New Practices to Enhance Perforating Results

Recent developments in tools and techniques dramatically increase productivity and injectivity in perforated cased-hole well completions. These advances address a wide range of challenges from near-wellbore formation damage and perforation damage removal, to sand influx and safe, efficient wellsites operations.

Perforating is a critical step in establishing connectivity between subsurface zones and wellbores that are completed with cemented steel casing. By understanding complex interactions between explosive shaped charges, charge carrier systems, a wellbore and the reservoir, and by applying customized perforating solutions, engineers can improve cased-hole well performance, optimize reservoir production and maximize hydrocarbon reserve recovery.

To achieve these objectives, engineers now incorporate reservoir parameters and well-specific conditions into fit-for-purpose perforating designs. The results are proven processes and procedures that generate additional production revenue for operators. Recently introduced tools and techniques help operators increase productivity or injectivity, prevent sand production and improve the safety and efficiency of perforating operations.

Deep-penetrating charges can bypass formation damage, increase the effective wellbore radius and reduce the need for additional perforating operations, acid washes or other perforation cleanup techniques. Recent advances in explosive shaped charges, charge manufacturing and gun systems have yielded increases in perforation penetration of 20 to 30% even compared with the deep-penetrating charges that were introduced in the late 1990s and early 2000s. Perforating farther into a formation beyond near-wellbore damage caused by drilling or completion operations is one of the key factors in improving the productivity of cased-hole wells.

Surge flow through perforations after shaped-charge detonation is critical in minimizing flow impairment and reduced conductivity caused by perforating-induced damage. Schlumberger researchers found that large-diameter, deep-penetrating, clean perforation tunnels could be created by controlling the transient, or dynamic, pressure differentials that occur in a wellbore immediately after the detonation of perforating guns.

An innovative design process and specialized systems exploit rapid changes in pressure that occur between perforating gun systems, a wellbore and a reservoir within a few hundred milliseconds after charge detonation. This dynamic underbalanced technique uses customized perforating designs, special shaped charges and fit-for-purpose gun configurations to generate a large transient underbalance from modest static underbalanced or overbalanced pressures.
This technique consistently generates clean perforation tunnels and optimizes results obtained with the latest extradeep-penetrating charge designs and advanced perforating systems. Downhole gauges with extremely fast data-sampling rates are used to capture transient-pressure data in the field and verify the dynamic underbalanced pressure differential. More detailed information is helping engineers further enhance perforating operations and results.

In high-angle and horizontal wells where overburden pressure dominates in-situ stress conditions, vertical perforations typically are the most stable. Under these conditions, perforations oriented more than 25° away from vertical may increase the risk of perforation collapse and sand influx. A new orienting system for tractor-conveyed, coiled tubing-conveyed or tubing-conveyed perforating (TCP) can accurately and reliably align shaped charges within 10° of a specified direction, usually vertical. This system also provides postjob confirmation of perforation orientation. These capabilities help completion engineers reduce the risk of sand production, even in wellbores with extreme variations in trajectory.

Other innovations in perforating systems increase wellsite safety and efficiency. The most recent downhole firing heads combine proven drillstem test (DST) technologies with detonators that are unaffected by radio frequency (RF). This electronic firing system increases wellsite safety by eliminating primary explosives, by providing direct operator control and by allowing gun detonation to be aborted at any time.

These electronic firing heads increase wellsite efficiency and reduce the rig-operating time required for well-completion operations by eliminating the need for parameter-gathering surveys and for radio silence during perforating operations. New detonation-initiation systems also allow selective firing or activation of two gun or tool systems during a single run.

New electronic firing heads also have a sufficiently high data-sampling rate to capture transient-pressure events that cannot be recorded by standard gauges. That feature is improving our understanding of wellbore physics during dynamic underbalanced perforating.
This article presents perforating designs based on specific reservoir properties and well parameters, advances in orienting and detonation initiating systems, and recent improvements in deep-penetrating shaped charges and gun systems. It describes dynamic underbalanced perforating and oriented TCP operations in the North Sea and in Southeast Asia. We conclude by discussing research capabilities and laboratory facilities that are essential in the development and evaluation of perforating techniques, systems and practices.

