The search for perfect perforations

Perforating creates a direct link between the wellbore and the producing formation by making holes in the casing and the cement sheath that surrounds it. The quality and quantity of the perforation holes (tunnels) in a given oil- or gas-bearing formation have a direct influence on well productivity. Completion engineers need to ensure that the perforations they produce are deep, clean, located in the right place, and correctly oriented.

In this article, Larry Behrmann and Chee Kin Khong review recent advances in key perforation technologies and examine how dynamic underbalanced perforating is helping to deliver new levels of performance for wells in the Middle East and Asia.
The economic value of an oil or gas well depends on the connection between the wellbore and the formation. The completion and production engineers, who define the form and the function of this connection, have three key objectives: allow the oil into the well, where it can flow naturally or be pumped to the surface; exclude water from the overlying or underlying units; and keep any formation rock particles out of the well.

Perforation, creating holes in the casing or the liner and the surrounding cement sheath to allow fluid communication between the formation and the wellbore, is a crucial part of the completion process (Fig. 1). Perforations are the key interfaces for fluid movement, and completion and production engineers have realized the importance of an effective design and execution process to ensure that each well has the appropriate number, size, and orientation of perforations. The characteristics of perforations and their placement have a direct influence on well productivity.

The development of perforation technology

Advances in perforation technology have reflected the changing needs of the oil and gas industries (Fig. 2). Early oil wells were shallow, simple boreholes that did not require metal casings. These wells typically had an openhole or shot-hole completion and were sometimes treated with explosive charges to stimulate the flow of hydrocarbons into the borehole. As average well depths increased and the reservoir conditions encountered became more complex, the perforated-casing completion method became an essential and familiar part of oilfield development. Then, as now, engineers had to decide how best to make holes in the metal casing that would allow hydrocarbons to flow into the well.

In the early 1900s, mechanical puncturing methods were introduced. These included the single-knife casing ripper, which relied on a rotating mechanical blade to make a hole in the casing.

Projectile perforation technology was pioneered during the mid-1920s. The first perforating mechanism to be used on a large scale was the bullet gun, which was introduced in 1922. In bullet perforating, a hardened-steel bullet was fired from a very short barreled gun. The resulting perforations caused little damage to the cement sheath or the casing, but the penetration depths achieved were usually short. These primitive devices were replaced in the late 1940s by the lined, shaped-charge perforator, known to the oil industry as the jet perforator or jet charge.

Over the decades, various perforation systems have been developed for a wide range of applications, and research has continued into the fundamentals of perforation physics. Today, sophisticated perforating gun assemblies with an appropriate configuration of specially shaped explosive charges and the means to verify or correlate the correct perforating depth can be deployed on wireline, tubing, or coiled tubing. Whatever their size or method of deployment, perforating guns are designed to create a predefined pattern of perforations over the correct wellbore interval.
Shaped charges have four basic elements: primer, main explosive, conical liner, and case. The conical cavity with its metal liner helps to maximize the penetration through steel casing, cement, and rock (Fig. 3). As a charge detonates, the liner collapses to form a high-velocity jet of fluidized metal particles. Perforating shock waves and high-impact pressure shatter the rock to break down the intergranular cements and sever the bonds that hold the clay particles together. This process creates a low-permeability crushed zone in the formation around the perforation tunnels. Perforating damages the in situ permeability by crushing the formation material and reducing the pore throat’s dimensions.

Shaped charges are used in the oil, gas, and other industries to pierce metal, concrete, and other solids. They sever the targets by jet cutting. Shaped charges have special housings that are designed to create a cavity or a void between the explosive material and the target wall. By employing a phenomenon known as the Monroe effect, the shock wave produced at detonation accelerates and deforms the shaped housing into a high-velocity (7,300–8,200 m/s) jet within the void space.

