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Cluster-Level Flow Mapping and Production Diagnostics Using Ultrahigh-Resolution Nanoparticle Tracers Embedded in Perforation Charges

Wallace Hendricks²; Eric Marshall³; Talgat Shokanov¹; Quan Guo¹; John Oliver¹; Posi Jejelowo¹. 1. QuantumPro, Inc. 2. True Oil LLC 3. GEODynamics.

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Abstract

Existing methods for production monitoring at the perforation or cluster level are often challenging, intrusive, and very costly. This case study presents a novel cluster-level flow monitoring technique utilizing ultrahigh-resolution and ultrahigh-temperature nanoparticle tracers integrated into the perforation charge liner during manufacturing. The modified perforating system maintains the same performance expectations as conventional systems without tracers, while the non-radioactive, inert tracers eliminate additional handling and regulatory burdens.

The methodology was first validated through comprehensive laboratory testing in accordance with [API RP 19B \(2021\)](#) standards which assessed the stability of nanoparticle tracers under the extreme heat and pressure conditions typical of charge detonation, confirming no impact on charge performance. High-energy dispersive X-ray fluorescence (EDXRF) analyses of fluid and solid particle samples collected from the perforation tunnels inside the concrete cores indicated high tracer recovery and favorable signaling characteristics across various charge types.

Field trials were successfully conducted in unconventional wells in the Williston Basin (North Dakota) and Powder River Basin (Wyoming). Tracer-embedded charges were deployed using a standard plug-and-perf method, with the manufacturing partner integrating the nanoparticle tracers during the manufacturing process. Preliminary results demonstrated sufficient tracer recovery at the cluster level, facilitating advanced flow mapping, quantification of production, and flow performance verification for each individual cluster.

The cluster-level flow monitoring technique signifies a groundbreaking advancement in the industry, providing a nonintrusive means to assess perforation-flow performance and inter-well communication. The method's applications extend to multi-stage completions in unconventional wells, offshore wells,

enhanced geothermal system (EGS) wells, and carbon capture, utilization and storage (CCUS) wells. The perforation level flow monitoring approach enhances clarity during the post-perforation analysis and reservoir development, offering critical insights for optimizing perforation design and overall completion completions strategies to maximize asset value and performance.

Introduction

Over the past two decades, technological advancements in unconventional well completions have steadily improved efficiency, driving significant gains in reservoir contact and production optimization. Key advancements include:

- **Enhanced Stage Design:** Increased number of fracturing stages to enable more precise fracture placement and maximize reservoir exposure.
- **Plug-and-Perf Completions:** Stage isolation and sequential fracturing facilitated by plug-and-perf technology.
- **Equal-Entry-Hole Perforation:** Introduction of uniform-entry perforating charges to improve fluid and proppant distribution consistency.
- **High-Rate Slickwater Fracturing:** More efficient proppant transport through high-rate slickwater treatments.
- **Engineered Proppants:** Development of robust proppants to enhance fracture conductivity and long-term production performance.
- **Advanced Modeling and Simulation:** Improved insights into fracture propagation and fluid flow behavior.
- **Diagnostic Technologies:** Integration of fiber-optic sensing, downhole cameras, and enhanced pressure diagnostic techniques.

These innovations have revolutionized oil and gas extraction from ultralow-permeability unconventional reservoirs. However, economic pressures necessitate continuous improvement in well completion efficiency, production optimization, and cost reduction. Operators must innovate to attract investment, enhance recovery, and streamline operational turnaround times.

Enhancing Well Completion Efficiency

Optimizing well completions presents significant challenges for upstream operators striving for improved financial returns. Incremental efficiency improvements increasingly depend on a comprehensive understanding of source rock variability. Lithological variations, even at the stage and cluster levels, influence completion designs, necessitating tailored perforation strategies to optimize proppant distribution and enhance overall well performance.

Historically, well stages and perforation clusters were evenly distributed along the lateral section of the target formation. However, production variability has demonstrated the need for more granular subsurface evaluation and production mapping. Enhanced understanding is also critical for well spacing and infill drilling programs to maximize acreage utilization and mitigate detrimental cross-well communication. Factors such as perforation placement, cluster density, hole size, orientation, fracture stage spacing, and fluid/proppant selection significantly impact completion effectiveness.

Data acquisition remains a challenge due to cost, complexity, and uncertain return on investment. Advanced logging and imaging tools have enhanced subsurface characterization, but high deployment costs, tool failure risks, and logistical constraints present economic hurdles. Additionally, the true value of acquired data is not always well understood, leading to ambiguity in decision-making.

