

Cluster-level flow mapping and production diagnostics using ultrahigh-resolution nanoparticle tracers

Existing methods for perforation or cluster-level production monitoring are often challenging, intrusive and costly. This case study outlines a novel flow monitoring technique and modified perforating system, which maintains similar performance to conventional systems without tracers, while also eliminating additional handling and regulatory burdens.

WALLACE HENDRICKS, True Oil LLC; **ERIC MARSHALL**, GEODynamics; **TALGAT SHOKANOV**, **JOHN OLIVER** and **QUAN GUO**, QuantumPro, Inc.

Technological advancements in unconventional well completion efficiency have been on a steady march over the last two decades. Some of the more well-known advancements have included:

- Increased stages for more precise placement of fractures and better reservoir contact
- Plug-and-perf completions, enabling stage isolation and sequential fracturing
- Introduction of equal entry hole perforating charges that yield higher uniformity of fluid and proppant distribution
- High-rate slickwater fracs, yielding more economically efficient proppant transport
- Engineered proppants that are more robust, to enhance fracture performance and long-term production
- Advanced modeling and simulation, allowing better insight into fracture propagation and modeling of fluid flow behavior
- Fiber optic sensing, downhole cameras, and improved pressure diagnostic techniques.

All these advancements contributed to a revolution in oil and gas production in ultra-low permeability unconventional reservoirs, dramatically transforming the industry. While this progress has been heralded, ever-tight margin pressure demands that operators continue to achieve better economic efficiency, increase recovery and improve turnaround time from one well to the next. As a result, the technological march continues, challenging operators to innovate, compete for investment, demonstrate incremental improvements, and challenge the status quo.

Enhancing well completions efficiency is a difficult challenge for upstream operators seeking to improve financial returns. Incremental improvements in completions efficiency increasingly depend on understanding the variable source rock. This understanding allows for completion programs that account for lithology variations—even at the stage level. By tailoring the perforation strategy more precisely, operators can improve proppant distribution and enhance overall well performance.

Well stages and perforation clusters were once thought to be best distributed evenly along the target formation lateral. However, they often produce at highly variable rates, highlighting the need for more thorough subsurface inspection. Well spacing and infill programs also require greater subsurface understanding, to maximize acreage and avoid costly cross-well communication. Factors like perforation placement, density, size and orientation—along with frac stages and spacing and frac fluid and proppant selection—can significantly impact results. Acquiring the necessary data can be complex, expensive and often out of reach, with an uncertain return on investment.

Advanced logging and imaging tools have expanded our understanding of the subsurface. However, their high deployment cost and the risk of tool failure and data loss can pose economic challenges. The value of the acquired information is often not fully understood, leading to more questions than answers. Deploying these tools also involves complexities, due to logistical constraints and downhole limitations. This necessitates additional staff at the wellsite, increasing costs by extending rig time. Newer logging tools offer improved robustness, efficiency and cost-effectiveness, but their high initial cost and limited long-term data may still be challenging—particularly for operators working with tight margins.

Microseismic monitoring, used to map induced fractures, delivers actionable insight. However, flow profile resolution is limited, and the cost-benefit analysis can be challenging. While cost reductions are making microseismic monitoring more accessible, it still has limitations. Chemical and radioactive tracers— injected during fracturing—are useful but also have drawbacks, including high costs, high absorption to the reservoir rock and a need for special handling.

Operators increasingly require a deeper understanding of the subsurface to more intelligently perf and frac a formation and answer many key questions. For example: is it still effective to perf and frac a zone, if the well path strays 10 ft or more from the designed path? Are the perforation hole size, penetration, and cluster spacing optimal, and at what point are adjustments needed in successive wells? Is there cross-well communication? If so, how can cross-well communication be confirmed? A deeper understanding, enabled by additional data acquisition, can deliver more insight into questions like these, as well as guide decisions, test hypotheses and lead to continued improvements and higher return on investment (ROI).

THE VALUE OF ASSESSING PERFORATION FLOW PERFORMANCE

Assessing perforation flow performance in long laterals is crucial for optimizing oil and gas completions. In long laterals, it's essential to ensure that hydraulic fracturing fluid and proppants are distributed evenly across all perforation clusters. Analyzing flow helps to identify any restrictions or preferential paths that could lead to uneven fracture growth and suboptimal levels of stimulation.

