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Universal production diagnostics: A 3D-printed, snap-on nanoparticle delivery system for gun-agnostic cluster-level flow mapping

Universal, snap-on nanoparticle cartridges offer a flexible, gun-agnostic approach to cluster-level production diagnostics. Leveraging 3D printing and internal gun geometry, the system decouples flow mapping from the manufacturing process. Validated results show high detection sensitivity, enabling precise completion optimization across diverse reservoir environments.

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Early last year, in the January 2025 issue of *World Oil*, in an article entitled “Cluster-Level Flow Mapping and Production Diagnostics Using Ultrahigh-Resolution Nanoparticle Tracers Embedded in Perforation Charges,” a novel approach to cluster or perforation level production flow diagnostics was outlined. The article presented a distinct application of uniquely tagged and highly detectable, inert nanoparticles embedded directly into the liner of perforation charges during the manufacturing process.

While the application and use case remains compelling—offering a non-radioactive, non-intrusive method to map production flow from individual clusters—the research team at QuantumPro, Inc. recognized an opportunity to further streamline the technology. They sought a simpler method that did not require the logistical complexity of custom manufacturing or dependence on specific perforation gun OEMs.

The result of this development effort is a universal, snap-on delivery system (PerfTrac-R). This evolution shifts the diagnostic capability from a “manufactured-in” feature to a flexible “add-on” operational tool. This article details the engineering journey from liner-embedded tracers to universal snap-on cartridges, illustrating how utilizing gun clearance geometry and 3D printing simplifies the manufacturing of the device and presents the quantitative nanoparticle deployment and detection validation from field testing.

THE IMPERATIVE FOR CLUSTER-LEVEL RESOLUTION

The drive for this innovation is rooted in the persistent industry challenge to innovate beyond the “geometric” assumption of well completion, in a manner that satisfies the valid concerns of cost and complexity that have limited widespread application of solutions. This challenge spans the full spectrum of the energy sector, from high-frequency unconventional shale plays to high-stakes deepwater assets and geothermal projects.

Although operations in deepwater reservoirs do not involve the extensive, multi-stage, hydraulic fracturing campaigns seen in shale, the need to discretely identify production flow diagnostics is practically unavoidable. In such environments, where well intervention is prohibitively expensive and risky, operators seek to understand which zones are contributing to the flow, in order to manage water breakthrough and reservoir drainage effectively. Even so, operators frequently design stages with geometrically, evenly spaced perforation clusters, relying on the assumption that fluid and proppant (or gravel pack) will distribute evenly across them.

However, acquiring the data to verify this distribution or to determine the clusters' efficiency is often deemed prohibitive and complex, with challenges ranging from cost to deployment. Production logging and fiber-optic data have repeatedly demonstrated that production across pay zones is rarely even; variable rock lithology, stress shadowing or geomechanical interference and competitive fracture growth often result in highly variable production rates along the lateral.

Historically, the industry's resistance to adopting "intelligent completions"—where operators actively learn from production flow diagnostics to make iterative adjustments—has rarely been due to a lack of engineering desire. Rather, this resistance has always been about the prohibitive cost and complexity of traditional flow diagnostics. While effective, conventional tools like production logging and fiber-optic sensing are operationally intrusive, carry significant risk of tool failure and impose logistical constraints that extend rig time. This necessitates additional staff at the wellsite, increasing costs and safety exposure. This economic barrier has forced many operators to forego critical data, as they are unable to justify the complexity and expense required to optimize their completion strategies.

The introduction of ultra-high-resolution nanoparticle tracers offered a cost-effective alternative to break this stalemate. These inert, sub-atomic particles could be identified with extreme precision (parts per billion) in surface fluids. With 220 uniquely tagged nanoparticles in the portfolio, highly detailed data are abundant. The initial iteration, discussed in the previous publication referenced, successfully embedded these tracers into the copper liner of the shaped charge.

When the charge detonated, the liner—and the tracers within it—collapsed into the jet, tagging the perforation tunnel. While successful, this "embedded" approach presented a logistical bottleneck, by tying the diagnostic technology to specific gun manufacturers and lead times. To make cluster-level diagnostics a standard, scalable practice, the delivery mechanism needed to become universal.

THE ENGINEERING PIVOT: UTILIZING THE "DEAD SPACE"

The research team at QuantumPro, Inc. set a clear objective for the next generation of technology: create a device that could be applied to *any* shaped charge, from *any* manufacturer, instantly transforming a standard perforating gun into a diagnostic tool.

