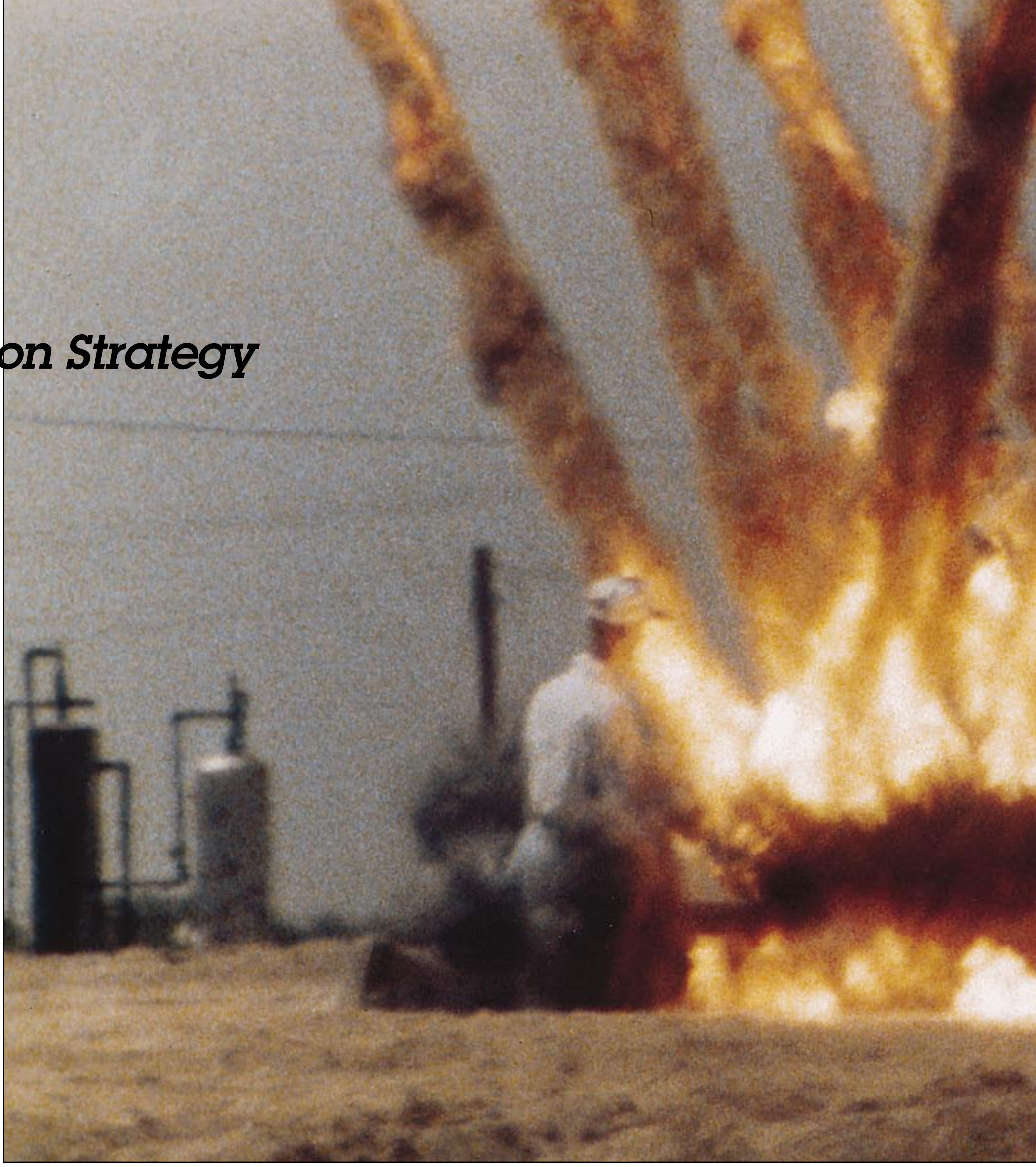
COMPLETION/STIMULATION

Choosing a Perforation Strategy



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The ultimate success of the well—its productivity and life expectancy—rests on making the best possible connection between the wellbore and formation. This update reports on what we know today about selecting a perforation strategy best suited to the reservoir and the completion.

The fate of a well hinges on years of exploration, months of well planning and weeks of drilling. But it ultimately depends on performing the optimal completion, which begins with the millisecond of perforation (*above*). Profitability is strongly influenced by this critical link between the reservoir and wellbore.

Perforations form conduits into the reservoir that not only allow hydrocarbon recovery, but influence it. Each of the three main types of completions—natural, stimulated and sand control—has different perforating requirements. In the natural completion (in which perforating is followed directly by production) many deep shots are most effective. In stimulated completions—hydraulic fracturing and matrix acidizing—a small angle between shots is critical to effectively create hydraulic fractures and link perforations with new pathways in the reservoir. And in gravel packing, many large-diameter perforations effectively filled with gravel[1] are used to keep the typically unconsolidated formation from producing sand and creating damage that would result in large pressure drops during production.

To meet the broad requirements of perforating, there many perforating guns and gun conveyance systems. Optimizing perforating requires selection of hardware best suited to the job. A good place to start, therefore, is with the basics of perforating hardware.

The Language of Perforating

There was a time when describing the perforation operation defined the perforator: running through-tubing guns, shooting casing guns or tubing-conveyed perforating (TCP) (*next page*). Not so with the present variety of completion methods and gun systems.

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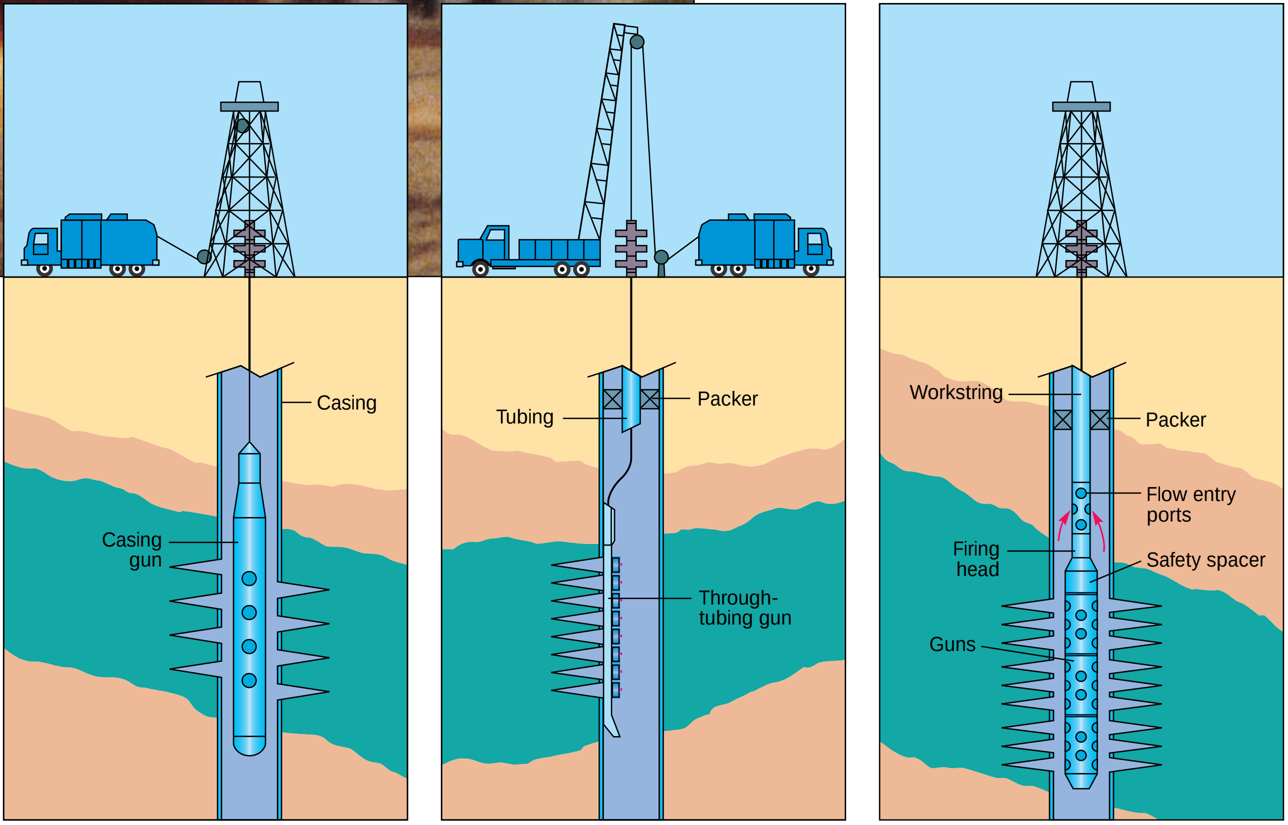
[1] Gravel is rounded particles of diameter typically greater than 2 mm [0.8 in.].

□*Up in smoke. Surface detonation of a standard 4-in. gun, staged during the making of a safety training video. Destruction of the mannequin at left, positioned about 1 foot [30 cm] from the end of the gun, shows the potentially devastating effect of a surface detonation, emphasizing that safety forms the essential foundation for perforation operations.*

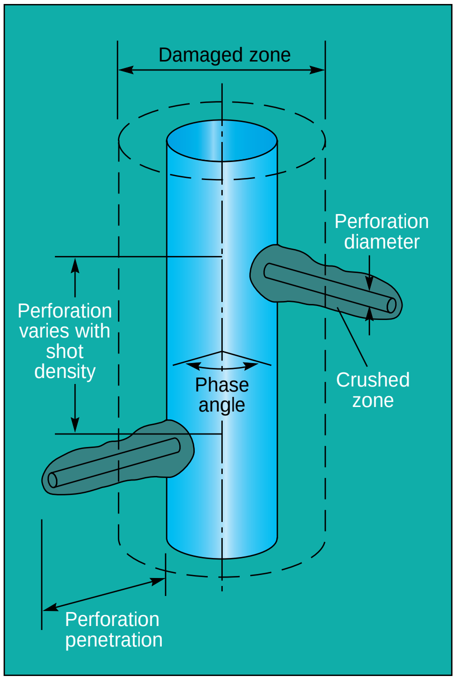


Through-casing perforation **Through-tubing perforation** **Tubing-conveyed perforation**

□*Three conveyance methods for perforating guns: through-casing and through-tubing, and tubing-conveyed systems. The through-tubing gun shown is held against the casing magnetically. The others hang free.*

The two broad categories of guns are exposed and hollow carrier guns (*bottom*). These can be used in two types of perforating operations: through-tubing, in which guns are run through a production or test string into larger diameter casing; and through-casing, in which guns are larger diameter and run directly into casing.