Maximizing Well Performance
To produce oil and gas, every well with steel casing cemented across productive subsurface intervals must be perforated. The perforating process connects subsurface formations with a wellbore, allowing hydrocarbon inflow or fluid injection downhole (right).1

Clean perforation tunnels with minimal perforating-induced damage are essential to maximize well performance. Unfortunately, the


Shaped-charge performance. Perforating charges consist of four elements—a primer, the main explosive, a metal or powdered metal liner and steel case—connected to a detonating cord (top left). A conical cavity shape maximizes depth of penetration through steel casing, cement and rock formations (bottom left). As explosive shaped charges detonate, the liner collapses to form a high-pressure, high-velocity jet of fluidized particles (right).

high-energy jets from explosive charge detonations generate shock-wave damage and create fine particles and residual debris by fragmenting and loosening formation grains.\(^2\)

In the 1960s, engineers recognized the benefits of perforating with an initial static underbalance—a wellbore pressure that is lower than the formation pressure. With the introduction and wider utilization of TCP systems in the 1970s, underbalanced perforating became the most accepted technique for preventing post-perforating invasion of fluids into a formation, for mitigating crushed-zone damage around perforation tunnels and for removing debris from perforation cavities (below).\(^2\)

In the 1980s and 1990s, perforating research concentrated on defining underbalanced criteria and on predicting the pressure differential required to generate clean, effective perforations.\(^4\)

Based on experimental work at the Schlumberger Reservoir Completions (SRC) Technology Center in Rosharon, Texas, researchers developed a minimum underbalance equation that is included in the SPAN Schlumberger perforating analysis design program.\(^5\)

Application of this equation led to development of extreme underbalanced (EUB) perforating, a technique that applies static pressure differentials two to four times greater than those previously used in conventional operations. The EUB technique is designed to generate surge flow from the formation and clean out perforation tunnels.\(^5\)

However, this technique has limitations and safety concerns related to wireline operations. Under high differential pressures, unanchored wireline-conveyed guns can move, or be blown, uphole during perforating, which can damage the electric cable or cause toolstrings to become stuck.

In most cases, both conventional underbalanced and EUB perforating require coiled tubing and pumping operations to establish initial hydrostatic conditions by displacing fluids to unload wellbore fluids. Also required is a wireline run to set a mechanical tool that anchors the perforating guns and several wireline or slickline runs to deploy and retrieve gun strings, and to recover the anchor. For long completion intervals, these combined operations may take three or more days.

In addition, underbalanced and EUB techniques sometimes yield inconsistent results and disappointing levels of productivity or injectivity, even in adjacent or similar wells. In contrast, perforating with initially balanced or even overbalanced pressures may yield surprisingly good results. Until recently, only minimal resources were focused on determining why the effectiveness of underbalanced perforating varies so much, or on the degree of pressure differential that is actually achieved during perforating.

The availability of pressure gauges with extremely fast data-sampling rates facilitated much needed research in this area. These new high-resolution gauges can record wellbore pressure variations during the first second after perforating. In the late 1990s and early 2000s, researchers at SRC conducted single-shot tests using high-resolution gauges.\(^7\)

These studies found that for a few hundredths of a second after shaped-charge detonation, wellbore pressure oscillates as high-velocity jets and shock waves pass through wellbore liquids. Test results indicated that perforation cleanup did not depend solely on initial static wellbore conditions before perforating, whether underbalanced, balanced or overbalanced.

The maximum pressure differential generated in a wellbore during the first 100 milliseconds (ms) after perforating directly influenced variations in perforated core productivity during post-perforating flow tests. Higher dynamic underbalanced pressures generated better flow efficiencies in perforated cores. Subsequent laboratory evaluations
confirmed that removal of perforating damage and perforation cleanup were directly related to the maximum dynamic underbalance and the timing of surge flow (above). Collectively, these results formed the basis for dynamic underbalanced perforating, a new approach to perforation cleanup. This PURE perforating system for clean perforations specifies unique wellbore conditions and gun configurations to generate an instantaneous drop in pressure around the perforating guns during shaped-charge detonation.

Dynamic underbalanced perforating can be performed independent of initial wellbore conditions to create the drop in pressure and rapid surge flow required to generate high shear stress around perforation tunnels immediately after charge detonation. Shear failure of the crushed zone caused by dramatic reduction in wellbore pressure rather than tunnel erosion due to fluid influx from the formation appears to play an important, perhaps vital, role in perforation cleanup.

For PURE wireline perforating applications with expendable capsule, or strip guns, the wellbore must be close to balanced or slightly underbalanced conditions, so that there is some positive flow from the formation after charge detonation. During wireline operations with
control the magnitude of dynamic underbalanced pressure and the rate of surge flow from the formation. A nearly instantaneous underbalance and influx are created around the guns when high-pressure wellbore fluids rapidly fill spent charge carriers immediately after perforating (below).

Shaped charges that do not penetrate the wellbore casing can be interspersed along a gun string. These PURE charges open additional holes in conventional charge carriers or in PURE chambers to control the underbalanced pressure differential and the rate of influx through the newly created perforations.

Compared with conventional underbalanced perforating, dynamic underbalanced designs increase well productivity and injectivity, and improve operational efficiency. Operators have applied PURE perforating designs and techniques to complete or recomplete more than 500 wells worldwide, including extensive use in Indonesia and the North Sea.

8. Dynamic underbalanced perforating is a Schlumberger patented process marketed under the Schlumberger mark PURE perforating system for clean perforations.