These jets can cut through steel targets of varying thicknesses, depending on the void shape and the standoff distance to the target wall. Because the cutting efficiency of shaped charges is much greater than that of bulk charges, they can often reduce the net weight of explosive needed to sever similarly sized targets. Conical-shaped charges (CSC) create conical cavities for round holes and deep penetration into the target. Industry’s primary use of CSCs is in perforating guns; multiple CSC assemblies placed down boreholes and detonated to penetrate through casing and into the surrounding geological strata for the extraction of hydrocarbons. The use of steel for charge cases instead of zinc eliminates the decrease in formation productivity and the damage to completion components associated with the detonation by-products from zinc charges and reduces the cost of the completion fluids required. Shaped charges are designed and arranged to optimize orientation and are deployed on a tubing-conveyed perforating system to provide an effective solution for perforating and increasing the productivity in long horizontal intervals.

In other engineering applications, shaped charges are valued for their versatility and speed. For example, small shaped charges are often used in steel manufacturing to pierce taps that have become plugged with slag, and a few hundred kilograms of well-placed shaped charges can demolish a building in seconds (Fig. 4).

A linear-shaped charge (LSC) has a chevron- or inverted-V-shaped void along its length. It is designed to cut linearly through the target and can be used for decommissioning operations in many different configurations, depending on the cutting requirements.
Finding the right balance

After completion and before perforation, the pressure in the wellbore is usually different from the pressure in the formation in a cased hole well. A well is underbalanced when the downhole wellbore hydrostatic pressure is lower than the formation’s internal fluid pressure, or overbalanced when the pressure in the wellbore exceeds the formation pressure (Fig. 5). In underbalanced conditions, formation fluids will flow into the wellbore if the rock is sufficiently permeable.

By the 1970s, completion and production engineers had realized the potential of creating underbalanced pressure conditions as a method for enhancing the quality of perforated completions. Studies during the 1980s confirmed that the most effective perforations were usually produced when there was a high static pressure differential between the wellbore and the formation. These studies concluded that the rapid fluid influx from the reservoir helped to clean the perforation tunnels (Fig. 6). This research was based on the assumption that the wellbore pressure remained constant during perforating and perforation cleanup.

During the mid 1980s, Amoco conducted a study of acidizing in 90 new wells after perforation with tubing-conveyed guns under a range of underbalanced pressures. The results indicated that acid stimulation was unnecessary when sufficient underbalanced pressure had been achieved.

Research at the end of the 1980s drew on the Amoco study and defined the minimum level of underbalance that was required to eliminate the need for acid stimulation. Another study indicated that flow and surging after perforation were less critical in damage removal but might sweep perforation debris and rock particles into the wellbore and so help to clean the perforated zone.

Extensive laboratory tests at the Schlumberger Productivity Enhancement Research Facility (PERF) in Rosharon, Texas, USA, in the 1990s showed that turbulent flow was not required to remove perforating damage. Most of the data indicated that higher underbalanced pressures than those previously used were required to minimize or eliminate perforation damage (Fig. 7). Having established the basic conditions for effective perforation, the challenge facing completion engineers was to find ways in which the underbalanced conditions could be optimized and controlled to enhance the perforation process.

Modern perforating techniques

Perforating using static underbalance has become the most widely accepted technique for optimizing perforated completions. However, this method still delivers many underperforming wells. The explosive charges used for perforating pulverize the reservoir formation to create low-permeability crushed zones around the perforations and leave loose crushed rock debris inside the perforation tunnels, which can hinder fluid movement.

Static underbalanced perforating establishes a static wellbore pressure before perforating that is lower than the pressure in the adjacent formation, but this static underbalance is not enough to ensure clean perforations.

However, careful completion design and a more appropriate perforating technology can minimize or eliminate the damage caused by the explosive charges. The PURE® perforating system can create an optimized dynamic underbalance (the transient underbalance established just after the creation of the perforation tunnel) during the perforation job. This underbalance delivers cleaner perforations and thus increases the ultimate productivity or injectivity of the well.

In addition to cleaner perforations, jobs designed using the PURE method can also improve wellsite efficiency and may remove the need for costly postperforation cleanup operations such as acid washes or near-wellbore skin fracture treatments.

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The PURE technique has been shown to minimize or eliminate perforation damage and maximize productivity or injectivity when applied to wells in many areas around the world, including the North Sea, Ecuador, Algeria, Canada, the USA, the Middle East, and Asia. It has been applied in hard and soft rock formations, high- and low-permeability reservoirs, sandstones, carbonates, oil and gas reservoirs, and producing and injection wells.

