore flow. However, it should be noted that after frac plug #3 was drilled out on April 21, flowback from Stage #5 was detected on April 22. This strongly suggests that frac plug #3 was sealed and the backflow from Stages #3R and #4 before April 22 was not through the wellbore.

Lessons Learned and Recommendations:

1. Flowback sampling before and after a frac plug was drilled out. This may provide information on whether the frac plug was open to wellbore flow or if fractures from different stages were connected away from the wellbore.
2. Had Stages #6 and #7 been traced, it would provide more information on whether Stages #3R, #4 were connected with Stages #7 and #6 or #8.
3. If perforation was performed with charges embedded with tracers such as PerfTrac™, this would help better understanding the flowback result's implication on connectivity among various stages. This would also help to understand whether the connections of the various stages were through the wellbore and frac plugs or through fractures away from the wellbore.
4. Deployment of more than one tracer per stage is another way for differentiating connection through the wellbore from connection by fractures away from the wellbore. In this method, for example, three tracers per stage was pumped with frac sand: one at the beginning, one in the middle and one at the end. Tracer flowback results provide information on whether the connection of the various stages is through the wellbore and frac plugs or through fractures away from the wellbore.

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4.2 Extended Circulation Test Tracer Data Analysis and Inter-well Flow Mapping

The tracer data analysis reported here was from samples collected from the 16B(78)-32 well during the Extended Circulation Test carried out from August 9, 2024, to September 5, 2024.

During the Extended Circulation Test, cooler water was injected into the 16A(78)-32 well, while hotter water was produced from the 16B(78)-32 well. The injection rate into the 16A(78)-32 Well started at 2.5 bbl/min and increased progressively to 5 bbl/min, then to 7.5 bbl/min before reaching and maintaining a rate of 10 bbl/min from August 11, 2024, onward.

Water samples were collected from the 16B(78)-32 well to analyze the recovery of FloTrac nanoparticle tracers, and determine the contributions from each stage from the multi-stage hydraulic fracturing treatment. Initially, samples were collected every 2 hours, followed by every 6 hours, and ultimately on a daily basis. The concentrations of each FloTrac nanoparticle tracer were analyzed, with Table 5 providing an example of the tracer recovery results.

Table 5: A stage-by-stage FloTrac nanoparticle tracer recovery in ppb for 16B(78)-32 during Extended Circulate Test

		Stage-by-stage Flow Profile Characterization (QuantumPro's FloTrac nanoparticles recovery in ppb) - Completion								
Well 16A(78)-32	FloTrac tracer #	8/9/2024 5:26 PM Water (ppb)	8/9/2024 7:26 PM Water (ppb)	8/9/2024 9:35 PM Water (ppb)		8/12/2024 11:30 AM Water (ppb)	8/12/2024 5:31 PM Water (ppb)		8/30/2024 5:29 PM Water (ppb)	8/31/2024 5:28 PM 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

Two analysis methods were performed on the measured tracer recovery concentration measurements. The first method was that the production flow of each stage is proportional to its tracer recovery concentration. Once concentration of the FloTrac nanoparticle tracer was established, the cumulative tracer recovery amount could be calculated based on the volume of water produced from the 16B(78)-32 well. The second method was that the production flow from each stage is proportional to its cumulative tracer recovery amount. The results from the first method had more details, while results from the second method provided easier understanding on the overall trend.

Figure 11 and Figure 12 illustrate the cumulative FloTrac nanoparticle tracer recovery in grams over the duration of the Extended Circulation Test. Figure 13 shows the stage-level flow mapping results for flow contribution between the injector Well 16A(78)-32 and the producer Well 16B(78)-32.