^ Optimal dynamic underbalance and perforation damage removal. In addition to conventional shaped charges (blue), PURE perforating systems can include special PURE chambers and PURE charges (yellow) interspersed along a gun string (far left). The PURE charges do not penetrate the wellbore casing, but instead open extra holes in conventional charge carriers or additional PURE chambers to maximize the transient pressure differential and optimize perforation cleanout (center left and center right). Immediately after charge detonation, high-velocity perforating jets generate perforation tunnels in the formation (0 to 100 µs). PURE designs manipulate wellbore conditions and gun parameters to instantaneously create an optimal underbalance across a perforated interval (100 to 200 ms). Tensile failure of the crushed zone around perforation tunnels and surge flow from the formation remove induced damage and residual debris (300 to 400 ms). Rapid application of a high differential pressure is the key to PURE perforating. Perforated laboratory cores examined under hydraulic stress with a color video probe show a perforation filled with pulverized formation material and surrounded by fragmented quartz grains (top right); a perforation without fragmentation, but with pulverized material remaining along the bottom of the tunnel (middle right); and a clean tunnel (bottom right).
In Well 1, CNR needed to complete several zones across a 2,200-ft [671-m] interval. Engineers decided to perforate using the PURE process with TCP guns and a DST string to create a closed-chamber system. The SP AN program indicated that perforating with a dynamic underbalance could improve well productivity by 15% or more compared with conventional static overbalanced or underbalanced operations. The key was to generate a rapid dynamic underbalance across the entire completion interval. The primary gun design called for a 3 3/8-in. TCP system to perforate 992 ft [302 m] of net pay. As a contingency, engineers prepared a design for 2 7/8-in. guns in case a smaller liner had to be run.

CNR and Schlumberger estimated the formation pressure to be 4,500 psi [31 MPa]. For this design, a hydrostatic wellbore pressure of 8,000 psi [55.2 MPa] was required to generate a dynamic underbalance of 3,500 psi [24.1 MPa]. This required the wellbore to be pressurized before perforating. CNR used a DST tool and downhole packer with the test valve closed to form a sealed chamber before perforating and to quickly create a dynamic underbalance.

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close the test valve before the guns fired. Schlumberger used a standard downhole gauge with a 5-second data-sampling rate to record wellbore pressure (previous page, right).

At this sampling rate, the gauge could not capture detailed transient-pressure responses during PURE perforating. However, the low-resolution data indicated that the wellbore pressure dropped dramatically from 8,000 psi when the guns detonated and then built back up quickly to equalize with the reservoir pressure, an indication that this operation achieved an effective dynamic underbalance.

Surface gauges registered a steady pressure of 850 psi [5.9 MPa] after the test valve was reopened. The initial pressure drop, rapid pressure buildup and high surface pressure indicated that the perforations cleaned up quickly and had little or no damage. After observing the well for several hours, CNR released the DST packer, circulated a nondamaging fluid to control the well and retrieved the TCP guns.

CNR installed permanent completion equipment and produced the well at an initial oil rate of 9,500 bbl/d [1,510 m³/d], significantly higher than the rate projected for conventional underbalanced perforating. The recovered guns contained large volumes of shot debris and formation sand, indicating a rapid and effective dynamic underbalance that caused the spent charge carriers to fill quickly, which helped retain shrapnel and other residual perforating debris inside the guns.

CNR perforated Well 2 using a similar PURE process and system. This design called for 3 1/2-in. guns loaded to perforate three zones comprising about 910 ft [277 m] of pay across a 1,600-ft [488-m] gross interval. This well was drilled as an injector, but produced oil for a short time before conversion to water injection. The initial surface pressure after perforating indicated a reservoir pressure of more than 6,100 psi [42.1 MPa], significantly greater than in the first well (above right).

CNR also perforated Well 3 and Well 4 using a closed-chamber DST string to trap high pressure around the guns before perforating. Standard gauge data from these two wells indicated that a dynamic underbalance was achieved (right).

Perforating operations on Well 5 followed the same procedures as on the previous four wells. This time, however, CNR used a PURE design and a DST system that included an eFire electronic firing head system (see “Improving Operational Efficiency and Safety,” next page).

(continued on page 28)
Improving Operational Efficiency and Safety

Explosive services and other downhole operations now can be initiated safely and efficiently using advanced electronic firing heads. Schlumberger uses eFire electronic firing head systems to detonate perforating guns, to set packers or bridge plugs and to activate chemical cutters, mechanical tubing punchers or other downhole tools, such as testing or sampling devices.

These programmable systems combine two proven technologies: the IRIS Intelligent Remote Implementation System and S.A.F.E. Slapper-Actuated Firing Equipment for initiating wireline perforating. 1 Dual-valve drillstem testing (DST) tools use the IRIS intelligent controller to open and close a test, or flow, valve and a circulating valve. Both technologies have been used extensively in harsh well conditions since the early 1990s. 2

The operation of eFire systems is similar to that of a DST tool. A computer in the IRIS controller detects a unique sequence of signals from the surface. These coded pulses are recognized and interpreted as commands to initiate downhole operations through a S.A.F.E. system for wireline perforating.