Exposed guns are run on wireline and have individual shaped charges sealed in capsules and mounted on a strip, in a tube or along wires. The detonator and detonating cord are exposed to borehole fluids. These guns are used exclusively through tubing and leave debris after firing. They include two designs, "expendable," (charges and mounting assembly become debris) and "semiexpendable" (mounting is recovered). For a given diameter, exposed guns carry a larger, deeper penetrating charge than a hollow carrier gun. But exposed gun outer diameter is generally not larger than about $2^1/_2$ in. [6 cm], because above this size, the casing, or hollow carrier design, becomes more practical, allowing use of larger charges, optimal angle between shots—called phasing[2] —and increased number of shots per linear foot—called shot density (*above, right*).



□Major geometrical parameters that determine flow efficiency in a perforated completion. Four key factors are shot density, phase angle, perforation penetration into the formation and perforation diameter. Productivity of a well also depends on the size of the crushed zone, whether the perforation extends beyond the damaged zone and how effectively the crushed zone and charge debris are removed from the tunnel.

Hollow carrier guns have shaped charges positioned inside pressure-tight steel tubes. This design is available for most tubing and casing sizes. It is used through tubing when debris is unacceptable and in hostile conditions that preclude exposed guns. There are four main types of hollow carrier guns:

- Scallop guns, so-called because charges shoot through dished out areas in the carrier, which is recovered and junked. Scallop guns are wireline-conveyed and shot only through tubing. They are used mainly in hostile environments or where debris is unacceptable.
- Port plug guns, in which charges shoot through replaceable plugs in a reusable carrier. These are wireline conveyed mainly for deep penetration and where 4 shot-per-foot (spf) density is acceptable.
- High shot density guns, which are designed for each casing size to optimize shot density, hole size, penetration and phasing. The majority of sand control completions use high shot density guns loaded with charges designed to provide large entrance holes. All TCP is performed with high shot density guns.
- The HEGS High-Efficiency Gun System, which is a wireline-conveyed alternative to port plug guns, with longer carriers that are faster to load and run. The HEGS system is available in $3^1/_8$- in. and 4-in. outer diameter. It is rated to 210°F [99°C] and 4000 psi, making it useful in many shallow wells. A big hole charge is available for the 4-in. size.

To determine the type of perforation and gun system best suited to the well, a practical first step is to consider the general interaction of the perforation and reservoir. A second step is to look at how perforation designs vary for each of the three main types of completions: natural, stimulated and sand control.

	Gun System	**Application**		
		Wireline through-tubing	**Wireline through-casing**	**Tubing conveyed**
Exposed gun	Strip	x		
	Pivot	x		
Hollow carrier gun	Scallop	x		
	Port plug		x	
	High efficiency	x	x	
	High shot density	x	x	x

□A taxonomy of perforating guns and systems.

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[2] The nomenclature of phasing may be a source of confusion. A 60° phasing means one shot every 60° azimuthally; a 180° phasing means one shot every 180°. Phasing of 0° has all shots in one line, meaning the angle between shots is actually 360°. Speaking of "reduced phasing" or "reduced phase angle" means the angle between shots is smaller. A 45° phasing is therefore "reduced" compared to a 90° phasing.

A Perforation Glossary

Big hole charge: A shaped charge that gives priority to entrance hole over depth of penetration, used exclusively in sand control completions. A "big hole" has an entrance diameter of 0.5 to 1.2 in. [13 to 30 mm], usually about twice that of a deep penetrator charge of similar size. Conventional deep penetrators have an entrance hole diameter of 0.3 to 0.5 in. [8 to 13 mm].

Booster: A secondary explosive attached to the end of the detonating cord, used to assure passage of initiation between the detonator and detonating cord or between detonating cords.

Carrier: In hollow carrier guns, a steel tube that carries a loading tube and protects it from the wellbore environment. The loading tube secures and aligns the detonating cord and shaped charges. The detonator is housed in a firing head attached to the carrier.

Completion: Work required to make a well ready to produce oil or gas. It generally includes—not necessarily in this order—running and cementing casing, perforating, stimulating the well, running tubing and installing control and flow valves. In a *permanent* completion, the well is not killed after perforating underbalance and is ready for immediate production. In TCP, the guns remain downhole after firing. In a *temporary* completion, the well is killed after perforating and the workstring retrieved before installing the permanent completion.

Deep penetrating charge: A charge design that gives priority to penetration depth instead of entrance hole diameter.

Detonating cord: A secondary explosive contained in a protective flexible outer sheath. The detonator is connected to the detonating cord, which transmits the detonation to each shaped charge. It may also pass detonation along to another gun via a booster.

Detonator: A primary explosive that initiates the detonating cord. Detonators can be fired electrically or by impact.

Drillstem test (DST): A temporary completion in which a downhole shut-in valve, controlled from surface, is incorporated in the workstring, usually with a retrievable packer. The well can then be flowed in a test program, either recording data in downhole memory or conveying them to surface in real time to analyze reservoir properties such as permeability and reservoir boundaries.

Explosive: There are two types used in well perforating, primary and secondary explosives. The main difference is in their sensitivity. A primary explosive, used in the detonator, detonates from heat (applied by electric power) or impact (from a drop bar or a pressure-driven firing pin). A secondary explosive, used in detonating cord, shaped charges and boosters, is detonated only by another detonation, from either a primary explosive or electrically generated shock, such as from the S.A.F.E. system.

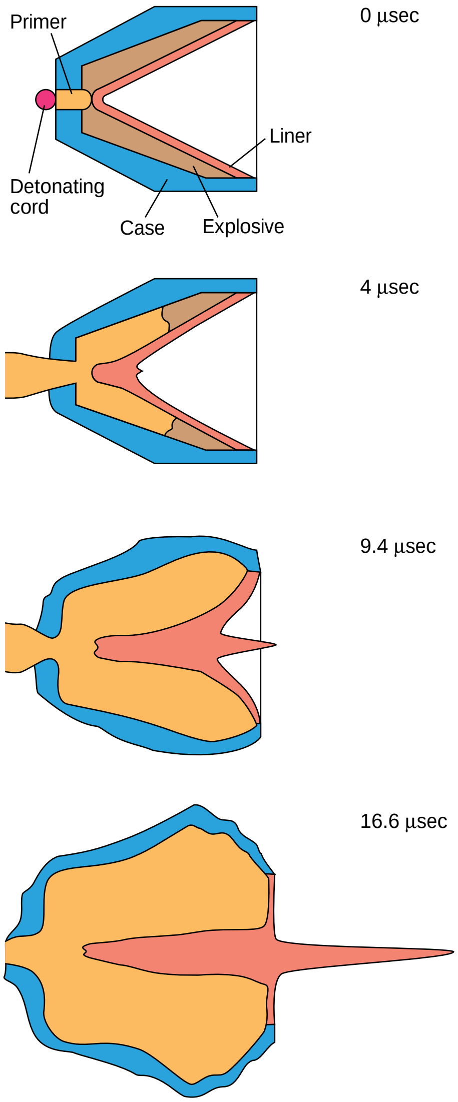
Limited entry perforating: Varying the number of perforations in each layer, depending on layer thickness and stress state, to achieve the desired fracture geometry. Fewer perforations in the layer taking the most fluid restrict flow and divert it into other layers.

Primer: A small amount of higher sensitivity secondary explosive at the base of the shaped charge, which ensures correct initiation of the charge by the detonating cord.

Proppant: Material pumped into a hydraulic fracture to prevent closure and provide a conduit for production once pressure is released. The most common proppant is sand. High-strength proppants, like sintered bauxite and zirconium oxide particles, are used where fracture closure stress would crush sand.

Shaped charge: A precisely engineered cone of pressed metal powder, or drawn solid metal, surrounded by a secondary explosive and case, and initiated by detonating cord. Detonation collapses the cone into a jet that penetrates the completion and formation (*right*).

Strip gun: An expendable gun in which individual charges in capsules are secured and aligned along a strip of metal.



□Progression of shaped-charge detonation. The schematic at 0 µsec shows the charge components. The volume of explosive is greatest at the apex of the liner and least near its open end. This means that as the detonation front advances, it activates less explosive, resulting in a lower collapse speed near the liner base. The subsequent drawings show the case deforming as the detonation front advances, thrusting the liner into a jet along the shaped-charge axis. The fully formed jet, at 16.6 µsec, is moving at about 21,300 feet/sec [6500 m/sec].

Perforation-Reservoir Interactions— Getting Started

Flow efficiency of a perforated completion and stimulation success are determined mainly by how well the perforation program takes advantage of the reservoir properties. The program includes determination of two main factors:

- The proper differential between reservoir and wellbore pressure (The usual preference is for underbalance, meaning wellbore pressure is less than reservoir pressure at time of perforating).
- Gun selection, which determines penetration tunnel length, shot phasing, shot density and perforation entrance hole diameter. The relative importance of the different components of shot geometry varies with the completion type (*below*).

The main reservoir property that affects flow efficiency is permeability anisotropy from whatever cause—in sandstone, typically from alignment of grains related to their deposition; in carbonates, typically from fractures or stylolites.[3] Shale laminations, natural fractures and wellbore damage, which can cause permeability anisotropy, are considered separately because they are so common. In most formations, vertical permeability is lower than horizontal. In all these cases, productivity is improved by use of guns with high shot densities.

