Chapter 4
Perforating

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4.1 Flow Path

Perforating is a process used to establish a flow path between the near reservoir and the wellbore. It normally involves initiating a hole from the wellbore through the casing and any cement sheath into the producing zone. The effectiveness of this process depends on the care and design of the perforating procedure. Because a high percentage of current wells use a cased-hole completion, the importance of the design and application of the perforating process cannot be overstated.

Perforations are an elemental piece of the inflow section of the well and have significant impact on the total completion efficiency. This chapter describes the methods of creating the best flow path for a particular completion. It also contains information on completion diagnostics and candidate selection for situations in which reperforating could improve production. The intent of this chapter is to familiarize the engineer with methods and techniques to improve the flow path, not all of which involve perforating equipment.

Establishing an optimum flow path requires the execution of a number of critical steps. These critical operations are identified throughout the chapter and are used in design, quality control inspection, and quality control.

A brief description is needed of the alternative completion methods to cased, cemented, and perforated completions. Openhole completions offer several options that should not be ignored in a quest for a high efficiency flow connection to the reservoir. Key to the completion process is the minimization of pressure drop across the completion, specifically the piece of the flow path from the near reservoir to the wellbore. In many cases, completion requirements extend to the need to modify the flow connection to reduce gas or water coning, to access multiple layers, and to assist in placing fractures. Completion requirements also extend to other aspects that involve initial completion or recompletion of the producing interval. A careful assessment of the benefits offered by both openhole completions and cased and perforated completion methods should be conducted.

4.2 Definitions

Because many of the perforating processes deal with explosive powders and gas expansion methods, a few definitions of the specialized nomenclature are needed.[1]

High explosives are very powerful explosives such as RDX, HMX, PYX, HNS, and others that find common use in the oil industry. High explosives are characterized by extreme energy release in a very short time, some with detonation front movement on the order of 6100+ m/s (20,000+ ft/sec). The detonation of an explosive is a chemical reaction and, like many chemical reactions, certain variables control the speed of the reaction. Peak energy generation with these materials is necessary to perform effectively and can be achieved only if they have high-order initiation. The initiation process for any explosive is critical in oilfield applications.

Gas generators are explosive materials designed to generate energy at a slower rate than the high explosives, and their primary function is to provide quick fluid volume. These materials are used for power fluids (gas drive), fracturing energy, and propulsion energy sources.

Order is a term associated with explosive firing. High order means that the high explosive has been initiated properly and reacts at the maximum speed. Low-order initiation of a high explosive fails to achieve maximum energy; the explosive may react, but the energy level produced is sharply lower than the maximum potential. In perforating charges, a low-order detonation usually means a failure to produce effective perforations, although gas pressure may rise sharply. Burning is one of the low-order reactions, usually producing gas, with no perforation possible. Low-order detonations may expand or burst guns, causing obstructions and fishing or recompletion decisions. Care in design and application of the perforating system can reduce sharply the incidence of low-order firing. Low-order detonations are caused by several factors, but temperature and poor condition of detonating cord are leading causes.

A *primary explosive* is an explosive that is used in initiators or other devices to initiate the explosive sequence. Primary explosives usually are more sensitive to firing (can be initiated more easily) than secondary explosives. Common locations for these explosives are in detonators (also called blasting caps) and some booster devices.

Secondary explosives are the main explosives used in charges. The secondary explosives (usually high explosives) are harder to initiate and must be initiated to get proper response (i.e., a high-order detonation).

Perforation flow efficiency is a measurement of how close flow capacity in the perforated hole approaches the flow capacity of an ideal hole of the same diameter and length. There can be enormous differences in flow rate between a perforated hole and a drilled hole of the same diameter and length. The perforation flow efficiency is a part of the total well flow efficiency. Achieving the highest flow efficiency, by perforation characteristic, by cleanup, or by a breakdown operation, is a critical step. Good perforation flow efficiency is greater than 80%.

Pressure differential toward the formation from the wellbore is overbalance. Pressure differential from the formation to the wellbore is underbalance. Fluid flows from high pressure toward the low pressure in a permeable formation. Special cases of overbalance manipulation include extreme overbalance perforating (EOP).

Phasing is the angle between the charges. The most common phasings are 0°, 180°, 120°, 90°, and 60°. Several specialty guns, offering higher density charge application and guns for sand control or casing protection, may offer phasings that increase the linear distance between the charges in a direct line along the gun body.

Shot density is the measurement of the perforations made per unit length of the gun. Normally given in either shots/ft (SPF) or shots/m (SPM), the ranges of shot density extend from 1 to 27 SPF. The most common shot densities are 4 to 12 SPF (13 to 39 SPM). Shot density requirements are a function of the completion design and the formation production requirements.

Pressure drop is a measurement of the hindrances in the flow system. Rate of fluid flow through a rock is determined by the differential pressure, the permeability of the system, the fluid viscosity, and the length and area of the flow path. To maximize flow rate, the permeability must be high. Crushed rock, debris, and other obstructions result in lower permeability and lower flow rate. In a well system, maximum production is achieved by minimizing pressure drop.

4.3 Perforating History

Bullet guns were the first commercial perforating devices.[2] A hardened steel bullet was fired from a short-barrel gun powered by a gas-producing explosive. These guns first saw commercial use in the early 1930s. The wall thickness and hardness of the casing and the hardness of the formation limit bullet perforating. Bullet guns are still used in some applications, usually in soft formations for deep penetration or brittle formations in which the shattering produced by the bullet can help break down the formation around the perforation.

During the 1930s and 1940s, work in the area of shaped charges progressed in the military arena. The bazooka, with its armor-piercing charges, was one of the first large-scale uses of the technology pioneered by Henry Mohaupt and others. This technology was accepted by the oil industry in the late 1940s and early 1950s and became the most used perforating method by the mid- to late 1950s.

Alternatives to explosives also were implemented, normally with an abrasive slurry of material such as frac sand and a carrier liquid, either sand or water.[3,4] Abrasive perforating methods are slower, require a rig, and contain several wear points in the treating equipment.

Specialty perforators, including laser, hydraulic punches, mechanical punches, water jet, combination bullet/jet guns, and electric arc perforating, have been used. Most of the specialty methods are used for special applications and do not find widespread use. Interesting perforation applications such as underbalanced perforating, tubing-conveyed perforating, and specialty phasings have their roots in much earlier applications, often 15 to 30 years before they became popular.

4.4 Perforating Methods

4.4.1 Bullet Gun Perforating. Projectiles from these guns (bullets) must penetrate the casing, cement, and formation. Bullet speed exiting the barrel is usually approximately 900 m/s (3000 ft/sec). Penetration is easiest in low alloy, thinner walled pipe (H-40, to K-55, and L-80 API casing series pipe grades). Penetration in higher strength casing alloy pipe and harder formations is more difficult in most cases and not feasible in others.[2] When successful, the bullet creates a very round entrance hole but may often create a hole with sharp internal burrs. **Fig. 4.1** shows a bullet-perforated casing from a surface test.

Tunnel length creation with a bullet gun drops sharply with increasing formation strength. Penetration extremes of 15 in. –/+ in soft chalks to 2 to 3 in. in dolomites are common. In contrast to shaped-charge perforating, however, bullets often shatter the rock rather than smoothly push back and compact the rock in their path. The shattering can be a definite advantage when the cracking improves the permeability next to the perforation.

Bullet penetration is primarily a function of the density and strength of the target in its path, as well as gun performance factors. The energy from the bullet is proportional to its mass, the amount of propellant, and the performance of the seal between the bullet and the barrel. Early performance-measuring tests with bullet guns showed a direct correlation between the penetration in a target and the use of new gun barrels. Performance dropped sharply with barrel enlargement and/or wear.

Entrance hole roundness and the pronounced shattering around the perforation tunnel help improve stimulation through bullet-perforated completions. Perforation ball sealers seal quickly and efficiently on bullet perforations. This is partly because of the additional brittle cracking of the formation (increasing permeability), the ability of the ball sealer to create a seal on the perforation, and the reduced number of bullet perforators normally used in a well. The reduced number of bullet perforators used in a well is an indication that a large number of perforations spreads out the flow entering the formation, resulting in a lower flow rate into a given perforation and less tendency to attract and seat a ball sealer.

Fig. 4.1—Bullet-perforated casing from a surface test.

