Perforating Services Catalog
2008

The services in this catalog are grouped according to their applications.

A brief description of each service and its measurement and mechanical specifications are included. For more information on designing a perforating program to meet your specific needs, contact your Schlumberger representative.

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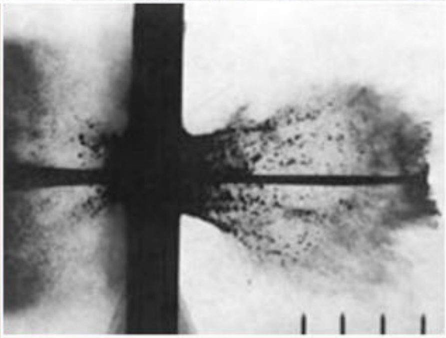

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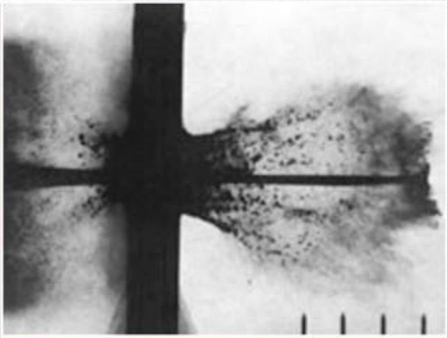

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Overview

Modern perforating technology has evolved from just making simple holes in the casing to customized, objective-oriented services integrated with sophisticated and versatile completion designs. Perforating is now used to optimize both permanent and temporary completions, such as drillstem tests and workovers. Along with services such as hydraulic fracturing, sand management, directional drilling of extended-reach and horizontal wells, completion fluid engineering, and well testing, engineered perforating to achieve communication between the formation and the wellbore has become indispensable to improving productivity.

This catalog follows the workflow of engineering perforated completions, beginning with the development of perforating theory, techniques, and equipment. A discussion of the operating environment gives the reader a practical understanding of completion design and perforating operations. Following that is detailed information on the perforating products and services provided by Schlumberger: gun systems, firing systems, accessory equipment, and operational procedures.

Perforating is but one of the integrated oilfield services delivered by Schlumberger to optimize your E&P performance in a safer, environmentally sound manner. For more information on perforating and other products, services, and solutions, visit www.slb.com or contact your Schlumberger representative.

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Safety

Quality, health, safety, and environmental policy

The long-term business success of Schlumberger depends on our ability to continuously improve our products and services while protecting people and the environment. This commitment is in the best interests of Schlumberger clients, employees, and stockholders.

The integration of quality, health, safety, and environment (QHSE) objectives into Schlumberger operations worldwide is the responsibility of line management, with the active commitment and support of all employees. Schlumberger strives to

- ensure the quality of our products and services
- protect the health, safety, and property of employees, clients, contractors, and third parties
- protect the environment in the communities where we work and live.

We are committed to proactive integration of QHSE objectives into our management systems at all levels, actively reinforced by reward and recognition programs. This commitment is critical to our business success because it reduces risk and adds value to Schlumberger products and services.

Safe operating practices

Safe operating practices are critical to the long-term success of any activity, especially when the results may be as devastating as the surface detonation of a perforating gun (Fig. 1). The Schlumberger commitment to safety includes strict operating rules; properly designed, constructed, and tested equipment; and well-trained, highly qualified personnel. This commitment extends to all activities, with the discussion here focused on the safety aspects of transporting and using explosives at the wellsite. This section is intended as a brief overview only. Detailed procedures are documented in the Schlumberger *Explosives Safety Manual*, field operations manuals, and maintenance manuals of each perforating service.

Personnel

All Schlumberger perforating crew members receive training on the characteristics of the explosives they use and proper techniques for handling and transporting them. Perforating engineers and technicians are also proficient in the specialized process of gun arming and disarming. They thoroughly understand Schlumberger procedures and applicable local regulations. Only the engineer or technician in charge is permitted to arm or disarm the perforating guns on a Schlumberger perforating job.

Schlumberger follows a certification process to ensure a uniform standard for all our perforating engineers and technicians. Each engineer or technician must demonstrate both theoretical knowledge and the necessary practical skills to properly perform the service. Certification is maintained through periodic recertification requiring the individual to demonstrate knowledge of current procedures and systems, as well as proficiency in operations. Only an engineer or technician with current certification may be in charge of a perforating job.

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Figure 1. A perforating gun detonated at the surface demonstrates the tremendous power of an oilwell perforator. The figure at left is a mannequin.

Equipment

Schlumberger uses only properly designed and built equipment. Downhole perforating systems are designed at the Schlumberger Reservoir Completions (SRC) Technology Center in Rosharon, Texas, USA. The SRC facility also manufactures most of the Schlumberger gun systems and shaped charges. Quality control is maintained using International Organization for Standardization (ISO) 9001 standards. Other perforating components are manufactured to similar quality standards by qualified suppliers.

Equipment used with explosives must undergo a comprehensive design review by the Schlumberger Explosives Safety Committee and pass stringent operational safety tests before authorization for use by the field organization. In areas such as electrical explosive initiating system design, Schlumberger uses third-party testing laboratories, recognized by the explosives industry, to confirm the safety of our designs and verify our testing.

Surface equipment associated with perforating plays an integral role in job safety. Units, cables, pressure equipment, and auxiliary components are subjected to similar design reviews and testing before being approved for use.

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Procedures

Schlumberger follows specific procedures when handling explosives to protect the safety and health of all personnel (Fig. 2). These procedures meet or exceed standards set by American Petroleum Institute (API) Recommended Practice (RP) 67, *Oilfield Explosives Safety*, as well as local regulations of the countries where we operate. The Schlumberger Explosives Safety Committee periodically reviews and revises procedures to reflect changes in the workplace.

Transportation and wellsite procedures are the two aspects of field operations that require special consideration for explosives safety.

EXPLOSIVES

Schlumberger Field Safety Procedures

Conventional Electrical Detonators

1. Hold consultation with client, if possible.
2. Check well area for hazards and correct when necessary.
3. Hold spot safety meeting.
4. No smoking except in designated areas. Smoking materials must be stored when leaving these areas.
5. Rig up cable. Remove rig wiring that might contact cable. Topdrive systems should be electrically isolated in accordance with the manufacturer's procedures.
6. Outside preparations before attaching an explosive device:
   a. Turn off electrical cathodic protection systems.
   b. Discontinue all electric welding operations.
   c. On water operations, install the positive grounding cable from truck to barge or wireline unit to generator skid.
   d. Check voltage between the rig, casing, and cable armor using a multimeter. Attempt to eliminate it at its source, if present.
   e. Test and install Casing-to-Rig Voltage Monitor.
   f. DO NOT PROCEED WITH OPERATIONS IF RESIDUAL VOLTAGE IS IN EXCESS OF 0.25 V BETWEEN RIG, CASING, AND CABLE ARMOR.
   g. Install safety grounding straps between the unit, rig and casing.
   h. Put out sign reading "Danger Explosives - Turn Off Radio Transmitters" or equivalent.
   i. Turn off all radio frequency (RF) transmitters (radio, cellular, radar, RF wireless networks, etc.) within 100 ft [30 m] of the well. Receiving units located within the established safe distance must be disabled such that an incoming call cannot activate the transmitter.
   j. All transmitters (such as radio or TV stations) greater than 200 watts and within 1 mile [1.6 km] of the well must be disabled such that they cannot transmit.
7. APPLYING POWER AT SURFACE ONCE THE EXPLOSIVE OPERATION HAS STARTED IS PERMITTED ONLY ON THE CONDITION THAT THE CABLE HEAD AND ENTIRE TOOLSTRING ARE IN CLEAR VIEW OF THE ENGINEER WHILE APPLYING TOOL POWER. Power must not be applied through a gun or explosive tool assembly at any time while on the surface, ARMED OR UNARMED. Explosive operations have started when explosives are no longer secured as required for shipment and or storage.
8. Instrument cab preparations for explosive operations:
   a. Ensure continuity of logging cable to the safety switch (CSS). Do not disconnect collector plug.
   b. Turn off all AC-powered instrumentation, main circuit breakers, inverters, USPs, AC power generators, and rig power connections. For units that use an isolated power distribution utility leg, follow the official powerdown procedures posted on the power distribution panel.
   c. Turn off safety switch (CSS) and remove key. The key MUST remain outside the wireline unit until the explosive device is introduced into the well to a minimum depth of 200 ft [70 m] below ground level or the seafloor.
9. Procedure for attaching any explosive device (such as CPST, perforating guns, etc.) to the cable:
   a. Arming or disarming a gun must not be performed during a lightning storm.
   b. Arming procedures must not be commenced if such weather, a helicopter or a boat is expected to arrive before the arming operation can be completed and the gun introduced into the well to a minimum depth of 200 ft [70 m] below ground level or the seafloor.
   c. Verify that the Casing-to-Rig Voltage Monitor reads less than 0.25 V.
   d. Clear the line of fire of all personnel.
   e. Attach the explosive device to the head. The individual performing this operation MUST have the safety switch key in their possession at the time. The key MUST remain outside the wireline unit until the explosive device is introduced into the well to a minimum depth of 200 ft [70 m] below ground level or the seafloor.
10. Arming perforating guns (Only the engineer or technician in charge of job may arm a gun):
   a. The cable must be attached to the gun string before the gun string is armed. However, guns that will not be electrically connected to the cable when the head is attached may be armed immediately prior to their use and then attached to the cable.
   b. Confirm that the line of fire is still clear.
   c. Check the gun wires for sparking.
   d. Trim the gun wires and detonating cord to length.
   e. Insert the detonator into the Blasting Cap Safety Tube. Close and secure the top of the tube.
   f. Connect the detonator wires to the gun wires. (Electrically arm the gun.)
   g. Remove the detonator from the Safety Tube and connect it to the detonating cord using detonator crimping pliers or other connector as appropriate (Ballistically arm the gun.)
   h. Store all explosive remnants.
   i. Prepare the gun to run in the hole.
11. Proceed into the well.
12. Safety procedures while in the hole:
   a. At a minimum depth of 200 ft [70 m] below ground level or the seafloor, turn on the safety switch, restore AC power, etc. Essential RF transmitters may be turned on. Continue into the hole.
   b. Tie in, position the gun, and shoot.
   c. Coming out of hole, at a minimum depth of 200 ft [70 m] below ground level or seafloor, reestablish RF silence and prepare the instrument cab as for explosives operations (8 a. through c.). Verify that the Casing-to-Rig voltage is less than 0.25 V. CAUTION - if a lightning storm, helicopter, or boat will arrive before the disarming operation can be completed, the gun must be kept in the well at a minimum depth of 200 ft [70 m] below ground level or the seafloor.
13. If hollow carrier gun(s) did not fire, perform the test to determine if an ongoing thermal event (a hang fire) is occurring. If there is , follow the recovery procedures. Otherwise, immediately relieve any trapped pressure and then disarm the gun(s) (ballistically before electrically using the procedure provided in the Field Operations Manual). Once disarmed, the gun may be disconnected from the cable. If the gun contains HMX explosives that were heated to more than 330°F, disarm it but do not download the explosives from the gun for 48 hr.
14. All guns must be safely relieved of any trapped pressure immediately upon removal from well according to the instructions in the Field Operations Manual.
15. Check the area for detonating cord remnants, charges, etc., and pack them in the explosives remnants box. Pack misfired detonators in the detonator carrying case after shunting their leads. All remnants must be returned to the magazine for storage and then properly disposed of.

S.A.F.E.* Slapper-Actuated Firing Equipment

For operations utilizing an initiator from the family of slapper-actuated firing equipment in place of conventional electrical detonators, the following exceptions apply to the procedures above:

- Radio transmitters can be left powered and used without restrictions
- Casing-to-Rig voltages can exceed 0.25 V, but MUST NOT exceed 40.0 V.
- Electrical cathodic protections systems can be left powered.
- Helicopter and boat operations can be continued.
- Electrical welding operations can be continued except in areas where explosives are stored or are being used.

ALL OTHER procedures must be followed.

An approved exemption is required per Schlumberger QHSE Standard S010 (MOC and Exemption) - Wireline Appendix if any of these procedures cannot be followed.

Refer to Field Operation Manual for details and clarification. REVISION 20-SEP-2005 Placard Part Number H709745 Rev AG

Figure 2. Schlumberger explosives field safety procedures for a wireline-conveyed perforating job.

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Transportation

Safely transporting explosives to and from the wellsite is a key consideration in the logistics of a perforating job. Schlumberger procedures protect the safety of people, equipment, and the communities where we work. Because these procedures incorporate local regulations, they may vary slightly from country to country. Transportation procedures generally require the use of adequate containers and labeling, security measures, and transportation means appropriate for the explosive components. In most cases, loaded guns may be transported to the wellsite; however, they are never transported while electrically and ballistically armed. The arming procedure is always performed at the wellsite.

Wellsite

Schlumberger has assessed the risks of the perforating process by integrating our experience with oilfield explosives and wellsite operations and our comprehensive QHSE management system. To mitigate the identified risks, we have developed a complete set of explosives field safety procedures. The objective of these procedures is to prevent accidental initiation of a perforating gun system or any explosive component.

For conventional electrical detonators, field safety procedures address the hazards of stray and induced voltages and unintentional user initiation. Common sources of stray voltage include faulty rig and unit wiring, incorrect grounding of generators, electrical welding, cathodic protection systems, and meteorological events (i.e., static charges from thunderstorms or dust storms). Common sources of induced voltage are radio frequency (RF) transmitters (used in mobile telephones, wellsite and wireless communications systems, and radio or television transmission). Faulty equipment that produces stray voltage must be repaired. Topdrive systems should be electrically isolated, and other voltage sources, such as welding, cathodic protection systems, or RF transmitters, must be shut down. Wellsite safety procedures also prevent unintentional user initiation through the systematic use of lockout systems and power shutdown procedures.

Adhering to the explosives safety procedures may be inconvenient, especially when radio silence is required, but these procedures are imperative to ensure safer operations when conventional electrical detonators are used.

With the advent of S.A.F.E.* Slapper-Actuated Firing Equipment and the Secure* detonator, the hazards posed by stray and induced voltages initiating unintentional firing have been greatly reduced for stray voltages and eliminated for induced voltages. Most wireline-conveyed perforating services can be performed using Secure or S.A.F.E. detonators.

Tubing-conveyed perforating (TCP) firing heads typically use percussion detonators, which are unaffected by stray and induced voltages. Following field safety procedures together with proper handling of equipment ensures safer TCP operations.

Well operators and all service companies at the location share the goal of safer wellsite operations. Each group typically has its own set of defined procedures for work it performs. If these procedures conflict or tasks overlap or interact, a process must be determined to satisfy all requirements before starting the operation.

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Perforating Fundamentals

History of the perforation

It happens in a flash and it has to be perfect. Millions of investment dollars and months of drilling culminate the instant the perforating charges blast through the steel and cement, clearing a channel for the hydrocarbons. It is a decisive event lasting only milliseconds.

From its beginnings as a black art through its evolution into an exacting science, perforating technology has drawn from many sources. For example, the investigation of a woman's death from a blasting cap revealed the destructive force of a fast-moving metallic jet; the Second World War saw lined shaped charges successfully deployed in various weapons.

By the 1920s, casing strings were commonly cemented throughout the well. The presence of casings across the production interval provided the biggest concern: how to punch a hole through several strings of casing and cement to reach the productive formation?

