Perforating Practices That Optimize Productivity

Establishing communication with oil and gas zones involves more than shooting holes in steel casing by choosing guns and conveyance methods from a service catalog. Perforating based on average formation properties and shaped-charge performance is being replaced by a more tailored approach. Perforation design is now an integral, often customized, element of completion planning that addresses reservoir conditions, formation characteristics and specific well requirements.

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Perforating completions play a crucial role in hydrocarbon production. From well testing for reservoir evaluation to completion and remedial intervention, perforating is a key to successful exploration, economic oil and gas production, long-term well productivity and efficient hydrocarbon recovery. The perforating process instantaneously generates holes—perforations—in steel casing, surrounding cement and the formation (next page).

Both well productivity and injectivity depend primarily on near-wellbore pressure drop, commonly referred to as skin, which is a function of completion type, formation damage and perforation parameters. In the past, perforations often were characterized simply as holes in steel casing made by mechanical cutters (before 1932), shooting bullets (since 1932), pumping abrasives (since 1958) or more commonly, by detonating special shaped-charge explosives made specifically for oilfield perforators (since 1948). Far from simple, perforating is a complex element of well completions brought into focus today by contemporary research and an understanding of basic principles.

Deviations from symmetry reduces shaped-charged performance. In terms of penetration and hole size, optimized designs and precision manufacturing are improving shaped charges. Strict quality-control and aggressive quality-assurance further ensure charge reliability. As a result, perforating test results are more consistent and translatable to downhole conditions for performance projections and productivity estimates.

Among the many advances in perforating technology are new deep-penetrating charges that increase well productivity by shooting beyond invasion, and big-hole charges for gravel packing. Increased performance per unit of explosive makes these high-performance charges more efficient. In the past two years, improved charges have yielded penetration depths and flow areas that are many times greater than those achieved using prior technology. Other developments control debris, especially in high-angle or horizontal wells, by reducing debris size or returning debris inside charge carriers—guts.

Perforating is the only way to establish conductive tunnels that link oil and gas reservoirs to steel-cased wells which lead to surface. However, perforating also damages formation permeability around perforation tunnels. This damage and perforation parameters—formation penetration, hole size, number of shots and the angle between holes—have a significant impact on pressure drop near a well and, therefore, on production. Optimizing these parameters and mitigating induced damage are important aspects of perforating. Ongoing research confirms that underbalance—a wellbore pressure before perforating that is less than the formation pressure—is essential to partially or, in some cases, completely remove damage and debris from perforations.

Modern perforating is inseparable from other services that improve well productivity, such as fracturing, acidizing and sand control or prevention. In addition to being conduits for oil and gas inflow, perforations provide uniform points of injection for water, gas, acid, proppant-laden gels for hydraulic fracture stimulations and fluids that place gravel to control sand in weak or unconsolidated formations. In other sand-management applications, perforating provides the required number, orientation and size of stable holes to prevent sand production.

Conveyance methods have also kept pace with perforating technology and practices. In the late 1970s and early 1980s, perforating strategies were limited to smaller through-tubing or larger casing guns conveyed primarily by wireline. Charges for each gun size and type were designed for either maximum hole size or deep penetration. By the mid-1980s, conveyance choices were expanding. Since that time, tubing-conveyed perforating (TCP) grew from limited use in a small niche market to an essential element of many well completions and an important perforating tool.

In addition to coiled tubing, slickline and snubbing units, systems are now available to run long gun strings in live wells under pressure. These perforating and conveyance systems also perform other functions that fulfill completion needs of varying complexity, such as releasing and dropping guns, setting packers and opening or closing valves. In the future, charges may be incorporated in and run directly with completion equipment during well construction.

This article reviews key aspects of perforating, including basic physics, new charges and manufacturing, perforation damage mitigation, optimized perforation parameters, perforating practices for natural, stimulated or sand-management completions, safety and conveyance methods. We also discuss the reasons for considering specific formation, well and completion requirements when selecting perforating techniques. Examples show how perforation designs customized for specific reservoir and perforation interactions can maximize well performance.

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Shaped-Charge Dynamics
Perforations are created in less than a second by shaped charges that use an explosive cavity effect, which is based on military weapons technology, with a metal liner to maximize penetration (below). Perforating charges consist of a primer, outer case, high explosive and conical metal liner connected to a detonating cord. Each component must be made to exact tolerances. At the Schlumberger Reservoir Completions Center (SRC) in Rosharon, Texas, USA, these charges are designed, manufactured and tested to meet strict quality standards.

A detonating cord initiates the primer and detonates the main explosive. The liner collapses to form a high-velocity jet of fluidized metal particles that is propelled along the charge axis. This high-energy jet consists of a faster tip and slower tail. The tip travels at about 4.4 miles/sec (7 km/sec), but the tail moves more slowly, less than 0.6 miles/sec (1 km/sec). This velocity gradient stretches the jet so that it penetrates casing, cement and formation. Perforating jets erode until all energy is expended at the end of a perforation tunnel.

Perforating jets act like high-velocity, rapidly-expanding rods. Rather than by blasting, burning, drilling or abrasive wearing, penetration is achieved by extremely high impact pressures—3 million psi [20 GPa] on casing and 300,000 psi [2 GPa] on formations. These enormous jet impact pressures cause steel, cement, rock and pore fluids to flow plastically outward. Elastic rebound leaves shock-damaged rock, pulverized formation grains and debris in the newly created perforation tunnels.

Charge Design and Performance
Shaped charges are designed to generate optimal combinations of hole size and penetration using a minimum of explosive material. Asymmetric, or crooked, jets reduce charge performance, so perforating jets must form exactly according to design specifications. Consequently, shaped-charge effectiveness depends on charge symmetry and jet characteristics. Penetration depends on consistently achieving long jets with optimal velocity profiles. A velocity profile must be established from tip to tail, and perforating jets need to travel as fast as possible. Incorrect velocity profiles decrease penetration.

Hole size is related to jet shape. Initially, solid-metal liners, often copper, were used to generate high-density jets and big holes, but this created undesirable metal slugs, or carrots, that plug perforations. This plugging was believed to be offset by large-diameter holes and the high permeability of formations where big-hole charges are used. Technology that eliminates slugs and maximizes area open to flow (AOF) has revised this approach. Although solid copper liners are still used in some big-hole charges, recent designs generate jets without a solid-metal slug.


^A fraction of a second. In a process that lasts microseconds, millions of dollars and months, if not years, of preparation culminate when perforating clears a tunnel for hydrocarbons to flow into a well. Shaped charges, with a capability to instantaneously release energy in an explosive, use a cavity effect and metal liner to maximize penetration (lower left). Shaped charges consist of four basic components—primer, main explosive, conical liner and case (top left). An explosive wave travels down the detonating cord, initiating the primer and detonating the main explosive. A detonation advances spherically, reaching pressures of 7.5 million psi [50 GPa] before arriving at the liner apex. The charge case expands and the liner collapses to form a high-velocity jet of fluidized metal particles that is propelled along the charge axis (right).
Deep penetration—Drilling and completion fluid invasion can range from several inches to a few feet. When formation damage is severe and perforations do not extend beyond the invaded zone, pressure drop, or skin, is high and productivity is reduced. Perforations that reach beyond the damage increase effective wellbore radius and intersect more natural fractures if these are present. Deeper penetration also reduces the pressure drop across perforated intervals to prevent or reduce sand production. Designed and manufactured to outperform other charges by at least 20 to 30% in high-strength sandstone cores, PowerJet charges are the latest and most efficient perforators available (left).

New liner designs—material and geometry—provide improved penetration performance (below left). Liners for PowerJet charges are made of high-density powdered materials which yield maximum jet length and impact pressures that maximize penetration.

It is well known that high-density liners produce deeper penetration, however, working with these materials is difficult. Improvements in manufacturing capabilities now allow high-density liners to be produced consistently. Manufacturing improvements include strict and consistent procedures, precision tooling and stringent quality control (see “Charge Manufacturing and Testing,” page 62).