Advantages of bullet perforating are high permeability connection to the immediate reservoir and very controlled hole size and shape. Disadvantages are shallow penetration, ineffectiveness in hard formations and high alloy or heavy pipe, leaving a solid mass of steel in the perforation tunnel, and low density perforating.

4.4.2 Abrasive Perforating Methods. Abrasive perforating methods use high-volume flow of abrasive-laden fluid to erode through the target pipe or cut it off when the nozzle or tubing string is rotated.[3,4] Abrasive impingement of hard particles such as sand on steel can cut through 0.25 to 0.3 in. of casing in a matter of minutes. Perforations in the casing or even 15 × 1.2 cm (6 in. × 0.5 in.) slots can be formed within 10 to 20 minutes per slot (hole). Abrasive methods often use a shaped nozzle that focuses the stream on the steel surface. The nozzle helps preserve energy, shorten cutting time, and decrease the effect of clearance distance, but the nozzle wears with use. Clearance distance between the nozzle and the target is important but not as critical as in nonsolids jet cutting.

Perforation depths formed by abrasives are typically short because the returning fluid and solids interfere with the ability of high-pressure fluids to access deeper targets. Depths of 2.54 to 23 cm (1 to more than 8 in.) have been measured in tests performed with backpressure. Abrasive perforating or cutting in surface targets often produces quicker cutting and may achieve deeper perforation depth, but these tests are not a valid representation of tool performance in a well. Adding backpressure on any type of a jetting tool rapidly diminishes its performance because of the reduction of pressure and flow velocity across the nozzle and collapse of bubbles and cavitation that may occur exiting the nozzle on a low-pressure test. Required equipment includes a rig with tubing large enough for the required rate with minimal friction drop. A fixed nozzle for perforating or a rotating nozzle for abrasive cutoff is the main bottomhole assembly.

The type of abrasive varies with the job, but sand is the most common material for perforating and pipe cutoff. Other abrasives such as calcium carbonate, soda glass, and other mineral and synthetic materials can be used. There are some differences in the cutting efficiency of materials. The quickest cutters are harder, more angular materials. Bauxite is the single most erosive material in the abrasive process but is used rarely because of its density and cost.

Liquid selection is less important and usually is dictated by the damage potential to the formation. Because some fluid is lost to the formation in any jetting job, the damage aspect of the carrier fluid should be investigated. The ability of the fluid to lift solids usually is limited to lifting the sand abrasive. The steel removed in the process is too fine to cause significant plugging problems.

Advantages of abrasive-perforating methods include the ability to make perforations with maximum flow area and with minimum damage to the formation or to the integrity of the steel pipe. The perforations are shallow in most cases, limited by the backwash of returning fluids, but are notably undamaged in most tests. The best applications have been in heavy oil completions in which large inflow area in the pipe is a necessity and pipe cutoff is advantageous. Disadvantages of these methods are the time needed to create each perforation, the amount of equipment required (coiled tubing or small tubing), the need to kill or control the well while creating the perforation, and solids cleanup.

4.4.3 Water Jets. Although water jets with pressure impact on the order of 20,000 psi are used as steel cutters in surface applications, they usually are not effective downhole when the backpressure is more than approximately 1,500 psi. The use of these tools is limited sharply by friction pressure drop in the small diameter, long-tubing strings used to supply fluid to the point of cutting. Water jets have been used to create perforation tunnels in openhole completions. A special adaptation of the water jet used a hydraulic punch to open a “door” in the casing through which a flexible water-jet lance was fed to extend a long perforation into the rock. With few exceptions, water-jet perforating is a special application.

4.4.4 Shaped Charges. The shaped charge or “jet” perforator uses a small amount of high explosive and a carefully shaped case and liner to create a focused pressure punch that is highly effective in piercing steel, cement, and rock. The jet is formed through a highly critical, but usually reliable, sequence of events. The sequence begins with the firing of the initiator or detonator cap, which ignites the detonation cord at high energy, followed by the initiation of the charges. The entire sequence of the explosive event must be carried out in high order. Failure to achieve or maintain high-order firing at any point in the explosive sequence will cause all subsequent explosive to initiate low order and burn with very slow energy release.

Fig. 4.2 shows the components of a shaped-charge perforator. Fig. 4.3 contains an X-ray of a 20-g, steel-cased charge that shows the detail assembly necessary for these charges. The charge case holds the explosive powder and focuses the firing explosive event. The primer area usually holds a small amount of slightly destabilized, secondary high explosive. The primer initiates the main explosive in the charge. As the explosive front moves through the charge, it strikes the apex of the liner deforming the liner and fluidizing part of its mass into a focused jet that punches a hole through the material in its path. Fig. 4.4 shows a jet formation from a shaped charge. As the jet forms, it stretches out with the jet tip approaching speeds of 6100 m/s (21,000 ft/sec), and the tail of the jet traveling at approximately 3,000 m/s (11,000 ft/sec). For illustration, several unusual targets have been used to capture jet performance with high-speed cameras.[5] In one of the most unusual experiments, the path of a jet through both sides of a crystal wine goblet was captured on ultra-high-speed film and shows full jet development before the goblet shattered. In effect, the hole is placed before the target “knows” that it has been hit.

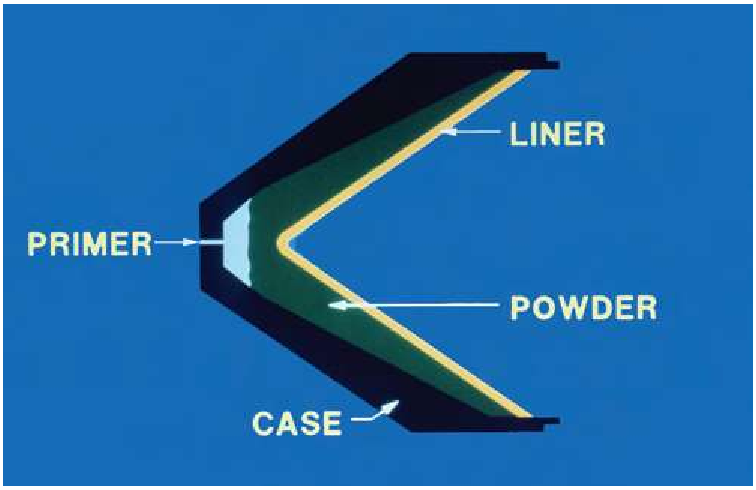

Fig. 4.2—Components of a shaped-charge perforator.

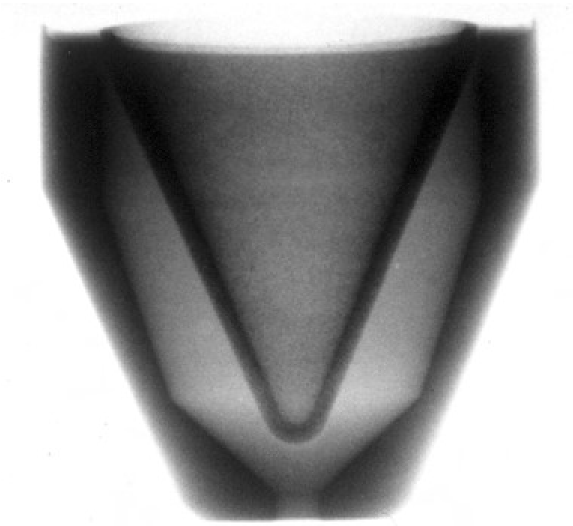

Fig. 4.3—X-ray of a 20-g charge.

