2009 NATIONAL TECHNICAL CONFERENCE & EXHIBITION, NEW ORLEANS, LOUISIANA

2009NTCE-02-01

Reactive Perforating – Putting the Exclamation Point on a Great Well

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INTRODUCTION

Many aspects of well engineering are highly optimized, with the general objective of minimizing cost by making the most efficient use of rig time, materials and manpower. Drilling and completion efficiency has improved dramatically in recent decades, as the result of both technology and concerted effort. Together with advances in well placement techniques, this has enabled the economic development of resources previously considered unviable, primarily through the widespread application of horizontal and multilateral wells.

During drilling and completion of the reservoir section, different optimization parameters come into play, such as borehole condition for successful data acquisition and cementing, and the avoidance of formation damage that might otherwise impair productivity. However, the same degree of rigor is not applied, often because of conflict between what is better for the reservoir and what is cheaper, or faster, for the drilling operation.

Small surprise then that perforation - the transitional step between well construction and well completion - is even less well engineered, and often neglected almost entirely. While perforation plays a critical role in the functional success of the well, it is seen by many as a necessary evil, delaying rig release and complicating the operation. Why invest time and effort, operators reason, when I have service contractors on hand to get it done? It's only a matter of punching some holes, right?

Perhaps not, as this paper will attempt to describe. What a pity that we are prepared to invest so much time and effort in constructing the well, only to neglect its vital connection to the horizons of interest. Nice building - now don't forget the doors!

FUNCTIONAL OBJECTIVES

The purpose of oil and gas wells can be simplistically divided into production and injection, but within each category are numerous well types that demand distinct functionality and, more specifically, set different functional objectives for perforations.

Straightforward shoot-and-produce (or shoot-and-inject) wells require an unimpaired flow conduit between the wellbore and the formation(s) from which production will be drawn, or into which fluids will be injected. Wells needing sand control typically require a large area open to flow and clean tunnels into which gravel can be placed, or from which a frac-and-pack can be initiated. Intervals requiring fracture stimulation call for clusters of perforations that are conducive to fracture initiation and the injection of massive volumes of proppant-laden fluid without bridging or screenout. In each case, the requirement is for more than just "punching some holes".

Furthermore, the target in which the holes must be created can vary dramatically from situation to situation. From unconsolidated sandstones to nano-Darcy shales to hard carbonates, off-the-shelf perforating systems are asked to deliver consistent results across a wide range of conditions. Taking into consideration this level of detail, cut-and-paste perforation design begins to look a little suspicious.

MYTHS ABOUT PERFORATING

Penetration, Penetration, Penetration

An overwhelming majority of shaped charge perforators on the market today have been developed and optimized for performance under surface conditions. This is the direct result of the industry's dependence on a single, API-certified benchmark - API Recommended Practice 19-B, Section 1 - which measures both depth of penetration into unconfined concrete and entry hole through a standard L-80 casing. None of these devices has been optimized for creating a hole into stressed rock, let alone for the variety of rock types and effective stresses that are commonly encountered.

Extreme caution needs to be taken when selecting shaped charges on the basis of penetration values presented in the manufacturer's catalog. Although penetration is important to well performance because it contributes to the effective wellbore radius, the quality of the tunnel – that is, whether or not it is plugged and/or damaged – is even more critical. Surface tests into concrete targets tell us nothing about the propensity for a particular system to deliver clean tunnels under downhole conditions. Only representative testing using stressed natural rock – and preferably involving a flow measurement in addition to the examination of tunnel geometry – can reliably determine the best system to use for a particular application.

Underbalanced Perforating Will Yield Clean Tunnels

Three primary damage mechanisms account for the under-performance of perforation tunnels: compacted fill at the tip of the tunnel where the shaped charge jet has piled up after ceasing to penetrate further, the "crushed zone" along the walls of the tunnel where rock fragments and other debris have been driven into surrounding pore throats, and general debris plugging the perforation tunnel itself. While debris inside the tunnel is typically unconsolidated and relatively permeable, the compacted fill and the crushed zone exhibit significantly lower permeability than the undamaged rock and are much harder to remove.

Underbalanced perforating involves creating a pressure gradient between the reservoir and the wellbore by lowering the wellbore hydrostatic pressure prior to perforating. Depending on the wellbore configuration and reservoir pressure, this can be achieved by displacing the wellbore to a light fluid, swabbing the well to lower the liquid level, or by displacing a proportion of the well to nitrogen. Assuming sufficient reservoir pressure, an underbalance of several thousand pounds can be achieved – although care must be taken to ensure the resulting surge flow does not damage the upper completion or perforating equipment.