After mechanical devices were tried and discarded, the next obvious technique was to adapt a bullet firing gun. Los Angeles oilman Sid Mims pursued a patent in 1926, but it was not until 1932 that a device was actually built and tested. Detonation was accomplished by passing an electric current down a conductive wire. It took 11 runs to fire 80 shots, and the well, which was once written off as uneconomical, began to produce commercial quantities of oil. All this was the effort of two men who had acquired Mim's patent, Walter T. Wells and Wilford E. Lane. Their company, Lane-Wells, was the first to offer perforating services to the oil industry and was acquired many years later by Dresser Industries, Inc.

During this period in the mid-1930s, Marcel Schlumberger was also thinking of bullet perforators. His first idea was to position a lengthy gun barrel vertically, with its muzzle bent at a right angle to guide the bullet into the formation. This extraordinarily simplistic solution, known as "the gun to shoot around corners," was soon abandoned. Marcel's final bullet-perforator design looked more conventional and launched Schlumberger successfully into the competitive perforating market in 1938.

Schlumberger offered bullet perforating into the 1960s, and to this day, it is still provided by some perforating companies for special applications. However, the heyday of bullet perforating was undoubtedly the early 1950s, just before shaped charge technology became dominant.

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The history of the shaped charge begins in 1888, when C.E. Munroe observed that explosive cotton indented with the letters USN (for U.S. Navy) left impressions when detonated next to steel plates. Further experimentation with different indentations, or cavities, yielded penetrations that were one-half of the cavity diameter (Fig. 3). The idea of lining a cavity came in 1936, when R.W. Wood, investigating the accidental death of a woman killed by the detonation of a blasting cap, speculated that the blasting cap liner had literally flowed when it detonated and formed a powerful projectile. A few years later, Henry Mohaupt discovered that the portion of the liner nearest the point of detonation reached significantly higher velocities than any other part. Attempting to capitalize on this effect, Mohaupt made a cone-shaped cavity and lined it. The effect was devastating. Enormous penetrations were obtained in solid steel targets.

The shaped charge was first developed for use in World War II antitank weapons, including the bazooka. After the war, shaped charge technology was extended in 1948 to its first commercial application, oilwell perforating. Since then, many advances in shaped charge design have been made through the use of computer simulations, high-speed photography, and development of materials. The basic shaped charge concept, however, remains the same.

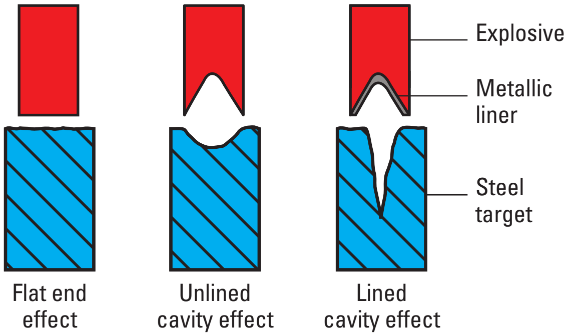

Figure 3. Effect of lined and unlined cavities versus no cavity on steel penetration.

Explosives

Explosives were invented first by the Chinese in the 10th century, and then independently by the Arabs in the 13th century. The “low” black powder explosive was characterized by slow reaction rates (1,650 to 4,900 ft/s) and relatively low combustion pressure. The first “high” explosive was discovered by Ascanio Sobreto in 1846 and made commercially by Alfred Nobel in 1867 with the development of dynamite, which is a combination of nitroglycerin and clayey earth. High explosives, unlike the earlier low explosives, detonate at very rapid rates of 16,400 to 29,500 ft/s and generate tremendous combustion pressure. The terms low and high explosive are still used to characterize chemical explosives.

- *Low explosives* (propellants) are used in modern oilfield applications as power charges for pressure-setting assemblies, bullet perforators, and sample-taker guns, as well as for stimulation procedures such as high-energy gas fracturing and perforation cleanout.
- *High explosives* are used in shaped charges, detonating cords and detonators, and blasting caps. High explosives are further classified by their sensitivity, or ease of detonation.
- *Primary high explosives* are very sensitive and easily detonated by shock, friction, or heat. For safety reasons, primary high explosives, such as lead azide, are used only in electrical or percussion detonators in Schlumberger gun systems.

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- *Secondary high explosives* are less sensitive and require a high-energy shock wave to be initiated (usually provided by a primary high explosive). Secondary high explosives are used in all other elements of the ballistic chain (detonating cord, boosters, and shaped charges). RDX (cyclotetramethylene trinitramine), HMX (cyclotetramethylene tetranitramine), and HNS (hexanitrostibene) are the secondary high explosives used in oilwell perforating.

Temperature affects the rate of reaction, combustion pressure, and sensitivity of chemical explosives. Consequently, maximum safe-operating temperatures are defined for all explosives. Exceeding the temperature ratings may result in autodetonation or reduced performance. The 1-, 100-, 200-, and 400-hr temperature ratings and uses for the various explosives in Schlumberger gun systems are listed in Table 1.

Table 1. Temperature Guidelines for Explosives in Hollow Carrier Guns†

Explosive Type	Temperature Rating‡			
	1 hr	100 hr	200 hr	400 hr
RDX	340°F [171°C]	240°F [115°C]	225°F [107°C]	210°F [99°C]
HMX	400°F [204°C]	300°F [149°C]	285°F [141°C]	270°F [132°C]
HNS	500°F [260°C]	460°F [238°C]	440°F [227°C]	420°F [216°C]

† Ratings for strip guns and other exposed applications vary.

‡ Temperature ratings are set at the highest temperature that retains 100% of the explosive performance. Above these temperatures, explosives show reduced performance and some may autodetonate.

Shaped charges

A shaped charge used in oilfield perforating consists of four components: outer case, main explosive charge, primer charge, and metallic liner (Fig. 4).

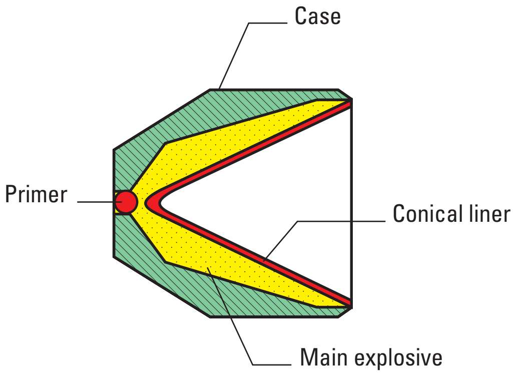

Figure 4. Elements of a shaped charge.

The *outer case* is a containment vessel designed to hold the detonation pressure of the charge long enough for the shaped charge jet to form. Containment is also critical to prevent interference with adjacent charges in the gun system. The case also serves as a mold that shapes the explosive pellet. Steel, zinc, and aluminum are the most common case materials; however, ceramics and glass are also used. Regardless of the material used, tight design and manufacturing tolerances are necessary to ensure correct perforator performance.

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The *main explosive* is normally chosen on the basis of the desired temperature rating of the shaped charge. Of equal importance is the explosive's ability to be mechanically pressed into the conical form typical of a shaped charge. The explosive pellet is pressed to an optimum quality that delivers maximum energy from the detonation to the jet. The explosive pellet is designed to cause the liner to collapse and form the jet. The more homogeneous and uniformly distributed the explosive mixture, the better the jet formation and the deeper the penetration for deep penetrating charges.

The *primer* provides the link between the detonating cord and the main explosive. It consists of the same explosive material as the main charge but has greater sensitivity.

Proper geometric design of the primer and the matching profile in the back of the charge case is of special importance. The explosive shock front must make a 90° turn, typically from a downward vertical direction to a lateral horizontal direction, at the interface between the detonating cord and the shaped charge. During manufacturing, testing verifies the sensitivity of the initiation of the shaped charge versus the thickness of any potential gap between the cord and the charge. Spacers are inserted between both explosive components until the cord no longer initiates the charge. This verification technique is called the Bruceton test.

At the center of the shaped charge is the *liner*. The collapse of the liner under the detonation pressure of the main charge is the critical action in the formation of the perforating jet. For deep penetrating charges, the tip of the jet must travel very fast and establish an optimal velocity profile along the jet. An incorrect velocity profile results in significantly lower penetration.

Initially, liners were constructed of solid metal. These designs successfully produced high-density jets but tended to plug perforation tunnels with debris, called a *slug*. Modern liner designs are based on mixtures of powdered metals that give the jet sufficient density for deep penetration without the undesirable side effect of formation plugging. Powdered metal liners have replaced solid liners in all deep penetrating charges manufactured by Schlumberger.

Big hole charges are used for sand control applications and some fracture-stimulated completions, for which penetration depth is less important than entrance hole size. Solid copper liners were used in older big hole charges because they tended to produce very large holes through the casing and cement. The undesirable effect of the slug was considered to be offset by the large hole sizes and high permeability of the formations where these charges are typically shot. The introduction of PowerFlow* slug-free big hole shaped charge technology eliminated the slug and maximized the area open to flow (AOF).

The high-speed X-ray photograph in Fig. 5 shows the jet created by a deep penetrating charge. The improved charge design produces a straight and symmetrical jet, which can achieve deeper penetration.

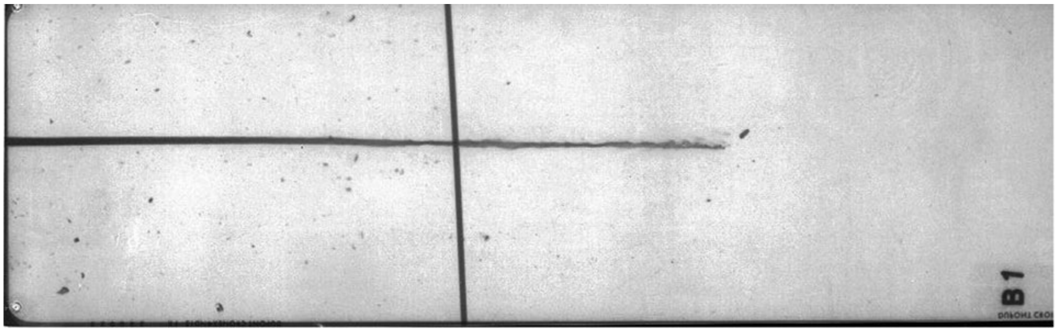

Figure 5. X-ray photograph of a deep penetrating shaped charge.

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Figure 6 shows the jet created by a big hole charge. This jet is designed to produce a conspicuous asymmetry that results from a deliberately heterogeneous velocity profile. The jet shape is the element that creates the big hole, which results from the mass of liner material gathered in such a small space. The jet heterogeneity produces a much shallower penetration as a trade-off for the larger entrance hole.

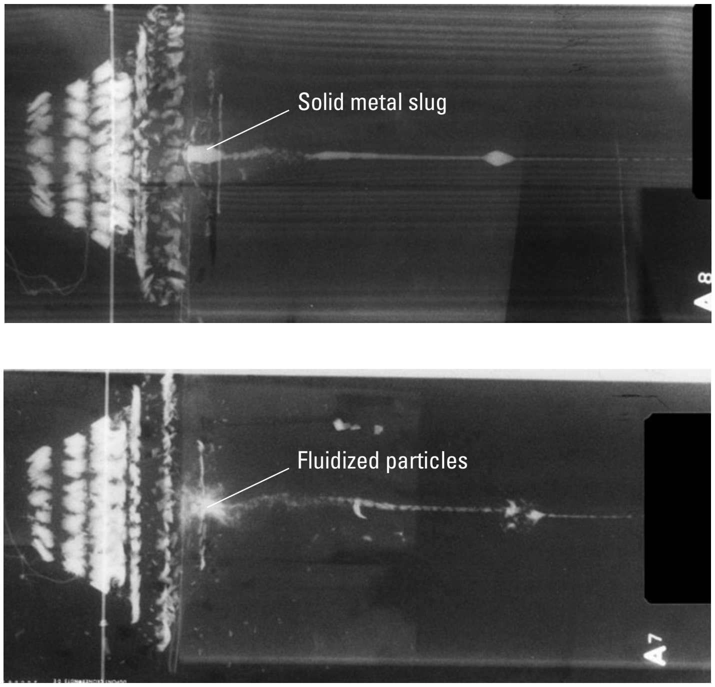

Figure 6. X-ray photograph of a big hole shaped charge.

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Dynamics of shaped charge detonations

Once the shaped charge has been placed in a gun (Fig. 7) and the gun positioned in a well, the detonation begins at time t_0 with the initiation of the detonator. This action initiates an explosive wavefront traveling down the detonating cord at about 4.3 miles/s with pressures of approximately 2.25 million to 3 million psi. The detonating cord, which is in close contact with the primer region of the shaped charge, detonates the primer, which initiates the main explosive. The explosive detonation front advances spherically, reaching a terminal speed of about 5 miles/s and pressure of 4.5 million psi (t_1). The case expands radially about the symmetry axis of the charge while the liner is accelerated inward. At the time of liner impact on its axis, the pressure increases to more than 7.5 million psi and the liner parts into two forward-moving axial streams: a faster stream forming the tip of the jet and a slower stream forming the tail. The jet tip travels at about 4.3 miles/s while the tail travels at about 0.3 miles/s, creating the velocity gradient responsible for the stretching of the jet required to achieve casing and formation penetration (t_2).

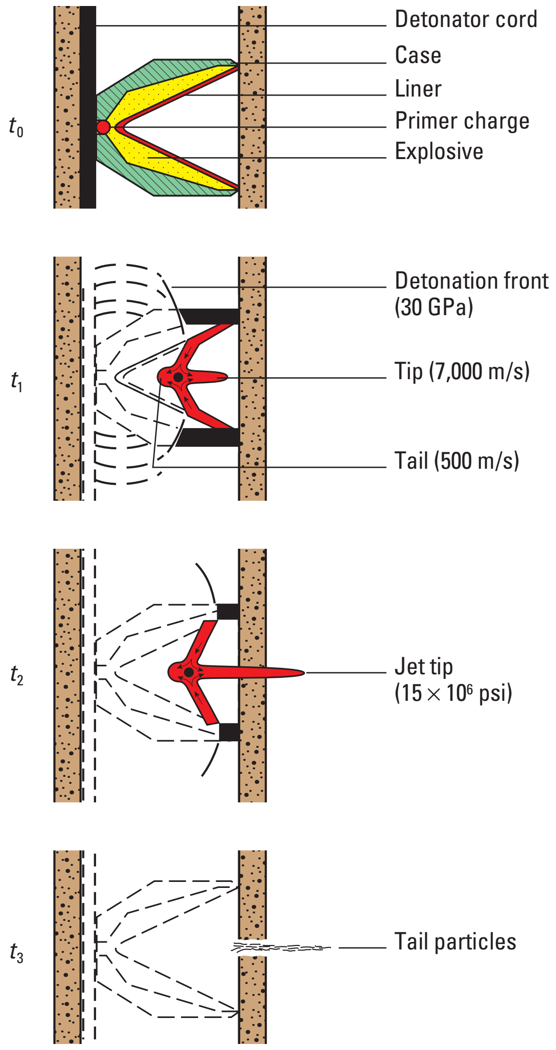

Figure 7. Detonation process of a shaped charge.

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To better understand the penetration process, the jet may be thought of as a high-velocity, rapidly stretching sacrificial rod with typical impact pressures of more than 6 million psi on the casing and 1 million psi on the formation. The enormous pressure of the impact of the jet on the casing causes the casing material to flow plastically away from the jet. As the jet passes through the casing, the cement and formation flow away in the same manner while eroding the tip of the jet until all the energy is expended at the end of the perforation (t_3). Penetration is achieved by the high pressure associated with the impact of the jet pushing aside the various materials, rather than by burning, drilling, or abrasion. Consequently, the quality of a shaped charge perforator depends on achieving a long, consistent jet with the optimum velocity gradient.