Testing transient pressures

During studies into postperforation, transient pressure variations, Schlumberger researchers collected data under simulated downhole conditions. In one set of tests, the research team perforated four standard Berea sandstone cores using identically shaped charges and an initial underbalance of 6.9 MPa (Fig. 10). A second set used similar Berea cores but perforated them with a 3.4-MPa overbalanced static pressure (Fig. 11). The results confirmed significant wellbore pressure variations immediately after charge detonation and that the quality of perforation cleanup is directly related to these variations.

The PURE process uses customized perforating designs, specially shaped charges and fit-for-purpose gun configurations to generate a large dynamic underbalance in a modest static underbalanced, balanced, or even overbalanced environment.
The benefits of dynamic underbalance

A dynamic underbalance eliminates the need for large static underbalance pressure differentials and makes the preparation work before perforation more straightforward. In addition, controlling the surge flow helps to limit the produced fluid volumes during perforation cleanup. This, in turn, reduces the risk of sand influx and the possibility of gun sticking. The method also saves the time and the costs associated with postperforation acid washes to remediate perforation damage.

Dynamic underbalanced perforating increases the effective shot density or the number of open perforations, thus improving the productivity and the effectiveness of any associated acid and fracturing treatments.

Potential applications

Many producing wells and injectors are potential candidates for the PURE perforation method. Completion and production engineers select candidates by examining rock types, fluid types, and formation porosities and permeabilities in conjunction with performing simulations using the PURE job design software. Other factors, including pore pressure and permeability, are also considered.

Successful PURE perforations have been achieved in reservoirs with pressures as low as 6.9 MPa and permeabilities as low as 0.1 mD. The lower permeability wells were usually characterized by higher pressures, and the lower pressure candidates tended to have higher permeabilities.

The PURE perforation method is very suitable for injection wells because clean perforations are a prerequisite for injectivity. The method can ensure sufficient surge flow to remove loose materials from the perforation tunnels before injection and prevent debris and fine particles from being injected into and scaling off the pore throats. The method has also proved particularly effective in low-permeability formations that may require extremely high static underbalanced pressures for perforation cleanup.

Perforation quality, offshore China

The CACT operations group (Chevron Overseas Petroleum, Agip China, China National Offshore Oil Group, and Texaco China) has evaluated the PURE perforation method in one of its new offshore fields where it was used to perforate four layers with permeabilities from 9.4 to 1,605 mD. Multiple PURE wireline runs at an overbalance of about 1.3 MPa resulted in skin factors from 0 to –0.97 over the range of permeabilities. An analysis of the pressure transient data showed stimulated completion skin factor values for each of the perforated layers.

The CACT group used the PURE system to maximize the productivity of cased perforated wells in their new offshore development. The productivities of the PURE perforated wells were above average and above expectations. However, the group wanted to evaluate the completion efficiency to quantify the benefits of the PURE perforation method.

Multilayer reservoir testing

In one CACT well, four zones had been perforated using the PURE method at overbalance and then produced commingled. A PLT* Production Logging Tool was run in this well to determine the flow rates of all the layers when water cut was close to zero (Fig. 13).

When engineers want to use pressure-transient data to evaluate the individual layers within a commingled system, they require a selective testing method. A test that measures the composite behavior of all of the layers can give misleading information about the overall system properties, and typically produces underestimates for skin factor and permeability.

The traditional approach isolated and tested each zone individually using techniques such as straddle testing. However, a multilayer test (MLT) enables engineers to measure the flow rate of each layer using a spinner flowmeter during a pressure transient test. Variable rate superposition analysis can then be applied in turn to the data from each layer to identify the appropriate reservoir model and obtain an estimate of permeability, skin factor, and other model parameters.

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Design is the key

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Perforation design and modeling software helps engineers by integrating all the available data (reservoir properties, completion parameters, and gun configurations) in a single design for achieving productive perforations.