Underbalanced perforating is an effective technique in situations where reservoir properties are favorable. However, if the formation permeability is low or varies significantly across the interval to be perforated, if there are existing open perforations in another zone, or if there is insufficient reservoir pressure (e.g. in a shallow or depleted reservoir), the probability of effectively cleaning a majority of the tunnels is dramatically reduced. "Perforating efficiency" after underbalanced perforating – meaning the fraction of perforations actually contributing to well performance – is typically assumed to be between 25% and 75%, although downhole video evidence and step-rate tests often suggest it is even lower, at perhaps 10-20%.

Dynamic Underbalance

Prior to detonation, a hollow carrier perforating system is a sealed chamber at atmospheric pressure. Once punctured by the shaped charges, wellbore fluids rush into the gun body, creating an effect known as "dynamic underbalance". The larger the gun system, the more pronounced and sustained this effect becomes. Dynamic underbalance enhances the effectiveness of underbalanced perforating by prolonging the period during which flow is induced from the formation, and by distributing the pressure drop more effectively across the perforated interval – of particular benefit when shooting heterogeneous zones. However, even when an engineered dynamic underbalance system is deployed (featuring punch charges and other modifications to further enhance and control dynamic pressure behavior), the limitations imposed by insufficient formation permeability or reservoir pressure cannot entirely be overcome. There are still many situations where uniform and complete tunnel cleanup cannot be achieved, despite this additional expenditure and complexity.

Nothing Works - Pump Acid

After experimenting with numerous essentially equivalent perforating systems and then adding complexity and cost to the completion operation to achieve static and dynamic underbalance, the embattled engineer can be forgiven for losing hope. Forget trying to cure the problem, why not treat the symptoms instead? A good dose of acid, bullheaded from surface, has acquired legendary status in the oilfield as "the cure for all ills".

Unfortunately, much like underbalanced perforating, bullheading acid tends to favor the already clean tunnels in better quality intervals. And, although some additional benefit can be gained using coiled tubing to spot-and-squeeze acid across the entire interval – and even to jet it into specific perforations – success is inevitably limited by the amount of acid-soluble material present in the crushed zone and compacted fill needing to be removed. This propagates another level of consequential efforts that generally compromise, rather than improve, technical performance; such as zinc-cased charges (which reduce penetration, increase gun swell, and may result in highly damaging precipitates) and acid-soluble cement, both of which are applied to give the acid stimulation something to chew on within the perforation tunnel.

If in Doubt, Hit it Harder

In true well engineering tradition, when faced with an apparently "stuck" situation the emboldened engineer reaches for a bigger hammer. In the case of an under-performing perforated interval this likely means fracture stimulation, either using gas-generating propellants or – pulling out the big guns – hydraulic fracturing.

Propellant stimulation certainly has its place in the production technology toolbox but is under-utilized, primarily because of safety concerns, complex design issues, and its relative sensitivity to wellbore conditions. When properly designed and applied, propellant stimulation will yield fractures extending 5-10 feet away from the wellbore, and can be effectively applied across a heterogeneous interval. However, the range of wellbore conditions under which this can be achieved is somewhat limited (by rock strength, rock stress, and hydrostatic pressure amongst others) and longevity of the created fracture conductivity is open to question.

Hydraulic fracturing is undoubtedly effective, but carries a massive cost and complexity penalty. The mobilization of a frac spread in order to achieve a zero- or negative-skin connection to the reservoir can only usually be justified when the natural reservoir permeability is insufficient to sustain an economic flowrate. Small-scale fracturing treatments – also known as "skin fracs" – are occasionally applied, but should remain an approach of last resort unless massive formation damage is caused during drilling, putting unimpaired formation beyond the reach of even the deepest penetrating perforators.

PERFORATING TECHNOLOGY

In reality, available perforating technologies are far more differentiated than the "punch some holes" advocates realize. Not only is there a marked performance difference between commodity and premium shaped charges, optimization for a specific application can yield a further 10-20% improvement in both penetration and productivity. More significantly, the latest generation of reactive shaped charges affords the designer another degree of freedom and makes it possible to deliver perforation geometries and flow performance that would otherwise be unattainable.