Microseismic monitoring provides fracture mapping insights but suffers from limited flow profile resolution, making cost-benefit assessments challenging. Chemical and radioactive tracers offer additional diagnostic capabilities but are expensive, prone to reservoir absorption, and require specialized handling with environmental disposal for radioactive tracer flowback.

Addressing Key Uncertainties

Operators seek deeper subsurface insights to optimize perforation and fracturing strategies. Key uncertainties include:

- The impact of well path deviation from the designed trajectory on perforation and fracturing effectiveness.
- Optimal perforation hole size, penetration depth, and cluster spacing to enhance recovery.
- Detecting and quantifying cross-well communication.

Additional data acquisition can drive more informed decision-making, validate hypotheses, and enable incremental performance improvements, ultimately enhancing return on investment.

Development Overview and Objectives

This study aimed to evaluate the detectability of ultrahigh-resolution nanoparticle tracers deployed via commercially available perforating charges and to validate their effectiveness in optimizing perforation and completion designs.

In 2023, researchers validated nanoparticle tracers through comprehensive laboratory testing conducted in accordance with [API RP 19B \(2021\)](#) standards described in the following section. The approach involved incorporating nanoparticle tracers into equal-entry-hole perforation liners ([Figure 1](#)). The primary objectives were:

- **Assessing Stability:** Evaluating nanoparticle tracer integrity under extreme perforation charge detonation conditions.
- **Quantifying Perforation Impact:** Determining the influence of nanoparticle application on perforation hole size and penetration depth across varying tracer concentrations.
- **Validating Detection and Recovery:** Confirming nanoparticle tracer recovery, detectability, and concentration measurements post-detonation.

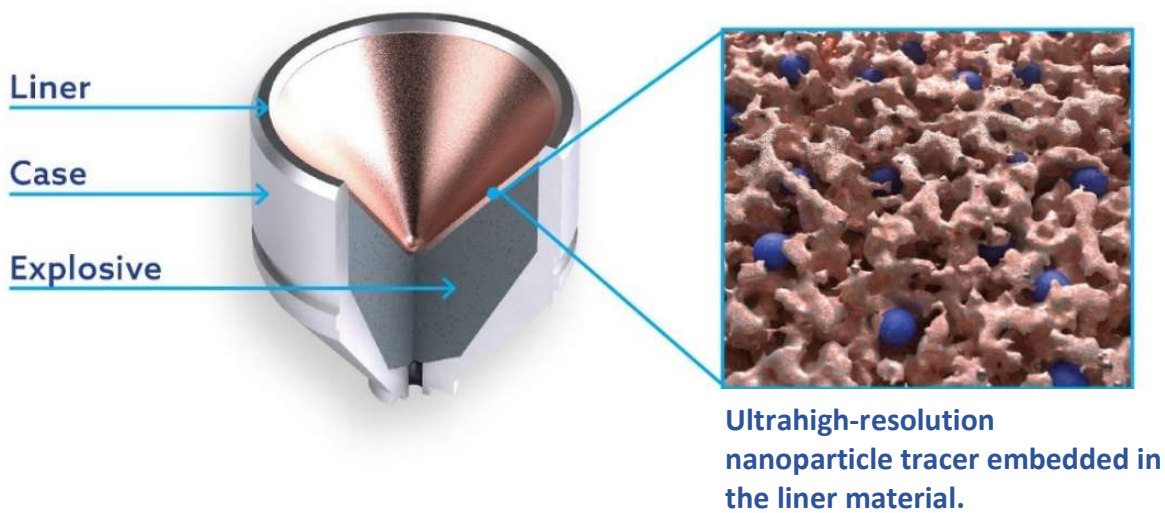


Figure 1: Ultrahigh-resolution nanoparticles added to the perforation liner

Laboratory Tests and Results

Both laboratory and field trials were designed and conducted to address the following key questions:

- Will the tracer integrated into the charge liner withstand detonation?
- Will the tracer remain detectable after significant quantities of water and proppant are pumped?
- What is the longevity of tracer detection?

This section presents the laboratory test design and results that address the first question. Field trials and results related to the second and third questions will be discussed in a later section.