The PURE perforation technique creates the optimum dynamic underbalance for the particular downhole environment. This approach greatly reduces errors and eliminates many of the operational issues that can arise when engineers rely on estimates of downhole pressures when creating a large static underbalance in the wellbore.

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The MLT method derived from PLT testing involves sequential measurement of flow rates and pressure transients from an individual layer or group of layers after a rate change, preferably starting with the bottom layer and working up. This process is referred to as a transient multilayer test or simply an MLT. Such MLTs can be performed on a producing well without pulling the completion and are therefore more cost-effective than straddle tests. In addition, the total production from all the layers is measured, whereas a series of straddle tests may be testing the same zone if the layers are not hydraulically isolated.

MLT data are crucial for reservoir management in commingled systems where more than one layer is producing and crossflow may be occurring between them. A good understanding of the reservoir is crucial, particularly for reservoir simulation, voidage control, pressure maintenance, and workover decisions.

The MLTs confirmed CACT’s observations of the productivities of PURE perforated wells and that PURE-perforated zones were likely to have undamaged completion skin factor values (Fig. 14). CACT has since extended the use of the PURE system to selectively reperforate zones during well workovers to increase productivity. The PURE method reduces drawdown pressure, which lowers the risk of sanding and water coning, reduces water cut, and increases recovery from worked-overs wells.

A dynamic combination

Having established the value of dynamic underbalance during perforating, many engineers are applying the PURE method with the use of the PowerJet Omega deep-penetrating shaped charge. This combination cleans the perforations and improves the well performance.

Combining the PURE process with PowerJet Omega charges provides clean perforations, increases the depth of penetration, and facilitates optimal production. In one job, the PowerJet Omega charge shot at 6 shots per foot provided the same productivity in less time as another deep-penetrating charge shot at 12 shots per foot. There was less casing damage, less debris, and, ultimately, a lower risk of problems. The PowerJet Omega charge can also be used alone to improve productivity in wells where the PURE technique is not an option, such as very low pressure reservoirs or where gas must be in the wellbore at the time of perforating.

Field results show that using a combination design, tight gas wells can be brought on-stream without near-wellbore acid washes. In addition to wells with significant potential for productivity improvement, candidates include those requiring expensive operations to establish underbalance, those requiring near-wellbore acid washes after perforating, and those requiring high underbalanced pressures for cleanup.

Deeper penetration provides increased well production and injectivity coupled with improved well efficiency, which directly help to reduce recovery costs. The PowerJet Omega charge is available for 2-in to 7-in high-shot-density (HSD) gun systems, which can be conveyed by wireline, slickline, tubing, coiled tubing, tractors, and permanent completions.

Improved operational safety

Safe and effective detonation at the appropriate time and place define good perforating practice. The eFire electronic firing head system developed by Schlumberger provides safer and more efficient and economical methods for a range of downhole explosive operations. These systems can be used for tubing-conveyed perforating, coiled tubing, slickline, and wireline operations. Designed for flexibility, they give engineers total control of the perforating operation. eFire technology creates pressure pulses that are converted into a special signature to communicate with the firing head (Fig. 15). Controlled from the surface, the system head does not require prerecorded downhole parameters. Engineers can arm, fire, or abort the operation at any time and thus conduct perforation tasks under less rigidly defined conditions.

Flexible solutions

Engineers want to penetrate past formation damage to increase well productivity or injectivity. Another challenge is to maintain penetration depths at high shot densities. A greater depth of penetration means that more natural fractures are intersected, which boosts hydrocarbon flow toward the wellbore.

Deeper penetrating charges are particularly important when dealing with damaged formations or tight and hard rocks. The PowerJet Omega charge can be applied in all types of reservoir and all fluids and is particularly useful for reperforating older wells.

Figure 15: The sequence of events in initiating the eFire firing head system: trap pressure below the tester valve, wait for the guns to fire, and open the tester. There are two pressure buildups: one following the dynamic underbalance and a second when the tester valve is opened.
Oriented perforating—finding the right direction

Reservoir rocks are usually heterogeneous—their properties vary with direction. In reservoir units that display large stress contrasts, properly aligned perforations help to maximize the stability of the perforation tunnels. In weakly consolidated reservoirs, selecting the best orientation helps to minimize the risk of sand production. Effective techniques for orienting perforations also help to reduce flow restrictions and friction pressures during fracturing. The resulting wider fractures permit the use of larger sizes and higher concentrations of proppant along with lower-viscosity, less-damaging fluids to improve fracture conductivity.