Charges are also test fired in different materials—high-strength sandstone cores, standard concrete and API Section 1 concrete—so that performance does not become optimized just for concrete targets.

In high-strength rock, penetration is reduced by up to 75% compared to API Section 1 concrete data. However, charges can be customized for specific formations. During PowerJet charge development, a project was initiated to optimize well completion efficiency in hard sandstone formations of South America. The objective was to increase perforation penetration in sandstones with 25,000-psi [172-MPa] compressive strengths. These high-permeability reservoirs have moderate porosity and corresponding large pore throats that contribute to fluid damage. A combination of reduced penetration and deep invasion resulted in low productivity from perforations that did not extend beyond the damage.

High-performance perforating. This graph shows the productivity ratio of perforated completion versus undamaged openhole for various depths of formation invasion. For a damaged zone of 16 in., perforating with a 3⅞-in. HSD High Shot Density gun and PowerJet charges results in more than twice the productivity of older HyperJet and UltraJet deep-penetrating charges.

Deep penetration. To ensure performance optimization for targets other than concrete, shaped charges are now tested in different materials—high-strength sandstone, standard concrete and API Section 1 concrete. However, improved designs and materials provide most of the increase in perforation penetration. Compared with previous deep-penetrating charges (top), new PowerJet high-density powdered liners and geometry yield optimal jet velocity and length as well as extremely high impact pressures (bottom).
To improve production, a three-phase approach was used. Drilling fluids were reformulated to reduce invasion and damage, the number of perforations was doubled and custom charges were designed to increase penetration. The first redesign changed only the liner geometry, which increased penetration from 12.6 to 14 in. [32 to 36 cm]. However, this was short of the 16-in. [40-cm] objective. Penetration was then increased to 15.9 in. by optimizing the explosive pellet design. In field trials, custom charges improved production and injection performance. In one case, a gas-injector perforated at four holes per foot using optimized charges outperformed other injectors with 12 holes per foot made by conventional charges.

In Australia, production from two wells with 7-in. casing that were reperforated using 2½-in. through-tubing guns with PowerJet charges increased from 300 to 780 BOPD [48 to 124 m³/d] and 470 to 1550 BOPD [75 to 246 m³/d]. In another example, an operator in Europe reperforated wells with PowerJet charges to improve productivity and reduce sand production. Prior to reperforating, more than 20 liters [2.7 gal] of sand were produced each day at a wellhead pressure of 2000 psi [13.8 MPa] and gas rates above 2 million m³/day [70.6 million scf/D]. After reperforating, sand-free gas rates of 2.5 million m³/day at a surface pressure of 2700 psi [18.6 MPa] were achieved. Efficiency is important not only for producing wells, but also for injectors. Gas injectivity was improved nine fold, from 17.6 to 159 million scf/D [500,000 to 4.5 million m³/d] by reperforating an injection well in the North Sea Norwegian sector with PowerJet charges.

Big holes, less debris and optimized casing strength—Proprietary liner geometry is also the basis of PowerFlow slug-free big-hole shaped charges, which generate large holes without a solid-metal slug (below). A large flow area improves gravel placement for sand control and reduces turbulent pressure-drop restrictions in high-rate wells, especially gas producers. In a unique packing arrangement patented by Schlumberger, PowerFlow shaped charges provide the largest area open to flow available, highest remaining casing strength and reduced debris. A hazard to well integrity and production, perforating debris should be minimized. Gun and shaped-charge debris increase the risk of stuck pipe, collect at the bottom of vertical wells, may not fall to bottom in deviated wells or may reach the surface and damage production equipment. Two strategies are used to control debris.

The conventional approach uses zinc cases that break up into small particles which are acid soluble or can be circulated out. A possible shortcoming of zinc is formation damage. Laboratory tests indicate that chloride-rich fluids and gas percolating into an idle well may combine to precipitate a solid from zinc debris that can stick guns. Another disadvantage is additional gun shocks from energy released when zinc is partially consumed during charge detonation.

Because of these disadvantages, operators are moving away from charges with zinc cases that produce small debris. The Schlumberger patented packing method, which causes steel cases to fragment into large pieces that remain in the carrier, is becoming the preferred option (next page, top).

Recent guns with increased AOF, optimized perforated casing strength and reduced debris are examples of customized solutions for perforating high flow-rate and gravel-packed wells. In 1998, Conoco requested a larger AOF than was currently available from any commercial guns for projects around the world that require high production rates to ensure commercial viability. To address this need, Schlumberger developed a 7-in. PowerFlow gun for 9½-in. casing that produces a 47% greater casing AOF than previous big-hole guns and 31% more than that of the nearest competitor.

By ensuring adequate casing strength after perforating, the newest PowerFlow guns also address an increasingly important aspect of completion design—formation compaction as reservoir pressure depletes that can collapse casing. Finite-element calculations for 9½-in. casing perforated with the above record-breaking AOF 7-in. gun indicate that casing collapse strength is 78% of the original value for casing that is not perforated.
**Damaged Permeability**

An undesirable side effect of perforating is additional damage in the form of a low-permeability zone around perforations. Single-shot flow and radial permeameter laboratory results confirmed and quantified this induced perforation skin.\(^{10}\) Perforating damage can consist of three elements—a crushed zone, migration of fine formation particles and debris inside perforation tunnels. Shock-wave pressures from the rock face to perforation tips shatter adjacent rock and fracture matrix grains, which damages in-situ permeability primarily by reducing pore-throat size (below). Migration of small particles from grain fragmentation, clay debonding and charge debris that block pore throats and further reduce permeability also has been observed in the laboratory.

Studies show that induced damage increases for larger explosive charges.\(^{11}\) The extent of perforation damage is a function of lithology, rock strength, porosity, pore fluid compressibility, clay content, formation grain size and shaped-charge designs.\(^{12}\) Research in conjunction with numerical modeling is providing a better understanding of permeability damage in perforated wells that can be used to improve completion designs.\(^{13}\)

Crushed-zone porosity is generally unaffected by perforating. At least in saturated rocks, density and porosity around perforations are about the same as in the undamaged matrix. Although perforating changes rock stresses and mechanical properties, it does not compact the formation as was believed previously. In addition to explosive by-products, another possible damage mechanism is transient injection of well fluids that may cause relative permeability problems.

In extremely hard rocks, microfractures created during perforating may serve as pathways that are actually more permeable than the formation and bypass perforation damage. With 3000-psi [20.7-MPa] underbalance, negative skins equivalent to a stimulation treatment have been measured in some high-strength reservoir and outcrop rock cores.\(^ {14}\) Shock-induced damage, however, most often contributes to total skin, restricts well performance and may offset production gains related to other perforation parameters such as number of shots, hole size, angle between perforations and penetration.

The crushed zone can limit both productivity and injectivity. Fines and debris restrict injectivity and increase pump pressure, which decreases injection volumes and impairs placement or distribution of gravel and proppants for sand control or hydraulic fracture treatments.\(^ {15}\) Erosion of the crushed zone as well as removal of debris from perforations by surge flow are essential to mitigate perforating damage and ensure well success in all but the most prolific reservoirs.

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Mitigating Perforation Damage

At one time, perforating was performed with mud or high-density fluids in wells—balanced or overbalanced conditions. Today, underbalance is more common to minimize or remove perforation damage. Underbalanced, balanced, overbalanced, and extreme overbalance (EOB) describe the pressure differential between a wellbore and reservoir before perforating. An underbalance exists when pressure inside a well is less than the formation pressure. Balanced conditions occur when these pressures are equal. An overbalance occurs when well pressure is greater than reservoir pressure. Extreme overbalance means that well pressure greatly exceeds rock strength—fracture initiation, or breakdown, pressure. Both EOB and fracturing attempt to bypass damage.18

The potential of underbalance perforating was recognized in the 1960s. Wells perforated with underbalance tended to show production increases. In the 1970s and early 1980s, researchers recognized that the flow efficiency of perforated completions increased when higher underbalance pressures were used. They concluded that post-shot flow was responsible for perforation cleanup and recommended general underbalance criteria.19 Since then, various aspects of perforating have been investigated using field and laboratory data. These studies consistently reinforce the advantages of an initial surge to erode perforation crushed zones and flush out perforating debris.