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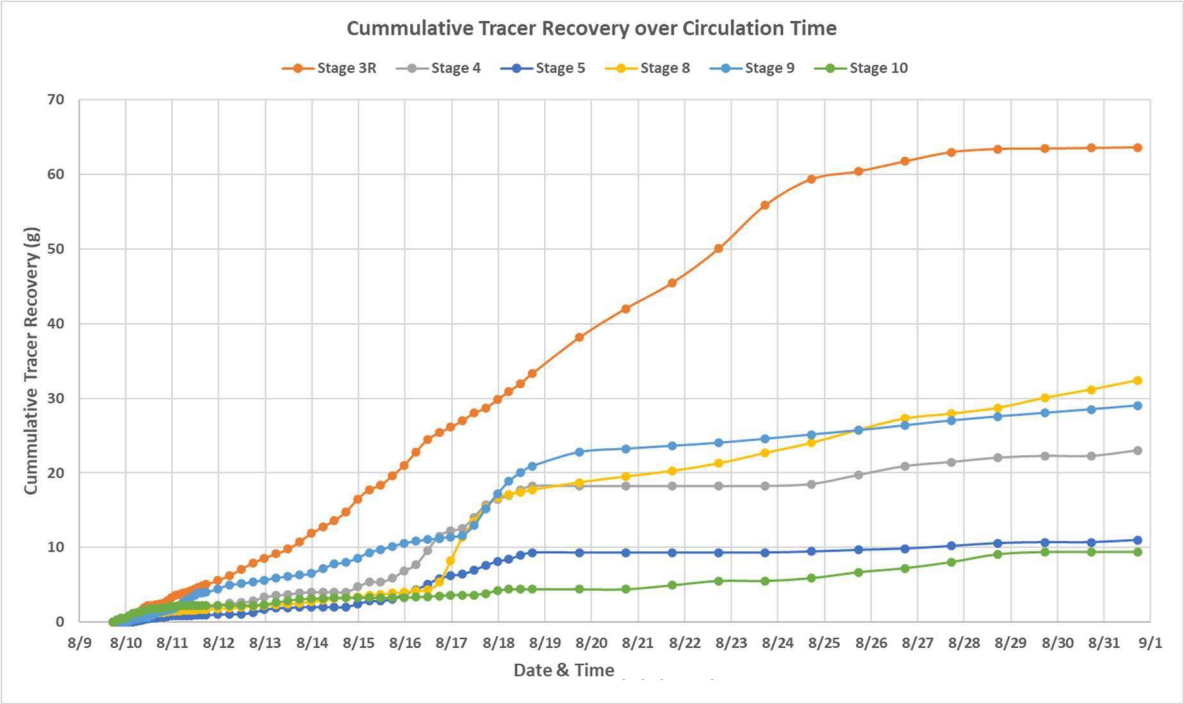

Figure 11: Stage-level FloTrac nanoparticle tracer recovery from the producer versus time during the Extended Circulation Test.

