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A New Technique for the Development and Quality Control of Flow-Optimized Shaped Charges

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Abstract

For nearly two decades, shaped charge optimization has focused on increasing entry hole – for “big hole” gravel-pack style charges – and depth of penetration into standardized cement targets – for deep-penetrating charges. However, it has been acknowledged for some time that the latter approach, which is based on the misguided use of a test protocol described in API Recommended Practice 19B, Section 1, for perforator performance benchmarking, does not necessarily lead to perforations that deliver optimum flow performance. On the contrary, perforators optimized for maximum cement penetration are highly unlikely to be optimized for maximum rock penetration, let alone to create perforation geometry conducive to maximum flow.

A technically superior approach is to optimize both geometry and flow performance by benchmarking into natural rock, stressed to representative levels, as described in Sections 2 and 4 of the aforementioned Recommended Practice. The downside of such an approach is the time and cost associated with repeated test shots into stressed natural rock media, which must first be characterized in order to normalize the results for target variations. Furthermore, production quality control of charges optimized for natural rock perforation should also be conducted using natural rock targets; this adds another significant cost as a result of performing frequent test shots during production.

GEODynamics designed and built the ‘Quick Development Cell’ to facilitate the rapid development and production quality control of charges optimized for flow performance in natural rock. The cell allows for rapid loading of the core, setup of test fixture, pressurization of the core vessel, shot execution, and extraction of the perforated core for evaluation. This facility significantly reduces the time and overhead associated with stressed rock tests; GEODynamics is now able to conduct a significant number of tests each day, compared to only two shots using a conventional arrangement. Such rapid turnaround allows the company to progress efficiently through design iterations and lowers the barrier to using stressed rock testing as a primary production quality control method.

The paper describes in detail the need for such a capability, development of the vessel, initial applications, and the significance of this development to the future of shaped charge design and performance.

Introduction

Since their introduction by Welex Jet Perforators in the early 1950’s, perforating systems utilizing shaped explosive charges have become the dominant method for connecting a cased-and-cemented completion to the desired reservoir interval. During the ensuing five decades of development and deployment, shaped charge performance has advanced considerably as the result of more potent explosives, tighter manufacturing tolerances, improved quality control, and overall design enhancements. However, it has also been recognized that the flow path created by perforation with shaped charges is seldom ideal. Researchers acknowledged early on that extensive testing would be required under “...the various conditions which may occur in a well” in order to satisfy the industry’s need to predict perforator effectiveness (Allen & Atterbury, 1953).

The Performance Benchmark Problem

In recent times, industry standardization has been applied in order to effectively benchmark alternative perforating systems. The American Petroleum Institute issued its first recommended practice on the evaluation of wellbore perforators in the 1980’s, and the revised version (Recommended Practice 19B, API, 2001) is the accepted guideline for perforator

evaluation today. The document provides four test procedures to be used when representing perforating equipment performance to the industry:

1. Performance under ambient conditions, using a concrete target;
2. Performance into stressed rock, using a Berea sandstone target;
3. Performance at elevated temperature, using a steel target;
4. Flow performance under simulated downhole conditions.

The tests specified in Sections 1 and 2 of the recommended practice were quickly adopted as industry benchmarks. Section 3 tests were reserved for systems destined for high temperature deployment, and Section 4 tests were seldom conducted because of the equipment and operating expense associated with testing under simulated downhole conditions.

When variability in the properties of Berea sandstone caused the Section 2 stressed rock test to fall out of favor, the industry's attention became focused on the Section 1 test. Tighter control was placed on the concrete formulation to improve consistency and a program of witnessed testing – including publication of witnessed test results on the API website – was instigated. With the Section 1 test becoming the established benchmark on which equipment selection and purchasing decisions were based, perforator manufacturers correspondingly focused on optimizing their products for maximum penetration into the prescribed concrete target (or maximum casing entry hole diameter in the case of “big hole” charges for sand control applications).

However, the use of Section 1 data to predict downhole penetration is widely acknowledged as problematic, since penetration is influenced by many different rock properties. Worse still, any prediction of perforation flow performance based on Section 1 data is misguided. Although depth of penetration does influence the effective wellbore radius, many other factors contribute to the flow performance of a perforation tunnel.