Efficient flow through perforations improves communication between the wellbore and the reservoir, maximizing the area contacted by the fracturing fluid and proppant and leading to improved hydrocarbon recovery. By analyzing perforation flow performance, operators can pinpoint zones where flow is restricted. This information is valuable in making the decision to adjust completion parameters in future wells, including:

- Perforation density: increasing the number of perforations in low-flow zones or skipping zones altogether.
- Perforating systems: modifying gun diameters, orienting perforations and changing charge types to maximize the uniformity of fluid and proppant distribution.
- Stage spacing: adjusting the distance between stages to optimize fluid distribution and maximize production.

Understanding perforation flow performance helps operators avoid overspending on stimulation in zones with naturally high flow capacity, allowing for more efficient allocation of resources. Efficient flow through

perforations also minimizes pressure drop along the wellbore, leading to improved production rates and lower lifting costs.

Furthermore, optimized perforation flow performance helps prevent proppant screen-outs, which can damage the formation, hinder production and lead to costly intervention. Analyzing flow also can help identify potential leak points or areas of weakness in the casing or cement, ensuring well integrity and preventing environmental issues.

ULTRAHIGH-RESOLUTION NANOPARTICLE TRACERS DELIVERED VIA PERFORATION SYSTEMS, A NEW FRONTIER

Nanoparticle tracers represent a significant advancement in production and flow monitoring capability. They are more robust than chemical or radioactive tracers, capable of withstanding extreme well conditions and require no special handling. At the perforation or cluster level, these tracers provide more detailed measurements, adding a new dimension and host of applications not possible with previously existing measurements. Nanoparticle tracers offer crucial insight into geological information and variability. As the oil and gas industry seeks to improve efficiency and maximize recovery, these nanoparticles hold an enormous opportunity for an increasingly important role by delivering valuable insights into reservoir behavior.

Given the cost, complexities and limitations of traditional methods, QuantumPro, Inc., envisioned using nanoparticle tracers, delivered through perforation charges, as an opportunity and innovation that the industry was ready for. The specific application—assessing perforation flow performance as discussed here—is one of the new approaches that is being assessed, successfully tested, and deployed as of writing. Nanoparticle tracer technology provides a new level of detail for evaluating well completion efficiency, exceeding the scale and detail of traditional measurements.

UNIQUELY IDENTIFIABLE, INERT NANOPARTICLE TRACERS ENABLE WIDE APPLICATIONS

QuantumPro's FloTrac ultra-high-resolution nanoparticle tracers are configurable in up to 220 different, uniquely identifiable and inert variations, **Fig. 1**. This large portfolio of unique tracers enables broad applications that can extend to adjacent wells, to record cross-well communication—critical for optimizing well spacing—and to replace trial-and-error approaches with data-driven optimization.

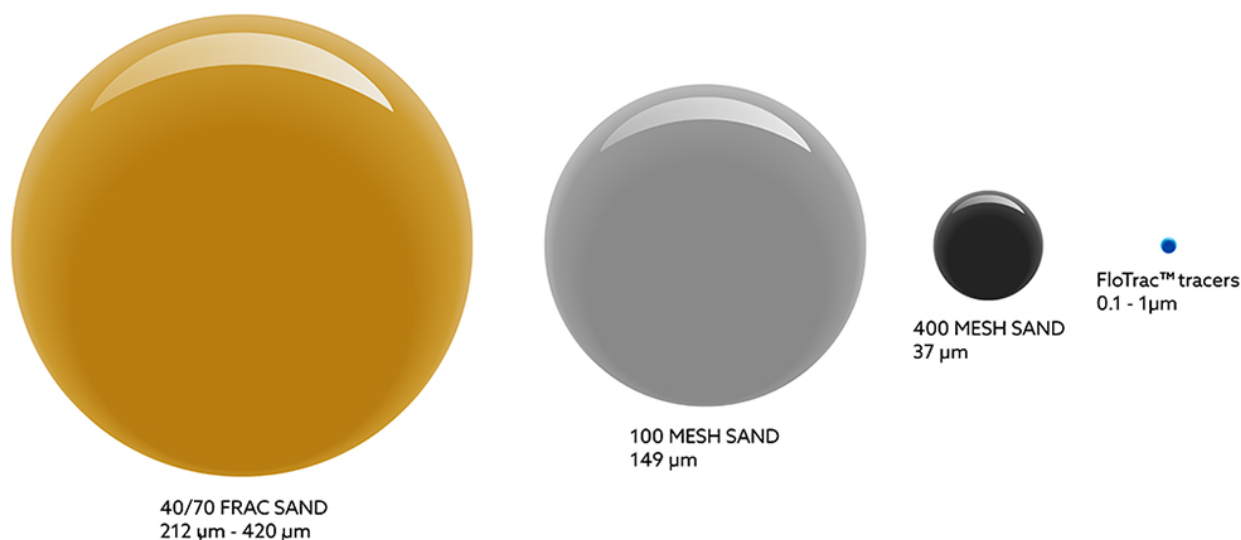


Fig. 1. Size comparison of FloTrac tracers, compared to different sand particles.