Cavity effect

The ability of shaped charge to perforate deeply into metals and rocks is called the *cavity effect*. Figure 3 depicts a cylinder of explosive detonated against a steel bar, with minimal effect. However, with a cavity in the explosive, a crater is formed in the steel bar when the explosive is detonated. If the cavity is lined with metal, the shaped charge effect is clearly seen, with deep penetration into the steel. Note that for oilfield perforating, “tunnel” refers to the portion of the perforation or hole in the casing and cement and “cavity” refers to the hole in the formation.

One of the most important factors affecting charge performance is the symmetry of all the components. A shaped charge is at best a semistable device. Therefore, any deviation that upsets its symmetry yields a crooked jet and thus reduced performance.

Detonating cords and boosters

The *detonating cord* transfers the detonation from the detonator to each shaped charge strung on the cord. The cord consists of a high-explosive core covered by a plasticized braided jacket or lead sheath. The cross section of the cord is either round or flat (Fig. 8).

An important detonating cord parameter is the explosive load per unit of length, which is expressed in grains per foot (gpf). There are 7,000 grains in a pound. Round cord usually carries an explosive load of 70 to 80 gpf. This load is high relative to other cord geometries, so the ballistic transfer is more reliable. Flat ribbon detonating cord carries a much smaller load of explosive—35 to 40 gpf. These cords require special operational precautions to ensure that ballistic transfer occurs without interruption along the cord (e.g., kinks, cuts, poor contact with the shaped charge primer).

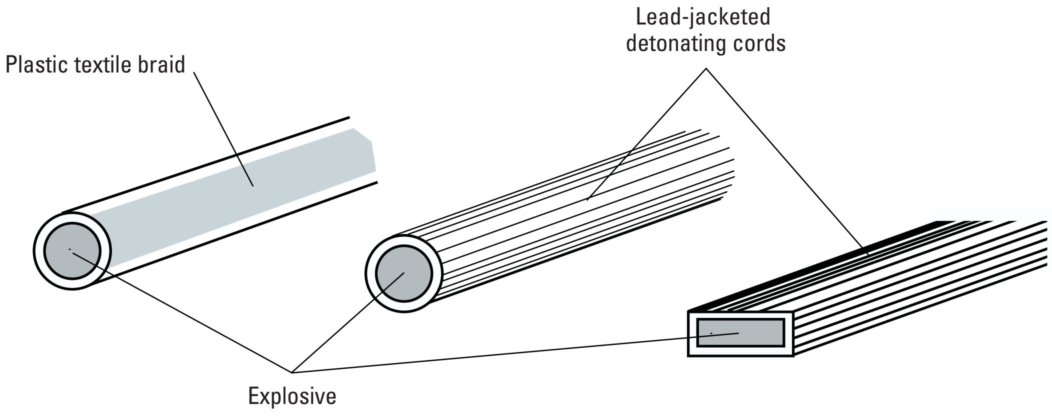

Figure 8. Cross sections of detonating cords.

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Different jacket materials (e.g., nylon, Teflon®, silicone, lead) are used to ensure compatibility with particular downhole fluids in exposed applications. Lead may react with completion fluids and is not used in exposed applications, but it is ideal for high-temperature applications because it resists longitudinal shrinkage and has a higher melting point than synthetic materials have.

The current trend is to eliminate the need for lead-jacketed cord because of cost, fluid compatibility, and environmental issues. Replacement cord-jacketing materials include new polymer compounds for standard applications and Teflon derivatives for high-temperature applications. Flat detonating cords are also being phased out because of their inferior ballistic transfer properties.

A *booster* is an auxiliary explosive charge crimped on the end of a detonating cord to ensure reliable transmission of the detonating wave. The booster consists of a thin aluminum shell containing a secondary explosive charge, which is held against the explosive core of the detonating cord.

Reliable detonation transfer requires the correct explosives combination of the detonating cord and booster:

- RDX cord and RDX booster
- HMX cord and HMX booster
- HNS cord and HP-10 NONA (nonanitroterphenyl) booster with HNS explosives.

Detonators

Conventional detonators

Two types of detonators are generally used to initiate the detonation of a perforating gun: electrical detonators and percussion detonators. Electrical detonators, sometimes called blasting caps, are used in electrically fired guns in wireline applications. The three components of typical fluid-desensitized electrical detonators are the ignition section, air gap, and booster section (Fig. 9).

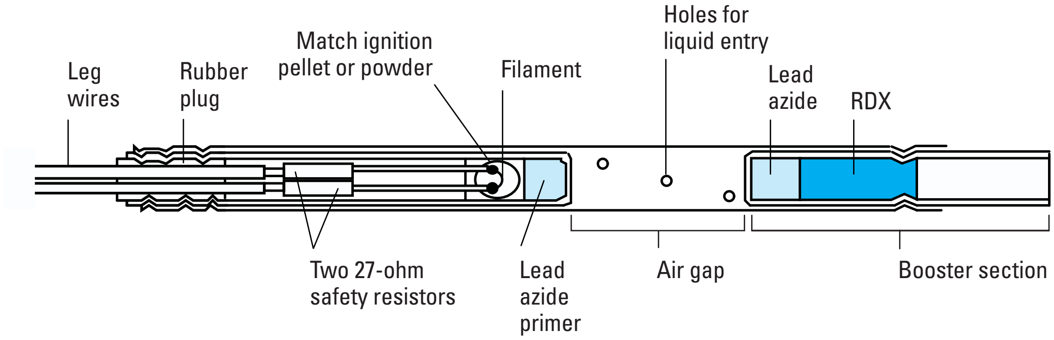

Figure 9. Fluid-desensitized electrical detonator.

The ignition section is energized by passing current through two safety resistors and a filament. The current causes the filament to generate enough heat to ignite the match compound. This burning detonates the primer charge, lead azide, which in turn detonates the booster section across an air gap. The two safety resistors are critical for safer operations overall. They increase the input resistance of the detonators to protect them from low-potential stray voltage.

The air gap prevents detonation of a flooded gun string by allowing fluid entry via the fluid entry holes to effectively prevent initiation of the booster section. This safety feature prevents catastrophic damage that could occur with detonation of a flooded carrier gun. In exposed guns the detonator is pressure sealed and is fluid tight, rather than fluid desensitized.

The booster section is the last link in the fluid-desensitized detonator. The explosive material in the booster section is selected on the basis of the temperature rating of the detonator. The temperature and pressure ratings of detonators used with exposed guns must never be exceeded or autodetonation may occur.

Fluid-tight detonators, with pressure-sealed components, are used for exposed applications (Fig. 10). These detonators are not fluid desensitized.

Percussion detonators are used in TCP systems (Fig. 11). They are mechanically fired by a firing pin striking a pressure-sealed membrane that covers a primer charge consisting of lead azide. The impact of the striking firing pin generates a force that detonates the primer charge, which in turn detonates the booster section.

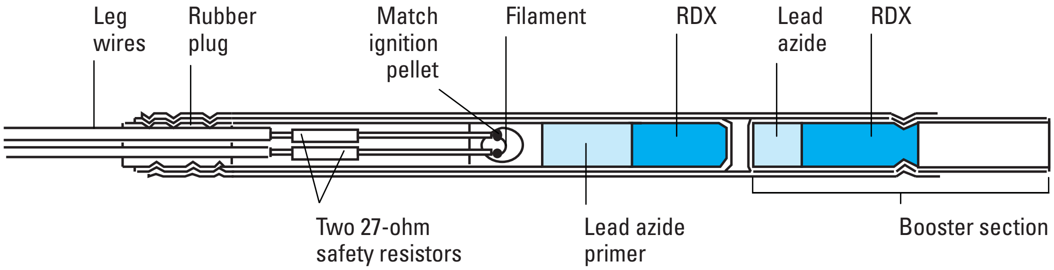

Figure 10. Pressure-sealed, fluid-tight electrical detonator.

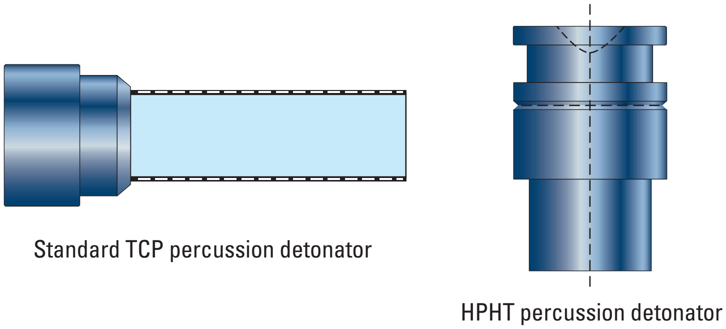

Figure 11. Percussion detonator.

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S.A.F.E. Slapper-Actuated Firing Equipment and Secure detonators

S.A.F.E. technology

The S.A.F.E. detonating system was developed to provide immunity to electric potential differences (EPDs) created by RF radiation, impressed current for cathodic protection, electric welding, high-tension power lines, and inductive coupling from large induction motors such as topdrives on drilling rigs. S.A.F.E. technology eliminates the need to shut down radio communication and other vital equipment during perforating jobs.

The S.A.F.E. detonating mechanism is an exploding foil initiator (EFI), which has proved resistant to stray voltages because of the high currents required for detonation. It contains no primary high explosives.

As shown in Fig. 12, the application of shooting power instantly vaporizes a metal foil, which causes a neighboring (secondary) high-explosive pellet to detonate and shear a small aluminum flyer. The flyer travels across a fluid desensitization gap in the EFI housing and strikes a booster that initiates the detonation of the gun.

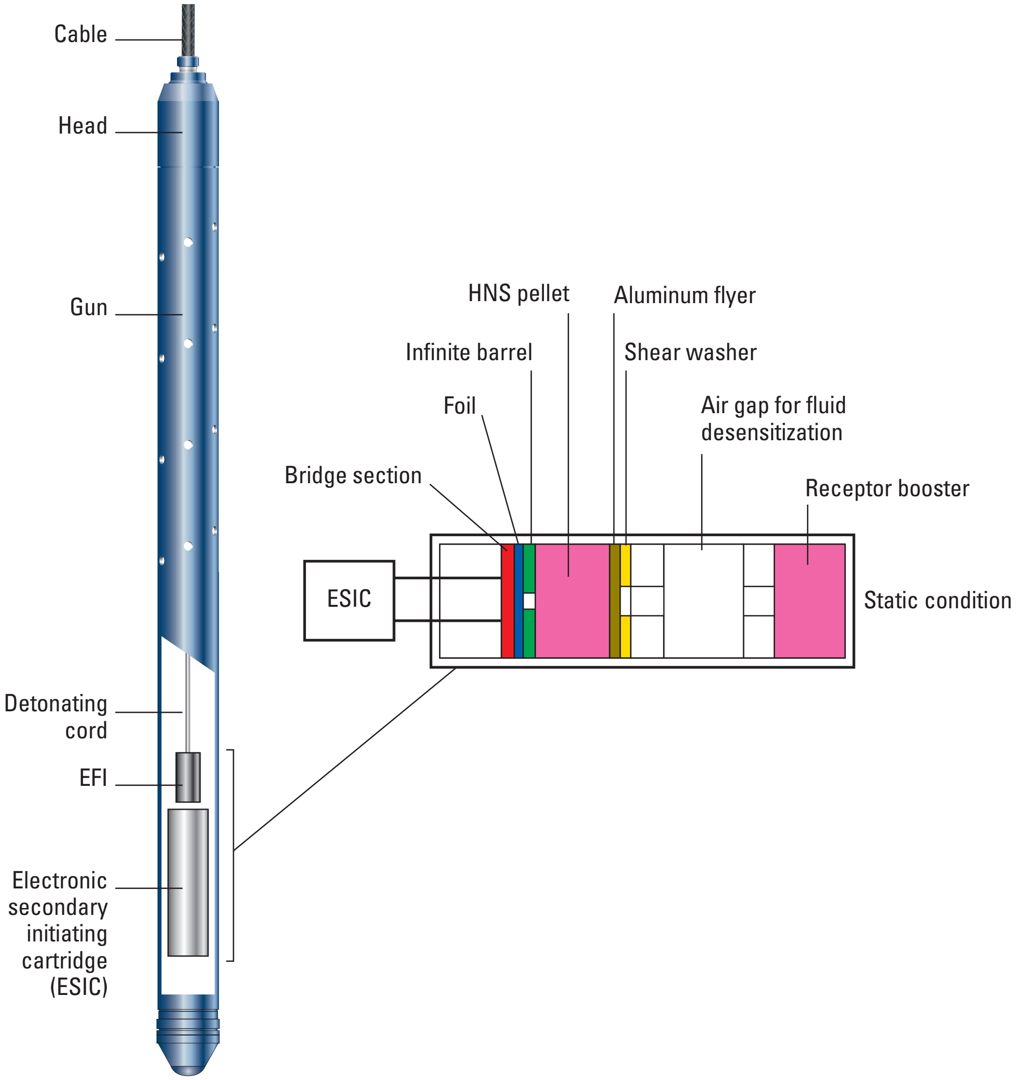

Figure 12. EFI operation.

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Secure detonator

The Secure detonator (Fig. 13) is the third generation of S.A.F.E. initiators. It performs like a conventional detonator but without the added safety concerns, cost, and inconvenience of shutting down RF transmitters, turning off cathodic protection, and postponing welding operations.

The use of EFI technology makes the Secure detonator one of the safest detonators in the industry. Its inherent safety results from the specific high voltage and current pulse required for detonation. The power threshold for the EFI technology in the Secure detonator is 3 MW, compared with 1 W for a typical standard resistor detonator and 2 W for a semiconductor bridge detonator. No primary high explosives are used in the detonator. The Secure detonator does not contain pyrotechnics, which may burn to detonation if exposed to fire.

The Secure detonator does not require a downhole cartridge to provide the electric pulse to initiate the firing sequence. All electronics are fully expendable and contained in the detonator package. As a result, operations are simple, reliable, and flexible.

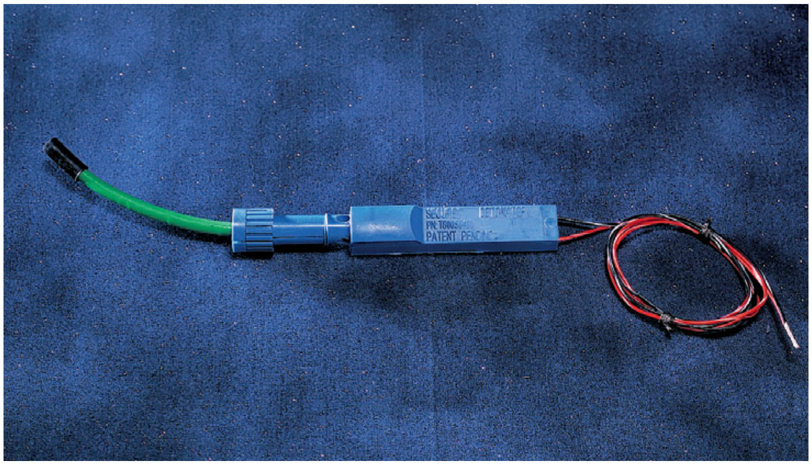

Figure 13. Secure detonator.

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Factors affecting perforator performance

The factors that affect perforator performance can be divided into two groups: target properties and gun system properties.

Target properties

Effect of rock strength

The strong effect of compressive strength on perforation penetration was recognized long ago by Thompson (1962) and later with modification by Weeks (1974). The empirical relationship shows that penetration in a high-strength rock (15,000 to 20,000 psi) is about one-half of that in a medium-strength rock (5,000 to 10,000 psi).