A comprehensive laboratory testing program was conducted in accordance with [API Recommended Practice \(RP\) 19B \(2021\)](#) to address the first question. [Figure 2](#) illustrates the test setup schematic, which simulates the charge, charge in-gun clearance, gun scallop, the water gap between the gun and the casing, as well as the casing and the concrete or rock core. In the current tests, concrete cores were utilized. All tests were performed according to the standards outlined in [API RP 19B \(2021\)](#).

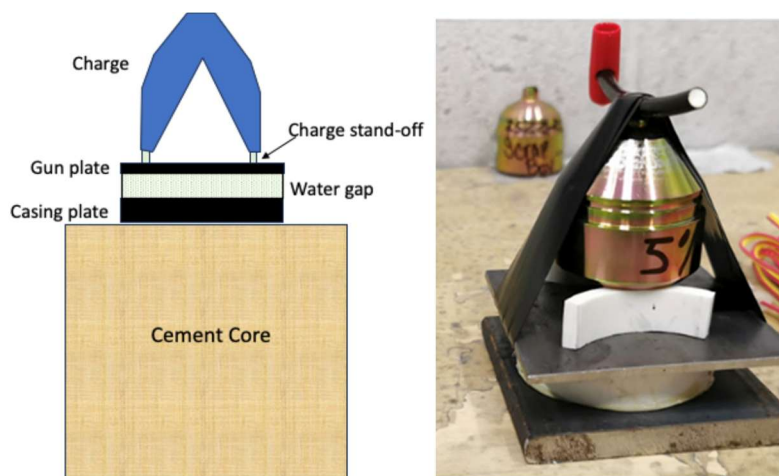


Figure 2: Perforation charge and [API RP 19B \(2021\)](#) setup: shaped charge, charge stand-off, gun scallop plate, water gap, casing plate, and cement core of perforation target.

The perforation charges, containing varying amounts of nanoparticle tracers, ranging from 1 to 5% by weight of the charge liner, were tested to determine the extent to which nanoparticle tracers could be embedded in a charge without adversely affecting their performance. The casing entrance hole (EH) and the depth of penetration into the concrete target were measured to assess the impact on charge performance. The tests demonstrated that there was no significant effect on the casing entrance hole with up to 5% tracer in the charge liner. However, the impact on depth of penetration was more pronounced, resulting in reductions ranging from a few percent to over 20%, depending on the specific charge and the amount of nanoparticle tracer used.

The tests confirmed that nanoparticle tracers embedded in the charge liner can withstand perforation detonation without significantly impacting charge performance. Fluid and solid particle samples were collected from the perforation tunnels within the perforated concrete cores. The sub-atomic analysis, using EDXRF analysis, revealed that the nanoparticle tracers incorporated in the perforation charges successfully endured the shock of detonation, as illustrated in [Figure 3](#).

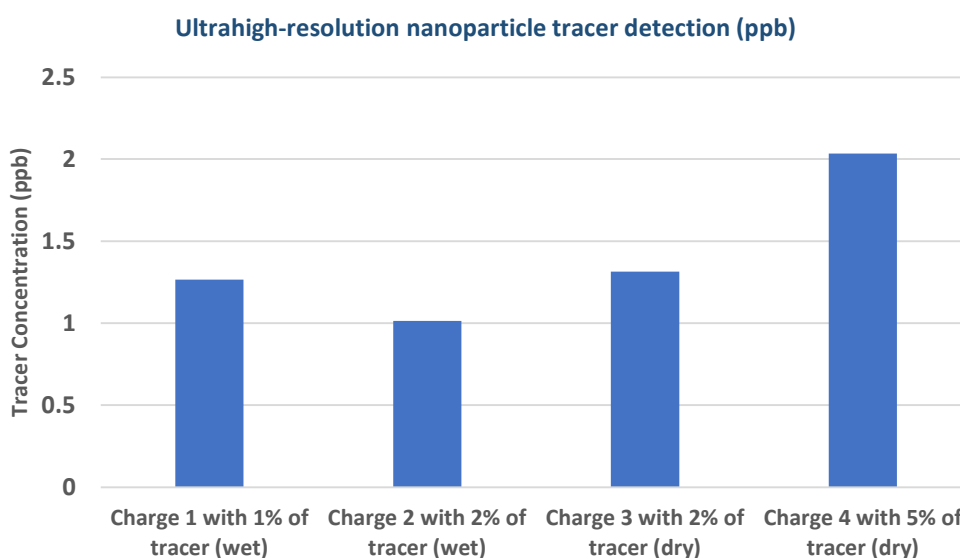


Figure 3. API RP 19B (2021) tests and nanoparticle tracer detection results. Note that tracer concentration is measured in parts per billion (ppb).