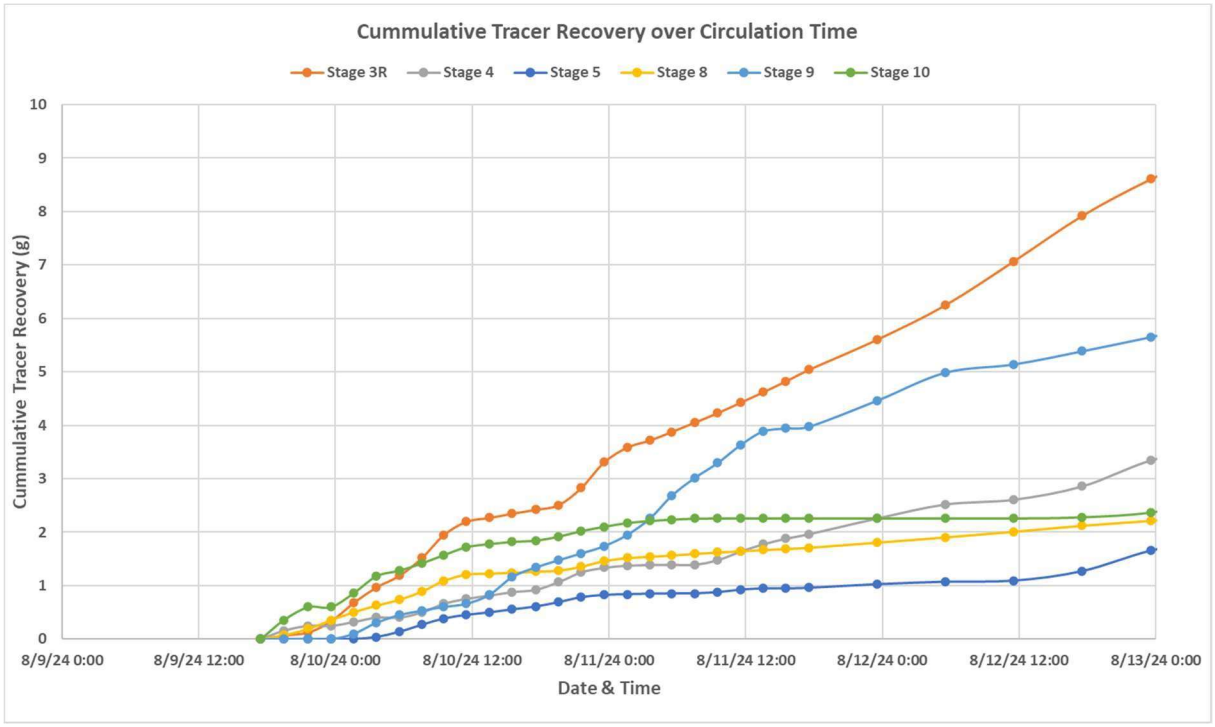

Figure 12: A zoom-in look of stage-level FloTrac nanoparticle tracer recovery from the producer versus time during the Extended Circulation Test.

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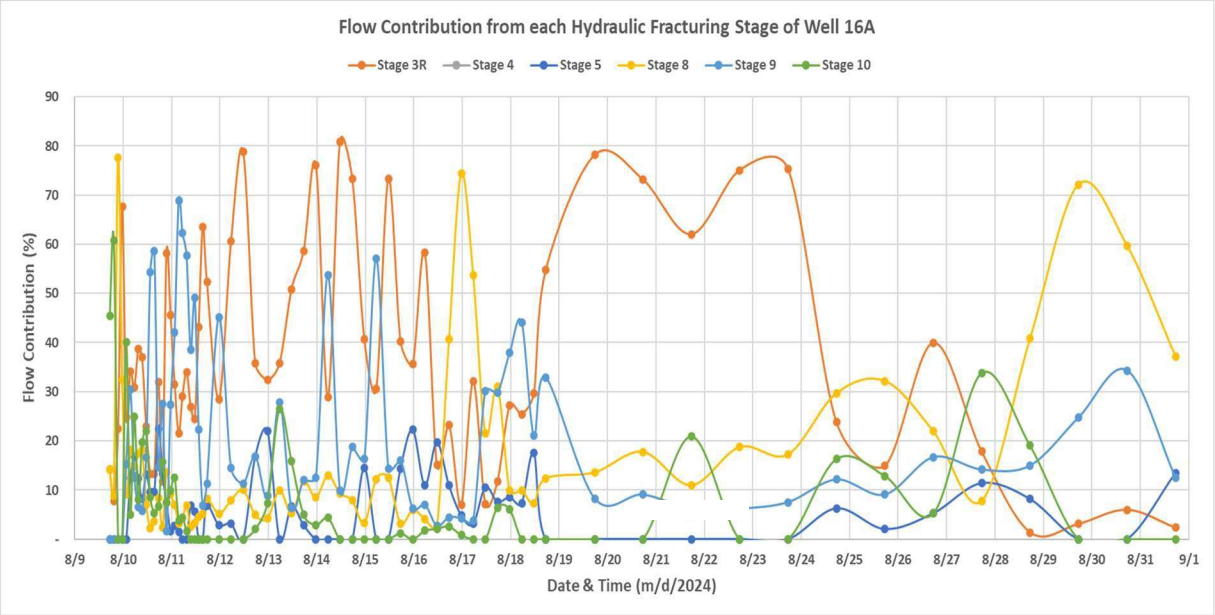

Figure 13: Stage-level flow mapping results of production flow contribution between well 16A(78)-32 and well 16B(78)-32.

Table 6 shows the cumulative tracer recovery amount from each stage measurement from August 9 to August 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.