The S.A.F.E. system uses an exploding foil initiator (EFI), which is reliable and fail-safe, to initiate a detonation chain. Developed for military use, EFI technology eliminated the need for primary high explosives in detonators. An EFI initiator is immune to radio frequencies and stray electrical voltage from welding operations, corrosion protection systems, electrical transmission lines and radio communications at a井site.

Previous firing heads required extra equipment and supporting wellsite services and operations, such as nitrogen tanks and pumping equipment. These systems operated automatically under preset pressure or temperature parameters, which often required that operators perform an initial parameter survey to define the existing wellbore conditions.

Conventional firing heads rely on well conditions remaining static during all operations and must be removed from predefined operating depths or pressure conditions to abort detonation. Alternatively, these systems might fail to detonate because of changing downhole conditions, which would require a new parameter survey. Of greater concern, downhole sampling or testing tools and perforating guns with conventional firing heads also might activate at the wrong depth in a wellbore or detonate prematurely.

An eFire system overcomes these disadvantages and limitations by providing total control of an operation from the surface. Wellsite personnel can arm, fire or abort operations at any time, eliminating the need for a parameter survey and allowing more perforating runs to be made in a day.

The firing head detects changes in pressure or flow through the tubing or tubing-casing annulus, changes in slickline cable tension or changes in wireline electrical current. By using different sensors, Schlumberger developed a family of electronic firing heads for tubing-, coiled tubing-, slickline- and wireline-conveyed operations. 3

Command signals require relatively low pressure, flow, tension or current differentials. This feature reduces the need for supporting surface equipment or pumps, and sources of nitrogen or other gases. Rapid command-execution times and the real-time capability to abort detonation provide more reliable control of explosive operations, which now can be performed safely even in low-pressure wells.

The IRIS controller recognizes a distinctive sequence of changes as coded signals that form a unique command structure for the IRIS controller. These specialized commands ensure that eFire systems are insensitive to unrelated surface or subsurface wellsite operations, such as jarring or moving equipment, and random pressure variations in the subject well or adjacent wellbores.

To enhance safety, two separate processors independently verify each command. Tool operators perform a setup and function test using a laptop computer before the eFire head is connected to the EFI or any explosive devices.

In addition to a fail-safe command structure, the eFire heads have to be enabled by a preset hydrostatic pressure followed by an arming command from the surface before the system will accept a detonation command. The eFire head then converts battery power to a higher voltage that activates the EFI initiator.

During 2002, BP identified a number of wells in the southern North Sea that could be reperforated or recompleted. This area included 39 platforms, primarily unmanned structures, with minimal surface infrastructure and facilities. Many of these wells were perforated more than 30 years ago at only 1 shot per foot (spf). Engineers determined that adding perforations could significantly improve well productivity.

Slickline perforating, which requires fewer personnel and simplifies both pressure-control and equipment requirements, was the most cost-effective method for performing these remedial well interventions. A single unit and one crew can perform all of the required work, reducing the number of crane lifts and associated risk to personnel.


BP engineers decided to use the eFire-slickline head for perforating after successfully performing several other operations with the system, including setting a packer and punching holes above a plug stuck inside a tubing string. This approach improved operational efficiency and significantly reduced costs by eliminating the time-consuming and costly prejob surveys, or parameter runs, that are required with conventional time-delay firing heads.

BP correlated perforation depths by marking, or flagging, the slickline cable during an initial logging trip. A memory gamma ray and casing-collar-locator tool was run in an empty carrier that replicated the length and weight of the actual gun system. The loaded guns then were run to the flagged depth and armed. The depth counter was reset based on the correlation log, the firing command was initiated, and the guns were positioned at the target perforating depth before detonation. A disarm command was sent before retrieving the guns.

Initially, BP verified slickline depth correlations by running a 40-arm caliper across newly perforated or reperforated intervals. These surveys indicated that slickline-conveyed guns could be detonated on depth with real-time control. BP realized significant time and cost savings by using the eFire slickline system, completing as many as three perforating runs to depths greater than 10,000 ft [3,048 m] in less than 12 hours using 40-ft [12-m] gun strings.

Compared with wireline operations, eFire technology for slickline perforating proved to be extremely efficient and led to a cost saving of more than 15% in the southern North Sea business unit of BP. The resulting production increase of about 10% represented a significant achievement in this mature area where fields have produced for more than 35 years.