After confirming that the nanoparticle tracers could withstand charge detonation, two field trials were designed and conducted to evaluate their detectability and longevity in field conditions. This was

particularly important in scenarios where large volumes of water and proppant are pumped, and wells may remain shut in for months before flowback and production begin. The subsequent trials affirmed the practical effectiveness of nanoparticle tracer technology in real-world applications.

Uniquely Engineered Nanoparticle Tracers

As demonstrated in hundreds of unconventional wells, the ultrahigh-resolution nanoparticle tracer portfolio consistently quantifies the flow behavior of individual stages, effectively bridging the economic gap that previously hindered stage-level or cluster-level flow mapping in mainstream shale wells. These non-intrusive nanoparticle-based tracers have proven to deliver accurate and near real-time detection, surpassing the capabilities of conventional liquid chemical and radioactive tracers.

The non-radioactive inert nanoparticle tracers are formulated for sub-atomic detection accuracy, resulting in exceptional surface recovery rates that correlate closely with hydrocarbon and water production. Diagnostic field data reveals that this technology achieves high precision in production mapping at both stage and cluster levels. When combined with sub-atomic measurements, the nanoparticle tracers offer accurate and robust detection capabilities. Furthermore, laboratory analyses incorporating big-data analytics, advanced 3D reservoir flow visualization, and nanoparticle detection techniques which yield accurate, calibrated, and cost-effective completion diagnostics.

The nanoparticle tracer portfolio consists of 220 uniquely tagged proprietary particles developed from cost-effective and environmentally friendly materials ([Figure 4](#)). These nanoparticle tracers are lightweight, with specific gravities ranging from 0.92 to 1.17 g/cm³.

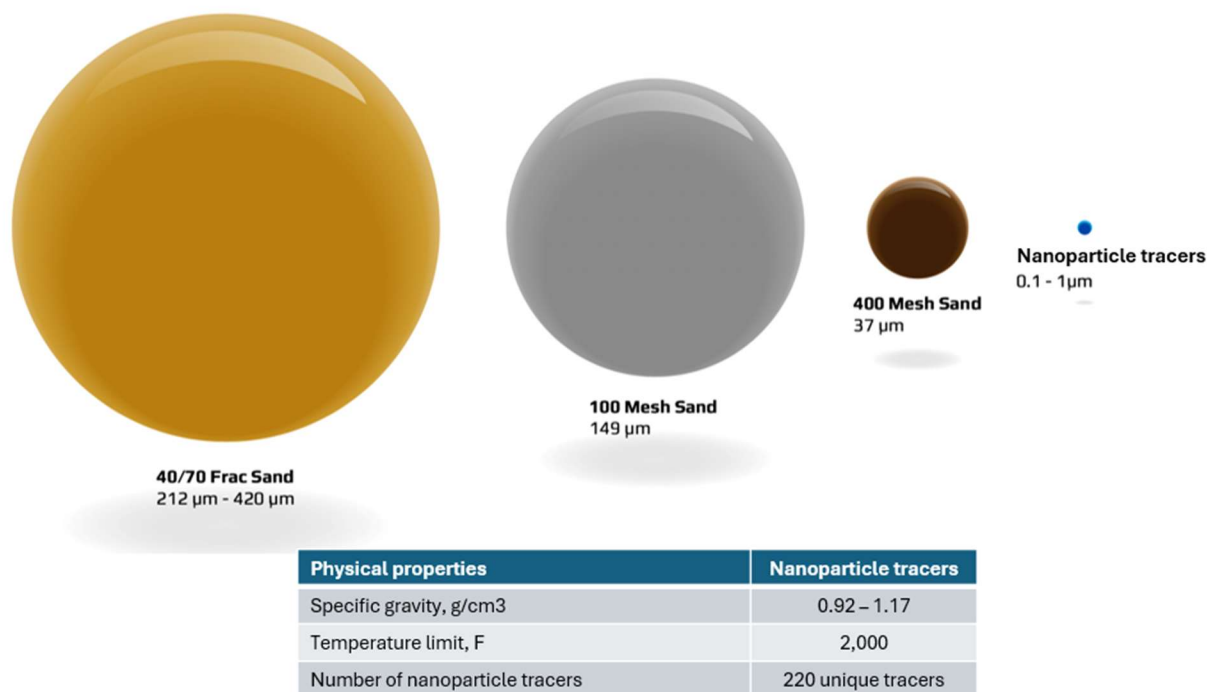


Figure 4. Ultrahigh-resolution nanoparticle tracer shown in comparison to the sizes of popular fracture sands.