Table 6: Multi-stage fracturing of injector Well 16A(78)-32 and tracer flow mapping results from producer Well 16B(78)-32

Stage #	Tracer #	Clusters	Fluid	Fluid vol. (bbl.)	100M sand (lb)	40/70 sand (lb)	Tracer rec. (g)	Flow contr. (%)
1		OH	S-Water	4261	0	0		
2		1 *	S-water	2785	0	0		
3		1 *	X-link gel	3016		0		
3R	3R	2+OH	S-water	10,319	136,260	199,300	63.62	37.8
4	4	1	S-water	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	S-water					
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	S-water	27,237	445,260	285,372	29.02	17.2
10***	10	1	S-water	4,550	54,000	79,800	9.37	5.6

Note:
* One 20-foot cluster perforated at 20 shots per foot (spf)
** Stage #6 – could not establish rate for sand so no tracer was injected.
** Stage #7 – no sand was injected and thus no tracer was injected.
*** 4,000-lb ultralight proppant was pumped after the 40/70 mesh sand.

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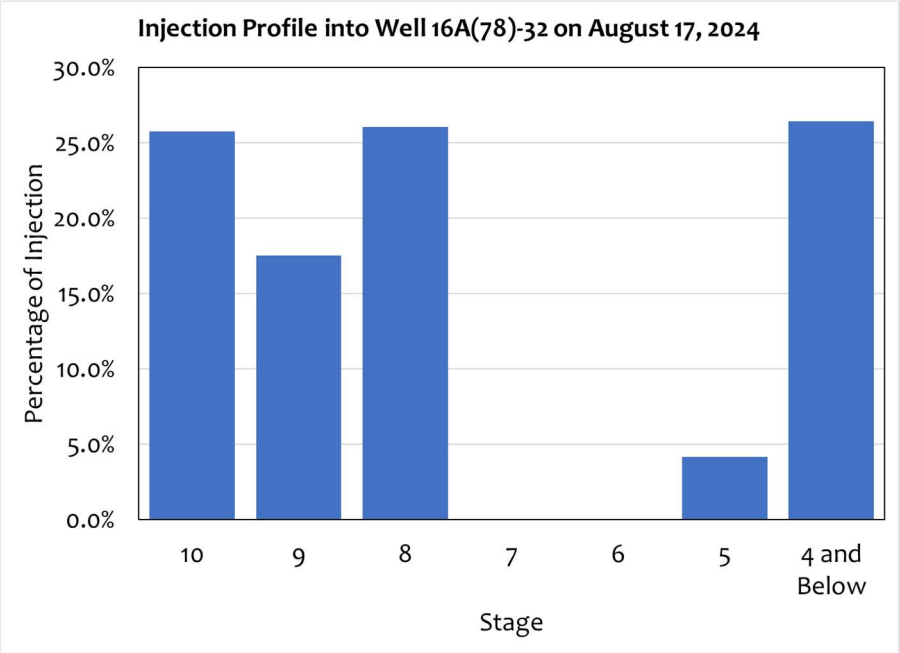

Figure 14: PLT on the injector, figure from "Extended Circulation Test Report – Final" by Kevin England, Leroy Swearingen and John McLennan. Comparison between the injection profile and production profile results shown in Table 6 suggests connection of Stage #10 with Stage #8 and #9 near the wellbore and diverting injection flow of Stage #10 into other stages.

Conclusions and key findings from the FloTrac nanoparticle tracers flow mapping results of Producer Well 16B(78)-32:

1. **Dominant Flow Pathways**: 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.
2. **Minor Contributions from Specific Stages**: Stages #5 and #10 showed minimal impact on production flow, contributing only 7% and 6% respectively, indicating less effective connectivity or conductive pathways of these stages.
3. **Injection into Stage #10 Produced from Stage #8 and/or #9**: PLT on the injector during the Extended Circulation Test showed much higher injection into Stage #10 (see Figure 14) than production from Stage #10 (see Table 6). This suggests that water injected into Stage #10 was produced back from Stage #8 and/or #9. This also suggests that Stage #10 was connected with Stage #8 and/or #9 by fractures away from the wellbore, which is consistent with the flowback results presented in Section 4.1.
4. **Slickwater vs. X-link Gel Performance**: Slickwater outperformed X-link gel in promoting flow connectivity, with Stage #4 (slickwater) contributing 14% compared to 7% for Stage #5 (X-link gel). This indicates that the choice of fracturing fluid significantly affects inter-well connectivity and 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 sand was pumped in the Stage #8 treatment than in Stage #9, while the production flow contributions from both stages were almost the same.