Penetration of a shaped-charge jet through a target proceeds with the jet pushing aside everything in its path. The effect is similar to driving a nail through a block of wood. The wood around the nail hole is compacted tightly. Permeability in porous rock is reduced frequently in the compacted zone. There is almost no heat transfer during the jet penetration, although some target heating usually is seen from the post-explosion byproduct gases. Almost any target, including paper, can be perforated with a shaped charge. A classic example of penetration and compaction is the penetration of a jet through a thick telephone book. The area around the perforation tunnel in the paper is highly compacted to a radius of approximately 0.4 in. (1 cm). Straightening out the uncharred paper in the crushed zone revealed that very little of the paper was lost during perforating. Because fluids must flow through this crush zone, understanding how and why it forms and how to remove or bypass it is of primary importance in completion engineering.[6,7]

With shaped charges, the perforation penetration usually is thought to be proportional to the weight of the charge. Although the charge size has an effect on the performance, the shape of the liner, the internal standoff in the gun, and the overall design are also important. In a through-tubing application in which the carriers are small, the charge size will vary from 2 to

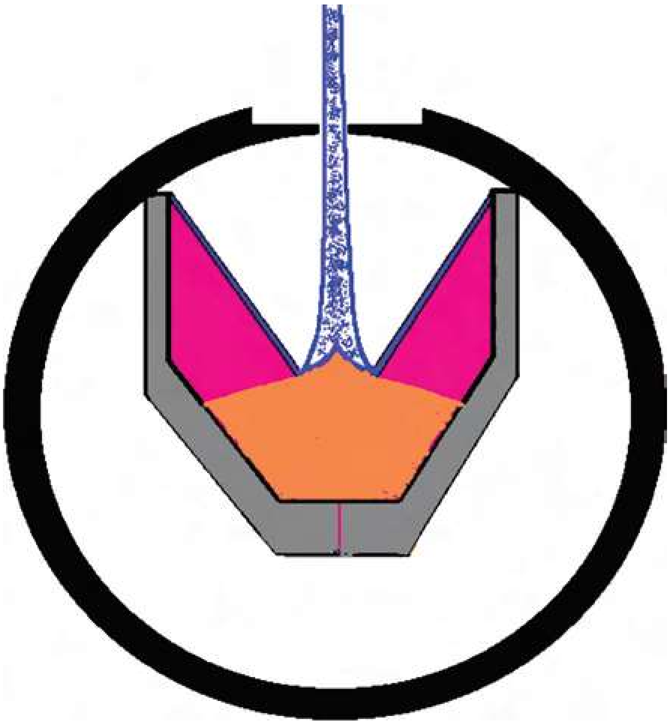

Fig. 4.4—Jet formation from a shaped charge.

approximately 8 g. The smallest charges are used in 1 9⁄16- and 1 11⁄16-in. hollow carriers and the larger sizes are used in expendable strips. In hollow-carrier casing guns with diameters of 3⅛ in. or larger, charge weights of more than 12 g are common (typically 22 to 37 g for 5-in.-diameter guns). Normally, the largest charges are used in the large expendable guns and casing guns in which the charges are more than 50 g. Openhole perforating guns that are designed to reach beyond mud damage in an openhole completion may use charges of 90 g or more.

4.5 Basic Perforating Design—Variables of Flow Through a Perforation

Shaped-charge perforations are used as the model for the rest of this discussion. Perforations are tapering tubes of usually less than 0.8 in. (2 cm) diameter at the entrance hole in the casing and depth of 1 in. (2.5 cm) to more than 30 in. (74 cm). Primary flow from the formation is through the end and walls of the tube. Flow behavior typically is dominated by radial flow with some pseudoradial character in longer perforations. Length, diameter, and permeability of the rock around the perforation control flow through a perforation.[8] Many early studies ignored the damage around the perforation tunnel and focused on the importance of length and entrance hole diameter. Putting damage effects aside, the length of the perforation tunnel is theoretically the most critical factor in a natural completion in which no further stimulation or sand control is planned. Entrance hole diameter becomes more important when some sand control completion designs are planned or fracturing is needed. Because of the early studies that ignored the effects of formation damage, the primary selling points of perforating charges became perforated length and entrance hole diameter. These two elements diminish in significance when the effect of formation damage is studied.[7,9,10]

Perforating charge performance in producing both entrance hole and perforation length is related more closely to charge design than charge size. The charge variables include propellant type, size, and design. The formation variables include formation strength, pressure, porosity, grain size, and fluids in the pores.[11] Perforating charge power is provided by the explosive and focused by the case and liner to produce a jet. The jet may be shaped to maximize either entrance hole or tunnel penetration. The completion type dictates the type of perforation needed

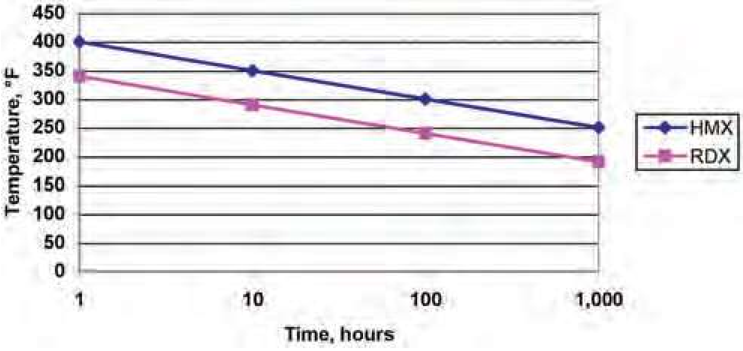

Fig. 4.5—Temperature stability estimates.

and thus the type of charge. No matter which charge is selected, however, the flow path must have a higher flow capacity than the formation can supply. Otherwise, it becomes a restriction in the reservoir-to-wellbore connection. Flow connection should be the primary consideration when selecting a perforating charge. Charge penetration can be optimized for specific nonpermeable targets such as cement and may produce a phenomenally long perforated length and very low flow capacity. Flow capacity should be the requirement in any producing environment.

As the jet penetrates the formation, the material in its path is thrust to the side, creating a zone of lowered permeability. The amount of permeability loss depends on the structure, porosity, and fluid of the formation and the size and design of the charge. Studies of permeability loss in targets and back calculation of damage in relatively homogeneous formations show permeabilities of approximately 35 to 80% of the initial formation permeability. There are three critical requirements to achieving a highly conductive flow path: select the optimum perforating equipment (including, but not limited to, charges) for the completion type, select the fluids and charge for the best formation interaction (minimize damage), and use the application method (underbalance, overbalance, surging, etc.) that provides the best cleanup and flow capacity in the perforations.[8,12–18]

The best-known design considerations for perforating are perforation length, shot-phase angle, perforation density, entrance hole size, and perforating flow efficiency. To design properly for optimum perforating requires preplanning and consideration of parameters such as filtered perforating fluid, amount of underbalance or overbalance, through tubing vs. casing or expendable guns, the method for conveying guns, and gun clearance. Special considerations, such as ultrahigh compressive strength rock (> 30,000 psi UCS), require special charges.[19]

4.6 Temperature Effect

The higher the wellbore temperatures, the shorter the time that the perforating jet charge is stable. **Fig. 4.5** illustrates stable time at temperature for charges made from common types of explosives. Guidelines for high-temperature charge selection vary, but most wireline-conveyed charges should be stable at the temperature for 16 to 24 hours. Tubing-conveyed perforating charges, for operations involving extended time at the bottomhole temperature, must remain stable for approximately 100 hours or more to allow for running the tubing and nippling up the wellhead. Higher temperature charges for operations involving extended time at temperatures greater than 300°F (149°C) are available, although they are more costly. When selecting a high-temperature charge, all parts of the system, including detonator, detonation cord, charges, seals and mechanical components, must be rated for the time at temperature and must work together.

When perforating charges explode low order or burn, large fragments of the charge cases will remain. These fragments are primary evidence of the problem. **Fig. 4.6** shows charged cases removed from a low-order gun. Gun breaches during low-order detonation or burning are common. **Fig. 4.7** shows a burst gun fished from a well after low-order firing. Anytime whole

Fig. 4.6—Charge cases removed from a low-order gun.

Fig. 4.7—Burst gun fished from a well after low-order firing.

charge cases or large sections of charge cases are found in the gun debris, the perforating job quality is highly suspect, and the perforating task should be evaluated or redone.