This necessitated a shift from modifying the charge liner to utilizing the free space available within the gun assembly. In a standard perforating gun, there is a critical geometric clearance—often referred to as the "charge stand-off" or "charge in-gun clearance"—between the top ring of the shaped charge and the inner wall of the gun carrier.

The PerfTrac-R device is engineered to occupy this specific "dead space." The device is a snap-on tracer cartridge that adheres directly to the charge face, effectively filling the clearance gap without obstructing the jet path, **Figs. 1, 2.**



Fig. 1. Snap-on nanoparticle tracer cartridge (left), cutaway (right).



Fig. 2. Custom (non-OEM) insert cartridge installed (left) and charge holder body (right).

AGNOSTIC SIZING VIA 3D PRINTING

The challenge, however, is that this clearance varies significantly between gun manufacturers and even between different charge models within the same manufacturer's catalog. A "one-size-fits-all" device would risk being too tall (preventing the gun from loading) or too short (failing to secure properly).

To solve this, the team leveraged 3D printing as the primary production method for the device housing and matrix sizing. By 3D printing the snap-on devices, based on the precise dimensions of the charge-to-casing clearance and the scallop size or recess profile in the perforating gun body adjacent to the shaped charge, the system becomes truly agnostic.

The process begins with a precise sizing questionnaire that captures the critical geometry of the gun system intended for use. Rather than requiring the operator to ship physical guns to the diagnostic provider, the operator simply provides key measurements, as seen in **Fig. 3**:

1. **Loading tube diameter:** the internal constraint of the carrier assembly.
2. **Charge diameter:** the base dimension of the explosive unit.
3. **Clearance height:** the exact distance between the top of the loading tube and the top of the charge face.

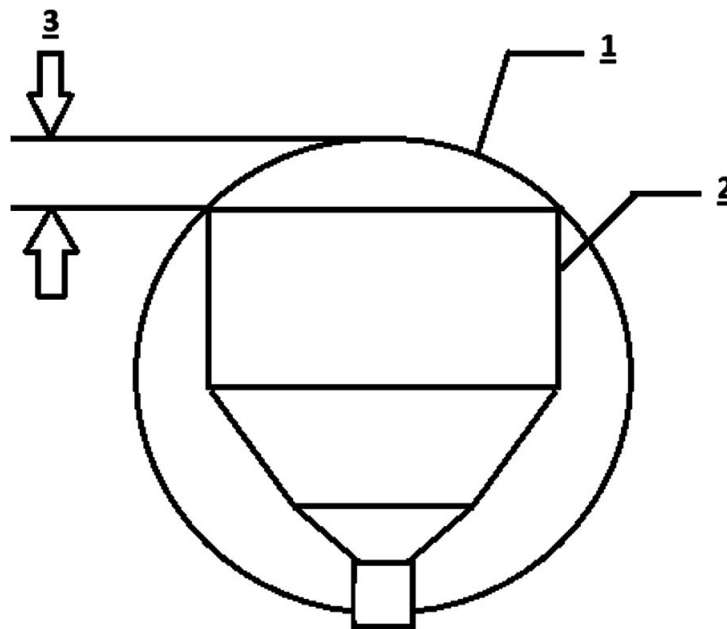


Fig. 3. Configuration inputs [Loading tube diameter, charge diameter, distance between top of loading tube and top of charge].

These inputs are fed into a parametric CAD model, which generates a print file for the specific job. This "print-to-fit" capability eliminates the need for expensive, permanent molds for every possible gun variation. It allows the technology to "snap on" to virtually any perforating system in the industry.

As shown in **Fig. 2**, the device sits flush against the charge, with the central aperture aligned with the liner apex to ensure no interference with the jet formation.

FIELD VALIDATION: WILLISTON BASIN PROOF OF CONCEPT

In the original liner-embedded design, the volume of tracer was limited by how much of it could be

embedded in the liner without adversely affecting the charge performance. Too much tracer material could potentially reduce the penetration depth of the charge and the size of the casing entrance hole. Consequently, the tracer payload was limited to a fraction of grams per charge. By moving to an external snap-on cartridge, the team was able to greatly increase the tracer payload per charge.

The transition from liner-embedded to external deployment was validated through rigorous field trials. The first major trial took place in the Williston basin (North Dakota) on a high-pressure, high-temperature well with a bottomhole temperature of approximately 275–295°F.

The objective was to directly compare the "embedded" vs. "external" methods, as seen below:

- **Stage 12 (embedded)** utilized charges with tracers embedded in the liner (Tracer 1 at 0.9 g total and Tracer 2 at 6.4 g total).
- **Stage 13 (external snap-on)** utilized standard charges with 3D-printed tracer rings attached to the face (Tracer 4 at 4.8 g total and Tracer 5 at 33.6 g total).