The eFire technology provides a step change in well interventions. For example, slickline perforating saves about one day per well during abandonment operations. More than 500 perforating operations have been performed with eFire slickline systems in the North Sea since this technology was introduced in 2001. In addition, about 50% of TCP operations in the UK sector now use the eFire system, primarily because of improved wellsite efficiency and safety.
Ninian field Well 5 perforating. Pressure data show the sequence of events during perforating operations on Ninian field Well 5, including low-pressure pulses to activate the eFire firing head, closing the test valve to trap pressure, the time delay before guns fire, gun detonation, achieving a dynamic underbalance, a pressure buildup after the dynamic underbalance, opening the test valve and a buildup back to the formation pressure (top). High-resolution data recorded by the eFire system at a 1-kHz sampling rate indicate that pressure dropped from 7,000 psi [46.2 MPa] to less than 2,100 psi [14.5 MPa] in 100 ms (bottom). The actual magnitude of dynamic underbalance was not captured by standard gauges used on the previous four wells. The eFire data provided CNR International with conclusive evidence of the extreme underbalanced pressures that can be achieved during PURE dynamic underbalanced perforating.

New versions of the eFire head record wellbore pressure at a 1-kHz rate and can capture transient-pressure events during the first few milliseconds after shaped-charged detonation. After perforating, fast-gauge data indicated that a dynamic underbalance of more than 5,000 psi occurred within 100 ms of gun detonation (above).

Fast-gauge data confirmed the magnitude and timing of the dynamic underbalance.

Standard gauges, such as those used on previous wells, could not record pressure data fast enough to fully evaluate PURE operations. Achieving rapid, high-pressure underbalanced conditions and nearly instantaneous surge flow ensured the removal of perforating damage and debris. Clean perforation tunnels are essential for maximizing oil production and water injection, and also for optimizing gas-well productivity.

Optimizing Gas-Condensate Output

As in the North Sea, dynamic underbalanced perforating also has achieved significant success in Southeast Asia where Total E&P Indonésie operates the Tunu field. Located on the eastern side of Mahakam delta in East Kalimantan, Indonesia, the reservoirs of this field comprise interbedded sandstones from 2,300 to 4,500 m [7,546 to 14,764 ft] deep. Since 1990, more than 370 wells have been drilled in the Tunu field (next page, top left).

In 1999, Total began completing these gas-condensate wells using extreme underbalanced (EUB) perforating. This approach required pumping operations to unload wellbore fluids and a wireline run to set an anchor, along with multiple slickline runs to position and recover stacked guns, and to retrieve the anchor.

In November 2004, Schlumberger recommended dynamic underbalanced perforating using wireline-conveyed guns for two new wells with 4½-in. casing. Engineers used SPAN software to account for wellbore geometry, fluid density, gun configuration, shaped-charge performance and reservoir properties.

Based on this analysis, Schlumberger developed a 2½-in. system with deep-penetrating shaped charges specifically for this application. Engineers designed the gun string so that the total number of holes in these chambers would generate the required underbalance to facilitate perforation cleanup. Total began performing these wireline jobs in November 2004.

Pressure gauges with a high data-sampling rate that could record pressure events during the first second after detonation were not available for these jobs. However, wellhead pressures in both wells increased immediately after perforating as wellbore fluids began to flow back and unload. Within 30 minutes, gas began flowing to the surface.

Well 1 and Well 2 produced gas at 15 MMcf/d [424,753 m³/d] and 27 MMcf/d [764,555 m³/d], respectively, with a flowing wellhead pressure of 435 psi [3 MPa]. Pressure buildup data acquired with a downhole gauge indicated skin values of...
1.1 for Well 1 and zero for Well 2. Well 3 produced 29 MMcf/d [821,189 m³/d] with a skin value of zero. Well 4 produced gas at 35 MMcf/d [991,090 m³/d] with a skin value of negative 2.25.

The average skin value for 35 wells perforated from 2000 to 2004 using the conventional static EUB technique was 4.73. Reliable pressure buildup data from the first four Tunu field wells perforated with the PURE technique had an average skin value of negative 0.29. These low skin values yielded a cumulative increase in gas production of more than 200% in those four completions.

The jobs were performed efficiently with significant cost savings compared to conventional EUB operations, yielding increased well productivity. Perforating and cleanup operations for each well required only one day to complete. Total perforated six more wells during this initial phase of PURE perforating, which resulted in a cumulative cost-saving of about 43% compared with previous EUB operations (above right).

Since 2004, more than 40 wells have been perforated in the Tunu, Tambora and Peciko fields using dynamic underbalanced designs that achieved an average productivity gain exceeding 150%. To date, there is no evidence of sand influx in these wells after perforating with the PURE technique. In some applications, accurately oriented perforation also may be required to prevent the production of sand.

Oriented TCP Operations
Oil and gas operators recognize that oriented perforating is an effective technique for mitigating sand production. In high-angle and horizontal completions and under normal in-situ stress conditions—the maximum stress direction is vertical—shooting along the high side of a wellbore improves the stability of perforation tunnels in a formation. This technique also prevents debris from blocking perforations on the low side of the hole.