Each tracer was evaluated for specific characteristics, including high thermal stability (up to 2,000°F), pressure stability, settling time, particle size distribution (PSD), elemental composition, and reservoir static and dynamic adsorption. This evaluation validates performance under real-world subsurface conditions, particularly regarding recovery efficiency at both minimum and maximum flow velocities.

Ensuring a low-cost structure was ranked as a primary criterion at the outset of the technology development program, leading to the engineering of a single nanoparticle tracer formulation compatible with both oil and water. As a result, only one type of nanoparticle tracer is needed for both measurements, effectively halving the cost compared to conventional chemical tracers.

Unlike their chemical liquid counterparts, the nanoparticle tracers tend to remain in the conductive proppant fracture rather than quickly dissolving within the discrete fracture network. This characteristic significantly extends the recovery time and enables continuous measurement and monitoring of the production profile after deployment. Additionally, the nanoparticle tracers do not penetrate the small fissures that can open during the hydraulic fracturing process, which helps to mitigate the false positive signals commonly associated with chemical tracers and avoids unnecessary and costly reactive measures.

The design of the nanoparticle tracer for each perforation gun was developed by experts in nanoparticle tracers, reservoirs, and perforations. For the first field trial, five unique nanoparticle tracers were manufactured, while ten distinct nanoparticle tracers were manufactured for the second field trial. The deployment strategy for the nanoparticle tracer at each gun is discussed and elaborated upon in the following sections.

Completion Design and Perforation Strategy

The study analyzed data from the Williston Basin (North Dakota) and Powder River Basin (Wyoming). The wells employed similar completion designs and perforation strategies, with variations in formation and wellbore trajectory influencing tracer deployment modifications.

Each horizontal well completion utilized 250-foot stage spacing, featuring eight perforation clusters per stage, each comprising four 0.40-inch EHD equal entry hole charges, loaded at a 45-degree angle (directed towards the toe of the well) to promote more uniform proppant distribution. All shots were phased at 90/270 degrees. The wellbore architecture for the first trial consisted of a 4½-in. liner in the horizontal section while the second trial utilized a 5½-in. monobore. Pump rates targeted 1,100 psi of perforation friction with 100% fluid acceptance. This friction pressure was determined to be in excess of the minimal horizontal stress variability along a typical later for each area and thus adequate for effective proppant distribution into each cluster.

Tracer Deployment Methodology

The first field trial focused on validating nanoparticle tracer detectability using standard perforating systems. Three deployment methods were evaluated as follows:

1. **Liner-Embedded Tracers:** Nanoparticles incorporated into the perforating charge liner (0.25 g per charge).
2. **3D-Printed Charge Rings:** Tracer-infused rings placed on the charge face (1.3 g per charge).
3. **Load Tube Vials:** Nanoparticle vials housed in the perforating gun load tube (400 to 600 g per charge).

[Table 1](#) depicts a more visual representation of the deployment strategy. Note that Gun 1 in each instance is at the heel side of the stage.

Stage X	Gun #1	Gun #2	Gun #3	Gun #4	Gun #5	Gun #6	Gun #7	Gun #8
Tracer in Liner	Tracer 1	Tracer 2	Tracer 2	Tracer 2	Tracer 2	Tracer 2	Tracer 2	Tracer 2
Tracer in Vial	Tracer 3	Tracer 3	Tracer 3	Tracer 3	Tracer 3	Tracer 3	Tracer 3	Tracer 3
Stage X=1	Gun #1	Gun #2	Gun #3	Gun #4	Gun #5	Gun #6	Gun #7	Gun #8
Charge Ring	Tracer 4	Tracer 5	Tracer 5	Tracer 5	Tracer 5	Tracer 5	Tracer 5	Tracer 5

Table 1. Deployment strategy for first field trial.

Following the first trial, a second field trial aimed to determine the minimal detectable tracer concentration in surface fluid samples. This trial exclusively used liner-embedded nanoparticle tracers across six stages with eight unique tracer variations. The deployment strategy is summarized below in [Table 2](#).