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5. **Effects of Ultralight Proppant**: The use of ultralight proppant reduced flow connectivity, evident by Stage #10's decreased contribution of 6% versus a similar treatment during Stage #4. Initially strong flow from Stage #10 quickly diminished (see Figure 12), likely due to pathway obstructions caused by the movement of ultralight proppant. The ultralight polymer proppant may also degrade over time. Migration of ultralight proppant away from the wellbore reduced fracture conductivity deep into the fracture. This supports the conclusion that injected water into Stage #10 was channeled into and produced back from Stage #8 and/or Stage #9.
6. **Optimal Sand Volume**: There appears to be an optimal sand volume for maintaining effective flow conductivity, as evidenced by Stage #3R's superior flow contribution compared to Stage #9, despite less sand usage. Excessive sand beyond necessary may not enhance the conductivity between the two wells. More than twice the amount of 40/70 sand was pumped in the Stage #8 than in Stage #9, but the flow contributions from both stages were almost the same.
7. **Flow Pathways Varied over Time**: Production flow contribution from each stage varied over time. This is clearly demonstrated in Figure 13. For example, the production flow contribution was 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 nature of inter-well flow pathways and production flow contribution from each stage.
8. **Poor Flow Conformance**: Overall flow conformance was poor, with approximately 75% of production from Stages #3R, #8 and #9. This imbalance suggests specific pathways are more developed, leading to suboptimal heat extraction across the wells.

4.3 Tracer Data Analysis and Implications on Reservoir Contact Time of Injected Water

During the Extended Circulation Test carried out from August 9, 2024, to September 5, 2024, ten FloTrac nanoparticle traces were deployed from well 16A(78)-32 according to the schedule shown in Table 7. The monitoring of those tracer recovery from the producer well 16B(78)-32 provided invaluable information on the reservoir contact time of the injected water, and the connectivity and flow dynamics between the wells. The longer the reservoir contact time, the more heat production from the injected water.

Also shown in Table 7 is the tracer travelling time (Δt) for each tracer, representing the period from injection to detection at the production well. By examining the tracer travelling times and recovery rates of each tracer, it may be possible to infer how connectivity evolved throughout the test period. Variations in these metrics may indicate changes in fracture conductivity or new pathways opening or closing over time. It should be noted that the uncertainty of the time is high because samples were only collected daily. The resolution of the tracer travelling time measurement can be improved by more frequent sampling.

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Table 7: Summary of tracers deployed into Injector Well 16A(78)-32 and recovered from Producer Well 16B(78)-32

FloTrac Tracer #	Deployed start at		First detected at		Δt (hr)	Comment
1	8/11	7:25 AM	8/12	5:31 PM	34.0	Sampling every 6 hr
2	8/13	7:00 AM	8/15	11:33 PM	64.5	Sampling every 6 hr
3	8/15	7:00 AM	8/15	11:33 PM	16.5	Sampling every 6 hr
4	8/17	7:00 AM	8/17	5:30 PM	10.5	Sampling every 6 hr
5	8/19	7:00 AM	8/19	5:42 PM	10.5	Samples every 24 hr
6	8/22	7:00 AM	8/22	5:31 PM	10.5	Samples every 24 hr
7	8/24	7:00 AM	8/24	5:30 PM	10.5	Samples every 24 hr
8	8/26	7:00 AM	8/26	5:30 PM	10.5	Samples every 24 hr
9	8/28	7:00 AM	8/28	5:30 PM	10.5	Samples every 24 hr
10	8/30	7:00 AM	830	5:30 PM	10.5	Samples every 24 hr

Figure 15 shows the cumulative tracer recovery amount versus time for each of the ten FloTrac tracers injected during the Extended Circulation Test. Figure 16 is a zoom-in view of stage-level production flow contribution during the time when Tracer #1 and Tracer #2 was injected.