However, completing extended intervals in inclined wellbores often requires tubing-conveyed systems with hundreds of gun sections that must remain closely aligned to maintain a near-vertical perforation orientation. Large compressional loads generate slight clockwise rotation and gradual misalignment at each gun section that accumulates over long strings with conventional connections.

Using caliper logs, North Sea operators found that past attempts at oriented perforating resulted in perforations that were misaligned by as much as 45° from the desired vertical orientation. In many of these completions, perforations aligned more than 25° from vertical in weakly consolidated formations have an increased risk of collapsing and producing sand. Alignment errors were greatest in wellbores with significant variations, or doglegs, in the wellbore path. Operators needed a TCP orienting system that would maintain a vertical charge alignment independent of changes in well
In response to a request from Hydro, Schlumberger designed, tested and deployed a new TCP orienting system for Norwegian North Sea wells within a five-month period. In addition to weighted spacers for passive orientation, this OrientXact tubing-conveyed oriented perforating system combined innovative aligning-locking adapters with special high-load, low-friction roller-bearing swivels that reduced average misalignments between guns to about 0.17°.

The OrientXact aligning-locking adapters are manufactured to extremely tight tolerances to eliminate rotational and cumulative misalignments inherent in conventional threaded connections. Low-friction swivels with a high-load capacity in both tension and compression support individual sections of guns and passive orienting weights. An OCD Orientation Confirmation Device at the end of each swivel-supported section verifies perforation orientation to within 0.5°.

The OrientXact system includes an OCD Orientation Confirmation Device that records perforation orientation during charge detonation to the nearest 0.5°. Two OCD units per gun section confirm perforation directions after the guns are fired and retrieved. A pendulum assembly inside the OCD unit contains a free-rotating collar, a detonation-cord port, a bullet tube, a bullet and an angular scale. Explosive energy from the detonation cord forces the bullet through the barrel tube toward the inside wall of each OCD unit, where it records gun alignment relative to a vertical, or 0°, orientation on the scale. Operators read these scales after spent guns are retrieved to determine the perforating orientation for that section of guns.
The OrientXact system uses guns with 4 to 6 shots per foot (spf) and a 20° phasing angle between charges that shoot on either side of vertical to maximize perforation density, spacing and stability. OrientXact systems have been used to perforate within 10° of vertical regardless of well trajectory, even with more than 1,600 ft [488 m] between OrientXact swivels.18

This advanced orientation system consistently perforates along the high side or the low side of inclined wells to prevent sand production. When the angle between a wellbore and the maximum stress direction, typically vertical, is greater than 75°, this oriented perforating technique helps prevent sand production.

To date, Hydro and Statoil have used this system to perforate more than 50 wells in the Norwegian sector of the North Sea. The OrientXact system is available for 2 1/8-in., 3 1/8-in. and 4 1/2-in. TCP guns. A 2 3/8-in. OrientXact system was used by BP to perforate Andrew field wells in the North Sea UK sector.

Preventing Sand Production
BP began developing the North Sea Andrew field in 1996. Water production from some wells in this UK sector reservoir began to increase during 1998, and the field declined from peak output in 2000.

BP first detected sand in two wells during 2001, three years after water breakthrough. Horizontal wells in the Andrew field were completed with cemented liners to facilitate future interventions, recompletions and water control.

Sand production appeared to be related to pressure depletion and perforation stability. BP perforated these wells using TCP systems and underbalanced perforating operations, which minimized perforation damage and routinely resulted in production from more than 90% of the horizontal section. The production tubing included an FIV Formation Isolation Valve below a permanent packer to provide well control during gun deployment and after perforating. After installing downhole completion equipment, permanent production tubing and the surface wellhead, BP deploys TCP guns with a hydraulic snubbing unit and perforates wells in underbalanced conditions. A shifting tool on the end of the TCP string closes the FIV tool as the spent guns are retrieved. An inflow test confirms that the valve has closed and that the spent guns can be removed from the well safely. Pressure pulses applied from the surface reopen the FIV tool to initiate production without performing a rig-assisted intervention.

In an attempt to minimize sand production, BP perforated some of the less consolidated intervals with oriented TCP guns using conventional passive weights and swivels with charges at phasing angles of 25° and 335°. However, orientation accuracy was uncertain, and actual perforation alignment on either side of vertical could not be verified.

Schlumberger sand-prediction models indicated that at about 32° from vertical, perforations could collapse and initiate sand influx.19 The onset of sand production from Andrew field wells could have resulted from misaligned perforations at 60° phasing angles or

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from inability to consistently achieve near-vertical perforation orientations using 25° and 335° phasing angles with a conventional TCP orienting system (above).

BP decided that a new gun design was needed to minimize orientation errors. Engineers chose TCP guns with charges at 10° and 350° phasing angles to help align perforations closer to vertical for increased stability. Optimally spaced, near-vertical perforations would improve total inflow, reduce the flow rate through each hole and maximize the distance between perforation tunnels in the formation for increased stability (next page, left).