Experimental data from concrete and actual rock samples demonstrates that the penetration reduction in real rock depends mainly on the compressive strength of the rock (Behrmann and Halleck, 1988a; Halleck and Behrmann, 1990). The reduction in penetration resulting from rock strength also depends on the shaped charge. Figure 14 shows the combined effect of rock strength and shaped charge type on a set of tests in various rock types. The dashed lines are the penetration model of SPAN* Schlumberger perforating analysis. The term alpha is the dynamic strength factor.

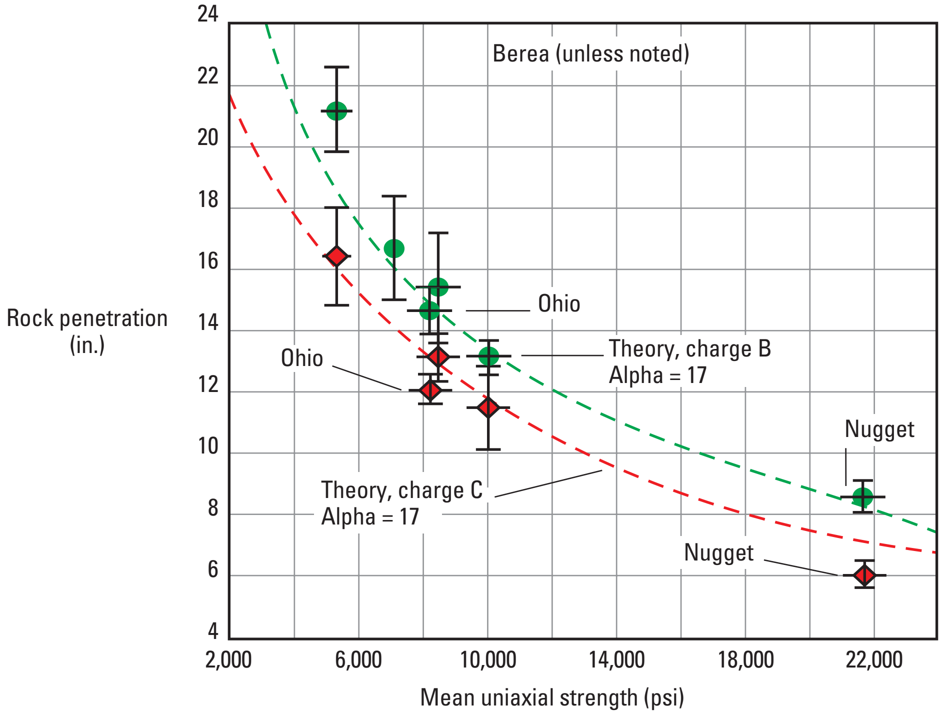

Figure 14. Effect of compressive strength on target penetration.

SPAN Schlumberger perforating analysis calculates the penetration of shaped charges at downhole conditions. SPAN analysis uses a semiempirical approach that combines experimental data (Berea slab tests and API RP 19B Section 1 tests) with penetration theory. This approach is necessary because rock penetration data are not available for all charges shot in rocks of all strengths. Normalized penetrations are calculated using penetration in a rock of 7,000-psi strength as a reference and corrected for effective stress (Fig. 15).

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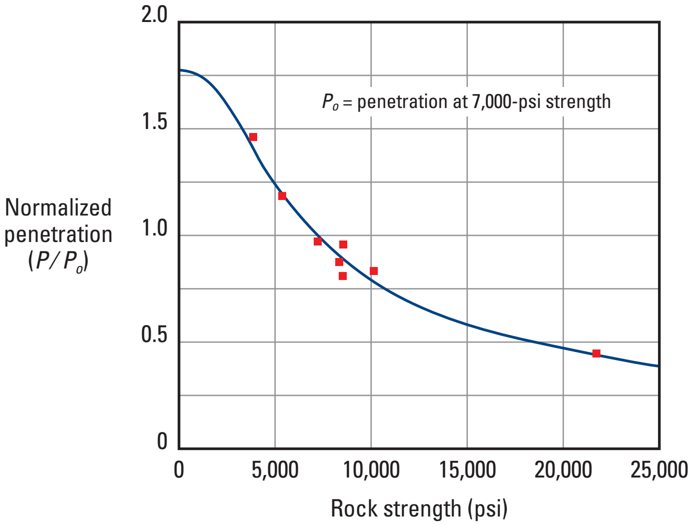

Figure 15. SPAN analysis normalizes penetration for rock strength and corrects for effective stress.

Aseltine (1985) generated striking X-ray photographs of jets being consumed as they proceed through rock targets. Rocks are active targets that interact with the jet. The jet is modified both by the texture of the formation and the nature of the saturating fluid. For example, Fig. 16 shows X-ray photographs of shaped charge jets after penetrating three different targets: dry limestone with a cylindrical boundary of cardboard, dry limestone with a cylindrical boundary of steel, and kerosene-soaked limestone with cardboard. He concluded that penetration is reduced further than expected and that the formation appears to have greater intrinsic strength because of jet formation interaction during penetration. This effect is not seen in steel or concrete targets, which do not interact with the jet.

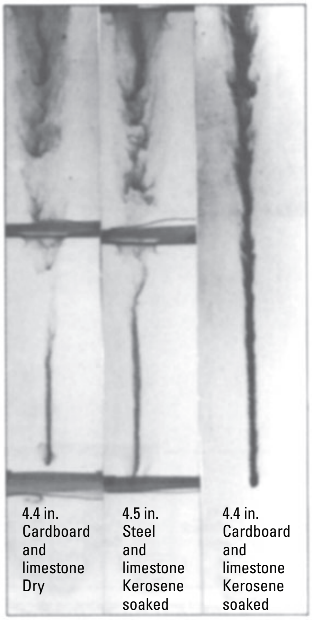

Figure 16. X-ray photographs of jets after penetrating three different limestone targets. (© 1985 Society of Petroleum Engineers Inc., Aseltine.)

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Effect of in situ stress

Other tests performed at the same time as the rock strength experiments (Halleck et al., 1988) were conducted in a polyaxial stress frame capable of generating large confining pressures on rock samples approximately 1 m^3 in volume. The confining pressure was partially balanced by pore pressure to show that effective stress (estimated as the confining pressure minus pore pressure) was the correct correlation parameter.

This study shows that penetration reduction caused by in situ stress depends on the charge, with smaller charges producing a comparatively greater fractional reduction. Figure 17 shows the ratio of stressed to unstressed rock penetrations for four different shaped charges shot in the same target type.

The reduction in penetration ranges from 10% to 50% of the penetration in an unstressed rock. Penetration reduction increases as rock stress increases, and therefore the effect increases with time in producing reservoirs because of pressure depletion of the reservoir.

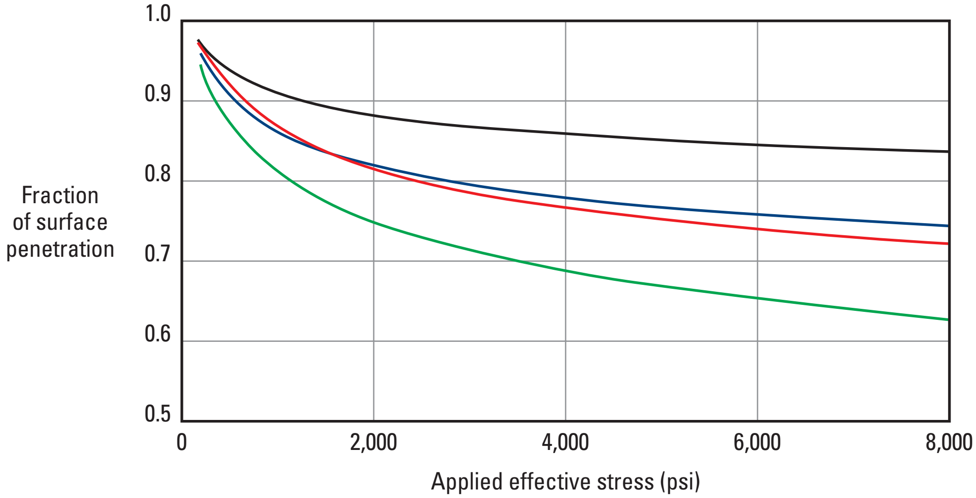

Figure 17. Normalized penetration reduction as a function of applied stress.

Combined effect of formation strength and in situ stress

The previously cited report by Halleck and Behrmann (1990) describes shot tests performed with different shaped charges in Berea, Ohio, and Nugget sandstones. These three formations differ widely in their intrinsic rock strength. The effect of increasing effective stress (e.g., caused by reservoir depletion) on perforation penetration is greater in soft rocks than in harder rocks.

SPAN analysis models the perforation reduction caused by stress and its interdependence on the rock strength based on experimental data from the previously cited studies. The data were used to develop the relation for perforation penetration reduction under stress for three generic charges shot into three different strengths of sandstone. Interpolation of these relations yields the penetration reduction versus stress for given rock strengths. Figure 18 shows the variation of the parameter m (the ratio of in situ penetration) over API Section 1 penetration as a function of rock strength for different values of effective stress. This ratio applies to in situ penetrations less than 30 in. SPAN analysis includes another formula for in situ penetrations greater than 30 in.

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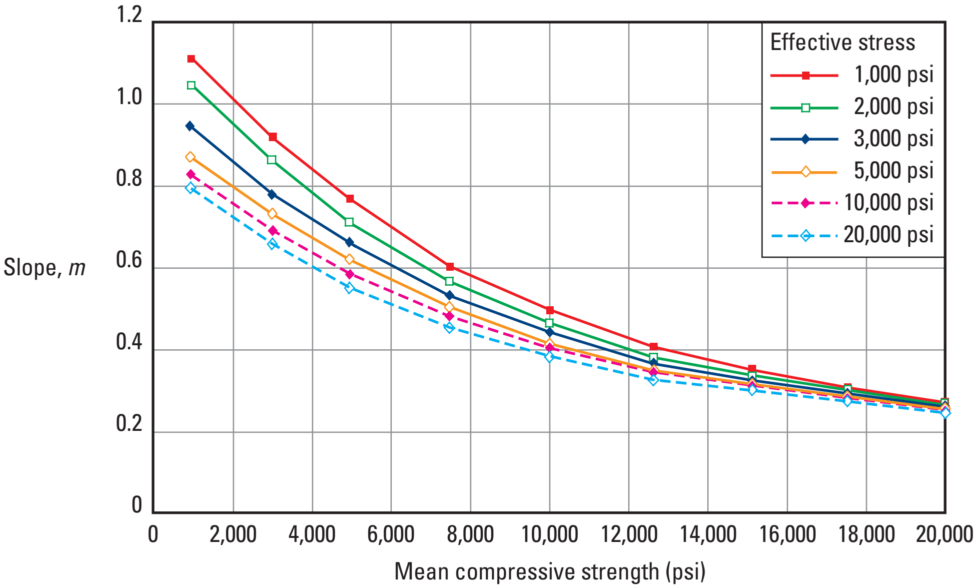

Figure 18. Ratio of SPAN-modeled penetration versus API Section 1 penetration as a function of rock strength and effective stress.

Effect of sand grain size and distribution

Experimental results of tests performed in concrete targets (Brooks et al., 1998) show that the size of the sand used in the targets can significantly affect shaped charge penetration. Penetration is less in coarse sand targets than in fine sand targets of the same compressive strength. The difference in penetration can be as great as 250% in very fine sand (0.2 mm) versus coarse-sand (38 mm) targets.

By implication, the grain size of the formation rock can greatly affect shaped charge penetration. A jet in coarse-grained rock penetrates less than in a finer grained rock. Figure 19 shows the effect of quartz sand size on penetration for a 34-g charge.

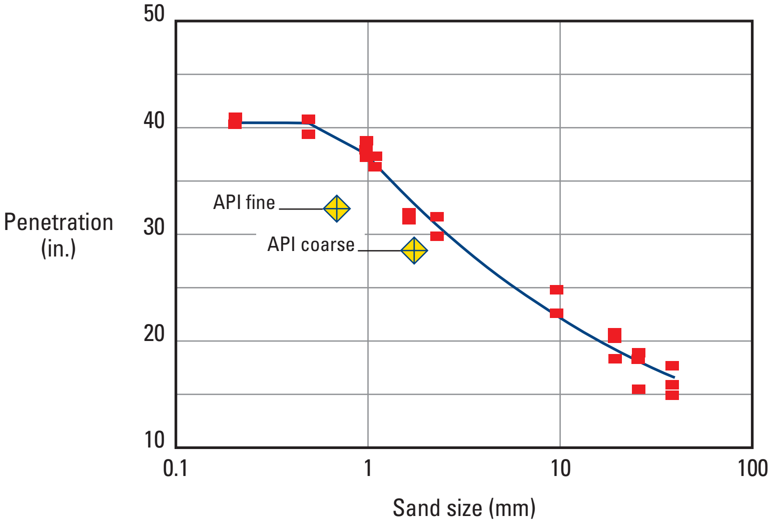

Figure 19. Effect of the size of quartz sand on penetration for a 34-g charge.
(© 1998 Society of Petroleum Engineers Inc., Brooks et al.)

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A 10% to 12% variation in penetration test results is expected in normal testing because of the current tolerances in the sand size specification for API Section 1 concrete targets. This variation has led API to modify its procedures. The current API RP 19B specifications call for 16–30 frac sand in the targets. Using sand of a calibrated size ensures far less variation than specified in the previous RP 43 specifications.

Effect of rock density

The effect of rock density on penetration generally receives little attention because formation rock densities do not vary greatly on a scale that is important to perforation. Basic penetration theory predicts that penetration is proportional to the square root of the jet/target density ratio.

Effect of pore-saturating fluid

Experiments show that penetration is less in formations with gas-filled pores than in formations with liquid-filled pores. This effect was first reported by Aseltine (1985). Figure 20 shows that the jet is far shorter in a Berea target saturated with gas than in Berea saturated with kerosene. Bird and Blok (1996) reported penetration reduction in gas-saturated versus liquid-saturated cores.

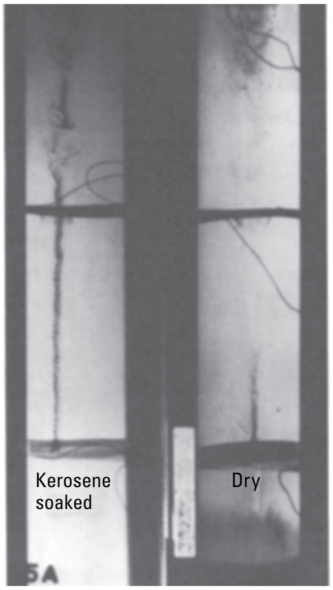

Figure 20. Compared lengths of jets in dry versus kerosene-saturated Berea cores.
(© 1985 Society of Petroleum Engineers Inc., Aseltine.)

Casing effects

Effect of casing strength on entrance hole

Several factors affect the diameter of the perforation entrance hole in casing, especially casing strength and thickness. The entrance hole diameter decreases as casing hardness increases. For example, the entrance hole diameter created in J55 casing, which has a Brinell hardness of 174, correlates to the hole diameter of other casings:

$$d_p = \left(d_{p\mathrm{J55}}\right)\left[\frac{2980.8}{\left(2{,}250 + 4.2H\right)}\right]^{0.5}, \tag{1}$$

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where

d_p = hole diameter in casing with Brinell hardness H

d_{pJ55} = hole diameter in J55 casing (Brinell hardness 174).

This correlation is plotted in Fig. 21. The x-axis scale also lists the standard casing grades. Table 2 shows the equivalence among casing grades, Brinell and Rockwell hardness values, and corresponding steel yield strengths.