A 1985 Amoco study evaluated 90 wells that were acidized after being perforated with tubing-conveyed guns in underbalance conditions and correlated productivity with permeability to establish minimum underbalance criteria.18 Results did not suggest that there was no perforation damage, only that acid was not needed or as effective if underbalance was sufficient. This study was the main source of field data for correlating underbalance with reservoir permeability and perforation performance.

From these data, minimum and maximum underbalance pressures based on potential sand production were calculated from sonic velocities for gas wells in 1989.18 The original Amoco study as well as new data were reanalyzed.20 To account for permeability, fluid viscosity and fluid density, equations for minimum underbalance were based on fluid velocity and turbulent flow through perforations. The disadvantage was that this model required knowledge of damage-zone thickness, tunnel diameter in rock and fluid viscosity. In addition, recent test results do not support the viscosity dependence of underbalance.

These models imply that flow after early-transient surge, including pseudosteady-state flow or surging wells after perforating, is less critical for perforation cleanup. However, post-shot flow may sweep some fines into the well and further clean up perforations.21 In some cases, this accounts for limited sand production when wells come on line. Magnitude and duration of an initial pressure surge are believed to dominate cleanup of crushed-zone damage. Instantaneous flow minimizes fluid invasion, loosens damaged rock and sweeps away rock debris in perforation tunnels (above). The degree to which material is loosened is primarily a function of underbalance pressure differential. The high-velocity surge is followed by pseudosteady-state flow, which is less effective because rates and associated drag forces are less than those generated during an initial transient surge. Fluid volume and flow that occur later are believed to be secondary.

The underbalance pressures required to effectively clean perforations and reduce permeability damage have been measured in single-shot perforate and flow tests that provide a basic understanding of damage mitigation.22 Immediately after perforating in underbalanced conditions, there is instant decompression of reservoir fluids around a perforation. The dynamic forces—pressure differential and drag—that mitigate permeability damage by eroding and removing fractured formation grains from tunnel walls are highest at this time.

Transient surge-flow velocities are dependent on underbalance and formation permeability. The pressure differential required to create clean, effective perforations is a function of permeability, porosity and rock strength in addition to charge type and size. For example, deep-penetrating charges are less damaging than big-hole charges. Less than optimal underbalance results in variable perforation damage and flow rate per perforation, and most data suggest that higher underbalance pressures than those often used in the field are needed to minimize or eliminate perforating damage.23

Although turbulent flow does occur at early times with low-viscosity fluids, test results indicate that turbulence is not required for perforation cleanup. Instead cleanup of permeability damage around a perforation has now been related to viscous drag.24 The key factors are pressure differential and subsequent transient, slightly compressible radial flow, either laminar or turbulent, which was the starting point for obtaining semi-empirical underbalance and skin equations with historic data sets.

The resulting combined theoretical and empirical equations provide a way to calculate optimal underbalance for zero perforation damage or perforation skin if less than optimal underbalance is used. Single-perforation skin can be used in flow simulators to obtain total perforation skin and evaluate or compare perforating options. Now the most widely accepted criteria for estimating underbalance to obtain zero-skin perforations, this methodology was the result of more than a decade of research on optimizing perforation cleanup. Underbalance requirements calculated using this method are two to four times greater than previous criteria (above).

Because underbalance impacts perforation performance and well productivity, it is essential to understand the fluid dynamics involved. Knowledge about perforating shocks, pressures and fluid flow is helpful in selecting an optimal underbalance and designing downhole tools. The advanced flow laboratory at SRC includes two test vessels for investigating perforation flow and other completion operations under downhole conditions with overburden stress as well as pore and wellbore pressure (below).

This setup allows researchers to shoot and flow through a single perforation in outcrop or reservoir cores oriented from horizontal to vertical with any perforating system. Oil and water two-phase flow and dry-gas flow can be evaluated at constant rates with a continuous record of absolute and differential pressure measurements. Perforations can be examined with a color...
Underbalance perforating has evolved as the result of research that concentrates on predicting the pressure differential to minimize perforation skin. However, the likelihood of sand production, casing collapse, gun movement and stuck tools must be weighed against potential benefits. Design guidelines include minimum underbalance pressure for perforation cleanup, maximum underbalance pressure to avoid sanding, and fluid cushions—a gas or liquid column—or mechanical anchors to minimize tool movement.

Optimizing Perforation Parameters
Damage removal and perforation cleanup are important elements of perforating design and job execution, but consideration must also be given to tunnel diameter and length in the formation, shot density, or number of holes specified in shots per foot (spf), perforation orientation, or phasing—angle between holes—and entrance-hole size in the casing and cement (next page, bottom left). Pressure drop from perforating damage, or total perforation skin, is a function of these key perforation parameters, formation permeability and crushed-zone thickness.

Well completions have different perforating requirements. Some wells produce commercial volumes naturally after perforating and do not require stimulation or sand management during completion. These natural completions are associated with permeable, high-porosity, high-strength sandstones and carbonates with little formation damage and adequate matrix conductivity. Perforation length and shot density are the dominant perforating parameters that dictate productivity in these applications. Perforations must overcome drilling-induced damage and fluid invasion. As a rule of thumb, deep penetration, at least 50% beyond damage, is needed to effectively connect with undamaged rock.

Shot density and phasing also play important roles. Increasing shot density reduces perforation skin, and wells produce at lower pressures. If formations are laminated or have high anisotropy—significantly different vertical and horizontal permeabilities—shot density needs to be high. As skin approaches zero, shot density is important. Phased charges reduce pressure drop near a well by providing flow conduits on all sides of a well. For naturally fractured formations, multiple phasing of deep-penetrating charges helps intersect more fractures. If the natural fractures are parallel, oriented perforations are best.

Video probe during flow through the core while under hydrostatic stress [above]. Other operations, like gravel injection and acidizing also can be evaluated. Wellbore dynamics can be simulated to measure transient pressures, surge flow and perforating shocks.

Surge-flow rate and duration are controlled by initial underbalance pressure, formation permeability, perforation damage, depth of near-wellbore formation damage, and the nature of wellbore and reservoir fluids. Fast transient data, not acquired previously due to the cost and difficulty of obtaining these measurements, are helping researchers understand underbalanced perforating [below]. Wellbore pressure, reservoir-wellbore pressure differential and surge-flow data recorded at millisecond resolutions indicate a short period of injection into the perforation associated with a transient overbalance due to injection of detonation gases from the gun. The magnitude of the pressure differential driving this fluid injection depends on charge size and rock-sample permeability.

Underbalance perforating was examined visually with a color video probe while cores are under hydrostatic stress. A perforation filled with pulverized formation material and surrounded by fragmented quartz grains is shown on the left. A perforation without fragmentation is shown in the middle, but pulverized material remains along the bottom of the tunnel. A clean perforation with no fill is shown on the right.

^ Flow lab video. Perforation flow can be examined visually with a color video probe while cores are under hydrostatic stress. A perforation filled with pulverized formation material and surrounded by fragmented quartz grains is shown on the left. A perforation without fragmentation is shown in the middle, but pulverized material remains along the bottom of the tunnel. A clean perforation with no fill is shown on the right.
Although useful for estimating well productivity and assessing trade-offs between different guns, computer analysis sometimes obscures the interaction and relative importance of competing parameters. Grouping parameters together reveals underlying dependencies. This type of analysis helped develop a simple method to estimate the productivity of perforated natural completions. Combining perforation and formation parameters in a single dimensionless group gives quick productivity estimates over a range of variables that agree with the established analytical estimates of commercially available computer programs. Applicable for perforations that extend beyond formation damage in a spiral phasing pattern, this method assumes that perforation length, shot density, perforation tunnel diameter, wellbore diameter, local formation damage around a well, perforating-induced permeability damage and permeability anisotropy are the primary variables governing productivity. The theoretical maximum well productivity ratio is defined by an ideal gun with infinite shot density that enlarges the wellbore radius by a distance equal to the perforation penetration (below, top right). This establishes the theoretical productivity that can be obtained for a perforated natural completion and defines a maximum productivity efficiency for perforating systems in terms of a dimensionless factor. Practical application of this method lies in determining trade-offs between perforation parameters, underbalance, productivity improvement and economics.