This system included passive orientation weights and swivels to align the charges and an OCD system in each gun section to record perforation direction. Deep-penetrating premium shaped charges were used to reduce near-wellbore pressure drop during production and minimize formation stresses on perforation tunnels.

BP initially planned to complete the new Well A-15 with a 5½-in. liner, so Schlumberger built 3¾-in. guns with 5 spf at 10° and 350° phasing angles. Difficult drilling conditions caused significant variations in wellbore trajectory that forced BP to run a 4½-in. liner and use a smaller perforating system.

In April 2002, BP perforated Well A-15 by deploying more than 1,000 m [3,281 ft] of 2¾-in. oriented TCP guns with 6 spf at 25° and 335° phasing angles. However, this gun system performed below expectations. The OCD devices recorded an average alignment error of 26° from the vertical (right).

Confirmation of perforation orientation allowed engineers to assess the risk of sand influx and helped BP make production decisions. This information provided a benchmark for evaluating future developments in tools and techniques. The large alignment error in Well A-15 raised concerns that perforations in weaker intervals might fail and produce sand as reservoir pressure decreased.

To achieve accurate near-vertical perforation orientations, Hydro and Schlumberger had jointly developed OrientXact technology. The new OrientXact swivels reduced friction by 90% and could withstand the high loads generated by long gun strings in both tension and compression. In addition, improved connections with tight manufacturing tolerances further reduced alignment errors between gun sections.

BP applied OrientXact swivels for the first time on two existing Andrew field wells to perforate bypassed oil zones identified by 4D seismic data and cased-hole logs. BP planned to add perforations at the upper end, or heel, of the horizontal sections in Well A-8 and Well A-7 using

Conventional oriented TCP guns. BP perforated Andrew field Well A-15 using more than 1,000 m of 2½-in. conventional oriented guns. These guns were deployed and retrieved through an FIV tool. The orientation data from OCD systems included in this gun string indicated an average perforation misalignment of 26° away from vertical. Sand-production models predicted that at this orientation, perforations in weakly consolidated sands could become a source of sand influx in weakly consolidated sandstones.

Accurate oriented perforating with coiled tubing-conveyance. The OCD systems in the perforating system used on Well A-8 verified that improved OrientXact swivels between gun sections could increase orientation accuracy even with an alternative coiled tubing-conveyance method. The average perforation alignment error in this well was 12°, a 14° improvement compared with Well A-15. Sand-prediction models indicated that perforations at this near-vertical orientation would prevent sand influx for several years.
Autumn 2006 33

33⁄8-in. TCP guns with the new swivel design and HSD High Shot Density charges at 10° and 350° from vertical.

Schlumberger deployed, fired and retrieved this TCP system in Well A-8 with coiled tubing and a surface deployment system. After recovering the guns, the OCD devices confirmed an average alignment error of 12°, 14° less than in Well A-15 (previous page, bottom right).

BP and Schlumberger projected that perforations at this orientation would not produce sand for several years, even in weaker sand intervals. Based on the success of Well A-8, BP planned to use the same technique on Well A-7. However, design models predicted that coiled tubing alone could not reach the perforating depth because of helical buckling. These complications and a longer perforating interval required BP to make two perforating runs. BP chose a combination of coiled tubing and two downhole tractors to convey the guns.

The average gun alignment error was 11° on the first gun run; on the second gun run, the gun alignment error was less than 8° (above).

BP subsequently perforated the new A-16 well using a 3¾-in. TCP system with new OrientXact swivels and shaped charges at 10° and 350° phase angles. Orientation accuracy was expected to be high because this wellbore had no extreme variations in trajectory. The average gun alignment error was less than 5° (left).

During cleanup, however, Well A-16 produced a substantial amount of debris back to surface, causing a processing shutdown. As a result, BP and Schlumberger focused additional engineering efforts on reducing debris in future perforating operations. A potential solution was the 4½-in. OrientXact system developed for Hydro. This system used low-debris shaped charges that do not fragment into small pieces, and the large fragments remain inside the gun. BP agreed to develop this technology for a smaller gun system to use on the next new well.

Well A-17 would encounter the same difficult drilling conditions as Well A-15, so BP decided to develop a 2¼-in. OrientXact system similar to the 4½-in. guns developed for Hydro. This design included OCD systems, low-debris charges at 10° and 350° phasing angles, and connections that reduced alignment error between gun sections.

In April 2004, BP perforated the new A-17 well using this new 2 7⁄8-in. OrientXact TCP system conveyed below 2 7⁄8-in. and 3 1⁄2-in. tubing. After operators fired and retrieved the guns, the OCD systems confirmed that the perforations were about 2.6° from vertical (above).

This degree of accuracy was impressive, but the OrientXact system also retained most of the residual charge debris inside the gun tubes. BP recovered only a small volume of debris, mainly rust from the casing walls, at the surface from more than 1,200 m [3,937 ft] of guns.