Tunnel performance is the result of tunnel geometry and quality. Geometric effects include the tunnel length and diameter. Quality effects include:

- Distribution of material inside the tunnel
- Condition of any material inside tunnel
- Condition of tunnel side walls
- Tip geometry
- Tunnel Cracking

The geometry produced by a given perforating system is dependent on:

- Shaped charge design
- Target composition
- Target stress state
- Initial relative pressure state between wellbore and formation (under, at or over-balance)
- Dynamic pressure events during perforation

Charges using conventional technology, optimized for a stressed rock target can deliver as much as 20% greater penetration into rock than similar charges optimized for a cement target. The flow performance delivered by such systems may be 10-15% greater. Furthermore, as shown in Table 1, some charges that perform well when tested into rock targets perform poorly when tested into cement targets, demonstrating the invalidity of the Section 1 procedure as a legitimate benchmark (Thornton, 2006). There is thus a need to revitalize – and improve upon – the Section 2 procedure for optimizing and benchmarking charges using a stressed rock medium.

Table 1 – Performance of Charges Optimized for Rock or Cement

Target	Penetration (inches)	
	Charge A	Charge B
Cement QC Target	42.0	20.0
Berea Sandstone QC Target	20.5	15.0
Stressed Berea Sandstone Target	10.6	11.4

(Thornton, 2006)

The Development and Manufacturing Problem

Charges using advanced technology - such as those that induce secondary reactions in the perforation tunnel - can reduce the dependence of tunnel quality on surge flow (normally induced by static or dynamically-induced pressure difference). Charges of this nature have been shown to deliver flow performance improvements of up to 40% when compared to conventional charges of the same explosive weight. However, they must be developed using a stressed rock target. Development using a cement target is misleading because it will drive the charge design towards a suboptimal energy

distribution – required to maximize penetration into concrete - and away from designs shown to deliver greater flow performance. In fact, were such technologies to be evaluated solely on the basis of Section 1 performance they would probably be discarded!

The quality control of shaped charges is also critical to ensuring product performance. The QC process provides feedback that allows adjustment of the manufacturing process in response to changing conditions, variations in raw materials, etc. The performance of a given charge design measured by quality control tests often improves during the course of manufacture, demonstrating a gradual re-optimization toward the QC target material. It is therefore essential to also conduct periodic quality control tests into the original target material – stressed natural rock, in the case of the advanced charges described above – in order to mitigate this tendency. Using the established Section 2 procedure to address this need adds significant cost and introduces an unwelcome delay, since only 2-3 such tests can be performed in a normal work day.

There is thus a need for a facility providing rapid, useful feedback from stressed natural rock targets, both during the charge design process and during manufacture.

The Quick Development Cell

In response to the opportunities described above, GEODynamics has designed and built a ‘Quick Development Cell’ (“QDC”). This test setup facilitates the rapid execution of tests into a stressed rock target, making it possible to quickly and cost-effectively use such tests for development, quality control and benchmarking purposes.

Key design considerations were:

- Use of an optimum target size for ease of handling and cost minimization
- Use of minimal consumables per test
- Rapid loading and unloading of the target
- Retain standard charge configuration (“stack”) used for quality control into cement targets
- Ability to apply representative effective stress to the target
- Operable by a single technician

A schematic of the vessel is shown in Figure 1. A key feature is the target ejection mechanism that minimizes loading and unloading time and effort. The target itself is a 5” diameter, 24-36” long cylindrical sample. Effective stress is applied by pressurizing the vessel while keeping pore and wellbore pressures at atmospheric conditions. Applied pressures of up to 6,000 psi are typically sufficient to adequately represent downhole conditions. After optimizing the overall laboratory setup and test procedure a significant number of tests can be completed each day, compared to only two or three tests using a conventional Section 2 type apparatus.

Prior to testing, rock targets are dried to a constant weight then vacuum saturated (normally with odorless mineral spirits) and stored according to API RP-19B recommendations. The ejection mechanism is retracted and a core is loaded through the top of the vessel, followed by casing and cement plates, which are secured in place by a retaining ring. A charge stack is placed atop the target consisting of:

- Fluid filled clearance ring (simulating gun-to-casing clearance)
- Scallop plate (simulating gun wall)
- Air filled standoff ring (simulating charge-to-gun clearance)
- Shaped charge
- Detonating cord and detonator

The main chamber is pressurized, applying axial and radial stresses to the rubber-sleeved core. The wellbore chamber remains open to ambient conditions and the pore pressure system is vented to ensure complete saturation of the core and ambient pore pressure. A shield is placed over the charge stack to retain shrapnel and the charge is detonated. All debris is collected for analysis. After depressurizing the vessel, removing the retention ring, and collecting the casing and cement plates for analysis, the target can be ejected and evaluated.