4.7 Basic Perforating Design—What Is Necessary for the Optimum Flow Path

Before selecting components for a perforating job, the first task is to understand how to get the best flow path possible for the time and money invested and the risk taken. The amount of flow capacity needed must be determined first. Flow capacity needs are a reflection of how much and what type of fluids that the formation can deliver to the wellbore. Inflow performance modeling with representative values of formation permeability and fluid viscosity is necessary. The objective of perforating is to place open perforations at the correct depth that extend through the casing and cement sheath into the formation. To be effective, the perforation tunnel must be in contact with a permeable part of the formation and must not be damaged by any mechanism that would stop or impede the transfer of fluids between the formation and the wellbore.[6,7,20]

Optimizing petroleum production is an exercise in removing pressure drops in a flowing system that stretches from the outer boundaries of the reservoir to the sales line. The perforating process is one element in this engineering exercise. To optimize the whole process, the most severe pressure drops must be examined and removed. As each pressure drop is reduced, the increased flow may change the requirements in another section of the well. Increasing the

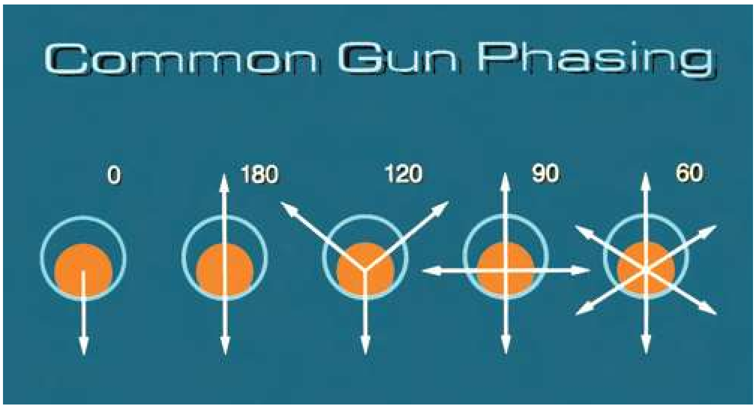

Fig. 4.8—Common perforator phasing.

flow capacity of the reservoir by stimulation or flooding places a greater capacity requirement on the perforations. Other well completion actions, such as gravel packing, change the flow requirement on the perforation by filling the perforation with gravel. Each action changes the criteria for perforation design; therefore, initial perforating designs may not be optimal for later well production. Well design should allow for flexibility in the completion type, which allows for adding perforation density in a zone or perforating other zones after the well has been evaluated or produced.

Phasing is the angle between the charges, and **Fig. 4.8** shows a common perforator phasing. Although there are many possible angles, the five common values are 0°, 180°, 120°, 90°, and 60°. 0° phasing aligns all the shots in a row. The gun should be decentralized, typically against the low side of the casing, so that performance from small charges is maximized by minimizing the clearance between the gun and the casing wall. 0° phasing normally is used only in the smaller OD guns or guns in very large casing. 0° phasing has some drawbacks because putting all the shots in a row lowers tubular yield strength and makes the casing more susceptible to splits and collapse at shot densities greater than 6 SPF. Fracture stimulating in wells that were perforated with 0° phasing may result in a slightly higher incidence of fracturing screenouts than with 60°, 90°, or 120° phasing. It is unknown whether the screenouts result from the smaller entrance holes or from one wing of the fracture wrapping around the pipe.

Of the other common phasing possibilities, 60°, 90°, and 120° are usually the most efficient choices from a fracture stimulation standpoint because they will produce a perforation just a few degrees from any possible fracture direction. These phased carriers may not need to be centralized to give good perforations because, regardless of where they contact the casing, at least two or three optimum perforations per foot should be formed. In small carrier guns in large casing, only 0° phasing should be used because the perforations closest to the gun will be fully developed, while the perforations with the largest gun clearance will be shorter and have a very small diameter. Casing guns offer much better phasing but often cannot be used to add perforations in an existing completion without major intervention.

Perforating phasing is known to affect production in both theoretical and practical applications. Locke, for example, showed that for a 12-in. penetration into the formation, a theoretical productivity ratio of 1.2 is predicted from 90° phasing of 4 SPF, while the productivity ratio is approximately 0.99 when the 4 shots are in 0° phasing.[8] This is ideal behavior and does not consider damage. When damage is considered, the actual formation character and perforation application details may create a much different outcome, although the effect of additional phasing is usually beneficial.

Perforation length usually is thought to be the most important characteristic in a perforation design. Surprisingly, there are several cases in which perforated length does not make a significant difference in well productivity. Only in natural completions does the perforation tunnel

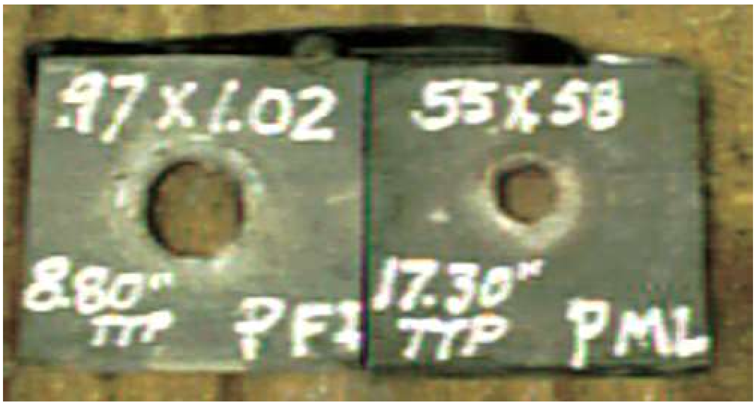

Fig. 4.9—Deep-penetrating and big-hole charge performance from 34-g charges.

length dominate the other factors. Even in natural completions, the flow capacity of the perforated connections is the most important factor. Factors such as hydraulic fracturing or prepacked gravel-pack operations negate the advantages of a few extra inches of perforated length. For hydraulic fracturing or gravel-pack treatments, a large, effective entrance hole through the pipe and cement is more important than total perforation penetration.

Although rarely considered, the perforation diameter also may influence the productivity ratio, especially in high productivity wells. Perforation diameter is dependent on charge design and the clearance of the gun in the casing. In instances such as sand control operations, unstable formations (including some chalks), and wells that are to be hydraulically fracture stimulated, the perforation diameter is important enough to dominate perforator selection. Flow through an open perforation should not be a restriction in the flowing system.

The choice between penetration length and entrance hole size is made available by the size of the charges and an element of the charge design. A charge's design affects the hole diameter and penetration. Fig. 4.9 shows deep penetrating and big-hole charge performances from 34-g charges.

A deep-penetrating charge has a different shaped liner (and sometimes a different case) from that of a big-hole charge. The deep-penetrating charge spends the bulk of its energy creating a long tunnel, while the big-hole charge focuses its energy on the casing wall and creating hole diameter. Deep-penetrating charges normally are used in natural completions, and big-hole charges are used more for gravel packing and fracturing, in which hole size offers less restriction to wither outflow during fracturing or inflow during production when the perforation is filled with gravel. Big-hole charges may have some disadvantages in both pipe and formation strength. The design of big-hole charges produces maximum force impact at the wall of the casing and can cause damage (and weakening) to the formation adjacent to the entry hole. For completions in weak formations in which sand production could be an issue and gravel packing or frac packing will not be used, deep penetrating charges at high density (12 to 16 SPF or 39 to 54 SPM) are recommended. If the zone collapses, however, reperforating with sufficient density of phased shots is required before gravel-pack operations are instituted.

The number of perforations is always a factor in completion design. Shot densities from 1 to 27 SPF (3 to 88 SPM) are available. High shot densities usually are required for very high flow rate formations, for single point application of fractures in deviated wellbores, and for laminated formations that will not be linked by fracturing. Optimum shot density for a well can best be determined with a nodal analysis simulator; however, judgment is needed when dealing with highly laminated formations or when the formation flow path is suitably inhomogeneous to create limited entry effects in the inflow. Adding perforations is often an excellent diagnostic tool.

Assuming all perforations are open to flow, shot densities of 4 SPF (13 SPM) with 90° phasing and with 13-mm (0.5-in.) holes usually are sufficient to ensure the equivalent of open-hole productivity. However, increased shot densities (greater than 4 per foot) may improve productivity ratios under certain conditions, such as very high flowrate wells or in gravel-packed wells. The real number of open perforations, those producing or taking fluid, is typically only approximately 50% of the total holes in the pipe. (The 50% value was reached after examining hundreds of hours of downhole television recordings in dozens of wells.) The cause of nonfunctioning perforations is usually traced to nonproductive layers in the formation or to damaged perforations. Perforating produces a damage zone around the perforation in which permeability may be reduced substantially below that of the native state formation. Longer perforations are less influenced by the crush zone than are short perforations. Phased perforations, such as 90° phased perforations, are less affected than 0° phased perforations. The damage in the near wellbore, plus the damage in the crushed zone, can cause severe pressure drops. However, most damage from drilling mud is confined near the face of the formation. In cases of nonwater-sensitive sandstones, the damage zone should not be of significance. The crushed zones will be created regardless of damage but may be minimized by underbalance or extreme overbalance perforating.

4.8 Improving Flow Capacity

Creating a perforation is relatively easy. Creating a low-pressure-drop flow path requires considerably more effort. As previously stated, most perforations have a crushed zone and other damage mechanisms that hinder production. To improve flow capacity, underbalanced perforating, extreme overbalanced perforating, surging, or one of several breakdown actions is necessary to clean the perforations and improve flow capacity.