Maximizing production and operational efficiency was important, but sand prevention was the primary reason for applying oriented perforating in this field. BP and Schlumberger achieved this objective on the A-7, A-8, A-16 and A-17 wells. Continuous monitoring of solids since May 2003 has indicated extremely low sand influx from existing completions with new oriented perforations, and from new wells, such as Well A-18, that were perforated with the OrientXact system (right).

In addition to sand prevention and oriented fracturing, engineers use orienting systems to achieve other objectives, including reperforating and recompletion of wells with complex downhole equipment configurations like those in the North Sea Otter field.

Subsea Recompletion with Oriented TCP
Total E&P UK plc needed an accurate, cost-effective method for orienting perforations in a horizontal North Sea well. This particular completion in the Otter field located northeast of the Shetland Islands was one of three subsea wells, each equipped with dual electrical submersible pump (ESP) artificial lift systems. Total had identified a bypassed zone that could be commingled with production from existing perforations.

However, the target interval was behind 7 5⁄8-in. casing, which presented several perforating challenges. The guns had to pass through the ESP bypass and a 2.66-in. [6.8-cm] landing profile and align the perforations vertically downward toward the low side of the wellbore to mitigate sand influx and maximize perforation penetration inside 7 5⁄8-in. casing (next page).

The gun design also had to minimize residual debris to avoid perforation plugging and damage to the two ESP systems. During the first phase of this project, engineers assessed the risk of sand production. Total conducted sensitivity studies to determine if oriented perforations would prevent sand production from weak formation intervals. Sand-prediction software confirmed that perforations aligned within 10° of vertical in the weakest pay zones would remain stable even at full depletion.

The second phase involved designing a small gun system with charges at a zero phasing angle. Schlumberger built and tested a highly accurate, low-debris 2 7⁄8-in. OrientXact system that could pass through the ESP bypass and a 2.4-in. [6-cm] restriction.

Engineers chose 2-in. PowerJet Omega deep penetrating perforating shaped charges to maximize penetration in the weak Otter sands and to eliminate debris that could damage the dual ESP system. These extra-deep penetrating charges, which achieve a 23.8-in. [60.5-cm] penetration in an API Section-1 target, also include a low-debris case that remains intact inside the carrier after perforating.

Normally perforations are oriented along the high side of a wellbore to optimize perforation stability and cleanup, and to avoid perforation plugging. However, firing a small gun system inside 7 5⁄8-in. casing would decrease perforation penetration depth in the formation if shaped charges were oriented upward. Gravity would cause guns to lie on the low side and require that charges shoot across the wellbore through well fluids. Schlumberger designed the gun system to...
rotate and shoot downward, which sacrificed perforation cleanup for penetration depth, but allowed Total to perforate this subsea well without pulling the permanent completion equipment.

Total successfully deployed the 2 1/4-in. system on a 2 7/8-in. wireline tractor during two perforating runs with 12.2-m [40-ft] gun strings. The low-friction OrientXact swivel and weights rotated the charges to the low side of the wellbore. The OCD orientation confirmation devices verified that all perforations were aligned downward within 2° of vertical. The additional perforations contributed substantial incremental production from the Otter field.

Oil production increased from about 8,000 to 15,000 bbl/d [1,271 to 2,384 m³/d] with no indication of sand production. The entire operation was completed in 36 hours with minimal residual debris, no downtime and no lost-time incidents. This successful operation helped Total avoid a difficult and expensive subsea workover.

**New Dynamics and Directions**

Efficient and effective perforating designs must address a number of factors, including shaped-charge performance, formation characteristics—rock strength, permeability and porosity—shot density and transient wellbore pressures before, during and after gun detonation. Perforating techniques and tools, including advances such as PowerJet Omega charges, the PURE process and OrientXact systems, contribute significantly to the success of stimulation treatments and sand-management methods.

Deep-penetrating charges can bypass invasion; big-hole charges for fracture stimulations or gravel packing maximize perforation flow area; optimal charge orientation and spacing can prevent or mitigate sand production and other factors that restrict production. Innovative perforating methods and techniques, such as PURE dynamic underbalanced perforating, ensure clean and effective perforation tunnels. By effectively cleaning up all perforations, dynamic underbalanced perforating maximizes well productivity and injectivity.

Research and laboratory analysis are additional elements in the development of new perforating techniques and systems. Only by considering all of the relevant factors can operators achieve optimal perforated completions. Schlumberger research and development efforts and state-of-the-art manufacturing capabilities at SRC continue to address the performance of shaped charges and gun systems. Researchers are seeking perforating solutions for a wide range of oil and gas applications, including carbonate reservoirs and coalbed methane production.

Modern perforating solutions efficiently deliver higher productivity and injectivity across many types of completions—new or existing oil, gas or gas-condensate wells—during every stage in the life of well or field, from initial development to plateau production. Ultimately, this will mean decreased costs, additional revenue and increased profit for operating companies. —MET