Measurements collected from each experiment include:

- Casing hole diameter
- Cement hole diameter
- Probe depth (using 1/8” blunt probe)
- Target entry hole diameter

And, after sawing and splitting the core:

- Penetration depth
- Photographs showing perforation geometry and quality

Initial Applications

As prefaced in the introduction, three distinct opportunities motivated development of the QDC: charge development and optimization using stressed rock targets; production quality control using rock targets; and legitimate performance benchmarking of alternative perforating systems.

Shaped Charge Development and Optimization

The development or optimization of a shaped charge is typically a mixture of art and science. Predictive computer modeling can be useful in the early stages of development, but an iterative process of testing and learning from design variations remains the most effective method of achieving peak performance. Rapid turnaround testing that provides useful feedback to the design engineer allows the company to progress efficiently through design iterations. When the optimization target is unstressed concrete, tests can be conducted quickly and cheaply using cylindrical cement targets. Optimization for a stressed rock target has traditionally been prohibitively slow and costly because of the Section 2 type test that is required during each iteration. The QDC lowers the barrier to using stressed rock as the primary optimization target.

GEODynamics has begun optimizing all of its next generation perforators in stressed rock using the QDC, achieving turnaround times as short as those traditionally associated with charges optimized for concrete. Furthermore, charges can also be efficiently optimized to deliver superior flow performance. Design iterations are tested using the QDC until the observed tunnel geometry and quality imply good flow potential. This design is then tested in the flow cell – generally in accordance with API RP-19B Section 4 – to determine its flow performance relative to a baseline charge. In this way, expensive and time-consuming flow tests can be reserved for designs already showing promise in QDC stressed rock tests.

During the development of GEODynamics ConneX™ reactive perforating product line, the QDC facilitated unprecedented levels of design iterations. This allowed the design team to experiment with a series of previously unexplored parameters, which ultimately allowed them to tailor reactivity for specific rock and stress conditions.

Production Quality Control

The QDC also lowers the barrier to using stressed rock as a quality control medium. QDC tests can be performed at a sufficient frequency and in a short enough time to be compatible with production quality control. This is critical during the manufacture of flow-optimized and Reactive™ shaped charges, which cannot be effectively tested using cement targets alone.

Although no flow data is collected, the QDC test provides confirmation that production charges are delivering the correct perforation geometry. Flow tests can be performed at a reduced frequency to further verify production charge performance. Since the characteristics of natural rock targets vary slightly from batch to batch, normalizing tests are also required to adjust the target performance of a given charge in each new lot of targets.

Although target and consumable costs have been minimized in the QDC design, the overall test cost remains somewhat higher than that of a conventional cement quality control test. Further work is ongoing to value engineer the process, including early stage testing of synthetic materials that may eventually be cheaper – and more consistent – than natural rock targets.

Performance Benchmarking

By significantly lowering the cost and time associated with Section 2 type tests, the use of stressed natural rock for benchmark experiments can be reconsidered. Multiple tests can be performed quickly and economically, mitigating the impact of variations in target properties – the most frequently cited reason for rejecting stressed rock tests as a benchmark.

The benefits of testing alternative perforating systems using stressed rock are a more reliable estimation of *in situ* performance and a greater probability of correctly selecting the system most likely to deliver superior well performance. Furthermore, careful analysis of the perforated targets may indicate reasons for suboptimal performance that can be addressed through charge optimization, thereby delivering a superior solution to any available off the shelf. Such information cannot be gathered from cement targets commonly used for benchmarking today.

If end users recognize these benefits and set Section 2 type benchmarks when procuring perforating products, manufacturers and service providers will be incentivized to optimize systems for perforating stressed rock rather than simply penetrating deeper into an arbitrary cement target.

Future Significance

As hinted at in the preceding paragraphs, the widespread application of this tool will provoke a step change in perforating charge design. By lowering the barriers to using stressed rock testing as a development and quality control tool, the QDC makes optimizing products for natural rock – and more importantly for flow performance – a viable proposition. Furthermore, the QDC helps assure consistent production of these improved charges - something that was previously very difficult to accomplish. Such products will bring tremendous benefit to asset holders and operators through consistently improved well performance. Perforating systems can also be rapidly customized to deliver maximum flow performance at specific field conditions, making region-, formation- or even field-specific charge designs a realistic proposition.