In most cases, overbalanced perforating drives the wellbore fluid into the perforation and has the capacity to create particulate damage in the perforations. Clean fluid becomes a perforating requirement. Studies of the flow rate needed to remove damage report that serious perforation plugging occurs when the pressure is higher in the wellbore than in the formation. The plugs consist of crushed formation, liner particles, case material from the charges, pipe dope, and mud. In many lab and field cases, a plug formed when overbalance perforating in heavy mud is almost impossible to remove by reversing pressure.

Underbalance perforating, or perforating with the pressure in the wellbore lower than the pressure in the formation, generally is acknowledged to be one of the best methods for creating open, undamaged perforations in which the permeability is high enough to create sufficient flow rate to break the crush zone loose and carry it out of the perforation tunnel. In a simplified view, the initial underbalance surge and the subsequent flow clean up the perforations across the interval. In the real world, the initial surge at the moment of perforating opens up the perforations in the highest permeability streaks in the formation. As the pressure quickly equalizes, only a few more perforations may be opened and cleaned. For this reason, long perforated intervals may not be as effectively cleaned by underbalanced perforating as shorter intervals with lower shot density.

The pressure differential required to remove damage from a perforation is affected by pressure, flow rate, and formation integrity. Initially, pressure differentials for underbalanced perforating were established by trial and error, but a connection finally was spotted relating underbalance pressure and flow to formation permeability.[10,11]

The results of underbalance studies of more than 100 wells that were underbalance perforated, tested acidized, and retested are shown in **Fig. 4.10** for oil wells and **Fig. 4.11** for gas wells.[14] The response of an HCl acid job in the sandstone formation showed whether or not the underbalance pressure applied adequately cleaned the perforations.

Although underbalance pressure is of critical importance in generating clean perforations, it is the flow rate created by the underbalance that is responsible for cleaning the perforation.

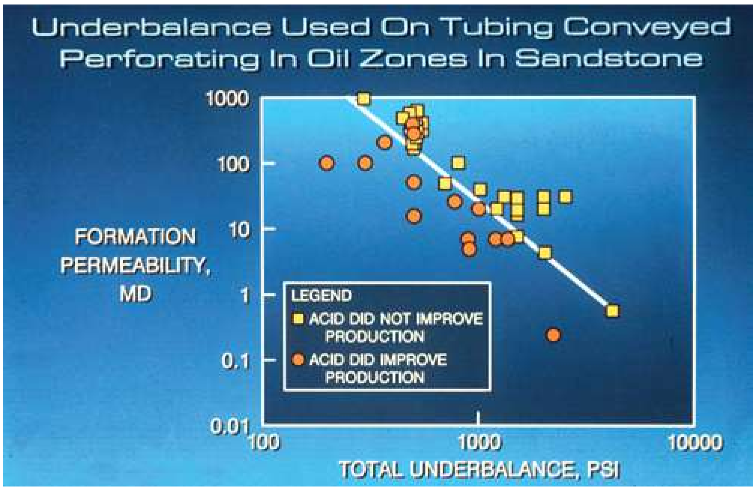

Fig. 4.10—Underbalance pressures used for gas wells.

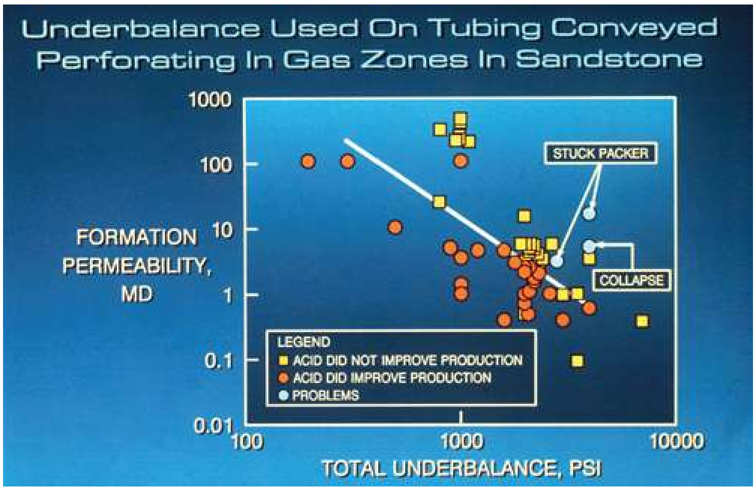

Fig. 4.11—Underbalance pressures used for oil wells.

The importance of flow after underbalance perforating cannot be overemphasized. The flow volume needed from a single perforation to clean debris is estimated at a minimum of 4 gal. In more recent work on deepwater wells in which surge volume is limited by operational and policy guidelines, a 20-bbl surge has shown to be very effective in cleaning the perforations. If the permeability is too low to achieve significant flow rate (< 1 md), underbalance perforating may not be effective. The most frequent causes of failure for underbalance perforating are low formation permeability and lack of flow immediately after the perforating gun fires. Candidate formations with permeabilities of more than 1 md are best, although sandstones are usually much better candidates than carbonates.

EOP is a microfracture-initiating process that is applied at the moment of initial perforating or as a surge process to existing perforations.[21,22] The technique uses stored gas energy in the tubing to break down the zone. Bottomhole pressure equivalents to 1.4 psi/ft and higher are applied instantaneously through the use of a nitrogen gas supercharge contained in the tubing. The energy is isolated in the tubulars of an unperforated well and behind a shear disk or other device in the tubing on a well that has already been perforated. The energy imparted is more sudden than a traditional hydraulic fracturing process and more sustained than an explosive or propellant treatment.

The fracture created by the EOP surge is more likely to fracture more perforations in an exposed zone than a traditional fracture process applied as an all-liquid hydraulic-fracturing process. Work with production logs and radioactive-isotope-tagged sand after EOP jobs indicates that multiple zones tend to break down more evenly when EOP is used. Although a fracture is created during extreme overbalance perforating or surging, its initiation does not appear to be controlled initially by formation stresses or traditional rock mechanics forces, probably because the 1.4 psi/ft gradient is considerably greater than most fracture gradients of 0.7 to 0.9 psi/ft. Because of the very high pressure of the initial surge, the pressure behind the surge is probably greater than the fields of maximum and minimum principal stresses in the formation. As a result, the initial direction of the fracture is in the plane of greatest mechanical near-wellbore weakness: the perforations. After the estimated 6-second life of the pulse, the fracture direction probably is controlled by the traditional stress forces, and subsequent fracture growth goes perpendicular to the plane of least principal stress.

Although treatment designs are still being refined, the initial successes have focused on maximizing the kinetic energy in the job. This is accomplished by minimizing the liquid in the tubing to eliminate friction pressure of liquid movement during the surge. Most job designs focus on filling the tubing with nitrogen and filling the casing below the packer with liquid.

A modification of the EOP process uses explosive propellant to deliver a pressure pulse that achieves the same type of breakdown as the fluid, but with minimum equipment.[23] The propellant is molded into a sleeve that is mounted on the outside of the perforating gun when adding perforations or as a stick when pulsing old perforations. Firing the perforating gun ignites the slower burning propellant, creating a gas pulse that breaks down the perforations. The pressure pulse lasts only a few seconds, but its location at the perforations helps break down crush zone damage. Fractures created by either the EOP or propellant process are not propped and will likely close after the event if not propped. The cleanout benefits of the process, however, have been well documented.

Surging perforations to achieve cleanup is an effective tool provided that the differential pressure is high enough to create enough fluid movement to clean the perforations. Few guidelines exist on surging other than at the local field level. Surges from 500 to 2,000 psi are common and are applied as suddenly as possible. The surges are most effective when the "valve" for the process is close to the formation. Long, small inside diameter tubing strings dampen the surge effectiveness because of high flowing friction resistance during the surge flow. Typically, not all perforations are opened by surging.

4.9 Cement and Casing Damage

Casing and cement damage during perforating has been debated for years.[24–30] There is probably little shattering or cracking damage to a good cement sheath from perforating. Tests have been conducted on more than 50 targets with unconfined compressive strength from 1,500 to more than 9,000 psi. When the perforation is more than approximately 4 in. from a free face (top or bottom of the target), there is almost no instance of cement shattering noted after firing. Splitting (longitudinal) along the perforated planes is seen in some targets but is an artifact of the test. In surface tests, cement cracking following perforating is the result of the test method, not the perforating process.