Natural fractures are common in many reservoirs and may provide high effective permeability even when matrix permeability is low. However, productivity of perforated completions in fractured reservoirs requires good hydraulic communication between the perforations and fracture network. To maximize the chances of intersecting a fracture, penetration length is the highest priority, with phase angle second. Shot density is less important because fractures form planes and increasing density does not increase contact with a fracture system. In fractured formations, a popular gun configuration uses 60° phasing with 5 spf. A Schlumberger version of this gun has a large charge that penetrates 30 in. [76 cm] into the standard API test target.[4]

An important geometric consideration of a perforation is how deeply it penetrates—whether it reaches beyond the zone damaged during drilling or connects with existing fractures. The penetration of various shaped charges is documented in surface tests and in tests under stress with API targets. Penetration in surface tests is different than under stress in the well.[5] Unconfined compressive strength of test targets is a minimum of 3300 psi, representing only low-strength reservoir rock (reservoir rock strength ranges from 0 to 25,000 psi). To estimate depth of penetration into a rock of arbitrary strength under a given stress, data measured at unstressed surface conditions have to be transformed. Because rock penetration data exist for only a few combinations of charges, rock strengths and stresses, a semiempirical approach is used that combines experimental data with penetration theory.[6]

Schlumberger calculates penetration change caused by formation stress using experimental data for three generic charge designs after first calculating the change due to formation strength at zero stress. These data provide transforms implemented in the SPAN Schlumberger Perforating Analysis program. The SPAN program consists of two modules: penetration length calculation and productivity calculation. In the penetration

Perforation Geometry	Completion Type		
	Consolidated		Unconsolidated
	Natural	Stimulated	Sand Control
Shot density	1 or 2	2	2
Perforation diameter	3 or 4	3	1
Perforation phasing	3 or 4	1	3
Perforation length	1 or 2	4	4

Perforation Geometry	Isotropic Permeability	Anisotropy		Natural Fractures	Wellbore Damage
		Of Any Cause	Laminar Shale		
Shot density	2	1	1	3	2
Perforation diameter	4	3	4	4	4
Perforation phasing	3	4	3	2	3
Perforation length	1	2	2	1	1

□***Relative importance of four main geometrical factors in the three completion types, where 1 is greatest and 4 is least. The optimum perforation design establishes the proper tradeoff of these factors. The lower part of the figure shows common considerations for perforating natural completions. When natural fractures are present, phasing becomes more important than density to improve communication between fractures and perforations.***

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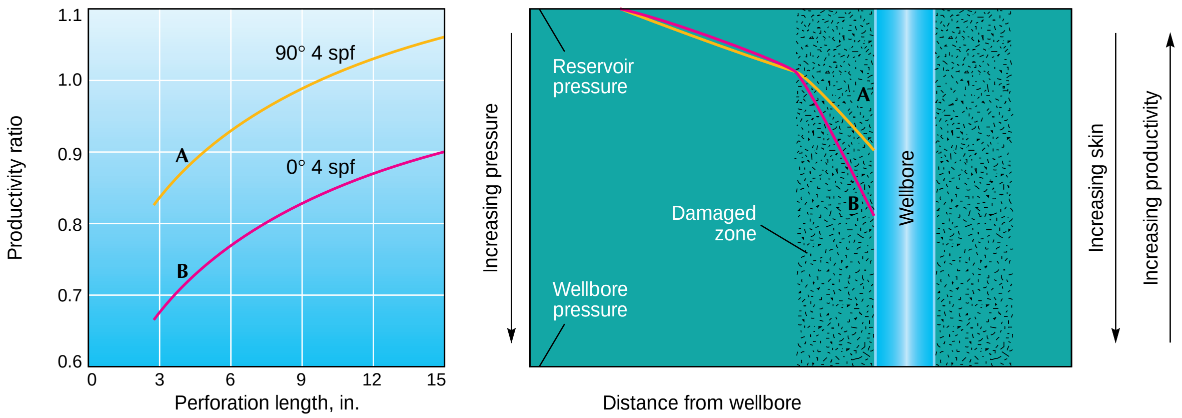
3. Stylolites, common in carbonates, function like shale layers in sandstones, inhibiting vertical migration of hydrocarbons. They are interlocking wave- or tooth-like seams that often parallel bedding, and contain concentrations of insoluble rock constituents, such as clay and iron oxides. They are thought to be caused by pressure solution, a process that increases contact area between grains and reduces pore space.
4. The American Petroleum Institute (API) publishes recommendations for testing shaped charges in a document, API RP-43. Section 1 specifies the length and entrance hole diameter produced by a gun system (charges and carrier) in a steel and concrete target. Section 2 gives this information for single shots into a stressed Berea sandstone target. As of this writing, the availability of target material for Section 2 is under review by the API.
5. Halleck PM, Saucier RJ, Behrmann LA and Ahrens TJ: "Reduction of Jet Perforator Penetration in Rock Under Stress," paper SPE 18242, presented at the 63rd SPE Annual Technical Conference and Exhibition, Houston, Texas, USA, October 2-5, 1988.
6. Behrmann LA and Halleck PM: "Effect of Concrete and Berea Strengths on Perforator Performance and Resulting Impact on the New API RP-43," paper SPE 18242, presented at the 63rd SPE Annual Technical Conference and Exhibition, Houston, Texas, USA, October 2-5, 1988.

   Halleck PM and Behrmann LA: "Penetration of Shaped Charges in Stressed Rock," in Hustrulid WA and Johnson GA (eds.): *Rock Mechanics Contributions and Challenges: Proceedings of the 31st US Symposium.* Rotterdam, The Netherlands: A.A. Balkema (1990): 629-636.
7. Karakas M and Tariq S: "Semianalytical Productivity Models for Perforated Completions," paper SPE 18271, presented at the 63rd SPE Annual Technical Conference and Exhibition, Houston, Texas, USA, October 2-5, 1988.

   Economides MJ and Nolte KG (eds): *Reservoir Stimulation*, 2nd ed. Englewood Cliffs, New Jersey, USA: Prentice Hall (1989): 1-17.
8. Pucknell JK and Behrmann LA: "An Investigation of the Damaged Zone Created by Perforating," paper SPE 22811, presented at the 66th SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA, October 6-9, 1991.

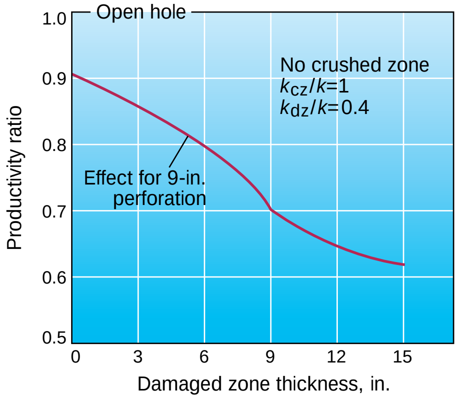


□***Relationship of perforation phasing and depth to productivity*** *(left)* ***and to wellbore skin*** *(right)*. ***Curves on the left are for undamaged conditions. Damage would reduce their absolute values, but they would maintain the same position relative to each other. For 0° phasing perforation, skin is higher at the wellbore because flow follows a less direct path to the perforation than for the 90° phasing case. Perforations with lower skin distribute the pressure drop over a greater distance from the wellbore, yielding a higher production rate for a given wellbore pressure. The left figure shows the increase in productivity with perforation length. In the theoretical case of no damage, a 9-in. [23-cm] perforation at 0° phasing has the same productivity as a 3-in. [8-cm] perforation of 90° phasing.***

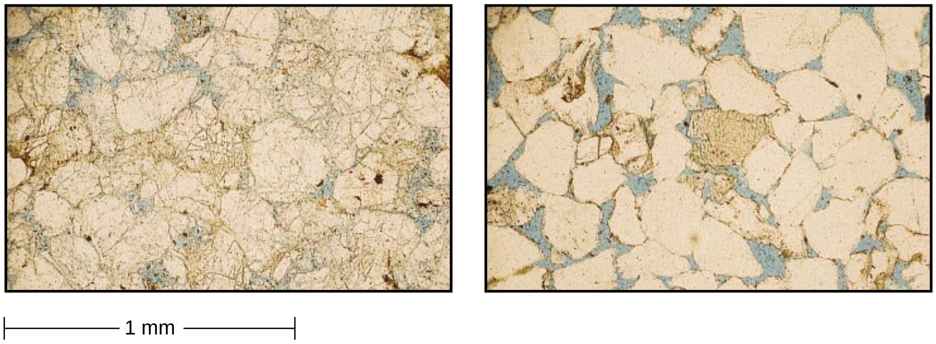
module, perforation length and diameter estimates are calculated under downhole conditions for any combination of gun, charge and casing size. It can also calculate penetration in multiple casing strings. These parameters are used in the productivity module to evaluate the anticipated productivity of the perforated completion.

Another influence on flow efficiency is formation damage, usually considered in the context of skin, an index of flow efficiency related to properties of the reservoir and completion. Skin comprises a variety of influences: flow convergence, wellbore damage, perforation damage, partial penetration (perforation of less than the total height of the reservoir) and the angle between the perforation and bedding plane. The goal is to design perforations that minimize skin and therefore maximize flow efficiency (*top*).

Formation damage is caused by invasion of mud filtrate and cement fluid loss into the formation, creating a zone of lower effective permeability around the wellbore (*above, right*). Extending the perforation beyond the damaged zone may reduce this skin significantly, enhancing productivity.[7] But even for perforations that do penetrate farther, the wellbore damage zone reduces the effective tunnel length.



□***How a damaged zone near a perforated completion affects productivity, for a 9-in. perforation with 0° phasing and 4 shots per foot. The influence of lowered effective permeability in the damaged zone can be combated by perforations that extend into the virgin formation. In this example, there is no crushed zone, so crushed zone permeability, k_{cz}, equals virgin formation permeability, k. But permeability of the damaged zone, k_{dz}, is 60% lower than that of the virgin zone.***



□***Photomicrographs of rock thin sections, showing the effect of perforation. The left image is from rock near the perforation tunnel, showing microfracturing. The right thin section is undamaged rock.*** *(From Pucknell and Behrmann, reference 8.)*

During perforating, a "crushed zone" of reduced permeability is created around the perforation. In laboratory experiments, the thickness and permeability damage of the crushed zone are influenced by all variables to varying degrees: the type of shaped charge, formation type and stress, underbalance and cleanup conditions. Pucknell and Behrmann found that permeability near the perforation is reduced because microfracturing replaces larger pores with smaller ones (*above*). The current rule of thumb is to assume a crushed zone $^1/_2$ in. [13 mm] thick with permeability reduced by 80% to 90%. Recent experimental data, however, cast some doubt on this assumption, with crushed zone thickness a function of charge size, pore fluid type, and the preservation of permeability when perforating underbalance.[8]

The Natural Completion—Perf and Produce

The natural completion is often defined as that in which little or no stimulation is required for production. This approach is usually chosen for reservoirs that are less prone to damage, have good transmissibility, and are mechanically stable.