Penetration and shot density clearly are important for natural completions. Penetration has an increasing proportional effect as perforations extend farther beyond formation damage. Shot density has a 1.5 exponential power effect. In addition, because perforation damage is inversely proportional to the dimensionless factor, it should be minimized by perforating with an appropriate underbalance pressure differential.

High shot density is particularly effective if deep penetration is not possible. In natural completions, tunnel diameter in the formation is the least important of the perforation parameters and increasing hole size usually occurs at the expense of penetration. A 10% increase in diameter sacrifices about 20% of the penetration and reduces the dimensionless factor by 15%. Another reason not to emphasize hole size when selecting guns for natural completions is that perforating jets that make big holes may also cause additional damage. Reduced flow from high anisotropy, perforating damage or formation damage can be partially overcome by selecting a gun with the highest dimensionless factor, whether by deep penetration, high shot density, underbalance damage mitigation or a combination of these factors. The best perforating strategies are defined as those that provide productivity efficiencies close to 100% (bottom right).

(continued on page 64)
Mixtures of metal powders, corrosion inhibitors and lubricants that help the powders flow have replaced solid liners in most Schlumberger charges. At the Schlumberger Reservoir Completions Center (SRC) in Rosharon, Texas, liners and charges are produced in a series of pressing operations. Powdered components are shaped into a cone using a mechanical punch. Copper, tungsten, tin, zinc and lead powders are commonly used to produce required jet density and velocity, properties critical to perforating performance. The main explosive is poured into a case, levelled and pressed to optimal density under a high load. A liner is then pressed into the explosive to complete the charge.

Although conceptually simple, shaped-charge manufacturing requires great precision. Charge components—case, primer, explosive and liner—must meet strict quality standards and be fabricated to exact tolerances to ensure that perforating jets form exactly according to design specifications. A nonuniform liner collapse will create heterogeneous jet densities, shapes and velocity profiles that adversely affect hole size and shape, and drastically reduce performance. To maintain proper tolerances, precision manufacturing tools are built and maintained in-house using a state-of-the-art machine shop.

Computerized pressing operations ensure high quality and minimize variations. Charge manufacturing is computer-controlled, but there is human intervention to handle liners and check for cracks, make visual inspections and clean die tools. Technicians manufacture and package millions of charges each year. A team approach with functions located in a single area facilitates efficient manufacturing and helps optimize charge performance. Multiple-bay work areas speed manufacturing and provide flexibility to meet changing well completion requirements. Manufacturing parameters are displayed in real time to detect process deviations.

Quality control is maintained on all materials used to manufacture charges, from cases and powdered-liner metals to explosives. A database with serial numbers, history cards, associated drawings and historical information tracks all charges. These records allow day-to-day oversight of shaped-charge production quality and highlight manufacturing improvements that impact charge performance. For example, procedures that were initiated while developing new deep-penetrating charges were implemented for other charges, resulting in further performance improvement.

Perforating systems are tested according to the American Petroleum Institute (API) RP 43, 5th Edition, Section 1. New RP 19B procedures are compatible with RP 43, except for a major revision to prevent target inconsistencies. The
Manufacturing functions. Teams of trained technicians assemble and package millions of charges each year. To facilitate high-quality, efficient fabrication and optimal charge performance, liner-pressing operations and charge loading are located in a single area (top). Multiple-bay work areas provide flexibility and the capability to respond quickly to changing perforating needs. A special weighing room is used to carefully control the explosive content of shaped charges (bottom).

Quality assurance. Control is maintained on all materials from steel cases and metal powders to explosives and the mechanical tools used to fabricate charges. A real-time display helps technicians identify manufacturing deviations quickly and a database tracks each shaped charge. These records are used to oversee daily operations and help quantify process improvements so that new procedures that impact perforating performance can be implemented across the manufacturing processes of other charges.

Sand used in concrete targets is specified as 16/30 U.S. mesh. This change, which was recently approved to address discrepancies in penetration-depth tests that result from large variations in the sand grain sizes used to make concrete targets, is being implemented.²

Schlumberger API tests are performed in large concrete targets at SRC (right). Tests include certification of new charges as well as periodic recertification to ensure that published data represent charges currently being produced. The API test site is also used for special client tests involving API Section 1-type targets. Of particular interest are custom tests involving multiple casing or completion geometry other than the standard API RP 43 configuration.

At the beginning of a new production run, a minimum of two charges is shot in targets built to Schlumberger standards using actual gun casings in a water standoff that simulates downhole conditions. These concrete targets have a minimum compressive strength of 5000 psi [34.5 MPa]. Expected penetration in these quality-control targets is calculated based on API Section 1, and a minimum penetration requirement for manufacturing is set. Full production begins once test results indicate that minimum requirements have been surpassed. Repeated measurements of total target penetration and minimum and maximum entrance-hole size are used to check charge quality.

During a manufacturing run, periodic tests are performed to confirm compliance with established performance specifications for penetration and hole-size standards. Samples are tested every 240 charges for large runs, and every 120 charges for the small runs associated with high-temperature charges. Case and liner integrity are verified by a shock, or drop, test, and ballistic transfer sensitivity is checked. For random batches of charges, detailed measurements are made on all components. A few charges from each manufacturing run are stored for audit purposes. During this period, charges are pulled from storage bunkers and test fired at regular intervals to check for aging effects. Internal audits also verify proper charge performance.

Test facilities at SRC, while used extensively to evaluate new charges and qualify perforating equipment, are also available for oil company use in completion planning and analysis of difficult well conditions. In addition to improving perforating performance, standardized and custom testing helps researchers and clients address confidence in perforating practices and operations by verifying that perforating systems perform consistently at rated temperatures and pressures for the duration of operations.

1. The American Petroleum Industry (API) consults with the oil and gas industry, considers advice and input from service companies, operators and scientific organizations, and recommends procedures that balance industry needs, technology and service-provider opinions.

2. API RP 19R, 1st Edition is a revised version of RP 19B in which tests are scheduled and registered with the API, and can be witnessed by third parties. The advantages of RP 19R are that manufacturing companies make a commitment to schedule and register tests, which carry greater credibility than those under RP 43.

Stimulated Completions

Fracture and acid treatments, alone and in combination, stimulate well productivity. Effective well stimulation requires communication through as many perforations as possible. This objective is achieved by perforating with optimal underbalance, limited-entry techniques or by using ball sealers or straddle packers that mechanically divert stimulation fluids to ensure that perforations are open. Rather than create long fractures for fracturing applications, while perforating can be used before a fracture stimulation to reduce breakdown pressure.

Because hydraulic fracturing is often performed in low-permeability zones, minimum underbalance to remove perforation damage can be extremely high. Maximum underbalance is required to ensure removal of perforation damage and debris. If damage is not removed, residual debris may form a filter cake in perforations that limits injectivity. Inflow is often not affected, but the restriction may create high pressures during injection. An acid job may be needed when perforation damage is not removed before fracturing.

Trade-offs between penetration and hole size have to be balanced when selecting shaped charges for fracturing applications. While perforations that penetrate more than six inches into a formation may not be necessary, adequate size holes are needed to avoid screenout—proppant bridging—in or near perforations. Premature screenout limits the fracture length and proppant volumes that can be placed. At moderate to high proppant concentrations, perforation diameter must be at least six times the average particle diameter to prevent screenout. A perforation diameter of 8 to 10 times the average particle diameter is preferred to allow for variations in charge performance and gun position.