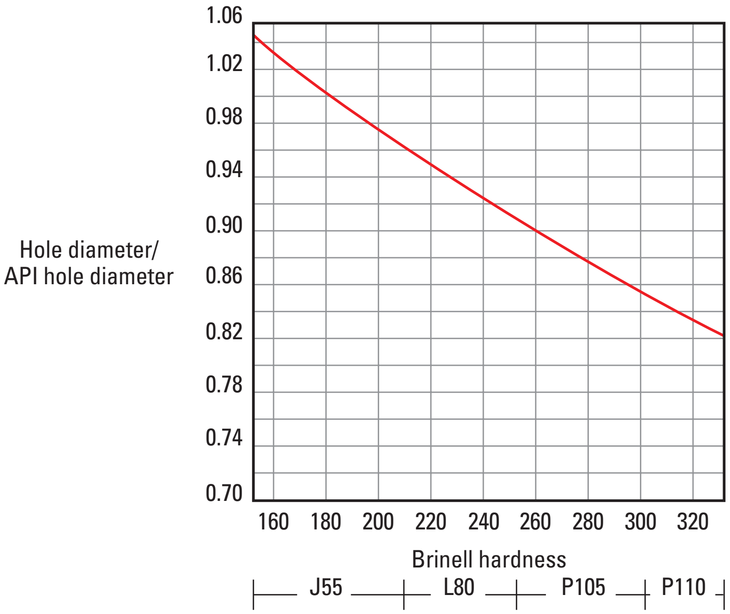

Figure 21. Effect of casing strength on entrance hole diameter of a shaped charge.

Table 2. Casing Grade Equivalents

Casing Grade	Hardness Number			Minimum Yield (psi)	Tensile Strength (psi)
	Rockwell B	Rockwell C	Brinell		
H40	68–87	–	114–171	40,000	60,000–84,000
J55	81–95	–	152–209	55,000	75,000–98,000
K55	93–102	14–25	203–256	55,000	95,000–117,000
C75	93–103	14–26	203–261	75,000	95,000–121,000
L80	93–100	14–23	203–243	80,000	95,000–112,000
N80	95–102	16–25	209–254	80,000	98,000–117,000
C95	96–102	18–25	219–254	95,000	103,000–117,000
S95	–	22–31	238–294	95,000	109,000–139,000
P105	–	25–32	254–303	105,000	117,000–143,000
P110	–	27–35	265–327	110,000	124,000–154,000
Y150	–	36–43	327–400	150,000	159,000–202,000

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Effect of casing thickness on entrance hole

Casing thickness affects the entrance hole size of all charges; however, the effect is greatest for big hole charges because they are intended to maximize hole size. Faced with increased wall thickness, a standard charge creates a tapered hole with a larger diameter on the inner casing wall than the outer casing wall. This geometry is not acceptable because flow is restricted by the area corresponding to the smaller hole in the outer wall. Special thick-wall charges are designed with a modified liner profile that distributes energy unevenly along the profile of the jet to create casing holes with the same diameter.

Effect of casing thickness on penetration

If all other parameters are assumed to remain constant, the penetration achieved by a shaped charge in the formation decreases as casing thickness increases. Decreased penetration occurs because the jet uses some of its energy making its way through the casing, whether thick or thin. Formation penetration in concrete is reduced by approximately 1 in. for every 0.25 in. of additional thickness in the steel casing.

Effect of entrance hole and shot density on casing strength

Perforations reduce the collapse strength of casing. The relative remaining casing strength depends on

- diameter of the perforation entrance hole in the casing wall
- number of perforations
- distance between perforations along the casing length (determined by shot density and phasing pattern)
- change in strength of the casing in the region around the perforation (i.e., casing mechanical properties are altered by work hardening caused by the perforation jet passing through the casing)
- support and integrity of the formation and cement sheath around the casing.

Calculation of the collapse pressure or remaining casing strength determines the worst-case value because many of the these factors are not taken into account. Open perforations mean little or no differential pressure across the casing at its weakest point, so the concept of casing collapse pressure is hypothetical. Figures 22 and 23 graph the variation in collapse pressure with shot density and phasing for some perforation patterns on the basis on finite-element calculations. The remaining casing strength for other combinations of shot density and shot patterns can be estimated as

$$\frac{\text{final strength}}{\text{initial strength}} = \frac{\left(L - d_{EH}\right)}{L}, \tag{2}$$

where

L = distance between shots in the longitudinal direction

d_{EH} = perforation entrance hole diameter for the particular grade of casing.

For example, a 4½-in., 12 spf, 135°/45° phased gun has a shot every 8 in. in the longitudinal direction. For an assumed 0.70-in. d_{EH} in the casing, the remaining casing strength is

$$\frac{\left(8 - 0.70\right)}{8} = 0.9125 = 91\%.$$

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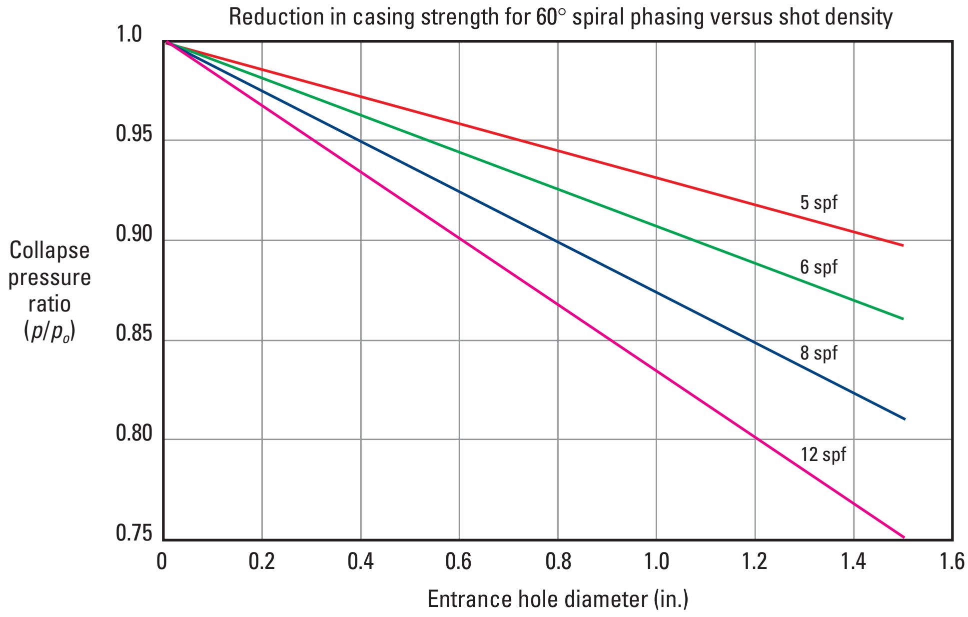

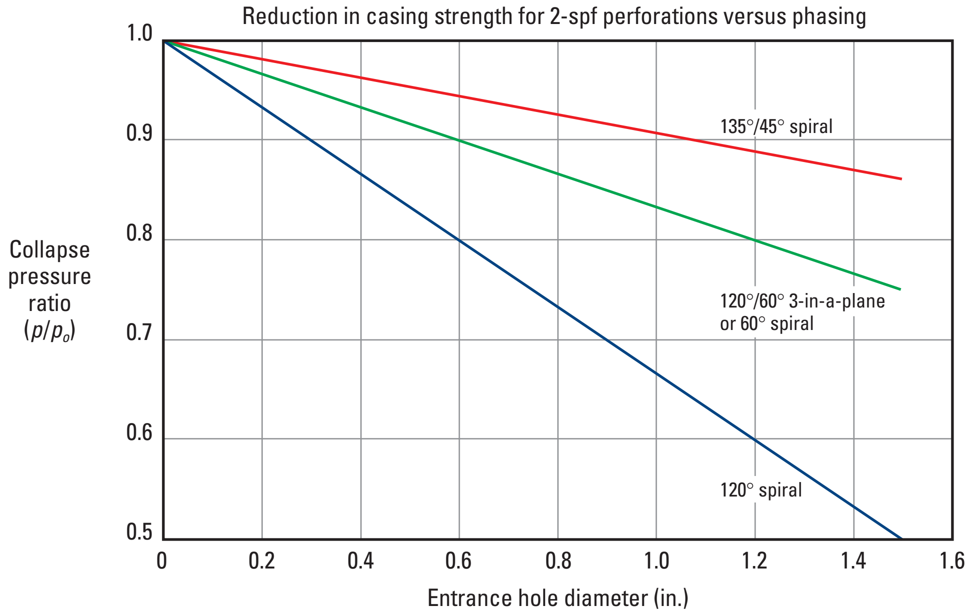

Figures 22 and 23. Reduction in casing strength for capsule guns and HSD gun systems.

If the casing is shot twice with the same gun, the worst case results if the charges align:

$$\frac{8-\left(2\times 0.70\right)}{8}=0.825=83\%.$$

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Table 3 lists some examples of remaining casing strength based on this calculation method.

Table 3. Remaining Casing Strength for Common HSD* High Shot Density Guns with Big Hole Charges

Gun	Shot Density (spf)	Phasing (°)	Longitudinal Distance Between Shots, L (in.)	Charge and Entrance Hole Diameter, d_{EH} (in.)	Remaining Casing Strength (%)
3⅛-in. HSD	10	135/45	9.6	PowerFlow 3412, 0.67	93
3⅜-in. HSD	12	135/45	8.0	PowerFlow 3412, 0.64	92
4½-in. HSD	12	135/45	8.0	43CJ UltraPack*, 0.75	91
4⅝-in. HSD	21	120/60	3.4	PowerFlow 4621, 0.83	76
6⅝-in. HSD	18	120/60	4.0	PowerFlow 6618, 0.91	77
7-in. HSD	18	120/60	4.0	PowerFlow 7018, 1.15	71

Effect of multiple casings on entrance hole

Multiple casing strings greatly affect the entrance hole of big hole charges. Tests of big hole charges have shown entry reductions of 50% to 70% in a second string and up to 40% to 50% in a third string. The distance and material between strings also have an effect: The greater the distance and the denser the material between strings, the smaller the resulting hole.

Table 4 lists typical hole size reduction factors for specific geometries in tests with big hole charges performed at SRC.

Table 4. Hole Size Reduction for Common Big Hole Charges

Gun Type	Charge	Test (No.)	$d1$ (Average in.)	$d2$ (Average in.)	$d2/d1$	$d3$ (Average in.)	$d3/d1$
2⅛-in. Enerjet*	Big Hole, RDX	1	0.54	0.30	56%	–	–
2-in. HSD	PowerFlow, 2006	1	0.46	0.26	56%	–	–
2½-in. HSD	35B UltraPack, RDX	2	0.63	0.27	43%	–	–
3⅛-in. HSD	PowerFlow 3412, HMX	2	0.67	0.25	37%	–	–
3⅜-in. HSD	PowerFlow 4621, HMX	1	0.63	0.35	56%	–	–
4½-in. HSD	34JL UltraJet*, HMX	2	0.325	0.25	77%	–	–
4½-in. HSD	51C UltraPack, RDX	2	0.72	0.52	72%	0.28	39%
5-in. HSD	PowerFlow 4621, HMX	2	0.65	0.28	43%	–	–
5-in. HSD	58C UltraPack, RDX	2	0.735	0.49	67%	0.41	56%
6-in. HSD	52C UltraPack, RDX	2	0.58	0.355	61%	0.215	37%

Note: $d1$ = diameter of inner casing entrance hole, $d2$ = diameter of intermediate casing entrance hole, $d3$ = diameter of outer casing entrance hole

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Table 5 lists similar statistics for deep penetrating charges. Entrance hole size is reduced by 65% to 80% in a second string and by about 60% in a third string. The reduction of entrance hole size has less effect on deep penetrating charges than on big hole charges because the optimization parameter is penetration rather than entrance hole size.

In the two datasets in Tables 4 and 5, the variation from an average value of the ratios of hole size reduction mainly represents the effect of various environmental parameters specific to test conditions, including gun-to-casing clearance, fluid type, material in the casing annuli, casing sizes and grades, and casing-to-casing eccentricity.

Another concern is perforating through one or more casings but not perforating a larger outer casing. Special shaped charges are designed for this need. Each charge must be customized for a specific geometric and fluid environment.

Table 5. Hole Size Reduction for Various Deep Penetrating Charges

Gun Type	Charge	Test (No.)	*d*1 (Average in.)	*d*2 (Average in.)	*d*2/*d*1	*d*3 (Average in.)	*d*3/*d*1
1¹¹⁄₁₆-in. HyperDome*	20A HyperDome, RDX	2	0.22	0.13	59%	–	–
1¹¹⁄₁₆-in. Power Enerjet*	1¹¹⁄₁₆-in. Enerjet 3, RDX	1	0.31	0.15	48%	0.11	35%
2⅛-in. Power Enerjet	2⅛-in. Power Enerjet, HMX	4	0.25	0.19	76%	–	–
2½-in. Power Enerjet	2½ Power Enerjet, HMX	3	0.33	0.22	67%	–	–
2⅞-in. HSD	PowerJet* 2906, HMX	2	0.245	0.195	80%	–	–
2⅞-in. HSD	38A UltraJet, HNS	2	0.295	0.23	78%	0.19	64%
3⅜-in. Port Plug gun	38A UltraJet, RDX	2	0.26	0.235	90%	–	–
3⅜-in. HSD	PowerJet 3406, HMX	1	0.43	0.25	58%	–	–
4½-in. HSD	PowerJet 4505, HMX	4	0.31	0.25	81%	0.25	81%
4½-in. HSD	51B HyperJet* II, RDX	2	0.455	0.34	75%	0.27	59%

Note: *d*1 = diameter of inner casing entrance hole, *d*2 = diameter of intermediate casing entrance hole, *d*3 = diameter of outer casing entrance hole

Effect of wellbore pressure

Rock tests conducted concurrently with those reported by Behrmann and Halleck (1988a) included experiments on the effect of wellbore pressure on perforator penetration depth. These pressure effects tests (Behrmann and Halleck, 1988b), performed on stressed Berea sandstone targets, showed that wellbore pressure can significantly reduce penetration, typically in the range of 22% to 28% for pressures as high as 15,000 psi. The reduction in penetration depends on the shaped charge used and the gun-to-casing clearance.

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Gun system properties

Effect of jet quality

If the jet is not perfectly straight and homogeneous, variations in its diameter increase interaction between the jet and formation, which further reduces penetration. Brooks et al. (1998) discusses *crooked jet* and *fat jet effect* characteristics of poorly manufactured shaped charges.

A crooked jet is not perpendicular to the target and thus interacts with the edge of the perforation as the jet proceeds through the formation. A fat jet has bulges and thinner portions. Both situations increase the perforation diameter at the expense of penetration.

Manufacturing of shaped charges plays a key role in actual penetration performance because the reduction in jet penetration caused by poor jet quality can be significant, even if the decrease in manufacturing quality is minor. Manufacturing must be virtually flawless to ensure that all charges achieve near-perfect performance. Lax or inconsistent manufacturing procedures invariably result in poor penetration performance.

Effect of charge and gun positioning

Penetration

Figure 24 represents a hollow carrier casing gun positioned in the wellbore for definition of the gun-to-casing clearance and charge standoff. The charge standoff allows adequate space for the liner to collapse and the jet to develop before it hits the interior wall of the gun. Gun-to-casing clearance negatively affects perforation penetration because the jet expends energy as it travels through the completion fluid.