Gun #	Stage X	Stage X+1	Stage X+2	Stage X+3	Stage X+4	Stage X+5
1	Tracer 4	Tracer 6	Tracer 10	Tracer 1	Tracer 2	Tracer 3
2	Tracer 4	Tracer 7		Tracer 1	Tracer 2	Tracer 3
3	Tracer 4			Tracer 1	Tracer 2	Tracer 3
4	Tracer 4			Tracer 1	Tracer 2	Tracer 3
5	Tracer 5			Tracer 1	Tracer 2	Tracer 3
6	Tracer 5			Tracer 1	Tracer 2	Tracer 3
7	Tracer 5	Tracer 8		Tracer 1	Tracer 2	Tracer 3
8	Tracer 5	Tracer 9		Tracer 1	Tracer 2	Tracer 3

Table 2. Deployment strategy for second field trial.

Field Trials - Deployment and Results

The two field trials were designed and conducted across three wells. The first trial took place at the high-temperature, high-pressure (HTHP) well SF-T2H in the Williston Basin (North Dakota). The second field trial was conducted on two wells, 24-T1H and 34-T2H, in the Powder River Basin (Wyoming). The bottomhole temperature is approximately 275-295°F for the Williston well and about 140-160°F for the Powder River wells.

The first field trial aimed to validate the detectability of the nanoparticle tracer at varying tracer concentrations, given that only a minimal amount of nanoparticle tracer can be incorporated into each charge, while large volumes of water and proppant are used during hydraulic fracturing process. For this trial, two stages—Stage 12 and Stage 13—were selected. Each stage comprised eight clusters and each cluster was perforated with four charges.

The trial was designed to evaluate various scenarios with nanoparticle tracer levels ranging from approximately 1 to 5 g, 30 g, and 500 g. Gun 1 in Stage 12 was loaded with four charges, each containing Tracer 1, resulting in a total of 0.9 g of Tracer 1 for the four charges. Guns 2 through 8 were loaded with charges that included Tracer 2, contributing a total of about 6.4 g of Tracer 2 for the 28 charges. Additionally, vials containing nanoparticles were placed in the perforating gun load tube, totaling 500 g of Tracer 3.

The guns in Stage 13 were loaded with conventionally manufactured charges that did not contain nanoparticle tracers, but with 3D-printed tracer-infused rings placed on the charge face. Gun 1 in Stage 13 contained 4.8 g of Tracer 4, while the total amount of Tracer 5 in Guns 2 through 8 was 33.6 g (Table 1).

The well was completed with 40 frac stages, with Stages 12 and 13 completed on August 1, 2024. Approximately 260,000 gallons of water and 200,000 pounds of proppant were pumped during each stage of the hydraulic fracturing treatment. The well was shut in for over two months prior to production. The flowback commenced on October 14, 2024, with an initial rate of approximately 1,000 barrels per day (bpd) of oil and water. Production fluid samples were collected at the wellhead on October 21 and 22, 2024 for analysis of nanoparticle tracer recovery and concentration, utilizing sub-atomic detection with EDXRF analysis.

[Table 3](#) presents the concentrations of nanoparticle tracers measured in parts per billion (ppb) in the oil and water phases of the samples. Based on the results, the following conclusions can be made:

- Nanoparticle tracers can be detected in flowback production after pumping 260,000 gallons of water and 200,000 pounds of proppant during each stage of hydraulic fracturing.
- A cluster with 0.9 g of nanoparticle tracer (Tracer 1) is detectable after one week of production, although the signal remains weak.
- Clusters with about 5 g of nanoparticle tracers (Tracer 2 and Tracer 4) are sufficient for robust detection, with both nanoparticle tracers showing strong tracer recovery concentrations after one week of production.
- Both methods – embedding nanoparticle tracers in the charge liner and attaching tracers to existing charges – proved effective and provided quantifiable tracer results.