Perforations are the point where pressure contacts a formation and fractures initiate. Except for limited-entry and diversion techniques, it is important to design perforations that minimize pressure drop across the perforations during pumping and subsequent production, including perforation friction, microannulus pinch points and tortuosity caused by curved fractures and multiple competing fractures.

Fluid injection rates directly affect surface pump and fracture initiation pressures. High rates and pressures promote fracture initiation at single sites. At low rates, injection pressure is reduced and multiple fractures may initiate from perforations and discrete points around a well. Shot density is calculated during fracture design. Minimum shot density depends on required injection rate per perforation, surface pressure limitations, fluid properties, completion tubular sizes, acceptable perforation friction loss and entrance-hole diameter. If a microannulus is present or might be induced by perforating, various factors need to be considered. To minimize pinch points and reduce flow-path tortuosity, wells with inclinations less than 30° should be perforated with 180°-phased carrier guns oriented within 10° of the preferred fracture plane (PFP). The PFP direction can be inferred from local geology or well logs.

A microannulus is often present after cementing, casing pressure-integrity testing, displacing drilling or completion fluids, establishing an underbalance, or after perforating and pumping operations that weaken the hydraulic bond between cement and formation. Because of accompanying tortuosity, flow restriction and increased pressure, a microannulus and associated pinch point should be avoided. If the angle between perforations and the PFP is greater than 30°, a fracture initiates from the sandface.

![Microannulus](image_url)

27. In hydraulic fracturing, fluid is injected at pressures above the formation breakdown stress to create a crack, or fracture, extending in opposite directions from a well. These fracture wings propagate perpendicular to the least rock stress in a preferred fracture plane (PFP). Held open by a proppant, usually sand, these conductive pathways increase effective well radius, allowing linear flow into a fracture and to the well. In matrix treatments, acid is injected below fracturing pressures to dissolve natural or induced damage that plugs pore throats. Acid fracturing, most often without proppants, establishes conductivity by differentially etching uneven surfaces in carbonates that keep fractures open.

28. Limited entry involves low shot densities—1 spf or less—across one or more zones with different strengths and permeability to ensure uniform acid or proppant placement by limiting the pressure differentials between perforated intervals. The objective is to maximize stimulation results. Rubber ball sealers can be used to seal open perforations and isolate intervals once they are stimulated so that the next interval can be treated. Because perforations must seal completely, hole diameter and uniformity are important.

Full-scale laboratory tests on fracture initiation through actual perforations show generic fracture initiation sites at the base of perforations and the PFP intersection with a borehole.\textsuperscript{32} The fracture initiation site depends on perforation orientation in relation to the PFP. Typically, if this angle is greater than 30°, fractures occur where no perforation exists. If a fracture does not initiate at the perforations, fluid and proppant must travel around the cement-sandface interface to communicate with a fracture, which results in higher treating pressures, premature screenout and the possibility of multiple or asymmetric fractures.

Perforation phasing and orientation also are important in fracturing. Tortuosity from a curved fracture path results from misalignment between gun phasing and the PFP. Phased perforations tend to create multiple competing fractures. Both these factors increase fracturing pressures.\textsuperscript{33}

Vertical wells with inclinations less than 30° should be perforated with 180°-phased carrier guns oriented within 10° of the PFP to increase the number of perforations open to a fracture, maximize fracture width near the well and reduce fracture initiation, or breakdown, pressure. If PFP direction is not known or orientation is not possible, 60 or 120° phasing may be more effective (below).

When well inclination is greater than 30° and a wellbore lies in or near the PFP, the recommendation is to use guns with 180° phasing oriented to shoot up and down. The Wireline Oriented Perforating Tool (WOPT) may be used to orient wireline-conveyed guns in vertical and nonvertical wells. Several methods are also available to orient TCP guns. As wellbores turn away from the PFP, perforated intervals should be decreased, and 60° rather than 180° phasing may be more effective (below).

For high-angle and horizontal wells where the angle between wellbore and PFP is greater than about 75°, perforations should be clustered over a few feet at maximum shot density and with phasing angles that optimize communication with one dominant fracture per interval.

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\end{itemize}
Sand Management: Control or Prevention?

Depending on formation strength, perforation stresses, flow rate and fluid type, sand may be produced with oil, gas and water when flow is sufficiently high, and there are unconsolidated or loose formation grains in and around the perforations. Changes in flow rate related to pressure drawdown, increasing effective stress due to depletion and increasing water production with time are the main factors in sand production.

Sand control utilizes mechanical methods to exclude sand from produced fluids. Sand prevention incorporates techniques to minimize or eliminate the amount of sand produced and also to reduce the impact of produced sand without mechanical exclusion methods. Choosing between these options is a function of perforation and formation stability and whether perforation failure can be predicted. The essence of sand management is quantification of sand production risk, which helps operators decide if, how and when sand control or sand prevention should be implemented.

Several methods help predict perforation tunnel stability over the life of a well. Theoretical borehole stability models adapted to perforations are useful in predicting perforation stability as stress conditions change due to pressure drawdown and depletion. Experimental methods involve testing reservoir cores or outcrop rocks with similar properties. Sand-prediction criteria based on production history, by far the most widely used technique, rely on experience from other wells and correlation of rock strength to calibrate theoretical models and help choose between sand control and sand prevention.

Perforating for sand control assumes that the production of sand is unavoidable and gravel packing, fracture packs or other mechanical techniques that exclude sand from production flow are needed. Perforating must address adequate underbalance to minimize pressure drop, or skin, and remove loose sand to clean out perforation tunnels for optimal gravel placement and efficient gravel packing. In sand prevention, perforations are designed to avoid sand production over the life of a well. Making the right decision impacts initial costs, production rate and ultimate recovery.

Sand-Control Requirements

In weak, unconsolidated formations, the conventional belief is that there are no open perforations in the formation. The only opening for placing gravel is the hole through casing and cement. This general theory proposes that if formations are incompetent and sand is produced with hydrocarbons, there is little chance that open tunnels exist. Single- and multiple-shot perforating tests have not shown this to be true in all cases. Instead, research indicates that perforation definition in weak sands depends primarily on rock strength, but also on other factors, including effective stress, underbalance, distance between adjacent perforations and fluids in the pore spaces and wellbore.

When perforation tunnels are not defined, the objective of perforating for conventional gravel-pack operations is to minimize pressure drop across the gravel-filled hole in casing and cement. This pressure drop is dictated by total AOF—the area of individual holes multiplied by the total...
number of shots—gravel permeability and flow rate per perforation. Tests on core samples show that when tunnels are defined, perforating debris and formation fines can impair gravel permeability (previous page, right). The objective is to minimize induced damage and gravel-pack impairment.

Perforation damage, formation fines and charge debris should be removed before gravel packing. Underbalanced perforating and flow before gravel packing are the best methods to achieve this objective. The maximum underbalance pressure must be selected to avoid perforation collapse and catastrophic sand production during perforating. Perforating with the surface choke open ensures post-shot flow to transport debris into the wellbore. Provisions need to be made to handle transient, finite sand production at surface until the perforations are clean. When pressure drop and flow rate per perforation are low, deep-penetrating charges can be used. Deep-penetrating charges cause less localized damage and debris, and provide a larger effective wellbore radius that reduces pressure drop. As in fracturing applications, perforation diameter needs be 8 to 10 times the gravel diameter.

Exposing formations to damaging completion fluids or lost circulation material (LCM) and chemicals during hydrostatic well-control operations should be avoided. Damage to open perforations was observed in tests on Berea sandstone blocks that were perforated, opened to flow, plugged by LCM and then reopened to flow. If a well must be killed, nondamaging brines or mutual solvents are best.

For conventional gravel packing inside casing, three steps are necessary: set a bottom packer, perforate and circulate gravel behind gravel-pack screens. Disadvantages include long duration of operations, and potential formation damage from fluid loss or LCM. Perforating guns and gravel-pack hardware can now be run in one step. The PERFPAC system is a single-trip sand-control method that limits fluid loss, reduces formation damage and saves time (above right).