Unlike liquid chemical tracers, every FloTrac nanoparticle tracer is compatible with both water and oil, requiring only a single tracer composition, regardless of the fluid stream, reducing costs considerably. Since the insoluble FloTrac tracers do not dissolve after deployment, operators can perform surface sampling for at least nine months—well beyond the capability of liquid chemical tracers. FloTrac tracers also maintain stability in temperatures up to 2,000°F.

The specially designed nanoparticles show broad application, and after laboratory testing, they were recently deployed via modified perforating charges by True Oil, LLC, in the Williston basin of North Dakota in a first-ever field trial with encouraging results.

LABORATORY VALIDATION OF NANOPARTICLE TRACER APPLICATION TO PERFORATION SYSTEMS

In 2023, researchers validated nanoparticle tracers and implementation methodology through comprehensive laboratory testing, in accordance with API RP19 standards, at the GEODynamics Inc. testing and manufacturing facility, located in Millsap, TX. Researchers added nanoparticle tracers to the perforation liner of the equal entry hole, FracIQ charge, **Fig. 2**.

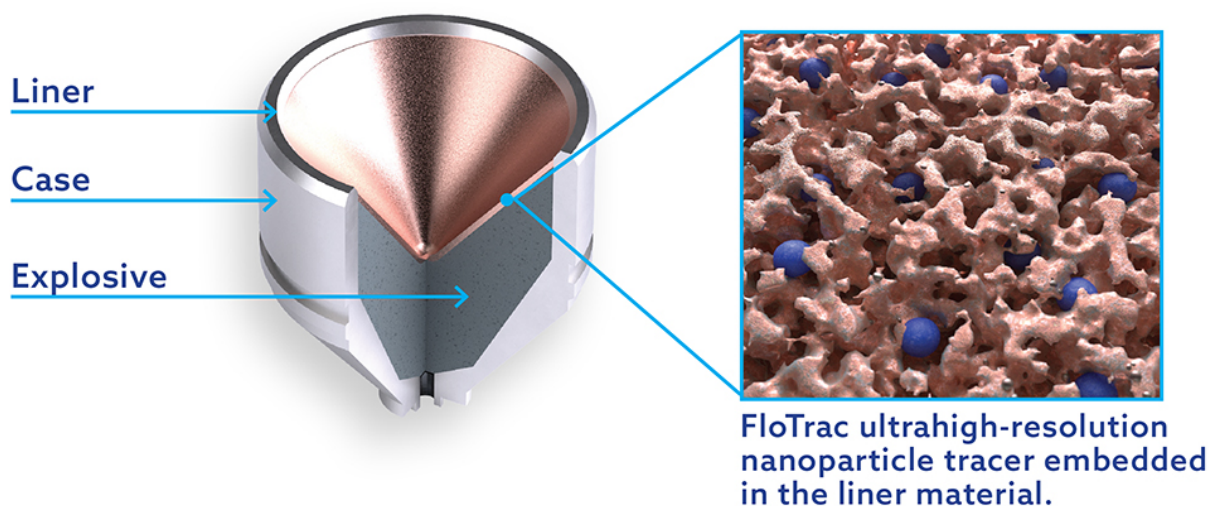


Fig. 2. Ultrahigh-resolution nanoparticles added to the perforation liner.

The test aimed to accomplish the following:

- Assess the stability of nanoparticle tracers under the extreme conditions typical of perforation charge detonation
- Determine if applying the nanoparticles had any impact on the perforation hole size and depth penetration, as well as how various nanoparticle concentrations impacted the respective measurements after charge detonation
- Confirm nanoparticle recovery, detectability and measured concentration

The test confirmed that the nanoparticle tracers could withstand the extreme conditions of the perforation detonation. Importantly, the test concentrations of nanoparticles applied to the perforation liner had negligible impact on the expected depth of penetration and the entrance hole size—a crucial factor for maintaining charge performance.

High-energy, sub-atomic X-ray 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. The different tracer concentrations permitted selection of the optimal concentration to use in field deployments. Nanoparticle detection was confirmed and field testing enabled.

After validating the approach with laboratory testing, researchers conducted a field trial to confirm real-world application of the nanoparticle tracers and delivery mechanism.