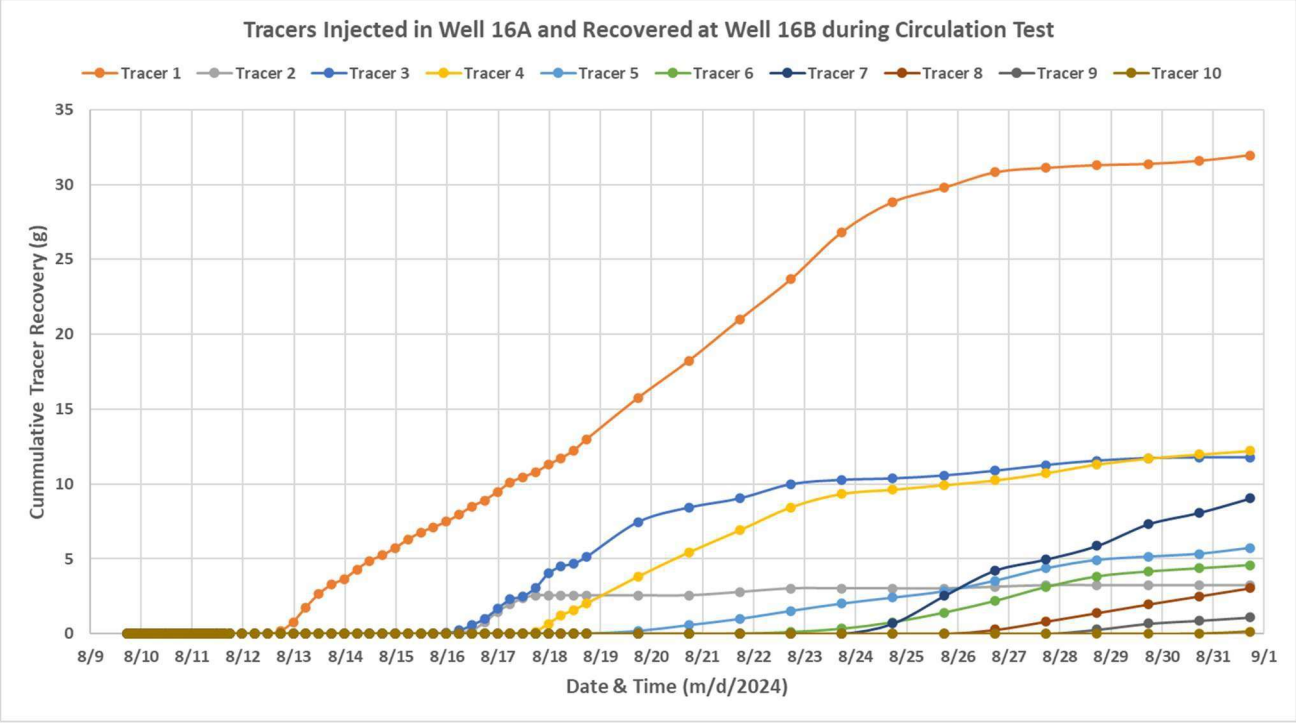

Figure 15: FloTrac nanoparticle tracer recovery versus time during the Extended Circulation Test. The tracer number in this figure is shown in Table 7.