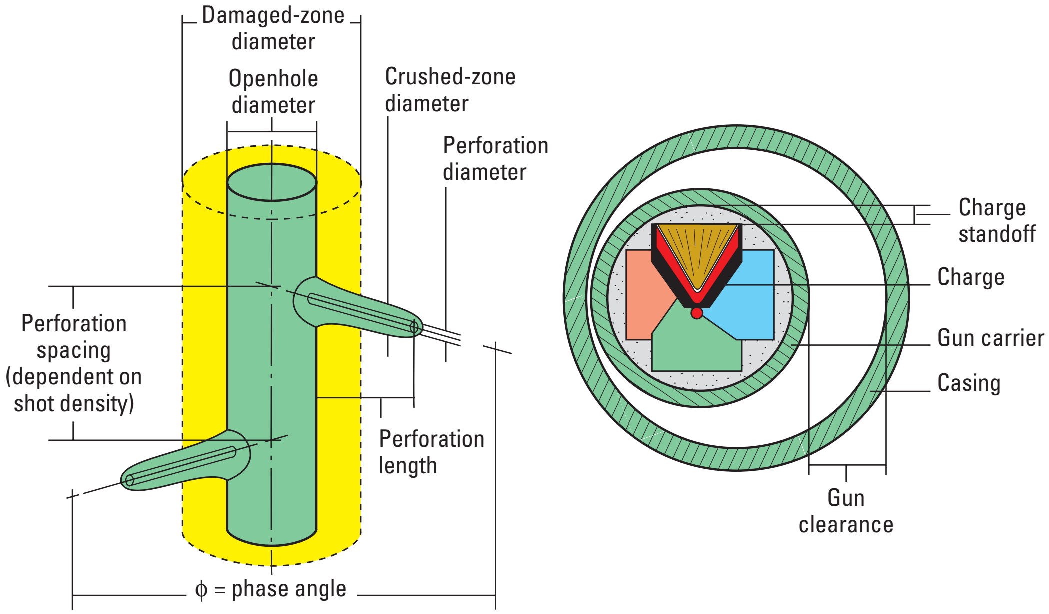

Figure 24. Gun positioned in wellbore with definition of the geometry.

The effect of gun-to-casing clearance on perforation penetration is more pronounced on deep penetrating charges than on big hole charges. The preferred practice is to run HSD deep penetrating gun systems eccentered, which creates maximum-penetration perforations where the gun and casing come into contact (i.e., where there is near-zero clearance). Nevertheless, gun-to-casing clearance generally does not significantly affect the penetration of deep penetrating charges until the clearance exceeds approximately 30% of the gun diameter. This effect is shown qualitatively on Fig. 25.

Big hole gun systems must be run with a controlled clearance, as explained in the following "Entrance hole."

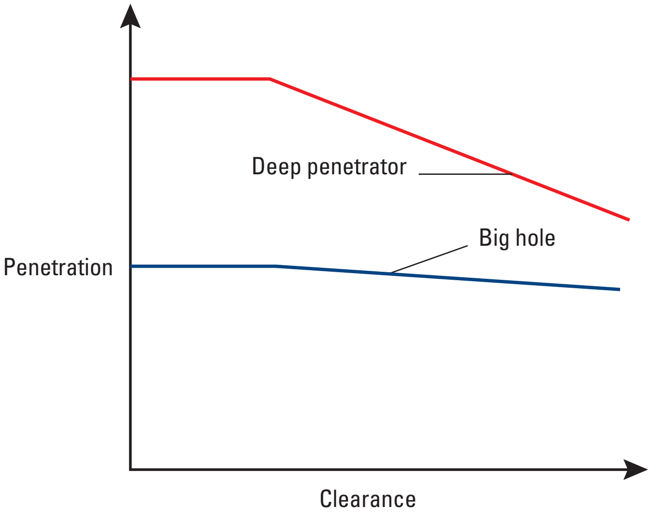

Figure 25. Qualitative effect of clearance on penetrative depth of a deep penetrating charge.

Entrance hole

Gun-to-casing clearance may greatly affect the size of the entrance hole even though it has a relatively small effect on penetration, especially of a big hole charge. Reduction of the entrance hole size correspondingly affects the total AOF, which is one of the key design parameters optimized for big hole systems.

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Figure 26 illustrates the relationship between the entrance hole and gun-to-casing clearance for a big hole charge. Optimum charge performance occurs with the gun positioned in the center of the wellbore, corresponding to point C on the figure. At this position, the entrance hole is largest, the total AOF is greatest, and the holes have consistent diameters. If the gun is eccentered (i.e., lying against the side of the casing), however, some charges will be shot at near-zero clearance (point A) and some will be shot at near-maximum clearance (point E). Thus, without gun positioning, entrance hole sizes may be anywhere along the curve from points A to E, depending on the random location of the gun in the wellbore.

The average entrance hole size can be improved substantially by standing the gun off the casing as illustrated by point B (minimum clearance with standoff) and point D (maximum clearance with standoff). With the gun in this position, the range of entrance hole sizes is between only points B and D on the curve.

Big hole charges provide optimum entrance hole diameter when the gun is positioned at the center of the casing. The hole in the gun is actually smaller than the hole in the casing.

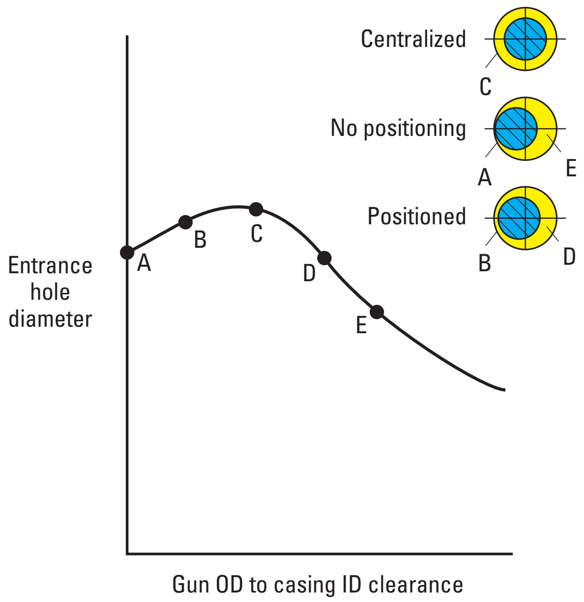

Figure 26. Typical effect of clearance on entrance hole size for a big hole charge.

Productivity and Skin Effect

Basics of skin effect

The productivity of a reservoir depends heavily on the value of the near-wellbore decrease in pressure. This value results from reduction in the total pressure drawdown available to bring fluids from a distance r_e (reservoir drainage radius) to the wellbore at a distance r_w (wellbore radius).

Figure 27 shows a typical pressure profile as a function of the distance r from the axis of the well. At distance r_e, the pressure equals the undisturbed reservoir pressure p_e, and at distance r_w, the pressure equals the flowing wellbore pressure p_{wf}. However, because of the *skin effect*, only a fraction of the total drawdown $(p_e - p_{wf})$ is available to bring fluids from remote regions to the near-wellbore region. The remaining pressure difference, which may be a substantial fraction of the total drawdown, is used to get the fluids past the skin, or damaged, zone and into the wellbore. Eliminating or overcoming the skin effect is critical to enhance the productivity of a perforated completion.

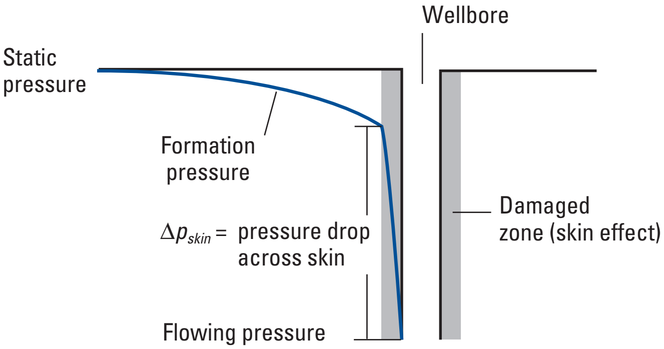

Figure 27. Pressure profile in a well with skin effect.

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Productivity index and productivity ratio

The radial flow model (Fig. 28) provides a good approximation of the geometry of fluid flow from a reservoir into a well. Radial fluid flow from the reservoir to the well implies straight flowlines, perpendicular to the wellbore axis and convergent toward that axis. Conventional radial flow equations also imply that the well is vertical. Thus, the flowlines are horizontal (otherwise, the effect of gravity requires modeling). Based on these assumptions, the reservoir-to-wellbore pressure drop (drawdown) is given by the steady-state radial flow equation:

$$p_e - p_{wf} = \frac{(qB\mu)}{2\pi kh}\left(\ln\frac{r_e}{r_w} + s_t\right), \tag{3}$$

where

q = flow rate at the surface

B = formation volume factor

μ = fluid viscosity

kh = permeability-thickness product

s_t = total skin effect and

ln is the natural logarithm function.

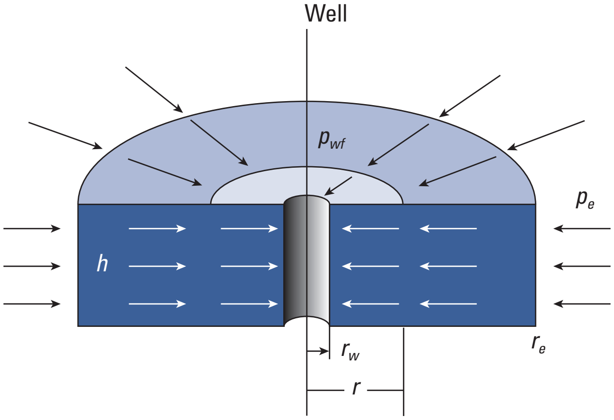

Figure 28. Model of radial flow in a reservoir.

Rearranging Eq. 3 gives the *productivity index* (PI), which is the flow rate produced (at surface conditions) per unit of pressure drawdown:

$$\mathrm{PI} = \frac{q}{\left(p_e - p_{wf}\right)} = \frac{2\pi kh}{B\mu\left(\ln\frac{r_e}{r_w} + s_t\right)}. \tag{4}$$

The PI is used to predict and evaluate initial well performance, track performance over time, and design and measure the effects of a production enhancement program.

The *productivity ratio* (PR) of a perforated completion is a reference parameter used to assess the completion's total efficiency. The PR is the ratio of the actual productivity index over the productivity index of an undamaged openhole completion in a reservoir with the same geometry and properties. To construct the formula for PR, Eq. 5 is written both for the perforated skin-affected completion and an openhole undamaged completion. The two equations are divided to determine the PR:

$$PR = \frac{\ln \frac{r_e}{r_w}}{\left(\ln \frac{r_e}{r_w} + s_t \right)}. \tag{5}$$

The PR concept applies only in the absence of turbulent flow, because flow turbulence (which is typical of moderate- to high-rate gas wells, for example) creates a rate-dependent skin effect. PR, on the other hand, does not depend on the flow rate.

Components of total skin effect

PR is defined by the total skin effect, not just the skin effect caused by the presence of perforations. The productivity of the perforated completion is affected by all components of the skin effect, including those indirectly related to the perforations.

Near-wellbore pressure losses resulting from a variety of causes affect the productivity of a perforated completion: wellbore damage, flow convergence, partial completion, wellbore deviation, and possible phase- and rate-dependent effects. Each cause is associated with an individual skin factor (Table 6), and the combination of all the skin factors is the total skin effect s_t.

Table 6. Components of Total Skin Effect

Skin Component	Cause
s_f	Partial completion
s_{dev}	Wellbore deviation
s_{do}	Formation damage in uncased completion (open hole)
s_{dp}	Formation damage in the perforated completion (cased hole)
s_p	Geometrical arrangement of the perforations
s_{pd}	Perforation damage (unclean perforations)
F	Decimal fraction of the reservoir interval that is perforated ($F < 1$)

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Partial completion skin and deviation skin effects

Partial completion (s_f) and deviation (s_{dev}) skin effects were described and formulated by Cinco-Ley et al. (1975).

The partial completion skin effect results from only a portion F of the reservoir being perforated. Thus the value of s_f is positive (i.e., associated with a positive pressure loss) because of increased friction as the flow converges into the perforated fraction of the reservoir interval. Although partial completion restricts production, it is sometimes accepted to reduce the risk of unwanted water or gas production.

The deviation skin effect is negative (i.e., associated with a negative pressure drop that enhances local productivity) because more reservoir area is open to flow into the wellbore in a deviated completion than in a vertical well.

Perforation skin and formation damage skin effects

Perforation skin effect (s_p) reflects only the decrease in pressure caused by the nonradial nature of the flow in the vicinity of the perforations, which results because fluid must follow crooked paths to enter the wellbore through the perforations. In other words, s_p reflects the pressure loss caused by the geometrical arrangement of the perforations in an otherwise undamaged reservoir. If the perforations are unclean, the result is the perforation damage skin effect (s_{pd}).

A simplifying assumption is that formation damage results from filtrate invasion during the drilling process. Formation damage can significantly reduce the productivity of an openhole completion, resulting in skin damage (s_{do}), and adversely affect perforated completions, especially if perforations terminate inside the damaged zone. In cased hole completions the effects of penetration and formation damage are not simply additive. Karakas and Tariq (1988) quantified the formation damage skin effect in both openhole and perforated completions. They also developed a technique to calculate the skin effect caused by the geometrical arrangement of the perforations, based on perforation density, phasing, and length. In combination with the effects of damage, the calculation yields a combination skin effect (s_{dp}) for the presence of the perforations and the wellbore (formation) damage.

Effects on productivity

New practical method for estimating well productivity

Brooks (1997) presents a new conceptual method for estimating the productivity of a natural completion. Well productivity is controlled by three dimensionless groups of perforation penetration, perforation diameter, and perforation damage that include the effects of all major governing parameters:

P = perforation length of penetration
N = shot density
D = perforation diameter
α = formation permeability anisotropy ratio
L = depth of the formation damage
b_c = perforation damage.

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Concept

The method is based on *productivity efficiency*, which is the ratio of the actual PR to the maximum productivity ratio (PR_∞), which assumes an infinite shot density at which the wellbore radius becomes equal to the actual wellbore radius increased by the perforation length.

Brooks found that his calculations of productivity efficiency collapse to one curve if PR_∞ is plotted against a dimensionless parameter β defined by

$$\beta = \left(P - L\right) N^{3/2} D^{1/2} \alpha^{-5/8} b_c^{\ -1}, \tag{6}$$

where b_c is a dimensionless measure of the perforation damage. This result enables immediate assessment of the relative importance of all parameters simultaneously affecting the efficiency of a perforated completion:

- Excess penetration over the depth of damage is raised to the power of 1.
- Shot density plays a greater role and is raised to the power of 1.5.
- Perforation diameter plays a minor role and is raised to the power of 0.5.
- Formation anisotropy and perforation skin effect always have an adverse effect (negative exponent).

Figure 29 depicts the variation of productivity efficiency as a function of β in the presence of wellbore damage and perforation damage.

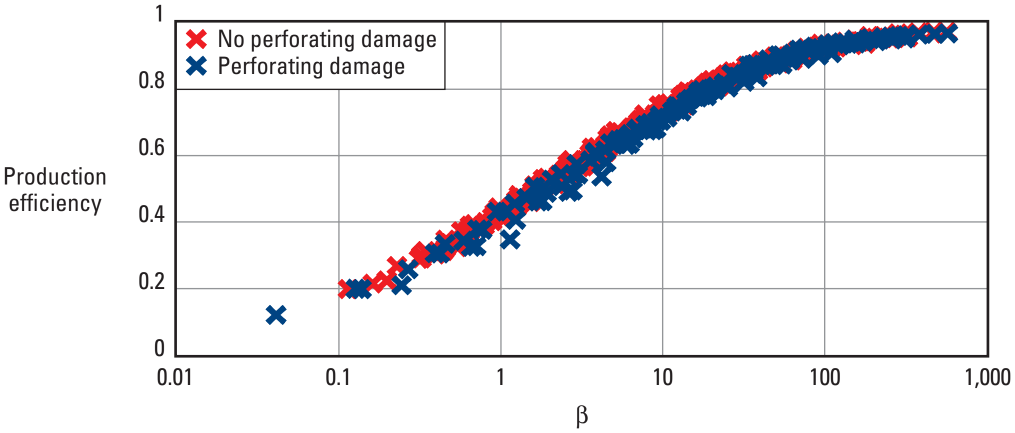

Figure 29. Productivity efficiency versus β, which includes the effects of wellbore and perforation damage.