FIELD TESTING VALIDATES APPLICATION AND METHODOLOGY

Like the lab tests, the objective of the field trial was to explore various nanoparticle concentrations and verify measurable nanoparticle recovery, including surface recovery in the field trial. The field test also allowed for the application of nanoparticles to not just the perforation liner, but to other areas of the perforation system outlined. Phase 1 field testing was conducted in October 2024 in a True Oil, LLC-operated well in the Williston basin.

The QuantumPro, Inc., team sent five unique nanoparticle tracers to the GEODynamics manufacturing facility for preparation and delivery to the wellsite. Prior preparation by the manufacturer eliminated the need for special work onsite, once the perforation guns arrived, other than placing the guns in pre-defined locations, since the nanoparticle tracers are uniquely identifiable and operators can link recovery to specific perforations or perforation clusters. The team designed a field test that identified well completion Stages 12 and 13 as representative stages for testing eight perforation clusters per stage.

The field test included additional variability—beyond the lab test—to investigate a wider range of applications, including placing a relatively large volume of nanoparticle tracers in a vial within the gun, in the space available. As in the laboratory tests, varying nanoparticle tracer concentrations were applied to determine tracer recovery. Each stage consisted of eight clusters and each cluster was perforated with four shots. Tracer-embedded charges were deployed, using a standard plug-and-perf method, with manufacturing partner GEODynamics integrating the nanoparticle tracers during the manufacturing process, **Fig. 3**.

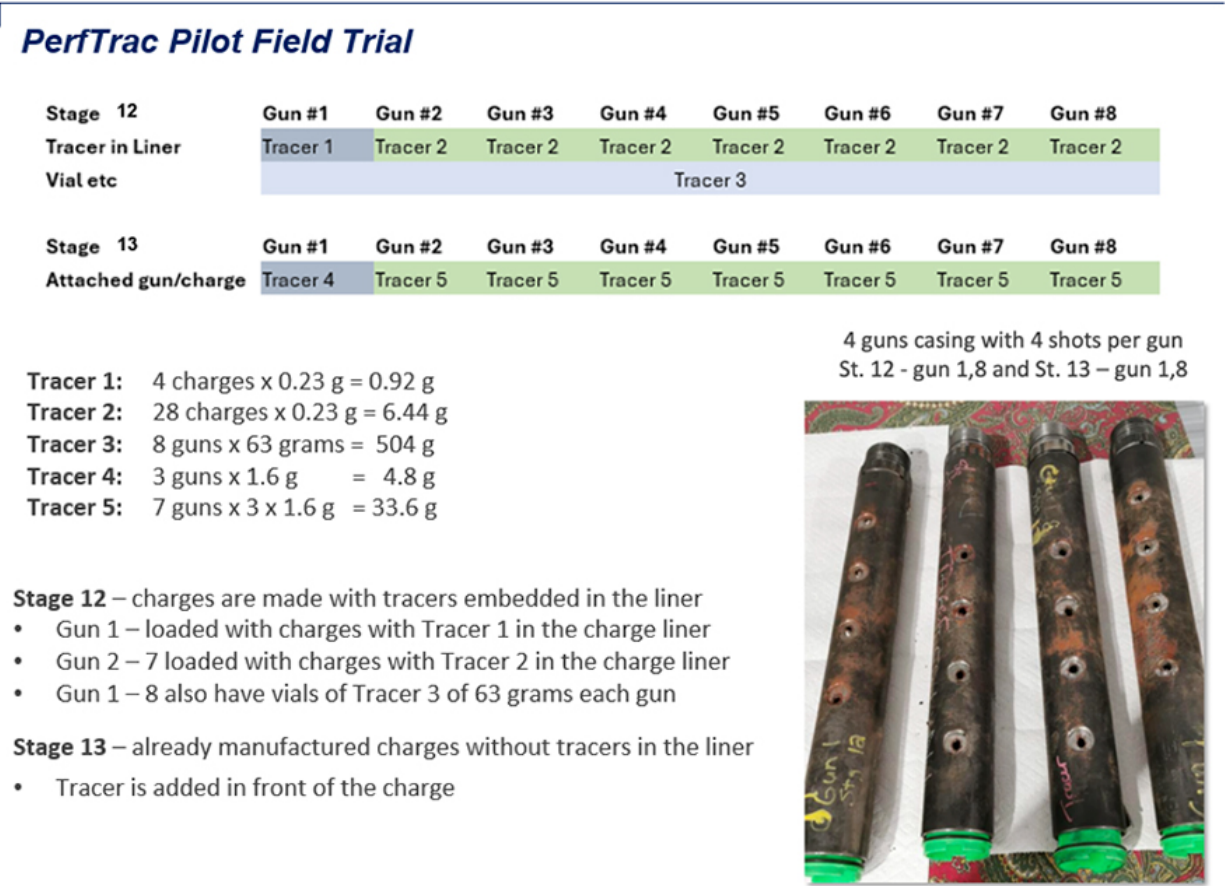


Fig. 3. An outline of the field test criteria identifying how the five unique tracers were deployed and the varying concentrations tested.