The well was stimulated with an intense hydraulic fracturing treatment, pumping approximately 260,000 gals of water and 200,000 lbs of proppant per stage. Despite this massive volume of fluid and sand, which acted to flush out near-wellbore materials, the tracers remained effectively placed.

Results. Post-flowback analysis conducted one week after production start showed definitive recovery:

- **External performance.** The externally mounted Tracer 4 (Stage 13) showed robust signals, with oil phase concentrations reaching 0.26 ppb and water phase concentrations up to 0.20 ppb.
- **Equivalency.** These values were comparable to the embedded Tracer 2 in Stage 12 (Oil: 0.31 ppb/Water: 0.17 ppb), proving that the external snap-on method is just as effective as the integrated liner method.

FIELD VALIDATION: LONGEVITY IN THE POWDER RIVER BASIN

Following the Williston success, a second trial was conducted on two wells in the Powder River basin (Wyoming), to test the longevity of the signal. In this trial, 41 stages were zipper-fractured, with each stage consuming 130,000 gal of water and 360,000 lbs of proppant.

This trial pushed the limits of the technology by testing detection limits over time. Sampling conducted 45 days after initial production—after approximately 30,000 bbls of fluid had been produced—continued to show clear tracer signatures.

- **Sustained release.** Tracers associated with the 7.4-g payload (8 clusters tagged) showed strong recovery concentrations (e.g., Tracer 2b at 0.73 ppb in oil), even after weeks of flow.
- **Granular resolution.** Even lower payload clusters (3.7 g) remained detectable for weeks, confirming that this technology is capable for long-term production profiling.

OPERATIONAL IMPLICATIONS: THE "JUST-IN-TIME" DIAGNOSTIC

The option of a snap-on architecture fundamentally changes the operational workflow for diagnostics. Previously, a decision to run diagnostics had to be made during the completion design phase, triggering a custom manufacturing order.

With the PerfTrac-R system, the diagnostic decision is decoupled from the gun procurement process.

- **Inventory flexibility.** Service companies do not need to stock specialized "tracer guns." They can maintain their standard inventory.

- **Late-stage decisions.** If an operator observes unexpected geological changes while drilling, they can decide to tag specific stages "on the fly." The snap-on cartridges can be installed in minutes by the wireline crew on location, using a high-temperature peel-and-stick adhesive.
- **Safety and compliance.** Because the device is an external polymer accessory, it does not alter the explosive safety envelope of the gun or require new API RP 19B safety certifications for the explosive itself.

NEW FRONTIERS: GEOTHERMAL AND CCUS

The successful deployment of a biodegradable, high-payload tracer system opens doors beyond conventional and unconventional oil and gas.

Enhanced geothermal systems (EGS). In EGS, understanding flow pathways through hot, dry rock is critical. The high thermal stability of the PLA matrix (functional up to 325°F and customizable for higher ratings) makes it an ideal candidate for mapping fracture networks in geothermal wells. The biodegradable nature of the carrier ensures that no permanent damage is done to the injector or producer wells, preserving the delicate transmissibility of the geothermal reservoir.

Carbon capture, utilization and storage (CCUS). For carbon storage, validating that injected material is entering the intended storage zones, and not leaking into caprock or adjacent formations, is a regulatory necessity. The PerfTrac-R system by QuantumPro, Inc., can be used to tag injection points in the storage well. If tracers are detected in monitoring wells or offset producers, it provides immediate, definitive proof of plume migration pathways. The inert, non-radioactive nature of the nanoparticles simplifies the environmental permitting process for these sensitive projects.

CONCLUSION: A NEW STANDARD FOR PERFORATION DIAGNOSTICS

The evolution from liner-embedded tracers to the PerfTrac-R snap-on system represents a significant maturity and tremendous opportunity in advancing diagnostic technology adoption. By utilizing the "dead space" clearance within the gun and leveraging adaptable 3D-printing manufacturing, the research team at QuantumPro, Inc., has successfully decoupled the diagnostic tool from the explosive hardware.

This advancement democratizes access to high-resolution, cluster-level data. It removes the supply chain barriers and cost complexities that previously restricted such precise monitoring. Now, with the ability to snap on diagnostics shortly before the guns run in hole, operators can finally close the loop on completion design and utilize empirical data to optimize perforation efficiency, confirm zonal isolation and maximize the recovery factor of every asset—whether in a shale lateral or a deepwater reservoir. The successful field validation of this technology confirms that the future of intelligent completions is not just about better sensors, but also about smarter, more adaptable delivery systems. **WO**



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