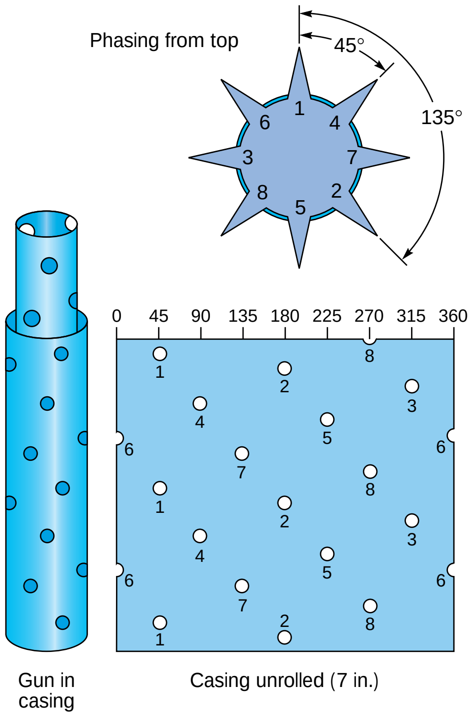
Of primary importance in selecting the perforating gun are its depth of penetration and effective shot density (see "Natural Completion," *next page*). Depth is important because the deeper the perforation, the greater the effective wellbore radius; also flow is less likely to be influenced by formation damaged during drilling. In the context of well productivity, a deep penetrator shoots to a depth 1.5 times that of the wellbore damage.

Shot density also ranks high because more holes mean more places for hydrocarbon to enter the wellbore and a greater likelihood that perforations will intersect productive intervals of an anisotropic reservoir. After shot density and depth of penetration, most important is phasing because, when properly chosen, it provides hydrocarbons with the most direct path to the wellbore (*below, left*). Under typical flow conditions, perforation diameter does not adversely affect flow once it exceeds 0.25 in. [6 mm], which today is provided by nearly all guns used in natural completions.

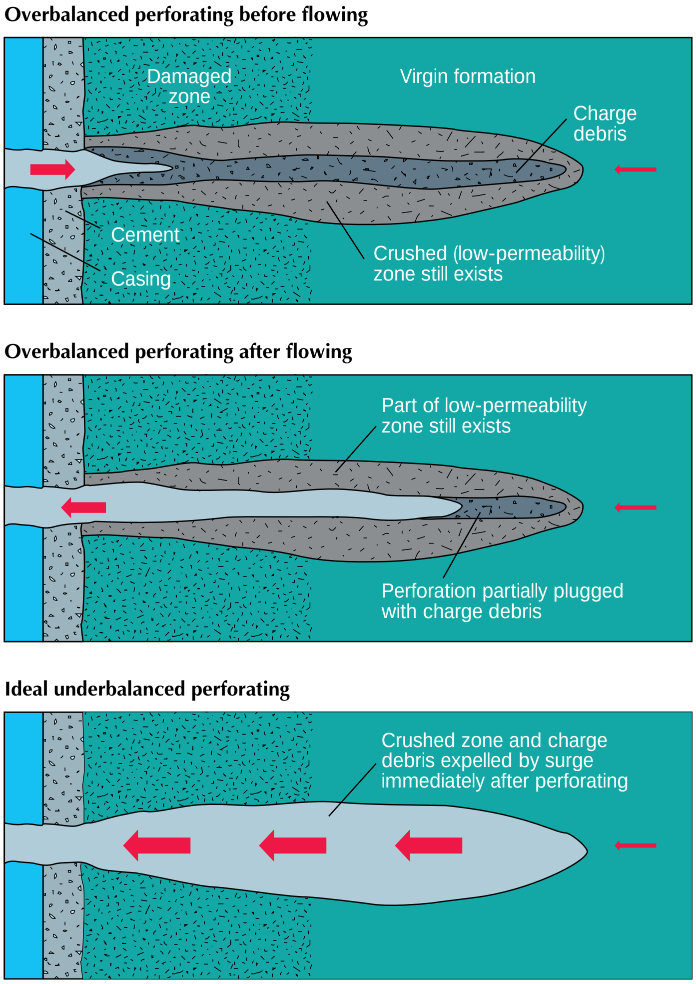
A key consideration in perforation design of natural completions is the selection of overbalance versus underbalance perforating. Overbalance means the pressure of wellbore fluids exceeds reservoir pressure at the time of perforating. Under this condition, wellbore fluids immediately invade the perforation. For this reason, clean fluids without solids are preferred to prevent plugging of perforations. Cleanup can occur only when production begins.

Increasingly, wells that have sufficient reservoir pressure to flow to surface unassisted are completed in underbalance conditions. Underbalance is the trend because of wider recognition that it provides cleaner perforations—therefore better production—and because of greater availability of gun systems that allow it. Underbalance perforating can provide large gains in reservoir productivity. The question is, how much underbalance is appropriate? Excessive underbalance risks mechanical damage to the completion or test string by collapsed casing or a packer that becomes damaged, stuck or unseated. It can also encourage migration of fines within the reservoir, reducing its permeability. Insufficient underbalance, however, doesn't effectively clean the perforations. Production may therefore be hindered, mainly by lack of removal of the crushed zone and, secondarily, by lack of removal of debris. The crushed zone is the damaged rock in and around the perforation tunnel; debris is mainly the liner material of the spent shaped charge, plus fragments of cement and rock (*below*).

The optimal underbalance, which removes both debris and the crushed zone and does not damage the formation, accomplishes virtually all cleanup during the portion of initial production that is dominated



□Three views of perforating with a 135°/45° phased gun: the gun fired in casing, phasing viewed from the top, and with the perforated casing unrolled and laid flat. The 135°/45° designation means the angle between successive shots is 135°, resulting in an overall phasing of 45°. There is 1 vertical inch [2.5 cm] between shots, making 12 shots per foot. In the natural completion, this phasing provides hydrocarbons with the most direct path to the wellbore.


Overbalanced perforating before flowing

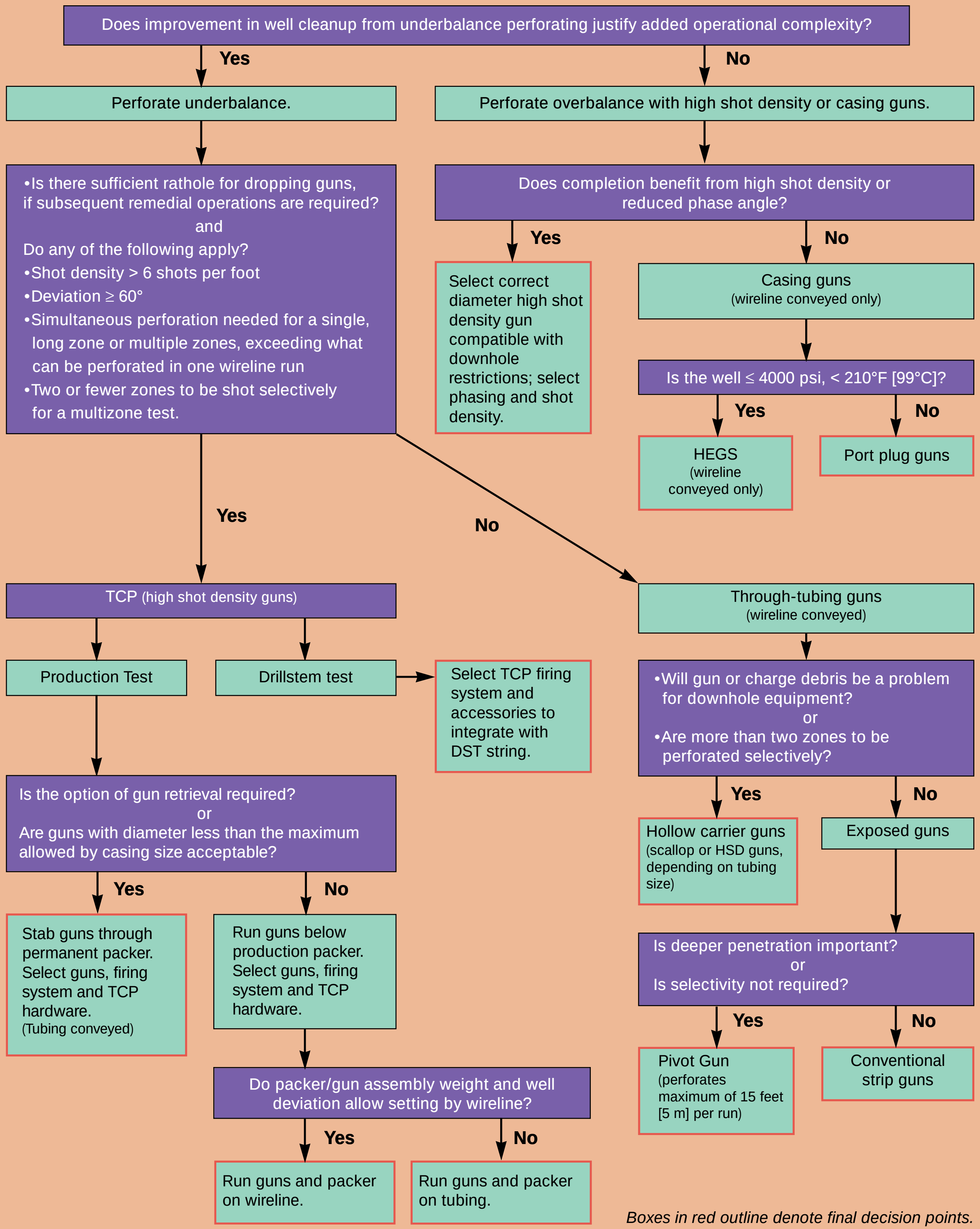
Overbalanced perforating after flowing

Ideal underbalanced perforating

□Three idealized conditions in a perforation tunnel: overbalance perforation before flowing, overbalance perforation after flowing and underbalance perforation. The top figure indicates that without cleanup, the perforation tunnel is plugged by crushed rock and charge debris. In the second case, flow has removed most charge debris, but some of the low-permeability crushed zone created by the jet remains. In the third figure, sufficient underbalance during perforating removed damage—both charge debris and crushed rock.