Either the casing or the carrier must absorb the explosive shock of charge detonation. Air-filled hollow-carrier guns absorb most of the detonation pressure; therefore, there is less possibility of casing splits caused by rupture. This becomes very important when shooting a large number of holes or whenever casing strength is important. The collapse resistance of the casing (and resistance to splits) depends on the number of holes in the pipe, the hole size, and their alignment (shot phasing). Casing guns with staggered phasing have improved the casing collapse resistance loss. These guns, which use deep-penetrating charges, often result in less than 10% casing strength crush resistance loss at shot densities of 16 or more SPF. Perforating with hollow-carrier guns causes only slight reduction in yield or collapse strength of the casing. Expendable and semiexpendable guns cause substantially more damage because the casing must stand the shock of detonation. Casing of low or unknown strength (corroded, old, flawed, or poorly supported casing) definitely should be shot with a hollow-carrier gun.

4.10 Perforating Multiple Strings and Thick Cement

Concentric casing strings reduce the penetration of any perforating charge.[31,32] The thickness of the extra string of casing, as well as the thickness of the two sheaths of cement that must be penetrated, reduces the perforation penetration length. In severe cases of small liners set through larger pipe, such as 5-in. liner cemented in 9⅝-in. casing, perforating both strings is considerably more difficult. For the best chance of perforating multiple strings, the largest, best designed deep-penetrating charge that can be run will generally have the best chance of penetrating through all the strings and into the formation.[29] Through-tubing guns are not recommended for shooting concentric strings because hole size and penetration are reduced with small charges.

In deviated wells in which concentric strings are to be perforated, the perforating gun will ride the low side of the pipe. When a casing gun is used for this operation, shot phasing of 60°, 90°, or 120° should be used to obtain the best chances of making perforations by the charges with the least clearance. The use of centralization techniques (if possible) on the guns run in deviated wells are recommended if hydraulic fracturing is to be used. This allows perforations to be placed near both fracture wings. Centralization also improves the roundness of the holes because the gun clearance will be near ideal. If inadequate perforations are a problem in wells with concentric strings, the innermost casing can be milled out (albeit at great expense) and the completion made through the outer casing.

When casing is run and cemented through washed-out sections, the cement sheath can be sufficiently thick to deny access to the formation with any perforator. When drilling a well into an easily washable pay zone, care must be taken to obtain a gauge or near-gauge hole so that the perforations will reach into the pay.

4.11 Perforating for Different Stimulations

The type of stimulation or ultimate well completion should influence the perforation design. In gravel-packing operations, a large number of phased, big holes usually are desired to enhance gravel placement and reduce the velocity of fluids coming into the wellbore.[33] Although entrance hole diameter is the principal concern, the perforation efficiency must not be overlooked.[34] Effective gravel placement requires leakoff, which is a feature of a high efficiency perforation. Decreased fluid velocity during production will result in less fines movement and plugging in the pack. Because the perforations may be filled with gravel, more perforations are required to generate the same productivity as open perforations.

Fracturing stimulations also require special perforating design.[35] Considerations include sufficient perforations to avoid detrimentally shearing the fluid (lowering the viscosity by degrading the polymer or crosslinked system) and to avoid needless high pumping costs. The viscosity of a fracturing fluid is a designed part of the stimulation treatment, and, if altered, the treatment may not meet expectations of proppant-carrying capacity. If this carrying capacity is destroyed by high shear, the sand may fall out of the fluid too soon, causing a blockage of the wellbore, perforations, or fracture with injected sand (a screenout). For more information, see the chapters on sand control and fracturing in this section of the *Handbook*.

4.12 Perforating in Highly Deviated Wells

The perforating design needed for a cased and cemented highly deviated (greater than approximately 60°) well may be different from the design needed for a vertical well, even in a similar formation. The main factors are placement of guns, cost of perforating in very long sections, need to produce selectively from a certain section of the wellbore, coning control, and need for focusing injected fluid into a single interval when fracturing or acidizing.

The number of perforations needed for well production, either deviated or vertical, depends on the inflow potential. Perforating costs can increase as pay contact increases, leading to reduced perforation density. A better method of perforating cost control is to use logging methods to identify zones of best porosity, oil saturation, and pressure (or flow in which production logging tool data are usable), and concentrate perforations in those areas. Leaving unperforated sections in a highly deviated or horizontal well also gives remedial operations such as plug setting a much better chance for success.

Fracturing in deviated wells requires a decision of whether to perforate the whole zone or to concentrate the perforations to ensure a single fracture breakdown. There is disagreement on the importance of numerous perforations in initiation of "starter fractures" formed in highly perforated zones. Localizing perforations can control the point of fracture initiation. Field performance has shown that perforating at 8 to 16 SPF over a 2- to 5-ft interval is sufficient to initiate a fracture. In field application of multiple fractures in deviated wells, perforating 3 ft (approximately 1 m) of the wellbore before each fracture job has produced good results. Although this approach is effective in providing sufficient wellbore contact with the main fracture to prevent early screenout, it does not address potential inflow from the unfractured matrix pays into the cased and cemented wellbore. Adding perforations along the length after all fracturing is one option, but obtaining any type of cleanup or breakdown of these added perforations can be accomplished only with a straddle packer.

4.13 Perforating Equipment

4.13.1 Guns/Carriers. In shaped-charge perforators, there are two basic carriers: the retrievable hollow carrier and the expendable or semiexpendable carrier. The most important consideration in selecting a perforator is choosing a gun system that matches the requirements dictated by the completion.

Hollow-carrier guns can be run either on wireline or on tubing. They may carry large charges, which normally minimize casing damage. The carrier contains most of the debris from the charge and the alignment system. Hollow-carrier guns are tubes that contain the shaped charges. The guns may be of a small size, able to pass through tubing and restrictions and place initial perforations or add perforations, or of larger sizes that are run through casing, conveyed by either work strings or the production tubing. Both reusable and single-use guns are offered, although higher pressure and more expensive wells typically use the single-use guns to minimize leaks and problems. Single-use guns are designed as expendables because the shaped charge perforates through the gun body. There is usually a "scallop" spot milled in the outside of the hollow-carrier tube at the charge location. The scallop contains the exit burr from the charge firing, which prevents scoring of polished bores if the gun is moved after firing and may minimize gun swelling. The scallop also may minimize the metal thickness penetrated, although this affects the perforation charge performance less than 10%. Keeping the charge exit point within the scallop becomes critical when through-tubing guns are used in which polished bores must be traversed with the gun after firing or when tubing clearances are critical.

There is some distortion (swelling) in the body of almost all hollow-carrier guns after firing. The amount of the distortion is a function of the size of the gun and the type and size of the charge used. The gun diameter, gun wall thickness, charge size, shot density, shot phasing, and well pressure are all factors in the gun distortion. On the larger diameter, thick-walled guns, there is much less distortion than on the small, thin-walled through-tubing guns. In wells in which clearances between the gun and tubulars are critical, the amount of distortion of the gun should be determined from the service company before the gun is used. Gun body swell

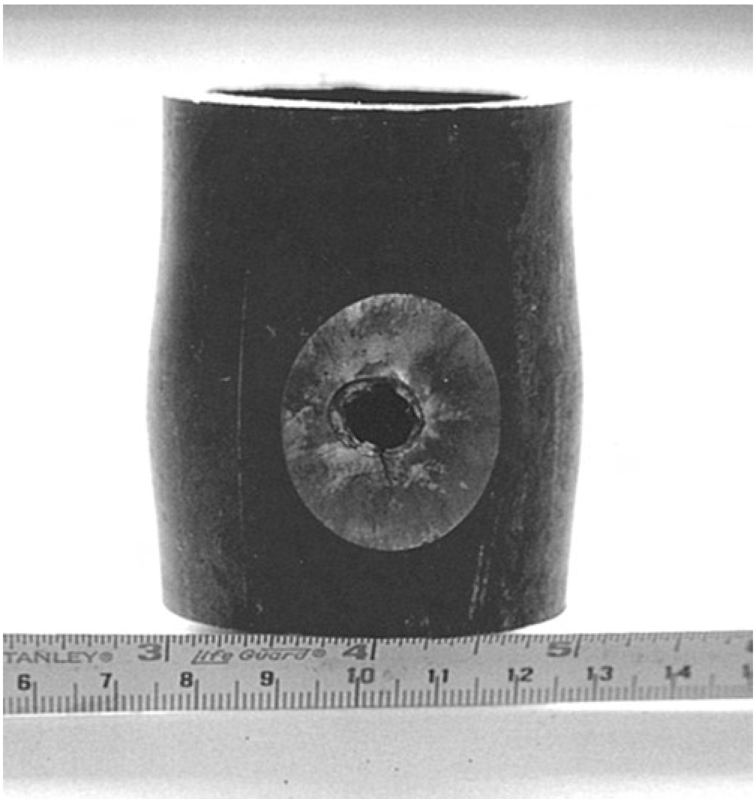

Fig. 4.12—Gun swell after firing in a low-pressure test.

ranges from approximately 10% diameter growth in small, 1 $^{11}/_{16}$-in. guns shot in low pressure wells to less than 1% diameter growth in larger guns and those shot at high pressure. Fig. 4.12 shows a gun swell after firing in a low-pressure test. Gun bowing is often noted in small guns of 2⅛ in. diameter or less, whereas larger guns, because of the increased resistance to bending with increasing diameter, show no evidence of bowing.