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Optimization strategy

It is clear from Fig. 29 that increasing β can increase productivity. Equation 6 shows that a higher value of β can be achieved by increasing the penetration or shot density. If there is no formation damage, higher shot density is more effective than increased penetration.

The value of s_p should always be reduced to maximize β, which means removing perforation damage.

Using this optimization methodology provides a wider range of weighted options for optimizing perforated completions compared with traditional approaches that address only a single parameter (e.g., perforation depth) to optimize productivity.

Remarks

The new optimization strategy assumes spiral gun phasing. In other words, the shot phasing is distributed around the circumference of the casing and in essence is nonzero. For this method the effect of other phasing configurations on productivity must be analyzed separately.

The calculations presented in the cited paper are for 45° phasing. Additional calculations must be performed for different phasing angles; however, the methodology is the same.

The methodology does not apply if the formation damage zone extends beyond the end of the perforation. Such situations are unlikely with current perforators, which employ ultradeep penetrators such as PowerJet deep penetrating shaped charges.

The methodology also does not address turbulent flow or inertial flow effects within the perforation.

Productivity theory

As previously discussed, a theoretical approach is still necessary to quantify the productivity of perforated completions as a function of all known influencing parameters. The productivity of a perforated completion is a function of three groups of variables:

- geometry of the perforations around the perforated casing
- formation damage
- reservoir characteristics.

Maximizing productivity—or minimizing the equivalent skin effect and the pressure decrease it causes—requires optimizing the influence of these three groups of parameters.

Effect of perforated completion geometry

Figure 30 shows the typical geometry of a perforated completion. The main geometrical parameters that determine the flow efficiency in a perforated completion are shot density, perforation penetration depth (also called length), phase angle (also called phasing), gun orientation, and the diameter of the perforation. Flow efficiency is also affected by perforation damage, which is discussed in the next chapter. The impact of the shaped charge jet creates a zone of reduced permeability (called the *crushed zone*) around the perforation tunnel; removal of this zone results in “clean” perforations. Partial penetration and well deviation are other important geometrical parameters, but there are few opportunities for optimizing these two parameters.

Table 7 lists the relative importance of the five main geometrical parameters and the cleanliness of the perforations based on completion type. A rating of 1 indicates the most important parameter and 4 is the least important for a completion type. For most completion types, clean perforations are an important parameter.

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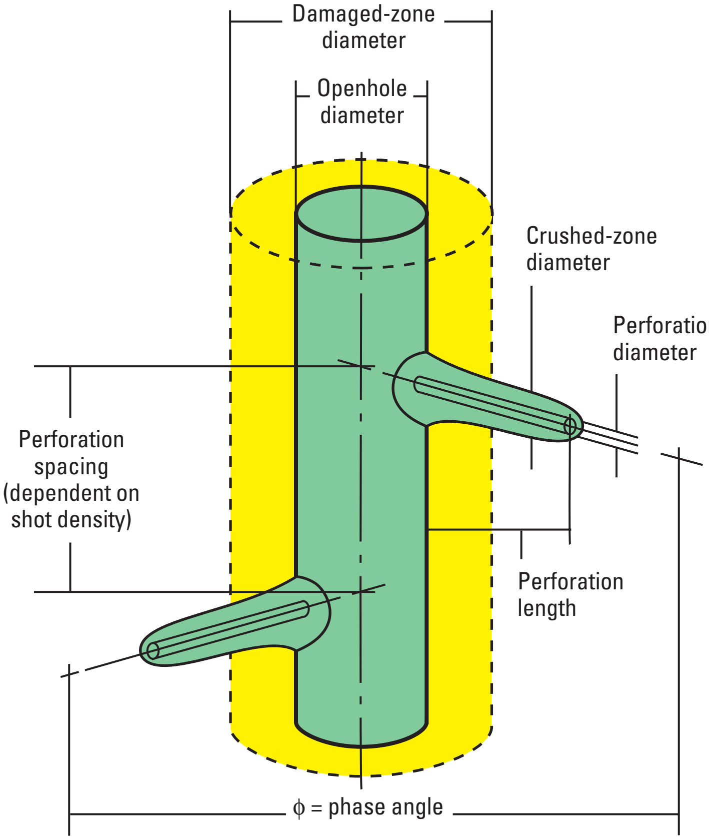

Figure 30. Typical geometry of a perforated completion.

Table 7. Relative Importance of Geometrical Perforation Parameters Based on Completion Type

Perforation Parameter	**Natural**	**Sand Control**	**Sand Prevention**	**Fracture Stimulation**	**Workover**
Clean perforations	1	2	1	3	1
Perforation length	1	4[†]	2	4	1
Shot density	2	1	1	3	2
Perforation diameter	3	1[‡]	1	2[‡]	3
Perforating phasing	4[§]	4[††]	2	1	4[§]
Gun orientation	4	4[††]	1	1	4

[†] Depends on reservoir strength and sand control completion

[‡] Refers to the casing or cement tunnel diameter

[§] Assumes phasing is not zero, otherwise the importance = 2

[††] For screenless sand control, phasing and orientation importance = 1

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Figures 31 and 32 illustrate the effects of the geometrical parameters on the productivity ratio in an ideal isotropic formation with no crushed zone and no formation damage. Figure 31 shows the importance of shot density associated with the phasing. At 0° phasing, shot density seems to play a minimum role, but only because the phasing is not optimized. At 90° phasing, for example, the productivity ratios are higher than for 0° phasing, and shot density is an important factor. Figure 32 confirms that the perforation diameter has a relatively minor effect on productivity in comparison with the effect of the other parameters.

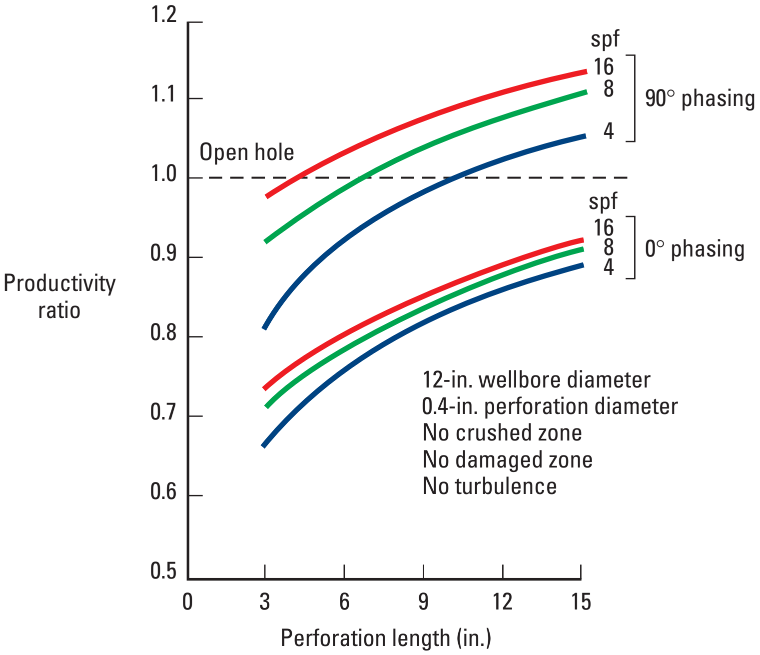

Figure 31. Effects of shot density and phasing on the productivity ratio.

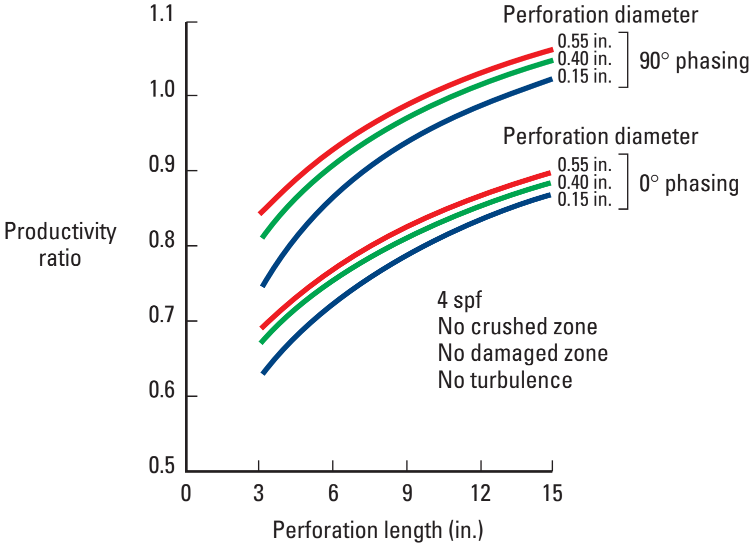

Figure 32. Relative importance of perforation entrance hole diameter on the productivity ratio.

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Effect of formation damage

Formation damage refers to the permeability change in the near-wellbore region that is induced by fluid invasion (change in relative permeability) and fines invasion (drilling or mud solids). Formation damage plays an important role in the productivity of a perforated completion. The direct effect of formation damage is further aggravated by perforation damage, which results from unclean perforations or perforations where rock failure under stress leaves permeability-damaging material in the perforation cavity.

Figure 33 illustrates the effect of the formation damaged zone on productivity. The PR is near maximum value if the depth of formation damage is much less than the perforation length. The curve graphed in Fig. 33 has an inflection point close to where the perforation length becomes less than the depth of the formation damage and the PR declines sharply to much lower values. Thus, for optimum productivity the perforation must extend sufficiently far into the undamaged zone. This distance can be quantified by modeling the β factor and basing selection of the optimization strategy on the result (see "New practical method for estimating well productivity" in this chapter). For low values of β, increasing the shot density may provide a valuable alternative to deeper perforations, even where formation damage is extensive. Determining whether this approach is the ideal strategy requires modeling the specific conditions.

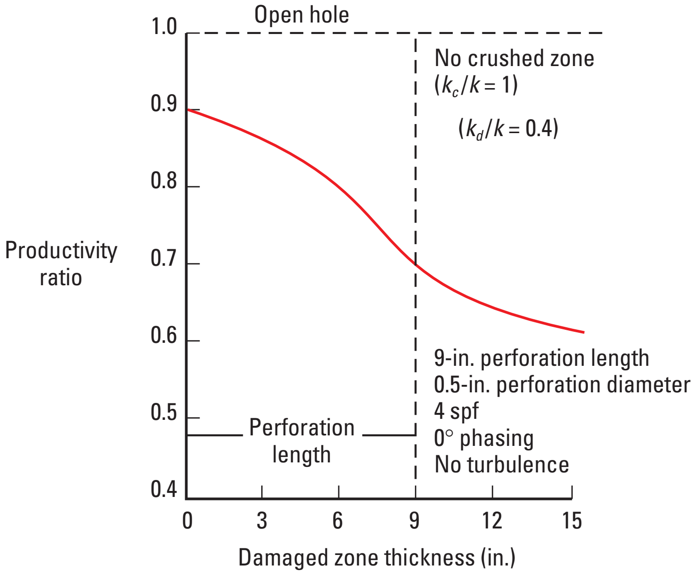

Figure 33. Effect of the damaged zone on the productivity ratio.

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The effect of the crushed zone on productivity is also linked to formation damage. The presence of a crushed zone around the perforation cavity is one of the many manifestations of perforation damage; however, it is the only one that can be modeled without experimentation. Figure 34 shows a PR simulation for 12-in. perforations made in a 9-in. borehole at 120° phasing and 4 spf. The formation is damaged (ratio of damaged zone permeability to horizontal permeability $k_d/k_h = 0.1$) and isotropic (ratio of horizontal to vertical permeability $k_h/k_v = 1$). Three values of reduced permeability in the crushed zone are depicted: $k_c/k_h = 0.1$, 0.3, and 1.0. Optimum productivity is achieved when formation damage does not exceed about 6 in. (in a 12-in. penetration) for all values of crushed zone permeability. If the other conditions are equal, the PR is a minimum when the perforations are shallow in the presence of little formation damage (see Fig. 35, 3-in. penetration).

For the same initial conditions, Fig. 36 shows how the effect of the crushed zone can be nullified by greatly increasing the shot density (20 spf for this example). This interesting result indicates an approach for optimizing productivity when the perforations cannot be cleaned out (e.g., in severely depleted reservoirs).

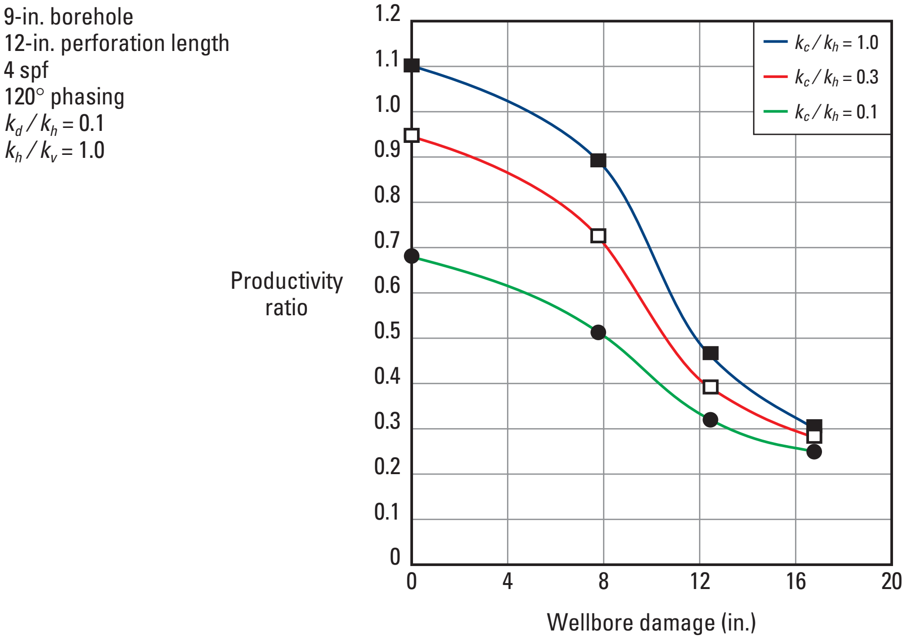

Figure 34. Effect of the crushed zone on the productivity ratio.

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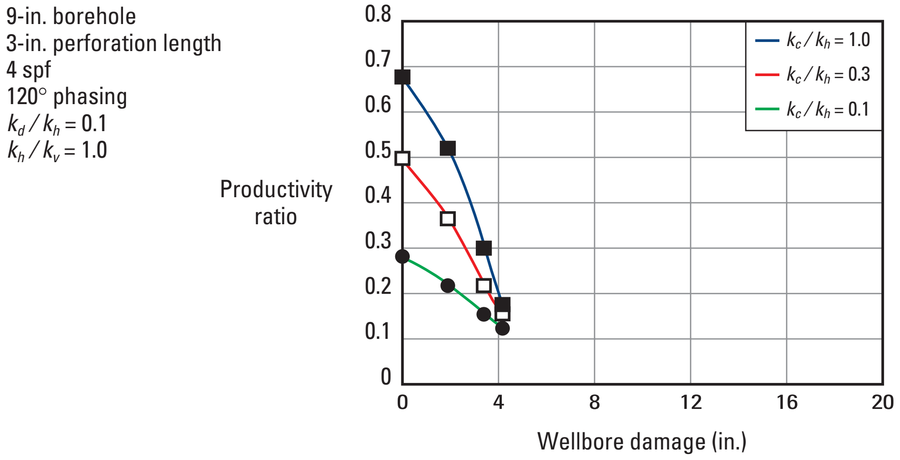

Figure 35. Effect of the crushed zone on the productivity ratio: shallow perforations.