Well SF-T2H	Tracer # & Amount	10/21/2024 - 9:00 AM		10/21/2024 - 2:00 PM		10/22/2024 - 12:00 AM		10/22/2024 - 3:00 AM		10/22/2024 - 9:00 AM		10/22/2024 - 12:00 PM	
		Water (ppb)	Oil (ppb)	Water (ppb)	Oil (ppb)	Water (ppb)	Oil (ppb)	Water (ppb)	Oil (ppb)	Water (ppb)	Oil (ppb)	Water (ppb)	Oil (ppb)
Stage #12 - Gun #1	0.9 g Tracer #1	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.02	0.00	0.00	0.00	0.01
Stage #12 - Gun #2 - 8	6.4 g Tracer #2	0.00	0.00	0.13	0.00	0.06	0.05	0.02	0.17	0.11	0.31	0.04	0.05
Stage #12 - Vial (all guns)	500 g Tracer #3	0.09	0.11	0.14	0.13	0.15	0.09	0.13	0.12	0.26	0.09	0.12	0.13
Stage #13 - Gun #1	4.8 g Tracer #4	0.16	0.15	0.13	0.23	0.06	0.26	0.07	0.04	0.11	0.13	0.07	0.16
Stage #13 - Gun #2 - 8	33.6 g Tracer #5	0.06	0.03	0.07	0.03	0.05	0.03	0.08	0.11	0.18	0.29	0.08	0.34

Table 3. Cluster-by-cluster nanoparticles recovery in ppb.

The second field trial was conducted on two wells, 24-T1H and 34-T2H, in the Powder River Basin (Wyoming). These wells were zipper fractured, with each well comprising 41 stages, conducted in late October 2024. Approximately 130,000 gallons of water and 360,000 pounds of proppant were pumped for each stage. Each stage consisted of eight clusters, and each cluster was perforated with four charges.

The primary objectives of this trial were to gather additional data points, ensure consistency, and assess the longevity of nanoparticle tracer detectability. The six frac stages were selected for testing during this trial. It should be noted that Stage 39 of Well 24-T1H was initially selected but was later replaced with Stage 31 of Well 34-T2H. This change was made because Stage 31 of Well 34-T2H was located outside the reservoir zone, and there was interest in determining if there was any production from this stage.

- **Stage 14, Well 24-T1H:** Guns 1-4 (Tracer 4), Guns 5-8 (Tracer 5)
- **Stage 15, Well 24-T1H:** Gun 1 (Tracer 6), Gun 2 (Tracer 7), Gun 7 (Tracer 8), Gun 8 (Tracer 9)
- **Stage 16, Well 24-T1H:** Gun 1 (Tracer 10)
- **Stage 23, Well 24-T1H:** Guns 1-8 (Tracer 1)

- **Stage 31, Well 24-T1H:** Guns 1-8 (Tracer 2)
- **Stage 31, Well 34-T2H:** Guns 1-8 (Tracer 3)

The flowback and production for Well 24-T1H commenced on November 27, 2024, while production for Well 34-T2H began on December 11, 2024, both at an initial rate of approximately 1,300 barrels per day (bpd) of oil and water. Three production fluid samples were collected from each well in the period December 15 – 17, 2024. [Table 4](#) presents the results of the nanoparticle tracer detection analysis, showing the cluster-by-cluster tracer recovery concentrations in parts per billion (ppb).

Based on the results, the following conclusions can be drawn:

- A good nanoparticle tracer recovery was observed even with tracers of only 0.9 grams. It is noteworthy that these samples were collected over two weeks after production commenced.
- The results are consistent and reasonable, with the five clusters containing only 0.9 g of tracers yielding similar results.
- Clusters with more nanoparticle tracers in the charge exhibited greater tracer recovery. Generally, tracer recovery concentrations were lowest in clusters with 0.9 g of tracers from a single gun, higher in clusters with 3.7 g of tracers from four guns, and highest in clusters with 7.4 g of tracers from eight guns.
- The results indicated that there was production from the out-of-zone Stage 31 of Well 34-T2H, which was a testing objective for this stage.

Well 24-T1H	Tracer # & Amount	12/15/24		12/16/24		12/17/24	
		Water (ppb)	Oil (ppb)	Water (ppb)	Oil (ppb)	Water (ppb)	Oil (ppb)
Stage #14 - Guns #1-4	3.7 g Tracer #4b	0.30	0.15	0.23	0.71	0.30	0.68
Stage #14 - Guns #5-8	3.7 g Tracer #5b	0.13	0.09	0.23	0.13	0.18	0.45
Stage #15 - Gun #1	0.9 g Tracer #6b	0.03	0.06	0.02	0.07	0.03	0.01
Stage #15 - Gun #2	0.9 g Tracer #7b	0.11	0.09	0.01	0.02	0.02	0.04
Stage #15 - Gun #7	0.9 g Tracer #8b	0.05	0.06	0.07	0.06	0.05	0.03
Stage #15 - Gun #8	0.9 g Tracer #9b	0.19	0.25	0.14	0.04	0.17	0.16
Stage #16 - Gun #1	0.9 g Tracer #10b	0.07	0.08	0.09	0.05	0.07	0.05
Stage #23 - Guns #1-8	7.4 g Tracer #1b	0.26	0.22	0.16	0.48	0.12	0.33
Stage #31 - Guns #1-8	7.4 g Tracer #2b	0.49	0.16	0.43	0.25	0.48	0.61
Well 34-T2H	Tracer # & Amount	12/15/24		12/16/24		12/17/24	
		Water (ppb)	Oil (ppb)	Water (ppb)	Oil (ppb)	Water (ppb)	Oil (ppb)
Stage #31 - Guns #1-8	7.4 g Tracer #3b	0.65	0.57	0.00	0.91	0.30	0.68