Natural Completion

Perforation Technique Selection



Boxes in red outline denote final decision points.

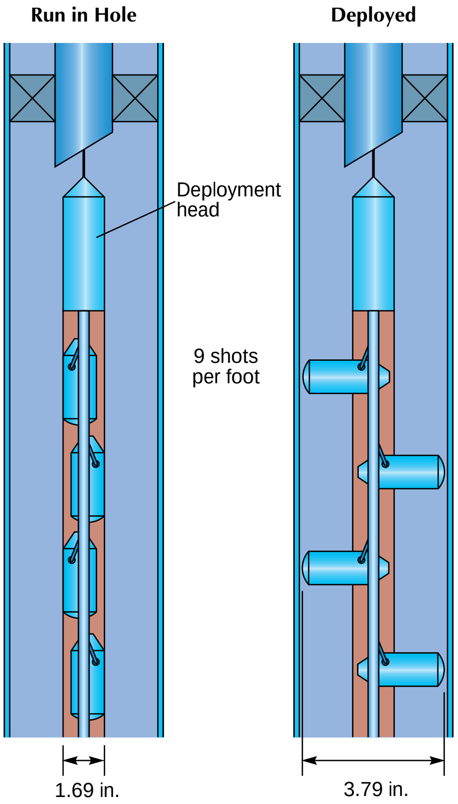
by surge of reservoir fluids into the perforations. Cleanup after this point is negligible because hydrocarbon follows the already cleaned paths of least resistance. During production, pressure drop across damaged areas is insufficient for further cleanup. Recent experiments have shown that if a suboptimal underbalance is used, some cleanup will take place during production, but productivity never reaches that achieved with optimal underbalance.[9]

When well testing is planned, underbalance perforating has become the standard, particularly when a drillstem test (DST) is included. Underbalance perforating is ideally suited because a DST includes hardware that allows establishing underbalance and running high shot density guns. This setup provides excellent well control and often saves time because the perforating guns are run below the test string. Pressure measurements can be recorded either downhole or in real time at surface, and are available for decision-making during the test. The MSRT MultiSensor Recorder/Transmitter and LINC Latched Inductive Coupling equipment allow real-time measurement and surface readout of downhole pressure. The main advantage of this system is the added mechanical and safety reliability of measuring pressure below the DST shut-in valve. In addition, memorized data can be read out at surface when LINC equipment is run, eliminating the need for the cable in the test string while the well is flowing.

From an operations viewpoint, underbalance perforating by wireline-conveyed guns causes a surge that lifts cable and guns. The high flow rate or liquid slugs associated with this surge can blow the guns and cable up the well. A common limit on underbalance when perforating via wireline is 700 psi, although this is often higher in tight reservoirs, which are not capable of delivering a substantial surge.

The choice of underbalance may be based on data collected since the early 1980s from laboratory and field studies and from increasing use of underbalance completions (primarily tubing-conveyed perforating).[10] More recently, computer programs have been developed. The IMPACT Integrated Mechanical Properties Analysis & Characterization of Near-Wellbore Heterogeneity interpretation program computes a value of safe underbalance based on the mechanical properties of the formation estimated from sonic and density logs. Local

□*A family of through-tubing, wireline-conveyed guns. From left, the 0° phased Enerjet (a semiexpendable strip gun); the phased Enerjet, with two rows of charges at 90° (an expendable strip gun); and the 60° phased scallop gun (a retrievable gun). Unlike the Enerjet, the scallop gun has negligible debris and can be run in hostile environments.*



☐***The Pivot Gun system in the run-in and deployed positions. Charge performance in surface tests exceeds that of most casing guns—25-in. [64-cm] penetration and 0.33-in. [8-mm] entrance hole diameter in an API RP-43 section 1 target*** *(see footnote 4)*. ***Shot density is fixed at 4 shots/ft with 180° phasing. The Pivot Gun system gives the deepest possible penetration when perforating through tubing. The main limitation is the maximum gun length of 10 feet [3 m]. It is rated to 330°F [165°C] and 12,000 psi.***

experience also helps guide the selection of optimal underbalance.

Overbalance perforating still has a role, however. Often significant are its speed for short intervals and the availability of larger, high shot density guns compared to those for through-tubing underbalance perforation. The selection of overbalance versus underbalance rests on weighting economic versus production variables.

A long-recognized disadvantage of through-tubing gun systems is their trade-off between phasing and depth of penetration—either 0° phasing with good penetration, or improved phasing with less penetration because of smaller shaped charges (*previous page*). A recent innovation that addresses this problem is the Phased Enerjet gun, which provides two rows of charges at 90° phasing. A second is the Pivot Gun system, which delivers casing gun performance with 180° phasing but can be run through diameters as small as 1.78 in. To do this, the gun is inserted into the tubing with the charges aligned along the axis of the gun. Once in casing, a deployment head is used to rotate charges 90° to the firing position. The charges then reach the full 3.79-in. outer diameter (*left*). In case of a misrun, each pivot charge assembly is designed to be broken, returning the gun to its original 1.69-in. diameter. This allows retrieval of the gun with deployed charges. Only the deployment head is recovered after successful perforation; the carrier and fired charges become debris that settles to the bottom of the well.

The Stimulated Completion—Getting More from Less

Stimulated completions fall into two categories, acidizing and hydraulic fracturing (see "Stimulated Completion," *next page*). Occasionally, the two are combined in an acid-frac, which improves productivity by using acid to etch surfaces of hydraulically induced fractures, preventing full closure.

Success of stimulation depends largely on how well the perforation allows delivery of treatment fluids and frac pressures into the reservoir. Because these fluids and pressure-induced fractures are intended to move beyond the perforation, shot phasing, density and hole diameter are of higher priority than depth of penetration. Underbalance perforating is often used because cleaner perforation tunnels give fluids more direct paths to the reservoir. In some cases, such as TCP with high shot density guns, underbalance can be increased to where stimulation is not required to improve productivity.[11] However, stimulated reservoirs are usually of low permeability, greatly limiting the surge available to clean the perforations. Further increases in underbalance may achieve no improvement in cleaning.

When stimulating long intervals—often considered more than 40 or 50 feet [12 to 15 m]—or multiple zones, the perforation strategy may change. Delivering treatment fluid to all perforations may be difficult. Once fluid enters a zone of higher permeability, a path is established that prevents stimulation of zones of lower permeability. Here, limited entry perforating can help. By making a lower number of perforations throughout the zone, stimulation can be applied more uniformly across zones of varying permeability. High-permeability zones may take more fluid than low-permeability zones, but because there are fewer holes, a high enough pressure can be maintained to encourage treatment of low-permeability zones. After stimulation, perforations are often added to optimally produce the zone.

Uniformity of perforation diameter is essential to accurately determine the cumulative area of the casing entrance holes. Knowing this area and pumping pressure allows calculation of flow rate into the formation, needed to monitor progress of the stimulation. Uniformity and smoothness of perforation diameter also provide consistently sized seats for ball sealers. These are balls of nylon or hard rubber pumped to temporarily block perforations with high fluid intake, thereby diverting injection.

Limited entry perforating is usually done via wireline. The Selectric system is designed specifically for this application. It consists of any number of short (1-foot [30-cm]) single-shot guns fired selectively from the bottom up, providing uniform entry holes. Unlike other systems, in which a misfire terminates the operation, this system has electrical switches, rather than mechanical switches, between guns. These allow firing the next gun even when there is misfire.

Perforation plays a key role in the success of hydraulic fracturing. Hydraulic fracturing has two main steps: fracture creation by application of pressure, and injection of fluid carrying proppant, which holds open the fractures to allow production (see "Cracking Rock: Progress in Fracture Treatment Design," *page 4*). Once the fracture is created, perforations provide the entrance to the fracture for the proppant. Perforation diameter must be sufficient to prevent "bridging," accumulation of proppant that blocks the entrance hole, preventing further treatment. To quantify causes of bridging, Gruesbeck and Collins performed experi-

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[9] Berhmann LA, Pucknell JK, Bishop SR and Hsia T-Y: "Measurement of Additional Skin Resulting from Perforation Damage," paper SPE 22809, presented at the 66th SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA, October 6-9, 1991.

Hsia T-Y and Behrmann LA: "Perforating Skin as a Function of Rock Permeability and Underbalance," paper SPE 22810, presented at the 66th SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA, October 6-9, 1991.