At the most basic level, taking a more rigorous approach to selecting an off-the-shelf perforating system can yield significant benefits. The translation of catalog penetration values into predictions of downhole performance must be treated with extreme care. The difference between 36 inches and 44 inches of penetration might reasonably be considered insignificant. However, after scaling these results appropriately for a stressed rock application, choosing between 9-10 inches and 11-13 inches might determine whether the perforations extend beyond near-wellbore damage and not. Worse still, shaped charge designs optimized for penetration into a relatively soft medium such as unconfined concrete can severely under-perform when shot into stressed rock. This can result in an entirely inappropriate selection, when charge 'A' out-performs charge 'B' in concrete penetration but the reverse is true in stressed rock.

This brings us to the next level of sophistication: conducting representative tests to support the selection and optimization of a perforating system. It is relatively inexpensive to conduct a series of stressed rock test shots to evaluate perforation geometry under downhole conditions. Six tests – three each with two different systems – may cost as little as fifteen thousand dollars. Pocket change when compared to the value destroyed by sub-optimally perforating a multi-million dollar well.

An even greater degree of realism, and corresponding increase in confidence in predicted downhole performance, can be gained by testing in a perforation flow laboratory. Such facilities allow control of the confining stress applied to the natural rock target, the pore fluid and pressure within the target, and the wellbore fluid and pressure. After detonating the shaped charge, productivity and/or injectivity tests can be performed before the rock sample is removed and split open to measure perforation geometry. This amounts to the most representative single-shot test currently carried out in the industry, enabling perforating system design and selection on the basis of productivity results measured for alternative shaped charge designs shot under identical conditions.

The next logical step after benchmarking perforators on the basis of flow performance is to optimize a design to deliver enhanced performance under specific rock and pressure conditions. This has been shown to deliver up to 20% greater productivity, even when starting with a premium deep-penetrating shaped charge design. However, although the price tag associated with such a development program is not enormous (typically less than two hundred thousand dollars), very few operators have taken this approach - except to develop bespoke designs for acute circumstances, such as perforation through multiple casing strings or under extremely high temperature and pressure conditions.

Most recently, the first family of shaped charges to be developed entirely on the basis of clean tunnel delivery in stressed natural rock was introduced. Capitalizing on reactive metal technology transferred from military ballistics, these systems have led to a step-change in achievable tunnel quality and performance.

THE REACTIVE REVOLUTION

Reactive materials have been revolutionizing military ballistics for more than two decades. The concept is simple: turn the formerly passive shell of a weapon into a reactive element capable of contributing to the device's effect on its target. The science involves the introduction of two or more materials that are normally stable, but, when subjected to sudden intense shock (such as the detonation of a shaped charge or a weapon striking its target) release a large amount of energy.

Within the oilfield shaped charge, this technology has been incorporated into the conical liner that is propelled through the wellbore casing, cement and surrounding formation by the explosive.

By carefully controlling the composition and structural properties of this liner, a secondary reaction is produced within the perforation tunnel in the microseconds after it is formed. The particular family of reactions selected for current reactive shaped charges are known as "intermetallic reactions", where two different metals combine under the pressure of detonation to form an "intermetallic" and in so doing release a burst of exothermic energy.

Since the reaction takes place after the jet of liner particles has created the perforation tunnel, the heat released acts on fluids within the tunnel and in the pore space of surrounding rock, generating a short, sharp spike in pressure. As this pressure relieves to the wellbore, the compacted fill and crushed zone that typically impair tunnel performance are broken up and expelled, leaving a large, unobstructed tunnel (see Figure 1).

This cleaning effect is independent of formation properties, reservoir pressure, wellbore pressure, and the behavior of any neighboring tunnels. As a result, reactive perforating systems deliver a very high percentage of clean tunnels under almost any wellbore situation, and without requiring underbalance. Furthermore, in moderate- to low-permeability rock the over-pressure is sustained long enough to break down the tip of the tunnel and form a small fracture. This is highly beneficial to tip-dominated production, injection, and the initiation of hydraulic fractures during stimulation.

Perhaps the most attractive aspect of these first generation reactive shaped charges is that they are drop-in substitutes for conventional products. This means that they can be deployed in existing hardware, using existing accessories and service tools, and following standard operating procedures. Health, safety, environmental and security risks are unchanged. There is, in fact, no downside whatsoever to deploying a reactive perforator in place of its conventional predecessor.