Hollow-carrier guns, depending on their diameter and design, may be loaded with 1 to 27 shots/ft and have all the commonly used phase angles as well as specialty phasings. The smaller through-tubing guns should be run through a lubricator and typically are limited to approximately 40 ft in length, less for larger, heavier guns. The advantages of through-tubing guns are low cost, the ability to perforate underbalanced, and the ability to maintain positive well control. The disadvantages of through-tubing guns are limited penetration, small entry hole, and the production limitation of 0° phasing.

Expendable guns have charges that are exposed to well fluids and pressures. The expendable guns are popular for through-tubing applications. They are more vulnerable to damage, but without the bulk of the gun body, larger charges can be run through any given small or buckled tubing restriction. The expendable and semiexpendable carriers normally can use a larger charge for a given tubing or casing size than the hollow-carrier guns because only the skin of the capsule around each charge separates it from the walls of the casing. With expendable guns, there is also more flexibility because some bending can be achieved. The expendable guns are popular for through-tubing applications. The charges are lined together by a common strip, wire/cable, or a linked body design. The expendable guns force the casing to endure a much higher explosive load during firing because the recoil is not contained in a sacrificial shell as in a hollow-carrier gun. Casing splits are sometimes seen with a downhole television camera after perforating with expendable guns in cased holes with poor cement or low-strength casing. Expendable guns are used because their perforating performance is significantly better than hollow-carrier guns in the smaller diameters. When the gun is fired, some or all the linking materials, as well as the charge capsule remnants, are left in the hole. Problems with these guns have centered on misfires from damage to the detonating cord, tubing and surface line plugging from debris, and carrier strip disintegration or severe bending after firing.

Two factors that affect the charge performance in hollow-carrier perforators are standoff and gun clearance. Standoff is the distance between the base of the charge and the inside of the port plug or scallop and is a fixed part of the gun/charge system design. Gun clearance is the distance from the outside of the port plug or scallop to the wall of the casing. The gun clearance distance for a 4-in. hollow carrier, 90° phased gun in 7-in., 23 lbm/ft, N-80 casing can be anywhere from 0 to 2.3 in., depending on the gun position. Unless centralizers are used on the gun, one edge of the gun will contact the casing wall, and maximum clearance will occur at 180° to the wall contact. For this reason, small guns are decentralized purposely by magnets, and the charges are all aligned to fire in the direction of the magnetic positioning (0° phasing). Larger guns with smaller clearance distances use charges phased around the gun. Typically, the maximum gun diameter selected should permit washing over the gun with washpipe in the given casing size.

4.13.2 Detonator Systems.

Once on depth, charges are fired by an initiator or detonator. Detonator systems have been redesigned in recent years to improve safety and to prevent several perforating problems that occur from leaks, pressure problems, and temperature effects.[36,37] Any wireline-conveyed, hollow-carrier gun should have a detonator system that will not allow the charges to fire if the gun is completely or partially filled with water. If a water-filled hollow-carrier gun is fired, the outer body shell may rupture and result in a fishing or milling job. Specialized detonators have methods of preventing wet (fluid-filled) gun firing, as well as offering a number of other safety benefits ranging from resisting stray currents, such as static and radio energy, to pressure switches that prevent accidental surface firing or resafe the gun when a live gun is pulled from a well. The standard explosives detonator (also called a blasting cap) is a mainstay of the construction industry but is not well suited to the petroleum industry. Several accidental discharges of perforating guns have been linked directly to stray currents or poor electrical panel operational procedures. The resistor detonator incorporates resistors that reduce the possibility of discharge from low-power electrical signals. More modern detonators, including flying foil, programmable chips, and other units that are radio safe and allow for extra safety, are available.

4.13.3 Conveyance Systems.

The conveyance system for a perforating gun may be electric line, tubing, coiled tubing, pumpdown, or even slickline. The choice of conveyance depends on the length of the interval to be perforated, the size and weight of guns to be run, the geometry and inclination of the wellbore, and the desire to accomplish other actions such as underbalanced or overbalanced perforating, gravel packing, fracturing, etc. Well control requirements are also a consideration because live-well perforating requires a lubricator or advanced snubbing techniques. There is a significant difference in cost between the conveyance systems. Wireline generally is the lower cost system in wells in which only a few gun runs are necessary to complete the perforating design.

In wells with deviations of less than 50° to 60° and short pay zones, electric line conveyance is the primary conveyance process. Electric line is quickly rigged up with a minimum of equipment, and the short guns fit the standard lubricator lengths. Running a lubricator allows the wells to be perforated live, without the need for expensive and potentially damaging completion fluids. Modifications to lubricator and pressure-control equipment also allow coiled tubing and some snubbing operations to run and retrieve perforating guns. When a well is perforated with a wireline gun with the differential pressure into the well, the flowing fluid tries to move the cable up the hole because of the lift effect produced by fluid drag and the effect of differential pressure on the area of the gun or cable. In normal operations, this drag is minimal and probably will not be noticed unless the well produces several thousand barrels per day.

The magnitude of the drag on the cable depends on the flow. Following perforating, the liquid column used to control the amount of underbalance pressure is lightened by gas production from the formation. The liquid in the tubing also starts to flow upward because of fluid influx from the formation. As more gas enters the casing, there is a period of time in which slugs of water are rapidly lifted by the gas. The velocity increases as the slugs rise because of the expansion of the gas. After all the liquid has been produced from the tubing, the gas flow can be described as quasisteady state. The maximum lift on the cable occurs during the flow of water and gas slugs when the liquid slug velocities are high. After firing underbalanced perforations with a wireline gun, the gun, if possible, should be lowered beneath the perforated zone to minimize the lift force on the gun body. If it is necessary to flow the well as the gun is run or pulled through the tubing, sinker bars will be needed on the gun, and the well should be choked back. Very close clearances between the gun and tubing will result in very high lift forces if the well is flowing.

Because of the need for depth control during perforating, electrical responses from logging tools to confirm depth are the best method. The logging cable may be standard electric line or electric line inside coiled tubing. Alternate conveyance methods such as tubing conveyed, nonelectrical coiled tubing, pumpdown, or slickline also may be used, but a separate method of confirming depth, usually relogging to the set gun or a mechanical option, is required.

Through-tubing, hollow-carrier guns are attractive because they can be run through the production tubing and packer and require only a service truck-based unit. Generally, the phasing for the smaller, through-tubing guns ranges from 0° to a staggered pattern of 15° to 45° either side of the 0° plane (low side of the hole). Complete circumference phasing rarely is used in small, through-tubing guns because increasing clearance from the gun to the casing wall substantially reduces performance of small charges. In 3½-in. and larger outside diameter (OD) tubing, through-tubing hollow-carrier guns with larger charges can be used with 180° phasing to provide adequate penetration.

A major drawback to tubing-conveyed perforating is that there is no way of knowing, except by pulling the guns, how many charges were fired. A signal charge device that either fires a small explosive charge or trips a hammer device a few seconds after the primer cord detonation reaches the bottom of the gun can be used in conjunction with a sensitive sound-recording device to determine that the detonation cord was ignited to the bottom of the gun. Although the detonation of the signal charge will not tell how many charges were fired, it does signify that the primer cord has burned past all the charges. Because the major mechanical problems of tubing-conveyed perforating systems have been in two areas, failure to initiate the guns at the firing head and failure to initiate the next gun at the gun junctions, the use of a bottom-shot detector is very advantageous. The reports of early use of this system indicate it has been very successful on land-based wells but has problems on offshore wells because of the high noise levels associated with platforms.