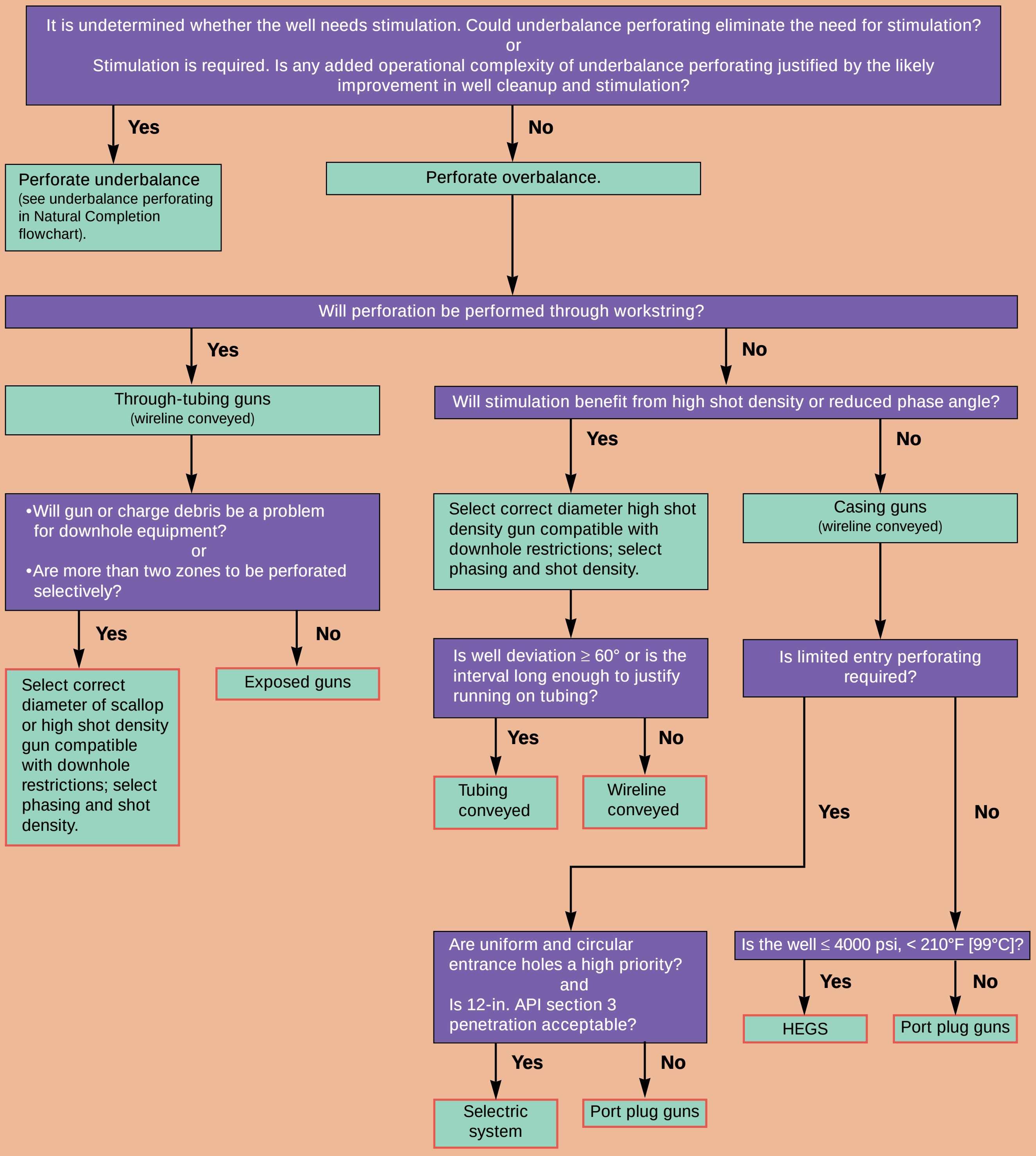
[10] Bell WT: "Perforating Underbalance—Evolving Techniques," *Journal of Petroleum Technology* 36 (October 1984): 1653-1662.

King GE, Anderson A and Bingham M: "A Field Study of Underbalance Pressures Necessary to Obtain Clean Perforations Using Tubing-Conveyed Perforating," paper SPE 14321, presented at the 60th SPE Annual Technical Conference and Exhibition, Las Vegas, Nevada, USA, September 22-25, 1985.

[11] King et al, reference 10.

Stimulated Completion

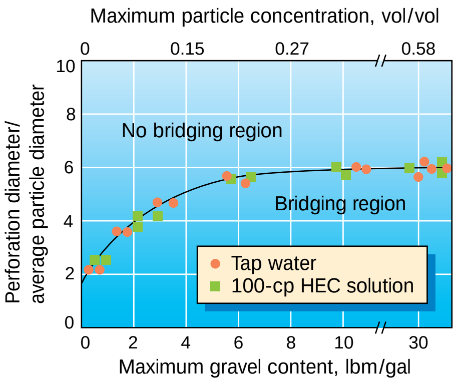
Perforation Technique Selection



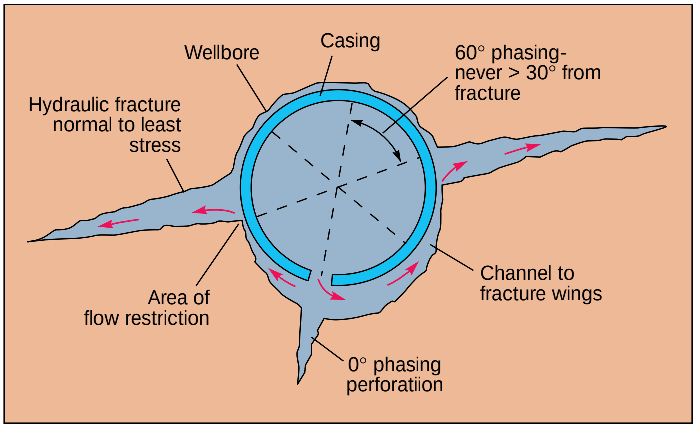
Boxes in red outline denote final decision points.

ments to determine the minimum allowable ratio of perforation diameter to proppant diameter for varying proppant concentrations[12] (*below*). They found that the perforation must always be at least twice the proppant diameter. When perforation diameter is at least six times proppant diameter, proppant concentrations can increase without risk of bridging.

A number of studies have investigated the relationship between perforation phasing and the development of hydraulic fractures. In general, hydraulic fractures propagate normal to the minimum stress in the portion of the reservoir undisturbed by the presence of the wellbore. The general conclusion is that for an ideal fracture job, perforations are aligned with the maximum stress direction, so fractures extending from the perforation will lie in the plane that has the least resistance to opening. Methods for alignment of perforations with hydraulic fractures are still under investigation. A method in deviated wells was reported by Pearson and colleagues.[13] Alignment of 180° phased shots with the known fracture plane reduced perforation friction and significantly improved fracture treatment. Guns were aligned by mounting them on bearings that allowed rotation. Gun angle was controlled by a steering tool or, on TCP jobs, with a weighted half-cylinder that seeks the low side of the hole. This practice, however, is not widespread. The most practical way to approach this today is by perforating with a phase angle that increases the likelihood of having shots parallel to the induced fracture plane.



☐***Importance of selecting perforation entrance hole diameter to prevent bridging of proppant in the perforation. To avoid bridging, the ratio of the perforation diameter to average diameter of the proppant must lie above the curve. These are data for tap water and carboxymethyl hydroxyethyl cellulose (HEC), a water-based polymer.*** *(After Gruesbeck and Collins, reference 12.)*



☐***The importance of shot phase angle to maximizing communication between perforations and stimulated fractures. Studies of fracture and perforation orientations show that for optimum well productivity, the two lie within 30°, preferably 10°. This minimizes fracture initiation pressure and the length of the channel between the perforation and fracture wings, and increases the likelihood the fracture will initiate along a perforation. Perforating guns with small phase angle and high shot density achieve this optimum angle most effectively. The figure shows that a 0° phasing could place the perforation far from the fracture, which initiates along the plane normal to the least stress. But in reality, wells to be fractured are often perforated with guns of 60° phasing or less*** *(dashed lines).* ***This means the perforation is never more than 30° from the fracture.*** *(See Warpinski, reference 15.)*

Laboratory experiments by Daneshy show that fracture initiation pressures are higher when the fracture and perforation are not parallel and do not intersect.[14] Later, Warpinski reported that hydraulic fractures may not lie in the same plane as the perforation.[15] This observation was based on in-situ mineback experiments in which a shallow, perforated wellbore was excavated to see how the fracture propagated. Warpinski also found that if the perforation and minimum stress planes differ by more than 30°, the fracture may initiate in a plane different from that of the perforation. This indicates the phase angle should be 60° or less so the perforation is always within 30° of a fracture. Minimum phasing of 60° is further supported by recent work of Behrmann and Elbel, who showed that minimum fracture initiation pressure and maximum fluid communication between perforations and fractures are achieved by minimizing "annular flow"—slurry traveling an annular path around the casing to communicate with the fracture.[16] This occurs when the fracture plane and perforation lie within 30°, preferably 10° (*top*). Nolte[17] previously pointed out that if the hydraulic fracture does not initiate at the perforations, annular flow may cause premature screenout[18] and asymmetric penetration of the fracture wings.

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[12] Gruesbeck C and Collins RE: "Particle Transport Through Perforations," paper SPE 8006, presented at the 3rd Symposium on Formation Damage Control of the SPE of AIME, Lafayette, Louisiana, USA, February 15-16, 1978.

[13] Pearson CM, Bond AJ, Eck ME and Schmidt JH: "Results of Stress-Oriented and Aligned Perforating in Fracturing Deviated Wells," *Journal of Petroleum Technology* 44 (January 1992): 10-18.

[14] Daneshy AA: "Experimental Investigations of Hydraulic Fracturing Through Perforations," *Journal of Petroleum Technology* 25 (October 1973): 1201-1206.

[15] Warpinski NR: "Investigation of the Accuracy and Reliability of In-Situ Stress Measurements Using Hydraulic Fracturing in Perforated Cased Holes," *Proceedings—Symposium on Rock Mechanics* 24 (1983): 773-786.

[16] Behrmann LA and Elbel JL: "Effect of Perforations on Fracture Initiation," paper SPE 20661, presented at the 65th SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, September 23-26, 1990.

[17] Nolte KG: "Application of Fracture Design Based on Pressure Analysis," *SPE Production Engineering* 3 (February 1988): 31-42.

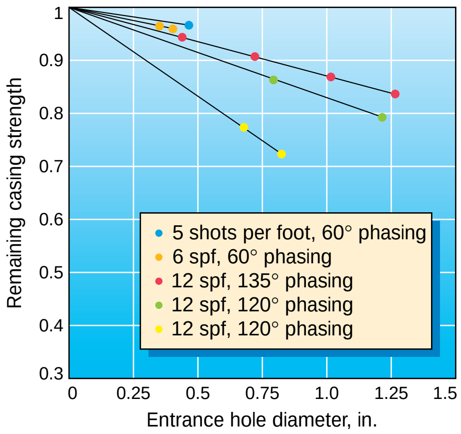
[18] Screenout occurs when the fluid carrying proppant is lost to the rock matrix, interrupting fracture growth. It results in rapid increase in pumping pressure.