Conclusions

In this paper we have reported that:

- Variations in natural rock targets make single Section 2 type tests unreliable as a performance benchmark;
- The cost and time required to conduct a Section 2 test has been preventing its widespread use;
- The consequential adoption of Section 1 tests using concrete targets for optimization and benchmarking of perforators is a barrier to the development of systems that deliver maximum flow performance;
- GEODynamics has developed a Quick Development Cell, which lowers the time and cost barriers to using stressed rock as a development, quality control, and benchmark target;
- By allowing multiple tests to be conducted in a timely and cost-effective manner, the issue of target variability can also be overcome.

From this we can conclude that:

- High performance charge designs that would previously have been ignored (due to poor cement performance), difficult to manufacture (due to design drift), or even impossible to develop (due to need for multiple tests into stressed rock) are now a viable proposition;
- Section 2 type testing can be usefully revisited as a performance benchmark, which will provide end users with more reliable information on which to base product selections.
- Perforating systems can now be rapidly customized to deliver maximum flow performance at specific field conditions, making region-, formation- or field-specific charge designs a realistic proposition.

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Nomenclature

<i>API</i>	<i>American Petroleum Institute</i>
<i>psi</i>	<i>Pounds per square inch (pressure)</i>
<i>QC</i>	<i>Quality Control</i>
<i>QDC</i>	<i>Quick Development Cell</i>

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Figures

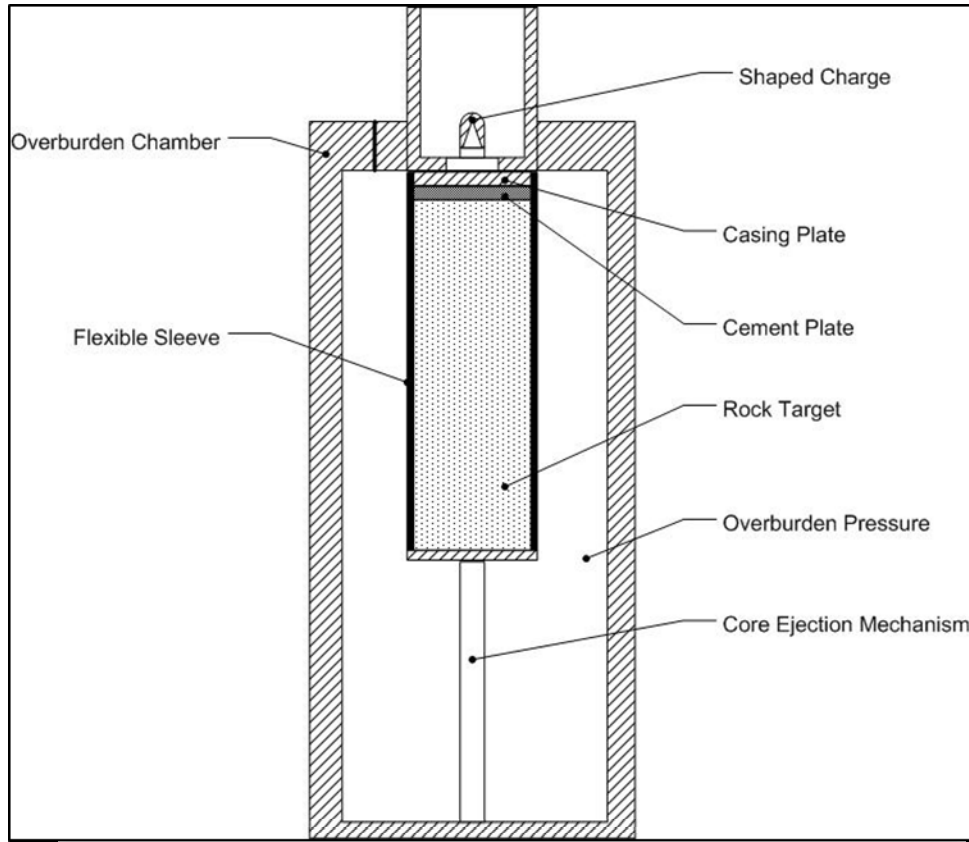


Figure 1 Schematic of the Quick Development Cell vessel