In addition to internal gravel packs, perforating plays an important role in external sand-control applications like fracture packing and screenless gravel packs. Perforating requirements for fracture packing are the same as for internal gravel packs because it is more important to minimize pressure drop through the pack and control sand production than to create long fractures. However, efficient proppant placement is required to create an external pack. Big holes with high shot density—12, 16, 18 or 21 spf—and 60 or 45° phasing maximize flow area and prevent proppant screenout, or bridging, in the perforations.

In screenless gravel packs, the formation is consolidated with resin and then fractured. Proppant injected in the fracture prevents the production of formation sand. Because proppant does not fill the perforations, perforating requirements are more like conventional hydraulic fracturing stimulations. The length of perforated interval should be limited. Perforations that do not communicate with the fracture may produce sand and need to be eliminated or minimized. Hole diameter needs to be 8 to 10 times greater than the proppant diameter and perforations with 0 or 180° phasing should be oriented to within 30° of the PFP.

^ Single-trip gravel packing. A typical PERFPAC assembly includes a TCP gun with an automatic explosive release, a bottom packer, sand-control screens, a gravel-pack packer with a flapper valve, pressure gauges and recorders, firing head and a dual-drillstring test valve. The TCP guns are positioned, fired, released and dropped (left). The assembly is then repositioned so that the screens are across the perforated interval (right). The upper QUANTUM gravel-pack packer is set and gravel is injected behind the screen. The workstring is then disengaged, leaving the packed screens in place. Operations take place in a controlled environment so formations are not exposed to overpressure, LCM or damaging fluids.

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Preventing Sand Production

Sand production in unconsolidated and some weak consolidated formations results from tunnel collapse or formation failure between perforations. To avoid subsequent problems that adversely affect productivity and profitability, and limit well-intervention options, sand prevention must address changes in producing rates, formation stress and water production. Once formation stability and perforation failure thresholds are determined by modeling, laboratory testing or analysis of historical data, perforating methods are available to minimize sand production.\(^\text{39}\) Prevention implies an acceptably low risk of sand production.

More powerful big-hole charges, phase angle and excessive underbalance contribute to perforation damage and potential interperforation failure. To prevent sand production, perforation designs should minimize hole size in the formation, pressure drawdown across perforated intervals and flow rate per perforation. Perforations also should be as far apart as possible. When a large stress contrast exists in the formation and stress directions are known, oriented perforating using various systems can increase tunnel stability by taking advantage of minimum stress directions.\(^\text{40}\) Selective perforating can avoid weak zones or formations altogether.

Because small-diameter perforations are more stable than those created by big-hole charges, deep-penetrating charges are recommended for sand prevention. This also minimizes perforation damage, provides more stability during drawdown and depletion, and increases the distance between perforations. Higher shot densities keep drawdown, flow rate and drag forces through each perforation below a critical value and minimize formation erosion.

Optimal underbalance perforating reduces perforation damage and avoids sanding from catastrophic tunnel failure that could stick guns. Perforation stability models help determine underbalance limits that keep pressure drawdown below the critical level of formation failure. Single-shot perforation and flow tests on cores can confirm underbalance values that prevent sand transport, quantify the impact of increasing water production and generally verify formation and perforation stability (above right).

In addition to single-perforation instability, interlinking of failure zones around adjacent perforations, which is dictated by the distance between perforations, leads to formation collapse and sand production. Smaller holes and decreased shot density increase perforation spacing, but this has the undesirable effect of increasing flow rate and pressure drop per perforation, which exacerbate transport of failed formation material and may lead to sand production.

A method for designing guns with optimal phasing and maximum distance between holes was developed to further reduce the risk of formation collapse between perforations (below).\(^\text{41}\) By adjusting phase angle for a given wellbore radius and shot density, the distance between perforations can be increased to avoid interaction between adjacent perforations. Optimized phasing minimizes interference and interlinking of adjacent damaged zones, which reduces the risk of formation failure without compromising flow rate per perforation.

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The effectiveness of optimal phasing was demonstrated in the BP Amoco Magnus field in the North Sea. The original perforating strategy used guns with 6 spf at 60° phasing (below left). In 1997, this was changed to 99° optimal phasing while maintaining the same shot density and charge type. Wells perforated with the new guns had fewer sand-related production problems. The increase in perforation spacing for an optimum gun phasing can be substantial compared with standard gun phasing. For Magnus field, assuming a centralized gun, minimum perforation spacing was increased from 4.88 to 7.61 in. [12.4 to 19.4 cm], a 56% increase, by changing from 60 to 99° phasing.

Optimal underbalance and phasing in conjunction with deep-penetrating charges are preferred in sand-prevention applications. Ultrahigh-shot density guns with deep penetration also have been used to prevent sanding in weak, but consolidated rocks. However, even with perforating techniques for sand prevention, production flow may transport limited volumes of debris from perforation crushed zones and tunnels. As in the case of sand control, transient sand production at surface needs to be dealt with until perforations are completely cleaned up.

### An Overall Perforating Strategy

Operated by Chevron and Conoco, the North Sea Britannia field is a gas reservoir (above). Before the wells were completed, potential sand production—perforation stability—and optimal underbalance pressure during perforating to minimize or eliminate perforation skin were major concerns. Theoretical models were used to predict optimal underbalance conditions based on log-derived formation properties. With detailed log permeability data, numerous simulations were carried out to evaluate guns, charges, shot densities and perforating strategies. Based on these simulations, final completion designs included specific charge designs and shot densities for various formation sections instead of using average properties to determine perforating parameters.22

In general, four key aspects of perforating have a major impact on productivity and play an important role in determining well completion success—perforation dimensions (length and diameter), shot density, phasing angles and degree of perforation damage. The choice of gun system parameters to optimize a completion was carried out using theoretical analysis of completion efficiency using inflow, or NODAL, analysis programs. For the Britannia study, lithology variations also were taken into account. Log and core data were used to determine the productivity of various individual layers based on conductivity and formation damage. For each layer, numerical productivity simulations were carried out to determine the optimal perforation parameters of shot density, penetration and underbalance conditions (below). An acceptable gun phasing was fixed.


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### Table: Britannia Field Data

<table>
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<tr>
<th>Zone</th>
<th>Formation thickness, ft</th>
<th>Permeability, mD</th>
<th>Unconfined stress, psi</th>
<th>Porosity, %</th>
<th>Drawdown, psi (rate, MMscf/D)</th>
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<td>15.77</td>
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<tr>
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<td>13.54</td>
<td>259 (5) 643 (10) 1181 (15) 1935 (20)</td>
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</table>

### Table: Perforation Strategy

<table>
<thead>
<tr>
<th>Thickness of near-wellbore damage, in.</th>
<th>Productivity index, MMscf/D</th>
<th>5 spf, charge A</th>
<th>12 spf, charge X</th>
<th>5 spf, charge A</th>
<th>12 spf, charge X</th>
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<td>3.12</td>
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<td></td>
</tr>
</tbody>
</table>

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4. Optimal phasing. Optimal phasing was used successfully in the BP Amoco Magnus field in the North Sea to prevent failure of the formation between perforations. The original perforating strategy used 3%-in. guns with 6 spf at 60° phasing (left). In 1997, this was changed to 99° optimal phasing while maintaining the same shot density (right). Wells perforated with the new guns had fewer sand-related production problems.
Current underbalance guidelines lead to large pressure differential requirements in high-strength, low-permeability zones. This issue was addressed during the Britannia study in single-shot perforate and flow tests on reservoir and outcrop rocks conducted in the advanced flow laboratory at SRC in Rosharon, Texas. Another concern during underbalance perforating is potential sand production from perforation collapse, which was also addressed in the single-shot studies that simulated downhole stress and flowing conditions.