The Schlumberger Wireline Oriented Perforating Tool (WOPT) system can be used to orient wireline guns in vertical or deviated wells (Fig. 16). Initially developed for use in oriented fracturing, the WOPT system can also be used to perforate for sand prevention. The WOPT system orients standard high shot density guns with 0°, 180°, or other optimal phasing in a predetermined direction. Engineers can select the charge type and the shot density to suit completion requirements such as sand control or sand prevention, and on fracture-design criteria such as proppant size, pump rate, treating pressure, and required production flow. Experience has shown that wireline tools will assume a preferred orientation in the wellbore at a given depth when the string parameters—length, weight, mass distribution, cable speed, and direction—are constant and a swivel is used to minimize the detrimental steering effects of torque. The swivel decouples torsion between the wireline cable and the gun string, which enables the tool to assume its natural position. The repeated adoption of this natural position was crucial to the development of the WOPT system. For vertical wells with inclinations of less than 8°, the tool requires two trips. The first trip, or mapping run, is made with unarmed perforating guns and a true-north seeking gyroscope to determine the natural orientation (toolface azimuth or direction) of the toolstring. Upper and lower weighted spring-positioning devices help to rotate the toolstring toward the relative low side of the wellbore.

Making several passes in each direction provides accurate orientation data that engineers can use to determine the required gun rotation. The system can map single or multiple zones during this initial trip. The wireline perforating inclinometer tool, an integral WOPT component, provides independent, continuous, and real-time measurements of tool deviation and toolface orientation (relative bearing) with respect to the high side of a wellbore. If reliable directional survey data are available and the target zones are in well sections with inclinations greater than 8°, oriented perforating can be completed without a gyroscopic run. In this case, inclination measurements are extremely accurate and correlate to wellbore azimuth.

Figure 16: A typical WOPT system has a weighted spring-positioning device and indexing adapter above and below standard guns (a). The toolstring includes a gyroscope and its carrier, an integral wireline perforating inclinometer tool with casing-collar locator, and a wireline swivel to decouple cable torque from the tool. The gyroscope measures well inclination, wellbore azimuth, and toolface relative bearing—the orientation of the toolstring—with respect to true north during an initial run with unarmed guns (b). Perforating is performed on subsequent trips without the gyroscope and after rotating the guns at surface (c).

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Every millisecond counts

The PURE system optimizes the well dynamic underbalance, the transient underbalance just after creation of the perforation cavity. The software it uses specifies a unique perforating system and an optimum completion process. This controls the optimum dynamic underbalance rather than relying on estimated reservoir pressure. This technique has been successfully applied in hard- and soft-rock formations, oil and gas reservoirs, sandstones, and carbonates.

The perforation process, from initial detonation to damage removal from the perforation tunnels, is completed in around 100 to 500 ms (Fig. 17). The PURE system creates pressure transients in the wellbore immediately after perforating. The underbalance effect starts within a few milliseconds of the guns firing and lasts for 100 to 500 ms.

The future

The challenge facing completion engineers is to find ways to control the power of their perforating techniques so that they combine maximum reservoir penetration with the creation of clean and effective perforations.

Perforation technology and methods have changed dramatically over the past 20 years. In comparison with the 1980s, there are now many more perforating systems and methods for conveyance. Over the same period, there has been a large increase in shots per 30 cm that can be achieved.

Having established reliable and effective tools and techniques for making holes in casing, cement sheath, and formation, completion engineers turned their attention to reducing the damage associated with perforation jobs and to the detailed planning of jobs so that each perforation task is optimized for the specific needs of the completion design and to the condition of the reservoir. It seems likely that this high degree of customization will continue in future efforts to optimize perforation operations in increasingly demanding reservoir conditions.

Reference