RESULTS ENCOURAGE FOLLOW-UP TESTING

Results demonstrated sufficient nanoparticle tracer recovery at the cluster level, facilitating advanced flow mapping, quantification of production, and flow performance verification for each individual cluster, **Fig. 4**.

Following the successful field trial, the team initiated a phase 2 field test, which is underway in a second True Oil well, where results will be available late in January 2025. As a further validation of the process and results, True Oil representative Wallace Hendricks commented that, “The ability to easily deploy and control the placement of individual tracers in specific zones along the lateral is a game changer.” He added, “In the field, deployment of the tracer was a seamless operation with wireline. No additional personnel or equipment was needed.”

PerfTrac Pilot Field Trial – Flowback sample analysis

- Flowback started on 10/14/2024
- Samples obtained after 1 week

		Stage-by-stage Flow Profile Characterization (QuantumPro's FloTrac nanoparticles recovery in ppb)											
Slash Fed 21-4-4-9 T2H	PerfTrac tracer #	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	PerfTrac 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	PerfTrac 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)	PerfTrac 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	PerfTrac 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	PerfTrac 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

Fig. 4. The results and analysis of the flowback sample, taken one week after initial production.

GROUNDBREAKING, COST-EFFECTIVE ADVANCEMENT IN PRODUCTION FLOW MONITORING

The cluster-level flow monitoring technique signifies a groundbreaking advancement in the industry, providing cost-effective and nonintrusive means to assess perforation flow performance and inter-well communication. Furthermore, this technology allows operators to:

- Achieve cluster-level flow mapping resolution, providing further verification of perforation efficiency beyond step-down tests
- Verify perforation efficiency of multiple perf designs in a single well, to complement the results of, or reduce the reliance on additional diagnostics, such as cameras or fiberoptics
- Gain a better understanding of stage level contributions of geologic layers in areas that are out of zone
- Verify zonal isolation and plug and cement quality
- Understand toe vs. middle heel contributions.

The early deployment of nanoparticle tracers embedded in the perforation tunnel means that operators will have a better understanding, not only of which clusters are contributing, but also how the frac is distributed and contributing to the overall production of the well.

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 strategies to maximize asset value and performance. **WO**

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WALLACE HENDRICKS is a completion superintendent at True Oil LLC. He holds bachelor's degrees in geophysics and civil engineering from the University of Wyoming. He is also a registered Professional Engineer in the State of Wyoming.



ERIC MARSHALL is a petroleum engineer with 23 years of experience in the oil and gas industry, specializing in hydraulic fracturing and reservoir engineering. He currently serves as senior technical advisor at GEODynamics, where he identifies new technology and intellectual property to drive future growth. Prior to joining GEODynamics, Mr. Marshall held the position of vice president of Engineering at FractureID, where he established an engineering consultancy division. He also managed a global technical implementation team for a coiled tubing stimulation service at Halliburton across 11 countries. Mr. Marshall holds a bachelor's degree in mechanical engineering from the Colorado School of Mines and is a registered Professional Petroleum Engineer in multiple states. He actively participates in professional organizations, such as SPE.



TALGAT SHOKANOV is CEO of QuantumPro, Inc., which he founded in 2017, following a 15-year career at SLB. There, he held a variety of international and technology development assignments and previously spearheaded SLB's cuttings re-injection via hydraulic fracturing business line, including subsurface engineering, disposal domain mapping and pressure diagnostics analysis. He holds numerous patents and has authored over 50 technical papers in complex fracturing and injection. He holds bachelor's and master's degrees in petroleum engineering from Satbayev University in Kazakhstan.



JOHN OLIVER is a business advisor to QuantumPro Inc. He has over 45 years of experience in the oil and gas industry, including a number of senior executive positions with M-I SWACO, an SLB company. He managed all the segments in the South American business unit as senior VP and served as Global Marketing manager. Mr. Oliver went on to lead Prince Energy, a division of Prince International, from which he retired in July 2018. He currently serves on a number of boards and is an advisor to several companies and energy private equity investment firms. He holds a BS degree with honors in biochemistry from University of St. Andrews in Scotland.



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 to 2003 and TerraTek from 1992 to 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 Ph.D in mechanical engineering from Northwestern University in Evanston, IL.

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