Laboratory tests confirmed theoretical underbalance predictions and perforation stability. Reservoir and outcrop cores were perforated using simulated downhole conditions and underbalance pressures determined from simulations. The perforation strategy for this field was selected based on results from this study. Flow performance of perforated reservoir cores verified earlier conclusions about formation sensitivity to aqueous wellbore fluids—brine—and confirmed perforation stability at high underbalance cleanup conditions. A 1000-psi (6.9-MPa) underbalance in outcrop sample tests resulted in low perforation skin. Analysis of performance after completion indicated low to negative skin in 12 wells. In addition to determining the best perforating design for each completion application, this approach emphasized the need to study optimal underbalance, especially in gas formations, to optimize overall completion strategies.

> Gun and Conveyance Choices

Shaped charges are placed in guns and conveyed downhole to the correct depth by wireline, slickline, tubing or drillpipe, and coiled tubing. There are two types of guns, capsule and carrier (below). Capsule guns, like the Enerjet and Pivot Gun systems, are used in through-tubing electric wireline and slickline perforating. Charges in capsule guns are exposed to well conditions and must be encapsulated in separate pressure-proof containers. Debris from these expendable guns is left in a well after firing. Carrier guns are conveyed on wireline or slickline, tubing or drillpipe run by drilling and workover rigs or snubbing units, and on coiled tubing with or without an electric line. In these guns, charges and most of the debris are contained in hollow steel carriers that are retrieved or released and dropped to bottom after perforating.

Casing and through-tubing guns, both capsule and carrier, were initially run on wireline; tubing-conveyed perforating (TCP) with HSD High Shot Density guns became popular in the early 1980s. Through-tubing guns, including casing and HSD guns, are limited in gun size and length by well completion design and surface pressure control equipment. The use of underbalance is also limited when guns are run on electric line. Guns deployed on tubing offer a wide variety of choices and allow for simultaneous underbalance perforating of long intervals.\(^4^3\)

> Gun types. Perforating guns are classified as capsule or carrier. A few examples are shown at right. Capsule guns are conveyed by wireline or slickline in through-tubing operations. Detonating cords are exposed to downhole conditions, so the charges are encapsulated in pressure-proof containers. Expendable through-tubing capsule guns generate debris, which remains in a well after perforating. Carrier, or casing, guns are conveyed by wireline, tubing and coiled tubing and can be designed to retain debris inside the carrier. Detonation occurs inside the carrier under atmospheric pressure.
Today, perforating often encompasses more than traditional running and firing of guns. Perforating systems are an integral part of well completion equipment and completion operations that are designed to perform multiple operations in permanent completions, such as setting packers, pressure testing, perforating one or more intervals and initiating tool functions, all in a single operation. The timing of perforating events, such as charge detonation, resulting shocks and gun release, are used to help ensure that perforating TCP guns release and drop, even in high-angle wells (right). Guns have been released and dropped successfully in well profiles up to about 84°.

**Downhole operations**—A family of X-Tools perforating gun-actuated completion tools—wireline/coiled tubing explosive-type automatic release (WXAR), superfuse explosive-type automatic gun release (SXAR), monobore anchor with explosive-type release (MAXR), superfuse explosive-type production valve (SXVP) and superfuse explosive-type vertical shock absorber (SXVA)—are designed to perform specific functions like fast release and dropping of gun strings after perforating and opening valves. These functions are initiated by an explosive on the same ballistic chain as the perforating guns. Actuation of these explosive devices after guns are fired greatly increases the versatility of perforating completion operations.

**Gun length and perforating without killing wells**—Total weight of long gun strings and running or retrieving guns under pressure restrict wireline, coiled tubing and tubing-conveyed perforating. However, these limitations are overcome by permanent completion perforating (PCP) systems.

The GunStack stackable perforating gun system, also known as Completions Downhole Assembly and Disconnect (CDAD), allows downhole assembly of multiple gun sections to any length with or without a rig. This equipment allows underbalanced perforating of long intervals in one descent. The system can be deployed and retrieved by slickline, electric wireline or coiled tubing. When necessary, gun sections can be retrieved without killing the well. This system can be used to perforate wells without interrupting production. In combination with techniques like WXAR or MAXR, the GunStack, or CDAD, system also allows guns to be run in sections according to available lubricator length and weight capacity of the conveyance method.

The first gun section is run and latched onto a downhole anchor, bridge plug or packer set by wireline for precise depth control. The gun string also can be landed against the bottom of a well. In this configuration, the string is not anchored. Consecutive sections are assembled and connected on top of each other until the required gun length is achieved. Rather than simply stacking or latching, the connectors solidly connect each gun section to the next. Guns can be disconnected mechanically at any time. The connectors disconnect automatically after a delay that follows gun detonation. This prevents gun sections from moving uphole during detonation and underbalance surge flow, and allows wells to be perforated with maximum underbalance.

The CIRP Completion Insertion and Retrieval under Pressure perforating system was designed so gun strings could be assembled at surface, inserted in wells, extracted and disassembled without killing the wells. The CIRP system facilitates running long guns in and out of wells under pressure using wireline or coiled tubing. This allows an entire interval to be perforated at one time with an appropriate underbalance. Retrieving and disassembling guns under pressure eliminate the need to drill deeper to allow for dropping guns or the need to kill wells after perforating. The CIRP system is used with gun diameters from 2 to 4.5 in. Gun lengths of 2000 ft [610 m] with up to 60 connectors have been run.

The completion FIV Formation Isolation Valve tool, integrated into the permanent completion design, allows long strings of perforating guns to be run in and out of wells without hydrostatic overbalance control. A fullbore completion valve that is normally run below a permanent packer, the FIV tool acts as a downhole lubricator valve and isolates perforated intervals from the production string above. The gun length per run is limited only by weight restrictions of the conveyance method used.

After perforating, guns are pulled above the FIV tool, which is closed by a shifting tool on the end of the gun string. Well pressure is bled off and the guns are retrieved. The FIV tool then is opened for production by applying a predetermined sequence of pressure cycles. The FIV tool also can be opened and closed an indefinite number of times with a mechanical shifting tool. This valve system was developed for the BP Amoco Andrew field in the North Sea.

> Success of the FIV tool was the basis for design of a liner top isolation valve (LTIV) that operates on the same principles. The LTIV is a fullbore ball valve that isolates formations from completion fluid after a zone is completed with an uncemented liner. The LTIV tool is run directly below a liner-hanger packer and can be opened and closed as many times as required. Once the ball is closed, the formation is isolated from completion fluid until the well is ready for production. The valve holds pressure from above and below, which makes it suitable as a long-term barrier.

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43. In June 1999, the longest gun to date, a special tapered HSD gun, was successfully fired in Well M-16 at the BP Amoco Wytch Farm field in southern England. This world record gun string was 8963 ft [2616 m] long from top to bottom and shot with more than 25,000 CleanSHOT charges.


**High-angle wells**—In high-angle and horizontal wells, wireline may not allow guns to descend unless a tractor is used. Coiled tubing is the preferred conveyance method, unless a horizontal section is so long that helical buckling occurs before the perforating interval is reached. Tractors have also been used successfully to extend the maximum reach of coiled tubing. In many of today's high-angle and extended-reach wells, there may be no alternative to TCP or PCP.

If mechanical pulling or pushing force must be exerted on a gun system, TCP, snubbing, coiled tubing and tractors offer more versatility than electric line and slickline. For long guns like those used in horizontal wells, gun-string design must consider tensile strength. High-strength adapters and tapered gun strings have been used successfully. Gun bending must also be modeled and addressed.

Perforating-deployment technology has evolved from early electric line and tubing-, or drillstring-, conveyed guns, and now includes coiled tubing with or without electric line, snubbing units, slickline and downhole tractors on wireline and coiled tubing. Each conveyance method has advantages and disadvantages related to performing downhole operations, gun length and pressure control, perforating without killing wells, mechanical strength and wellbore angle, depth correlation, rigless intervention and gun type. To optimize perforation designs, these pros and cons must be weighed for all gun systems being considered for a specific completion (above right). Other considerations include underbalanced perforating and timing or duration of operations.

**Underbalance**—Options for perforating with underbalance have reached a high degree of sophistication as a result of hardware for TCP or PCP and wireline anchoring devices. Whatever the conveyance method, it is usually possible to perforate with sufficient underbalance. Practical exceptions when optimal underbalance cannot be achieved are depleted reservoirs, shallow wells or wells with existing open perforations.