THE RESULT

Application of reactive shaped charges is delivering spectacular results across a wide range of well types:

- Step-change improvements in new well productivity and injectivity – flow rates as much as 50% greater than expectation have been documented;
- Massive productivity or injectivity enhancement when re-perforating wells previously completed with conventional perforating systems – increases from 20-2000% documented;
- Reductions in fracture initiation pressure – from 20-70% reduction reported, notably in North American resource plays, creating tremendous value when less hydraulic horsepower can be mobilized and when equipment can be

scaled down, e.g. by keeping peak pressure below the 5kpsi or 10kpsi threshold;

- Elimination of near-wellbore pressure losses ("tortuosity") and reduction in perforation friction during fracture stimulation (see Figures 2 & 3), resulting in more reliable fracture placement and fewer prematurely flushed or screened-out treatments;

Hundreds of thousands of reactive charges have already been deployed by more than forty different operators. New applications are being tested and proven each week, as operators gain familiarity with the product line. On the development side, reactive technology is being extended to applications such as casing-conveyed perforating (via the EXCAPE® consortium) and into new product lines, such as reactive "big hole" charges (expected in production during 2H09).

THE (EXCLAMATION) POINT

After spending countless man-hours optimizing the well construction process to make best use of rig time and other resources, it is illogical to neglect the critical step of connecting a cased-and-cemented wellbore to the formation(s) of interest. It's not just about "punching some holes".

At a minimum, great care must be taken when selecting a standard perforating system. More importantly, attention should be paid to delivering perforations that meet the functional requirements of the well. Since this will generally be predicated on the delivery of clean, unobstructed tunnels, consideration should be given to deploying a premium perforating system and, in particular, to applying reactive perforating technology. It is the authors' belief that more than half – and potentially almost all – of the perforating systems being deployed today could be beneficially replaced by a reactive perforating system.

This will assure the greatest probability of delivering a high percentage of effective perforations, irrespective of formation heterogeneity and without requiring additional effort and expenditure to perforate underbalanced. Any requirement for post-perforation treatments such as acid washing, surging, or skin fracs should also be eliminated.

When designed and deployed correctly, an optimized perforating system will deliver superior productivity or injectivity, and will ensure reliable execution of gravel packing, matrix stimulation, and hydraulic fracturing treatments. In short, the functional specification of the well will be more effectively delivered, at lower overall cost and risk.

FIGURES

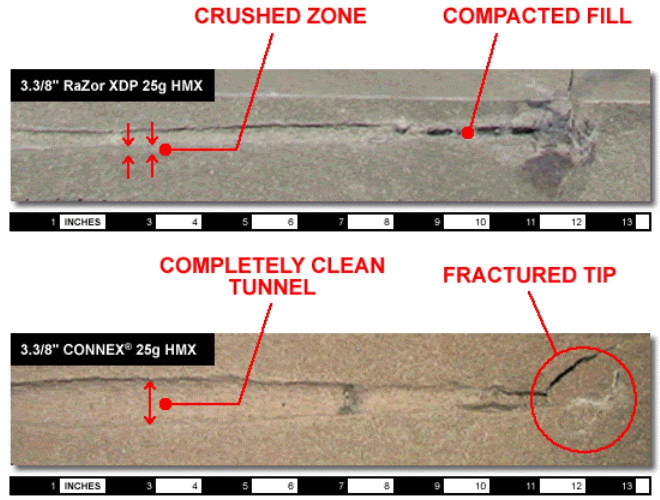

Figure 1: *Comparison of perforating tunnels in stressed Berea sandstone produced using a conventional deep-penetrating shaped charge (top) and a reactive shaped charge (bottom)*

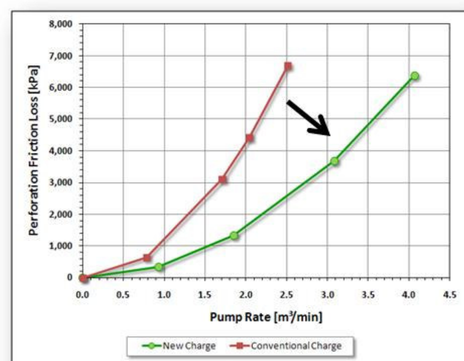

Figure 2: *Step rate test data showing reduction in perforation friction as a result of using reactive shaped charges.*

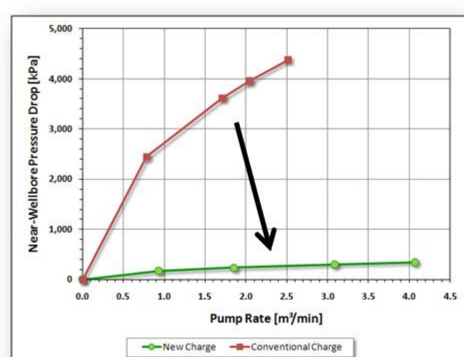

Figure 3: *Step rate test data showing near elimination of near-wellbore pressure drop ("tortuosity") as a result of using reactive shaped charges.*