Table 4. Cluster-by-cluster nanoparticles recovery concentration in ppb

A second batch of samples was collected from January 7 to 15, 2025 to investigate the duration of nanoparticle tracer detectability. This time, only oil samples were collected. These samples were taken approximately 45 days after production started for Well 24-T1H and 30 days after production began for Well 34-T2H.

[Table 5](#) shows the results of the nanoparticle tracer detection analysis from the four samples. The findings indicate that after approximately 30,000 barrels of oil and water production:

- Tracers 1b, 2b, and 3b, corresponding to all cases containing 7.4 g of tracers in eight clusters, continued to demonstrate strong nanoparticle tracer recovery.

- Tracers 4b and 5b, associated with all cases containing 3.7 g of tracers in four clusters, also exhibited good nanoparticle tracer recovery.
- Tracers 6b to 10b, related to 0.9 g of tracers in a single cluster, began to show significantly weaker nanoparticle tracer recovery for some cases, suggesting that the detection limit for these tracers may have been reached.

Well 24-T1H	Tracer # & Amount	1/7/25		1/13/25		1/14/25		1/15/25	
		Water (ppb)	Oil (ppb)	Water (ppb)	Oil (ppb)	Water (ppb)	Oil (ppb)	Water (ppb)	Oil (ppb)
Stage #14 - Guns #1-4	3.7 g Tracer #4b	100% Oil Sample	0.13	100% Oil Sample	0.17	100% Oil Sample	0.08	100% Oil Sample	0.07
Stage #14 - Guns #5-8	3.7 g Tracer #5b		0.19		0.23		0.15		0.03
Stage #15 - Gun #1	0.9 g Tracer #6b		0.00		0.00		0.00		0.00
Stage #15 - Gun #2	0.9 g Tracer #7b		0.07		0.09		0.06		0.07
Stage #15 - Gun #7	0.9 g Tracer #8b		0.04		0.04		0.07		0.04
Stage #15 - Gun #8	0.9 g Tracer #9b		0.22		0.19		0.24		0.23
Stage #16 - Gun #1	0.9 g Tracer #10b		0.24		0.26		0.24		0.09
Stage #23 - Guns #1-8	7.4 g Tracer #1b		0.29		0.33		0.07		0.00
Stage #31 - Guns #1-8	7.4 g Tracer #2b		0.73		0.64		0.62		0.00
Well 34-T2H	Tracer # & Amount	1/7/25		1/13/25		1/14/25		1/15/25	
		Water (ppb)	Oil (ppb)	Water (ppb)	Oil (ppb)	Water (ppb)	Oil (ppb)	Water (ppb)	Oil (ppb)
Stage #31 - Guns #1-8	7.4 g Tracer #3b	100% Oil Sample	0.30	100% Oil Sample	0.64	100% Oil Sample	0.85	100% Oil Sample	0.96

Table 5. Cluster-by-cluster recovery of nanoparticles; concentration recorded in ppb.

Ongoing research and refinements in deployment methods will increase the efficiency of nanoparticle tracer applications, ultimately enhancing well completions and overall field economics.

Conclusions

Extensive laboratory testing and field trials have confirmed that nanoparticle tracers remain detectable at various deployment concentrations, allowing for more accurate well-performance analysis. This study emphasizes the potential of nanoparticle tracers to improve perforation-level flow diagnostics, optimize completion design, and support data-driven decision-making in complex unconventional reservoirs.

This method can be also applied to offshore wells, enhanced geothermal system (EGS) wells, and carbon capture, utilization, and storage (CCUS) wells. The perforation-level flow monitoring approach improves clarity during post-perforation analysis and reservoir development, providing essential insights for optimizing perforation design and overall completion strategies to maximize asset value and performance.

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