For certain conditions, a high underbalance is needed to clean out perforations and generate post-shot flow. With wireline-conveyed guns, this is possible only if anchoring devices are used while shooting to prevent guns from being blown uphole. Anchoring devices are also recommended when the level of underbalance is unknown and guns are exposed to a sudden fluid influx, as for example, when perforating new intervals in formations with differentially depleted producing intervals.

<table>
<thead>
<tr>
<th>Through-tubing</th>
<th>SKAR</th>
<th>MAXR</th>
<th>WXAR</th>
<th>FIV</th>
<th>Wireline CIRP</th>
<th>Coiled Tubing CIRP</th>
<th>GunStack (CDAD)</th>
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- **Advantage**: First in monobores
- **Limitation**: Rig required for installation, but not for perforating
- **Conveyance choices. To optimize perforating operations, the advantages, disadvantages and limitations of all gun systems that are considered for a specific completion must be weighed. This table lists reservoir, economic and technical benefits of equipment that is used to perforate without killing a well.**

A Wireline Perforator Anchoring Tool (WPAT) device was developed to anchor guns in slimhole monobore completions and prevent guns from moving after detonation. The WPAT device, now available in two sizes, one for 2-in. guns in 2½-in. tubulars and another for 2½-in. or 3¼-in. guns in 3½-in. completions, counteracts potentially large forces generated by flowing fluids that can force guns uphole with disastrous consequences.

The main application of the WPAT anchor is to perforate with extremely high underbalance. Another application is to protect cable weak points from high-tensile loads.

The tool has positive anchoring and releasing mechanisms. Mechanical slips are designed to be nondamaging and can be retracted by jarring upward if guns become stuck after perforating.

A calibrated orifice that meters oil at a specific rate provides the holding period, which can be set for up to an hour. This allows sufficient time to establish an underbalance, perforate and conduct a pressure drawdown test. The tool releases automatically after the programmed time elapses. The tool may be configured in two ways; one operates on well pressure and the other, for a dry hole, operates on pressure supplied by a gas bottle that is part of the system.

**Duration of operations**—The timing of operations varies for each well. If intervals are vertical and short—less than 40 ft [12 m]—and perforated in balanced or overbalanced conditions, wireline perforating usually can be performed in a few hours and may be the most efficient method. If the interval is longer or has multiple sections, wireline operations require more than one trip, which prevents use of underbalance during subsequent gun runs. As well deviation increases, operating time increases, especially if the gun-string weight is low and surface pressure-control equipment is used. When well deviation exceeds about 65°, other conveyance methods like TCP and PCP that require a longer running-in time must be used. If perforating intervals become significantly longer, the overall duration of TCP is shorter than wireline operations and the entire interval can be perforated with underbalance for optimal perforation cleanup.


Safety
Two types of detonators are used in perforating guns: electrical detonators, or blasting caps, and percussion detonators. Conventional electrical detonators are susceptible to accidental application of power from electric potential differences (EPD), which constitutes a safety hazard. Percussion detonators that are used in TCP systems actuate mechanically when a firing pin strikes a pressure-sealed membrane and detonates a primary high explosive.

The S.A.F.E. Slapper-Actuated Firing Equipment system was developed to be immune from potential differences created by radio-frequency (RF) radiation, impressed current from corrosion cathodic protection, electric welding, high-tension power lines and induction motors such as topdrives on drilling rigs. This system eliminates the need to shut down vital radio communications and equipment during perforating operations.46

The detonating mechanism in the S.A.F.E. system is an Exploding Foil Initiator (EFI) rather than a primary high explosive. To fire a gun, a capacitor in the downhole electronic cartridge is charged and then allowed to discharge abruptly. The heat produced by this discharge vaporizes a section of metal foil, which slaps an adjacent explosive pellet with sufficient energy to detonate it. This detonation shears a small aluminum flyer that impacts a booster that fires the gun. A major advantage of S.A.F.E. equipment is that wellsite assembly is quicker than for conventional electrical detonators. Disadvantages of the S.A.F.E. detonator are cost and size, which takes up lubricator space.

The Secure detonator is a third-generation S.A.F.E.-type device that also uses an EFI. It does not contain primary high explosives or a downhole electronic cartridge. A microcircuit performs the same functions as the electronic cartridge and EFI together in a package that is similar in size to a conventional electric detonator. The Secure system has all the technical advantages of S.A.F.E. detonators, but is more reliable, fully expendable and smaller so that gun strings can be shorter.


47. Behrman and Eibel, reference 32.


Perforation Design and Analysis
Perforated completions can be designed using the SPAN Schlumberger Perforating Analysis software, which predicts perforating efficiency under downhole conditions.46 The program combines modules that estimate perforation geometry, fluids and underbalance calculations are based on the most current criteria. If the actual pressure differential is less than the minimum underbalance for zero damage, skin due to residual damage is calculated to show how productivity is reduced. Here well productivity is calculated for five gun types at different shot densities and phase angles.

In design mode, this software helps select gun systems based on specific well parameters—completion geometry, fluids and underbalance (above). When actual underbalance is less than the minimum required for zero damage, perforation skin due to residual damage is calculated to show how productivity is reduced.

The SPAN program also can be used to analyze production after wells are completed or recompleted. If actual production data match SPAN program calculations, a perforated completion is considered successful. When production objectives are not realized, the reasons—formation invasion, incomplete damage removal or incorrect assumptions—need to be determined. Because the SPAN program incorporates geological aspects, it is helpful for integrating reservoir descriptions in perforation designs.48
Smart Perforating

Every cased well must have perforations to produce hydrocarbons, but different reservoir and completion combinations have different perforating requirements. Because perforating is such a critical element of well productivity, the requirements of each well should be optimized based on specific formation properties. The best way to achieve this is to understand how reservoirs respond to natural, stimulated and sand-management completions. Factors that need to be taken into account include formation compressive strength and stress, reservoir pressure and temperature, zone thickness and lithology, porosity, permeability, anisotropy, damage and fluid type—gas or oil.

Hard—high-strength—formations and reservoirs damaged by drilling fluids benefit the most from deep-penetrating perforations that extend beyond the formation damage and increase the effective wellbore radius. Low-permeability reservoirs that need hydraulic-fracture stimulation to produce economically require appropriately spaced and oriented perforations. Unconsolidated formations that may produce sand need big holes which reduce pressure drop and can be packed with gravel to keep the formation particles out of the perforation and the wellbore. Perforations also can be designed to prevent tunnel and formation failure associated with sand production.

In the past, integrating formation and perforating considerations, including underbalance, was an exception rather than a rule. Theory and software were available to analyze perforation performance, but completion decisions were often based on average formation properties or perforating limitations unrelated to productivity. Today, thinking in terms of what’s best for a reservoir is the predominant approach. Operators consider what a particular field development requires and then select the best completion techniques and hardware that are available.

Standard “off-the-shelf” equipment and services sometimes do not meet those needs. New tools, procedures and services—shaped charges, completion equipment, conveyance alternatives and applications for underbalance, overbalance or extreme overbalance—often need to be developed. As a result, significant Schlumberger research and engineering resources are dedicated to developing customized solutions. Many of these new developments eventually become standard products and services that extend the range of options available to operators. The best perforation designs are based on specific well requirements to optimize production. This total-systems approach—smart perforating—emphasizes practices that maximize well productivity and helps operators realize the most benefit from the perforating solutions that are available to overcome dilemmas associated with perforated completions.

By adapting perforation designs to specific reservoirs, perforating technology can be integrated with geology, formation evaluation and completion techniques to determine the right equipment, shaped charge, carrier system, conveyance method and pressure condition for performing efficient and effective perforating operations. Computer simulations can be used to compare performance versus design expectations. Existing tools and methods can then be improved and used more effectively. The ultimate goal is to design custom perforating solutions for each well to maximize productivity. —MET