The Sand Control Completion—Home of Big Holes

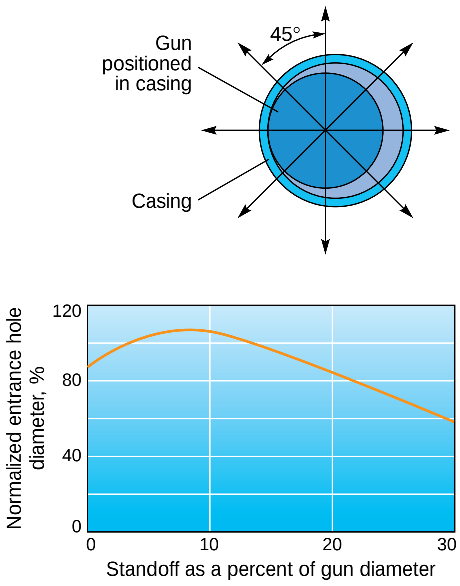
Sanding is a problem in weak or unconsolidated sandstones. The objective of a sand control completion is to eliminate sanding while maintaining a production rate that is economic, minimizes reservoir damage and thus maximizes recovery. Near the wellbore, sand movement can reduce permeability locally. Produced sand can erode downhole and surface equipment and its removal can be costly. In sufficient quantities, sand can plug the completion or surface facilities.

An objective of perforating in these highly productive and often unconsolidated sands is to reduce the near-wellbore pressure gradient during production (see "Sand Control Completion," *next page*). There are two schools of thought on the best way do this. The established method is to perforate in a way that takes advantage of protection afforded by subsequent gravel packing. Theoretical studies show that perforation geometry can sometimes be optimized to obviate gravel packing.[19]

For gravel packing, many large-diameter perforations are preferred to few small holes. This is because larger holes provide a larger area open to flow and therefore less pressure drop on production. To achieve this, perforators producing large diameter holes and high shot density are used. A uniform shot distribution further reduces formation stress in addition to preserving casing strength (*below*). Because of the high productivity of the reservoir, deep penetration is a lower priority. Depth of penetration is sufficient if it assures good communication with the reservoir.



Relationship between perforation entrance hole diameter and phasing on casing strength. The 135°/45° phased HSD guns achieve the greatest area open to flow while maintaining maximum casing strength. Here, casing strength is normalized to 1, the strength of unperforated casing.



Cross section of a gun in casing *(top)* ***and the effect of gun/casing standoff on entrance hole diameter for a bighole charge.***

To create large, clean perforation tunnels, these wells are typically shot underbalance with TCP using high shot density guns. The ideal underbalance will sufficiently clean perforation tunnels without breaking down the formation. Sand control could perhaps be provided by maintaining production rates low enough to prevent collapse of the perforation tunnel's stable arch—interlocking grains, like a keystone arch over a doorway. But such a low production rate is generally uneconomical and arches are unstable when flow conditions change. Instead, the arch is usually stabilized by filling the perforation with gravel (see "Sand Control: Why and How?" *page 41*).

In gravel packing, a wire-wrapped screen or slotted liner is positioned along the perforated interval. A slurry of thickened brine carrying gravel of closely controlled size is pumped downhole. The gravel fills the perforation tunnels, creating a "pack." One key to tightly packing the perforations is use of a fluid that rapidly leaks off into the perforations so the gravel slurry continues flowing until the perforation is completely full. This slurry is followed by an additional slurry to fill the screen-casing annulus with gravel. The pressure drop during production can now be distributed across both the near-wellbore area and the gravel pack, which helps to reduce stress at the formation.

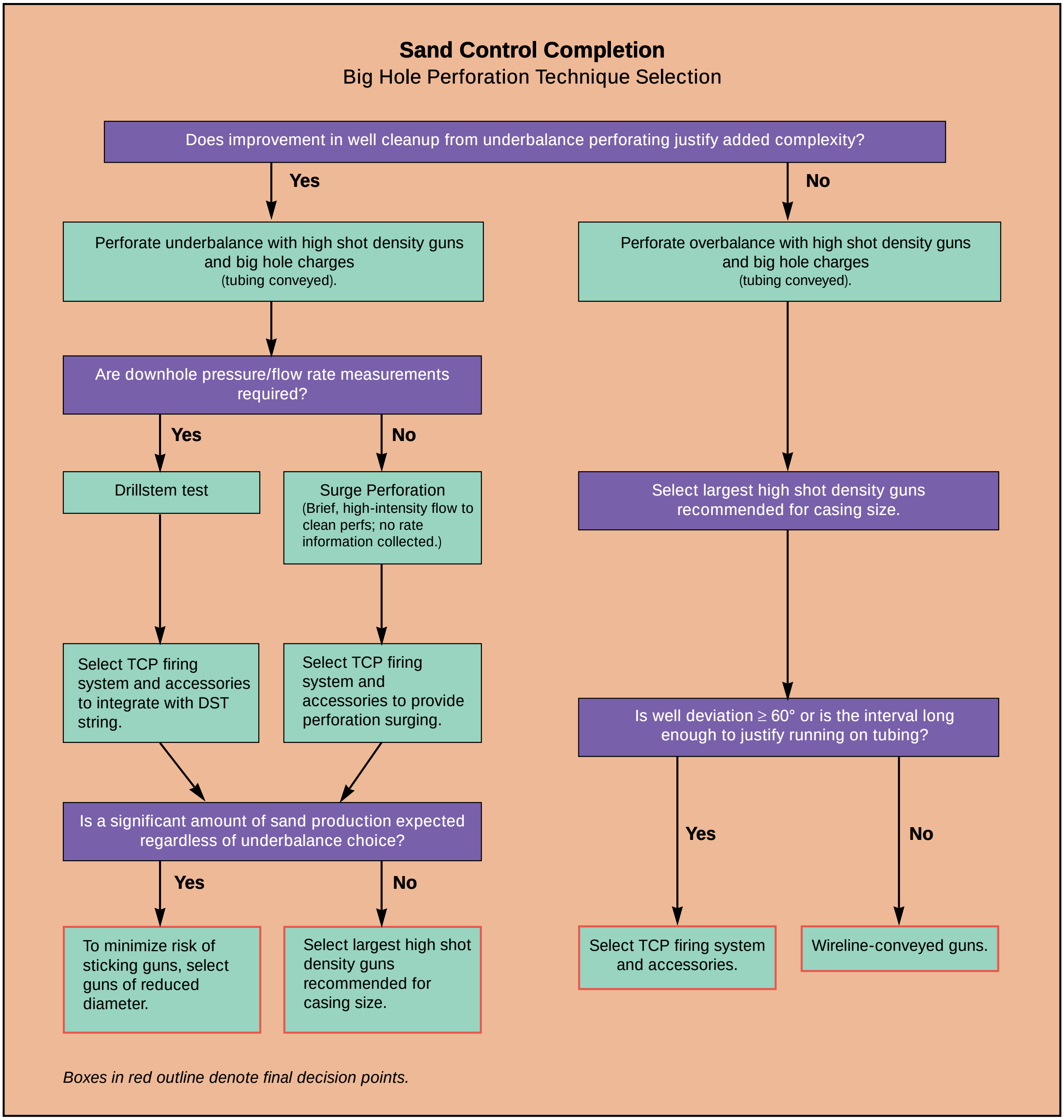
Clearance between gun and casing has a significant effect on entrance hole size of big hole charges (see "A Perforation Glossary," *page 57*). Adverse effects of standoff are much less for deep penetrating charges. Running the largest gun size practical for the well casing provides entrance holes that minimize the differential pressure across formation and pack (*left*).

Optimizing Perforation Operations—Environment and Safety

Each perforating system has ratings intended to ensure safety and minimize operating risk. Foremost are ratings for maximum and minimum pressure and "time-at-temperature"—the duration of exposure at a given temperature. The time-temperature rating is determined by the explosive material, which degrades at elevated temperatures and extended exposure times. This degradation results in a loss of sensitivity—leading to a potential misfire—and loss of strength—leading to reduced charge performance. Today's ratings have been established by both laboratory tests and extensive field experience.

The most common explosives in current use are cyclotrimethylene trinitramine, RDX for short, and cyclotetramethylene tetranitramine, HMX for short. When conveyed by wireline, RDX is limited to exposure of 1 hour at 330°F [166°C], or when tubing conveyed, to 100 hours at 200°F [93°C]. Similarly, HMX survives 1 hour at 400°F [204°C], and 100 hours at 300°F [149°C]. At higher temperatures or longer exposures, explosives and special elastomers and lubricants are available to perforate reliably at up to 500°F [260°C] for wireline-conveyed applications and up to 460°F [238°C] for TCP. Explosives for high temperatures, called HNS and PYX, are much more expensive and generally stocked only in areas where high-temperature wells are common.

It is generally recognized that guns have a maximum pressure rating. Exceeding this value can cause the gun to collapse or fluid to enter, possibly splitting the gun and sticking it in the casing if detonation occurs. Less well-recognized are gun limitations when perforating in gas. Not all guns that can be fired in a liquid-filled borehole can tolerate the higher shock associated with firing in a gas-filled borehole, which lacks the damping effect of wellbore fluid. Some guns must



Sand Control Completion

Big Hole Perforation Technique Selection

Boxes in red outline denote final decision points.

be supported by liquid at atmospheric pressure or higher. Special carriers are available for some guns for use in gas and high-pressure settings.

Although perforating guns are sometimes exposed to hostile environments, ratings are rarely specified. The reason is both practical and technical. A hostile environment comprises many variables—wellbore temperature, pressure, hydrogen sulfide [H_2S], treatment acid, carbon dioxide [CO_2], duration of exposure and stress during exposure. Not all can be quantified to determine if serious risk exists. Because of the demands of perforating, hardware must be robust and of high quality steel, well suited to hostile environments. For wireline-conveyed guns, exposure time is minimal. In TCP, where guns and accessories may be exposed for an extended period, H_2S-resistant accessories are available.

Each perforating system has a number of features, often redundant, to ensure safe

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19. Santarelli FJ, Ouadfel H and Zundel JP: "Optimizing the Completion Procedure to Minimize Sand Production Risk," paper SPE 22797, presented at the 66th SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA, October 6-9, 1991.