New perforating methods recently have centered on the use of casing-conveyed perforating.[38] In these methods, the perforating gun is attached to the outside of the casing string, and the guns are deployed during the initial running of the casing string. After the string is cemented in place, the guns may be fired by a signal, from either the surface or inside the casing itself, opening the well to production at initial time or at a later time when a zone is ready to be brought on. This type of perforating could be very beneficial when sequential stimulations of stacked pay zones are planned.

4.13.4 Getting On Depth. No matter how good the perforating system, it is useless if the perforations are not made in the best pay zone. Typical methods of depth control include gamma ray tie-in and correlation to the original openhole gamma ray system. Until the development of sturdy gamma ray logs that could stand the shock of firing, the primary depth control method was to match openhole gamma ray to cased-hole gamma ray strip log and then tie into the collar locator log. When this method was executed properly, the depth control was accurate to within half the length of the collar. Unfortunately, a miscount would result in shooting the gun one joint off depth, which is a complete miss for many zones. With gamma ray logs that run with the gun, the process is simplified and more reliable.

The second piece of the depth-control puzzle is the distance from the gamma ray detector to the top shot of the perforating gun. A record of all the measurements of the gun should be available before the run, and depths should be worked out in advance.

Wireline measurements, even if corrected for stretch, may still be in error. The wheels in the depth-measurement device on logging trucks are calibrated for new cable. Cable wear, cable stretch, and wear of the measurement wheels can all cause inaccuracy. Magnetic marks or depth flags on the cable are helpful but can be thrown off by cable stretch. To account for creep in the wireline and to accurately zero in on the depth, the collar locator should be raised very slowly into the collar above the pay and stopped when the signal for the peak (collar location) is only half formed, which indicates that the tool is exactly in the center of the collar. To find the spot where the tool is centered on the collar and remains without changing may take several very slow passes. Once located, the wireline depth of the collar above the pay can be correlated to the openhole gamma ray log. If the casing (or the tubing in a tubing-conveyed operation) is run with a short joint or pup joint near the pay, it will be much easier to correlate tool depth on repeat runs.

Openhole and cased-hole gamma ray logs rarely agree exactly on depth because of differences in cable and chart paper. The depth correlation is to be made to the openhole log. If two sections are to be perforated and a single shift will not align the cased-hole log to the openhole log, each section should be aligned independently to the openhole log.

Improving depth control is relatively easy if a short pup joint of casing is run near the top of the pay during the initial completion. Recognition of the short joint by the collar locator log is easy and relatively foolproof. Other methods of depth-control assistance are radioactive tags in the threads of one casing coupling joint near the pay. The most common depth-control problem with perforations is shooting them one joint off. The well's plug-back depth (or float collar) also may be "tagged up" with the bottom of the gun in some wells to check depth. If the float collar has been drilled out, it also can be used as a short joint for identification.

4.13.5 Perforating Fluid. The ideal fluid for perforating operations is a solids-free fluid that will not cause byproducts when exposed to the formation. Acceptable fluids may include 5 to 10% HCl, 10% acetic acid, 2% (or more) KCl water, 2% NH4Cl water, clean brines, and filtered diesel. If a dirty fluid is used, there is a distinct possibility that formation damage will occur because of particle plugging at the surface of the perforation tunnels. Even when a higher pressure differential toward the wellbore is used, clean fluids are still recommended to avoid flow of particles into the perforations in the event of a mechanical breakdown, when formation pressure of productivity is less than expected, or when the well has to be shut in before all the wellbore fluids have been produced.

Occasionally, high-solids-content fluids must be used during perforating, either for well control or because of other restrictions. High particulate fluids such as drilling mud usually are designed to form a mud cake on the face of a permeable formation. If drilling mud is used as a perforating fluid and the pressure differential (either by design or by accident) is toward the formation from the wellbore, a drilling mud cake will form in the perforations that may be difficult to remove unless the formation can be produced at a high drawdown for a long period.

Lighter fluid columns such as oil or diesel may be used as perforating fluids if the full column is diesel or oil, but 6.8 lbm/gal diesel cannot be kept spotted below 9 to l0 lbm/gal brine water. Produced oil and diesel also should be filtered before use. Filtration requirements

Fig. 4.13—Flare produced after explosive cutoff.

may vary with the task, but typically a 2- to 5-µm filter with a beta rating of 1,000 is adequate for most applications.

4.14 Limited Penetration Charges

Tubing puncher charges are used when a hole is needed in tubing for circulation or flow, but damage must be avoided to downhole equipment outside the target pipe. The tubing puncher charge is designed to expend all its energy penetrating the wall without forming additional penetration.

4.15 Pipe Cutoff Methods

Tubing cutoff is important during salvage operations, fishing operations, certain production operations, and any action that requires severing the tubing. The most common pipe cutoff methods involve either explosive or chemical cutters. Explosive cutters use the same explosive technology used in perforating charges. Instead of a cylindrical cone, however, the explosive and the liner are arranged in a wedge so that the explosive front of the device will push out on all sides and sever the pipe. Although the technique is effective in most cases, the external part of the pipe is left with a flare that is often difficult to wash over during pipe recovery operations. Newer explosive cutters have largely reduced this flare to an acceptable level. **Fig. 4.13** shows a flare produced after an explosive cutoff.

Chemical cutting has become one of the most common pipe cutoff methods, especially for tubing. The cutting fluid reacts extremely quickly and generates intense heat. It is sprayed through a nozzle assembly at the walls of the tubing all around the cutoff tool. As the fluid contacts the steel wall, a vigorous reaction occurs and the pipe is separated smoothly without leaving an external flare. **Fig. 4.14** shows an example of a chemical cut pipe. Chemical cutters can produce very smooth cuts but are very dependent on both orientation and even coverage or contact between the cutting chemical and the steel pipe. Heavy walled pipe, higher alloy, increased depth, imperfections in the pipe, scale, paraffin, plastic liner, or incorrect gun sizing can either slow the chemical cut on that side of the pipe or defeat it entirely so that pulling operations are needed to finally separate the pipe. **Fig. 4.15** shows an example of a partial chemical cut.

Radial explosive cutters, either continuous or segmented cutters, produce a pressure wave that is oriented outward and usually produce a flare in the steel at the cut point. **Fig. 4.16** shows an example of a cut produced by a Thermite cutter. The severity of this flare can pro-

Fig. 4.14—Chemical cut pipe.

Fig. 4.15—Partial chemical cut.

vide problems in recovering the pipe or in washing over the stuck section. A mill is often run to dress off the upward-looking connection before running the wash pipe.

Mechanical cutters based on mill design have been used successfully on both jointed and coiled tubing applications to sever pipe. These cutters are considerably slower than the chemical or explosive cutters but can be run on conventional equipment. The mechanical cutters are best used on softer, lower alloy pipes with a thinner wall. High alloy pipes and very thick pipes are more difficult to cut with a mechanical cutter.

Abrasive cutters have been reintroduced recently to the market and have the potential to rapidly sever almost any type of pipe at any depth. These cutters use a particulate such as sand, glass beads, or calcium carbonate pumped through a rotating nozzle, and the abrasion erodes the steel. Cuts through even heavy-walled drillpipe are possible if the cutter can be kept in the same place during the entire cutting operation. Cuts at surface with abrasive cutters are very fast; however, the cutting process is slowed because of backpressure when the cutters are applied downhole. Nonetheless, these cutters are beginning to see extensive use as pipe cutoff tools.

The cutting system necessary for a particular application depends on the well depth, temperature, and size of the tubing and alloy grade and weight of the tubing. However, the most

Fig. 4.16—Cut produced by a thermite cutter.

important factor is any restriction above the cut point and the ability to pull tension on the pipe. Requirements for cutting tubing include knowledge of the specific design of the well and any restrictions above the point to be cut. Once the cut point is selected, the cutting method should be studied carefully to determine if a clean cut can be made that will requiring a minimum of overpull to separate the uncut sections of the pipe. Additional considerations include the conveyance system and the manner of depth control that will place the cutter at the correct position.

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SI Metric Conversion Factors

bbl	×	1.589 873	E – 01	= m^3
ft	×	3.048*	E – 01	= m
°F		(°F – 32)/1.8		= °C
gal	×	3.785 412	E – 03	= m^3
in.	×	2.54*	E + 00	= cm
lbm	×	4.535 924	E – 01	= kg
psi	×	6.894 757	E + 00	= kPa

*Conversion factor is exact.