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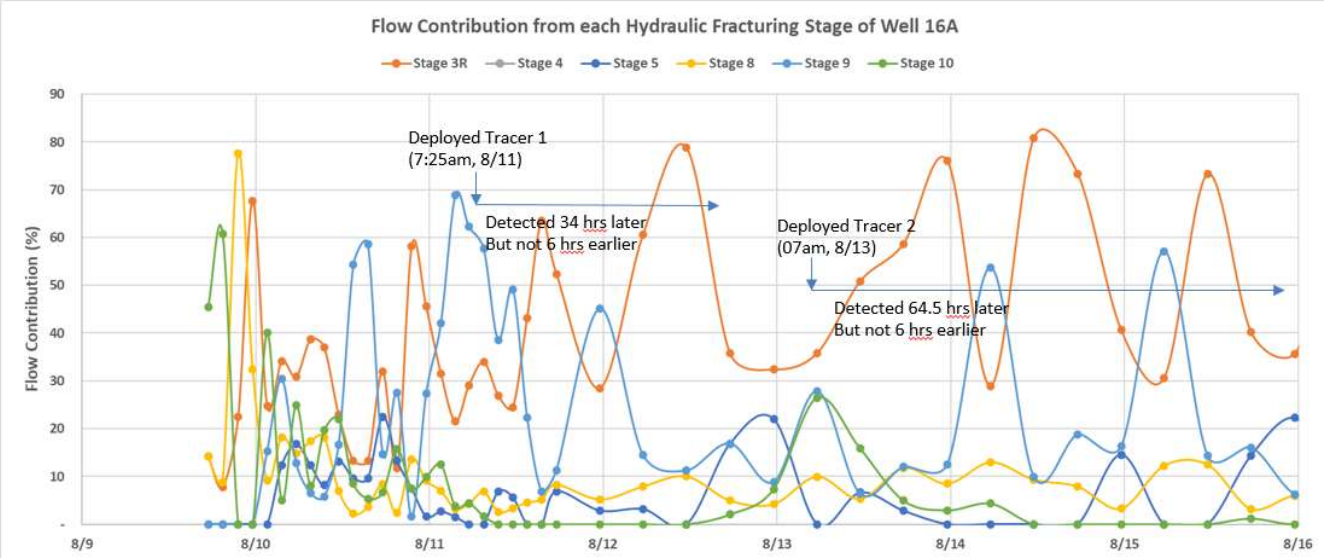

Figure 16: A zoom-in view of stage-level production flow contribution during time when Tracer #1 and Tracer #2 were injected during the Extended Circulation Test. It shows that no production from Stage #10 when Tracer #1 was injected and about 20% production from Stage #10 when Tracer #2 was injected, suggesting flow pathways opening or closing over time.

Conclusions from the tracers injected during the Extended Circulate Test:

- The longer the reservoir contact time of the injected water, the hotter the produced water and the more efficient in heat extraction. The reservoir contact time of the injected water can be monitored from how long it took from the time when a tracer was injected at the injector to the time when the tracer was recovered at the producer.
- The tracer travelling time (Δt) between the start of tracer injection and the first detection from well 16B(78)-32 varied significantly among the first three tracers. The first tracer registered at the producer well after 34 hours, while the second tracer took 64.5 hours, and the third tracer only 16.5 hours. These differences may reflect the ongoing filling of fractures and changing flow pathways over time. This variation indicates that it took several days for the fractures to be filled sufficiently when injecting from well 16A(78)-32, resulting in fluctuating flow pathways between the two wells during this filling period.
- From Tracer #4 onward, detection times were all within 10.5 hours. Since samples were collected either every 6 hours or daily, the actual travelling times for each tracer were uncertain and may have been much shorter than 10.5 hours. As an example, the actual travelling time for Tracer #4 should be between 4.5 and 10.5 hours, as it was not detected from the sample collected 6 hours earlier.
- Tracers #1, #3, #4, and #7 exhibited similar recovery signatures as shown in Figure 15, suggesting similar circulation flow pathways at the time of their injection. In contrast, Tracer #2 displayed a distinct recovery signature, perhaps indicating different circulation pathways during its injection.
- Tracer recovery monitoring provides inferences regarding major flow pathways between the injector and producer wells. A low tracer recovery rate implies that the tracer was

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injected into a stage or stages that had a low production flow contribution and therefore a low recovery rate, as demonstrated by Tracer #2 as an example. As shown in Figure 16, no production was detected from Stage #10 during the time when Tracer #1 was injected, while about 20% production was from Stage #2 when Tracer #2 was injected, suggesting new pathways opening or closing over time.

- High tracer recovery rates such as Tracers #1, #3, #4, and #7 suggest that the primary circulation paths were through Stages #3R, #8, and #9 during and after tracer deployment.

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6. Appendix

6.1 FloTrac™ technology page

https://quantumprot.com/flotrac

6.2 OmniTrac™ technology page

https://quantumprot.com/omnitrac

6.3 PerfTrac™ technology page

https://quantumprot.com/perftrac

6.4 SoluTrac™ technology page

https://quantumprot.com/solutrac

6.5 Recognized publications, SPE papers, and case studies

https://quantumprot.com/media

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