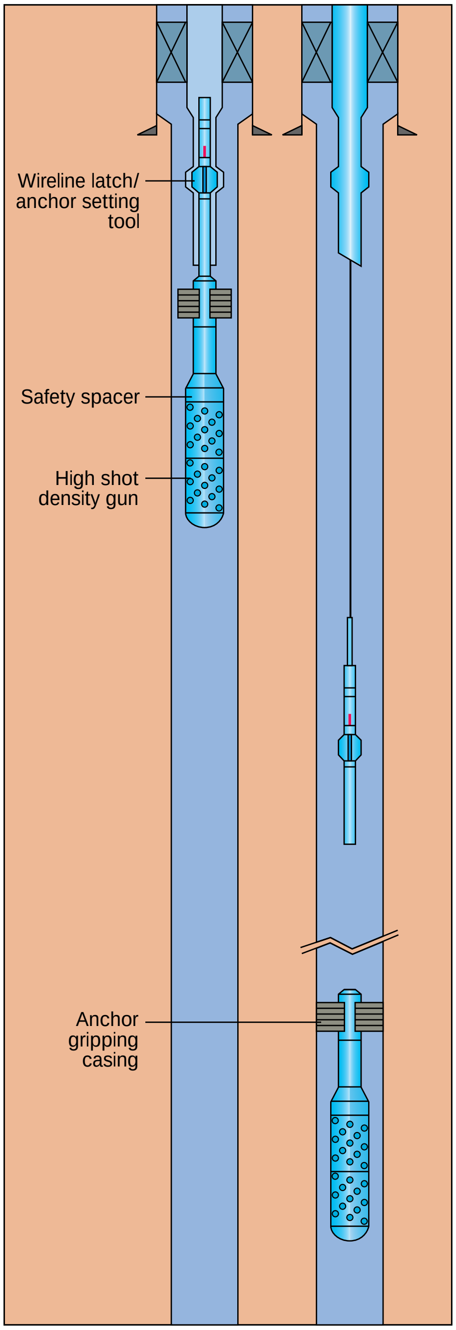
wellsite operations. Guns themselves contain only secondary explosives (charges, detonating cord, boosters) and are armed with the primary explosive (detonator) just prior to running in the well. This allows for safe loading and handling. Guns are commonly transported to the wellsite loaded, but armed only just before being run in the hole. Firing assemblies are designed to protect the detonator and position it to initiate the detonating cord. In the event guns are retrieved unfired, disarming is simple and may be performed immediately.

In wireline-conveyed perforating, electrical detonators are used, fired by applying power from surface. The detonators are disabled if fluid floods the gun, preventing accidental detonation.

Surface equipment is shut off and grounded prior to running and pulling the guns, eliminating accidental application of power. In addition, radio transmission, welding and cathodic protection systems are shut down to eliminate possible stray voltages. This requirement can be a serious operational limitation, for example, eliminating radio communication to offshore platforms. To safely overcome this limitation, the S.A.F.E. Slapper Actuated Firing Equipment system has been developed.[20] In the S.A.F.E. system, a special initiator is used that fires only from a very high voltage pulse of short duration—a pulse not produced by routine rig operations. The S.A.F.E. initiator contains no primary explosive and initiates only from a specific signal from surface.

TCP has safety features common to many other techniques. In Schlumberger systems, firing heads are connected to the top of the gun string with a blank interval of at least 10 feet [3 m] above the top shot. This allows arming of guns only after the charges are below the rig floor, away from personnel. Firing pins require a minimum of 150 to 300 psi to drive into detonators, ensuring no possibility of firing until below surface.

The Trigger Charge Firing system allows running and positioning the TCP guns in the well with no detonator. The firing head is subsequently run on wireline. This provides additional safety while running the guns and retrieving the firing head prior to pulling misfired guns.



☐*A variation of the monobore completion, using a permanent packer. Monobore completions are most common in the North Sea and Venezuela.*

New Completion Methods—Access for Big Guns

Efforts of well operators to be more cost-effective have led to variations in completion techniques, and concomitant innovations in perforating. A completion that has gained popularity in the North Sea and Venezuela is called the monobore. As the name implies, a monobore completion has a production string of uniform diameter, from the reservoir to surface. Casing is set well above the reservoir, up to half the well depth. Then, a smaller diameter hole is drilled to total depth and a long liner run (Liner is any casing that doesn't reach surface). Once the liner is set, production tubing of the same diameter as the liner is run and engages a sealing assembly on top of the liner. The well now has a "monobore," with the liner serving as both casing, providing protection, and as tubing, conveying production. This approach has the advantage of requiring a less expensive, smaller hole with lower tubular costs, yet provides a large-diameter production string. The well is then perforated with high shot density guns, either wireline conveyed or anchored in the liner after running on wireline or tubing. The guns are then dropped, either automatically upon firing or mechanically via a wireline trip.

Variations of the monobore technique are already in use. One is to set a permanent packer on production tubing at the top of the liner with guns suspended below (*left*). This allows use of the largest possible high shot density guns, while retaining the economic advantage of the monobore technique. Underbalance is established and a wireline assembly is then run in and latched to the guns, which are lowered to target depth. They are set using an anchor that hangs them in the casing. The wireline is then pulled out and the guns fired by pressure actuation. The guns are then released

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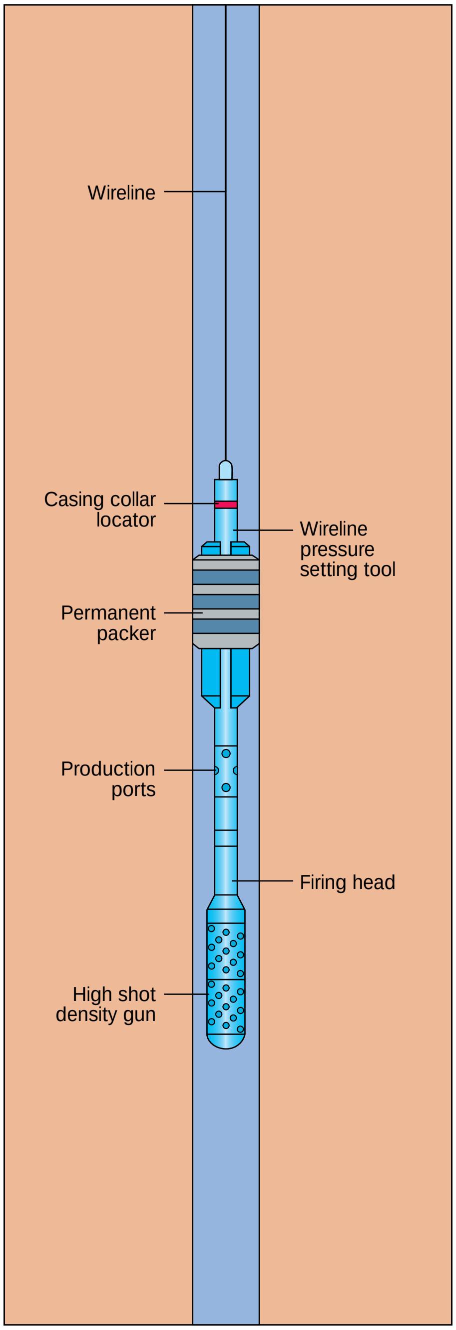
[20] Huber K, Pousset M and White D: "New Technology for Saving Lives," *Oilfield Review* 2, no. 4 (October 1990): 40-52.



☐*High shot density guns run below a wireline-set packer. This permanent completion allows underbalance perforating with the largest possible diameter guns in a permanent completion. Guns are usually dropped after firing.*

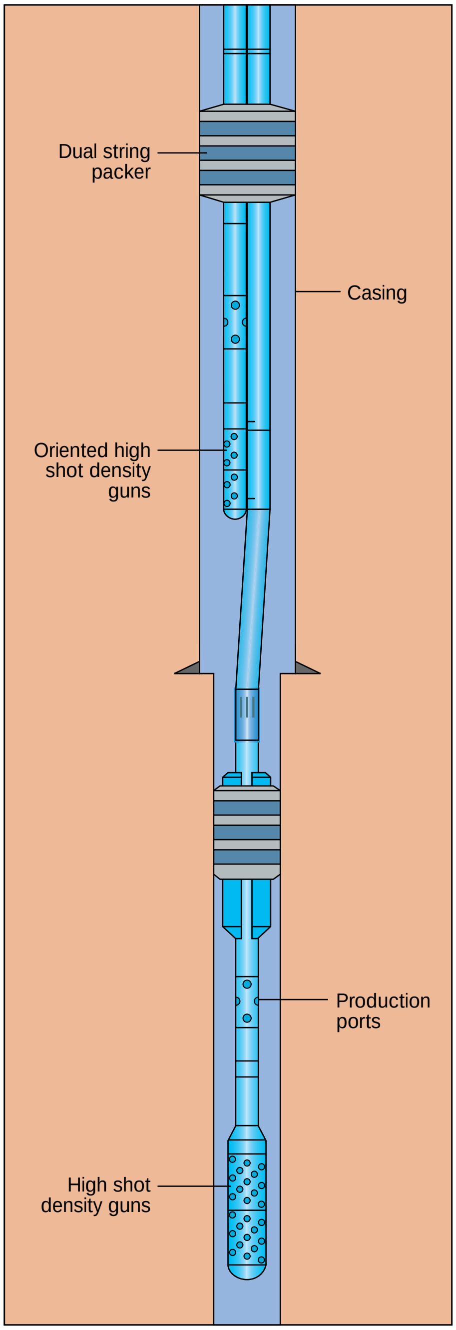
as in the standard monobore method, either automatically or by wireline trip. In perforating long intervals, where gun string weight exceeds the wireline limit, the guns can be run and anchored in the monobore prior to running the permanent packer and production tubing.

Another type of completion allows larger diameter guns than could be stabbed through a permanent packer or run through tubing (*left*). To achieve this, a permanent packer is set on wireline, with high shot density guns suspended below. Then, tubing is run, underbalance established and the guns fired and dropped.

A third perforation system is used for dual-string completions—two tubing strings run adjacent to each other to isolate production from two zones (*right*). This allows underbalance perforating of the upper interval without killing the well prior to production.

Developing a perforation strategy involves analyzing the reservoir using all data available to design the job for the anticipated conditions. A common pitfall is to bypass this process, repeating what is considered tried and true or what worked last time. This results in some wins and some losses. The best approach is to arrive at a perforation strategy by combining both field and operating experience. Only this approach allows the operator to duplicate what went right in previous jobs, avoid repeating mistakes, and test new techniques that hold promise.

—JMK



☐*A dual-string completion that allows underbalance perforating of both strings. In this instance, the lower zone is perforated with high shot density guns stabbed through a packer. The upper zone is perforated with high shot density guns suspended below a dual string packer. These guns are loaded and oriented to perforate the half of the casing opposite the adjacent long string.*