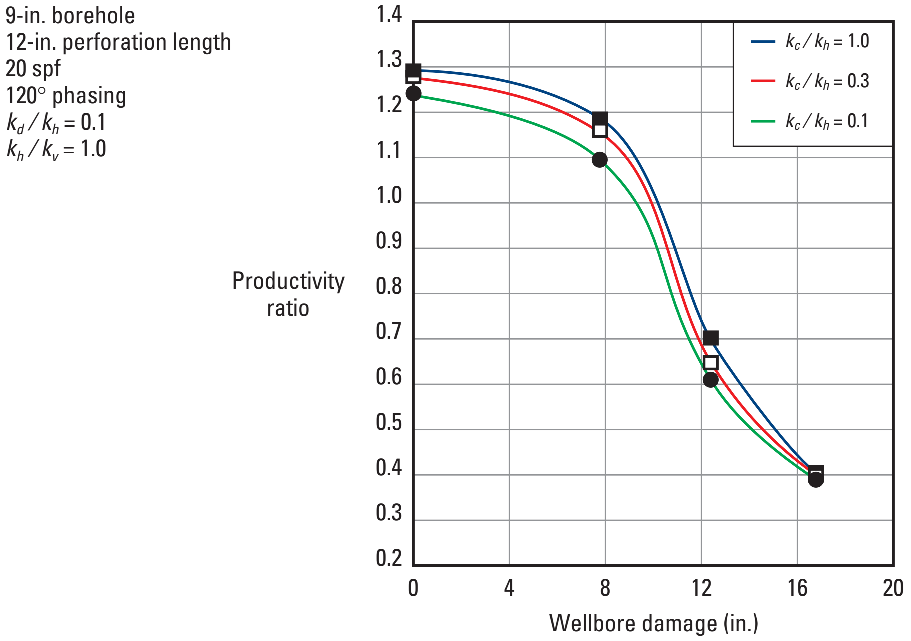

Figure 36. Nullifying the crushed zone effect with very high shot density.

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Figure 37 illustrates the effect of the crushed zone, along with effects of *non-Darcy flow*. Although non-Darcy flow is commonly called “turbulent” flow, this is a misnomer. The flow is not turbulent; the fluid is still moving rather slowly. An extra pressure loss arises from inertial effects associated with the fluid taking tortuous paths through the pore structure. The extra pressure loss can be mitigated by reducing the fluid velocities, which can be achieved by increasing the AOF. AOF is a direct function of shot density and entrance hole diameter.

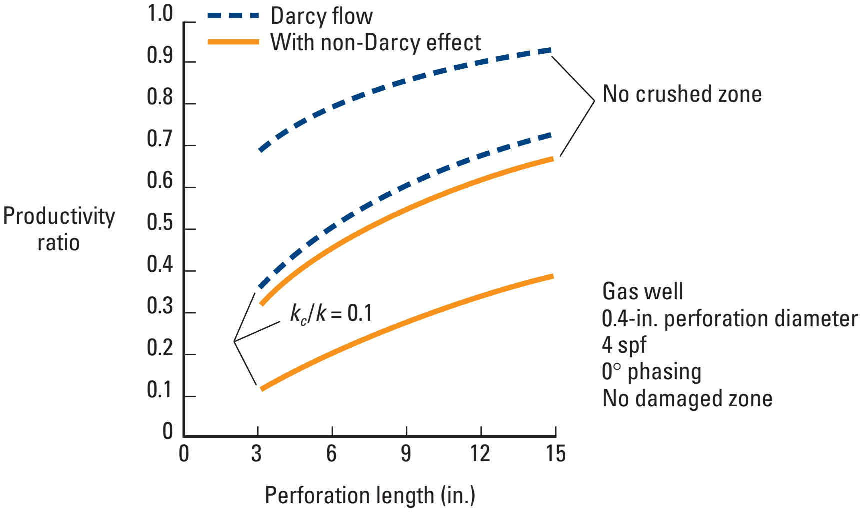

Figure 37. Effects of the crushed zone and fluid turbulence on the productivity ratio.

Effect of reservoir characteristics

Effective design of a perforation program includes consideration of the various types of heterogeneities in the formation. This information is available from cores, openhole logs, and other geological and petrophysical data. Figure 38 illustrates three common sources of formation heterogeneities.

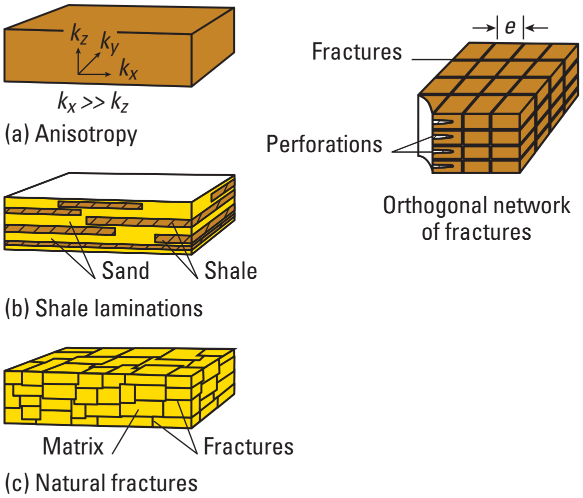

Figure 38. Common types of formation heterogeneities (a, b, c) and fracture block spacing.

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Permeability anisotropy

Because of layering, the k_v value of most reservoir rocks is much lower than that of k_h. The permeability anisotropy, defined as the ratio k_h/k_v, is always greater than 1. This condition affects the PR because perforated completions always involve a vertical component of the fluid flow near the wellbore. Figure 39 shows the effect of permeability anisotropy on PR in a vertical well. Because the reduction in productivity is much smaller at high shot densities (which sharply limit the vertical flow component near the wellbore), increasing the shot density is an effective way to overcome the adverse effects of permeability anisotropy.

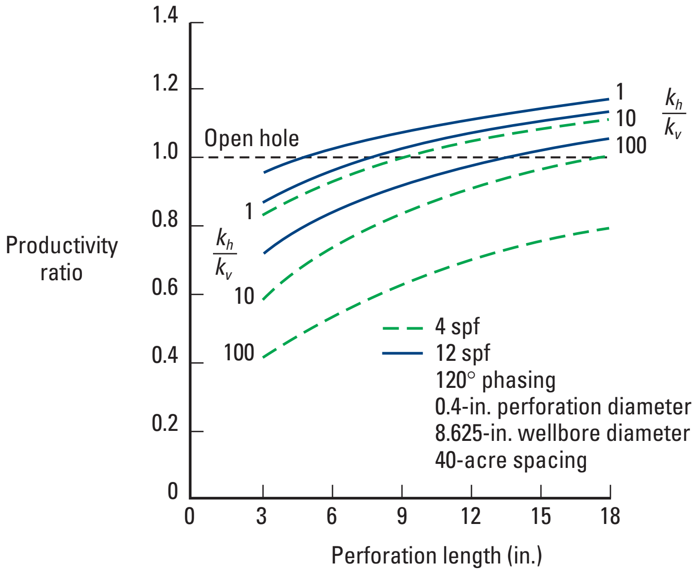

Figure 39. Effect of formation anisotropy on the productivity ratio.

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Shale laminations

Virtually every sandstone reservoir contains significant amounts of shale. Although structural and dispersed clay material simply reduces the intrinsic permeability of the reservoir rock, laminated shales negatively influence the rock's transport properties by enhancing the nonlinearity of the fluid flow between the reservoir and the wellbore. Figure 40 shows the effect of shale laminations on the productivity of a vertical well. Increasing shot density is an effective way to improve the productivity of a reservoir that contains shale laminations, because higher shot densities allow straighter flow paths near the wellbore.

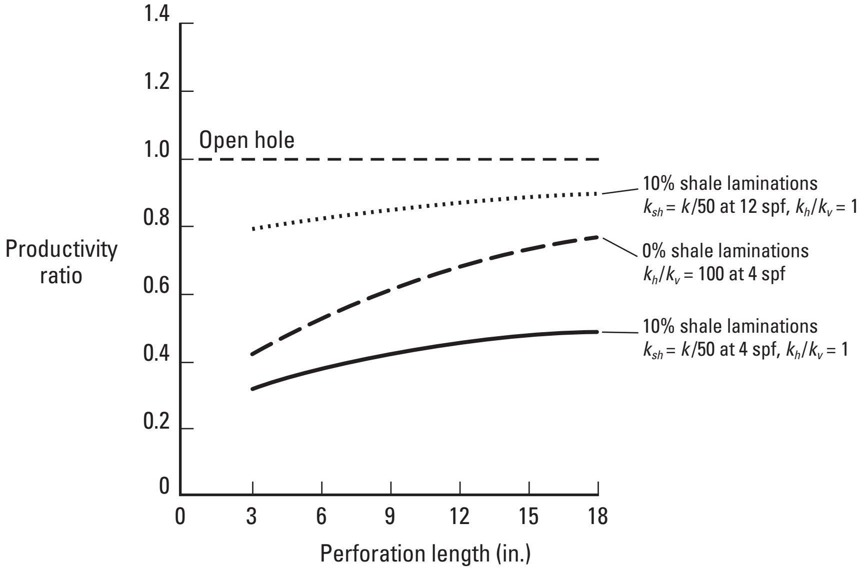

Figure 40. Effect of shale laminations on productivity ratio. k_{sh} = permeability of shale.

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Natural fractures

Many reservoirs have one or more sets of natural fractures that provide conduits for the matrix fluid to reach the wellbore through perforations. Figure 41 illustrates different types of fracture-matrix systems and their relation to perforation orientations. The productivity of perforated completions in these systems depends on both the reservoir parameters (type, orientation, and spacing of natural fractures) and perforation parameters, which vary in significance for the different fracture systems.

Perforations must intersect as many fractures as possible to effectively improve communication between the perforations and the fracture network. Thus, perforation length and phasing have a primary effect on the PR in naturally fractured reservoirs.

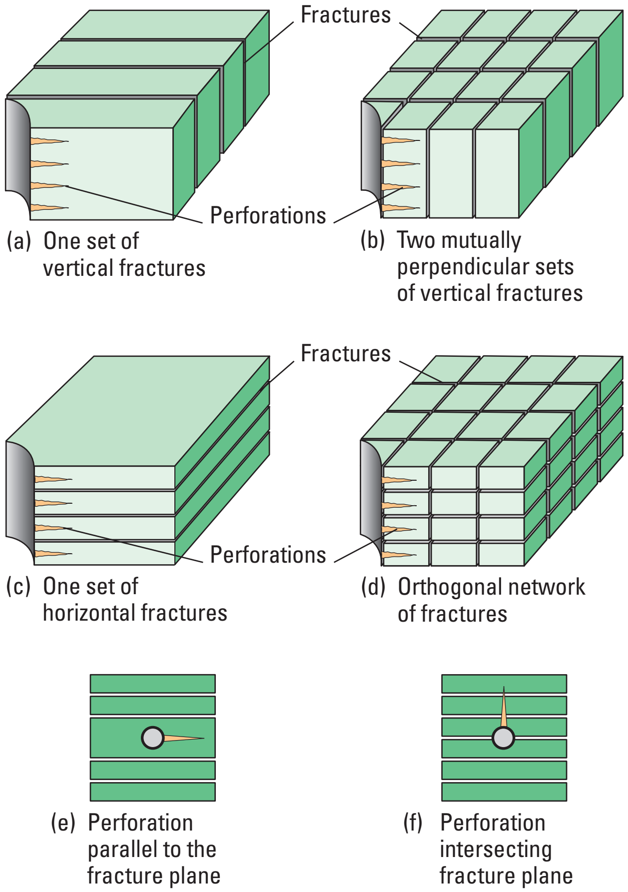

Figure 41. Different types of fracture-matrix systems.

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Figure 42 illustrates the importance of perforation length on productivity for various values of fracture spacing. The effect of shot density appears minimal on the figure because increasing the shot density is unlikely to increase the probability of intersecting fractures, unless the average fracture spacing is commensurate with shot spacing, in which case higher PRs are the result (as the figure shows). Figure 43 further demonstrates the relative insignificance of shot density, especially in the presence of large blocks of matrix.

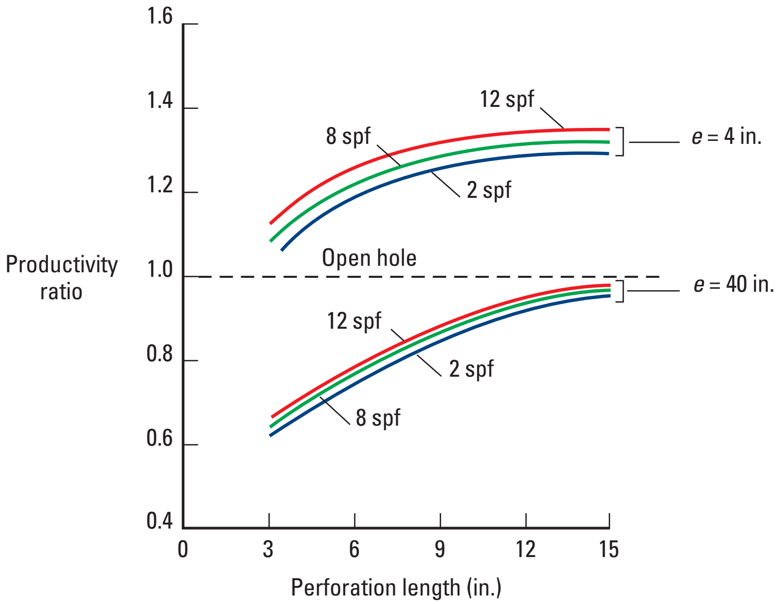

Figure 42. Effect of perforation length and fracture spacing on the productivity ratio.

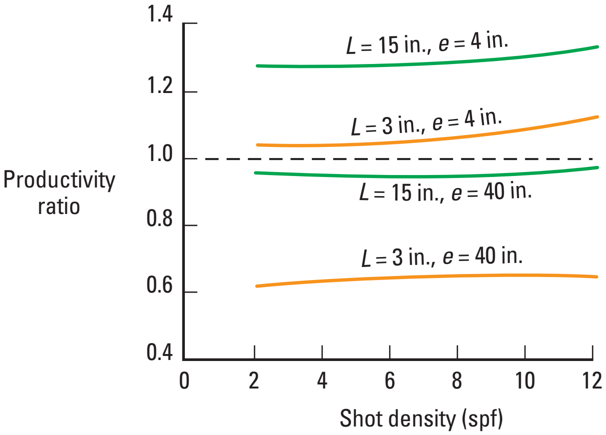

Figure 43. Relative insignificance of shot density on the productivity ratio, especially for large matrix blocks. *L* = perforation length.

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The effect of perforation phasing is illustrated in Fig. 44, which shows the fracture intersection probability for a wellbore of a specified diameter. To improve this probability, perforations must be placed all around the wellbore to virtually increase its diameter (i.e., as far as fracture intersection is concerned).

Except in the case of very large fracture blocks (block spacing as defined in Fig. 38), perforated completions perform better than openhole (unperforated) completions (Fig. 45). Perforated completion performance is further improved by high values of the perforation length *L*.

Perforating requirements for naturally fractured reservoirs are discussed in "Specific perforating requirements" in the "Reservoir Completion Types" chapter.

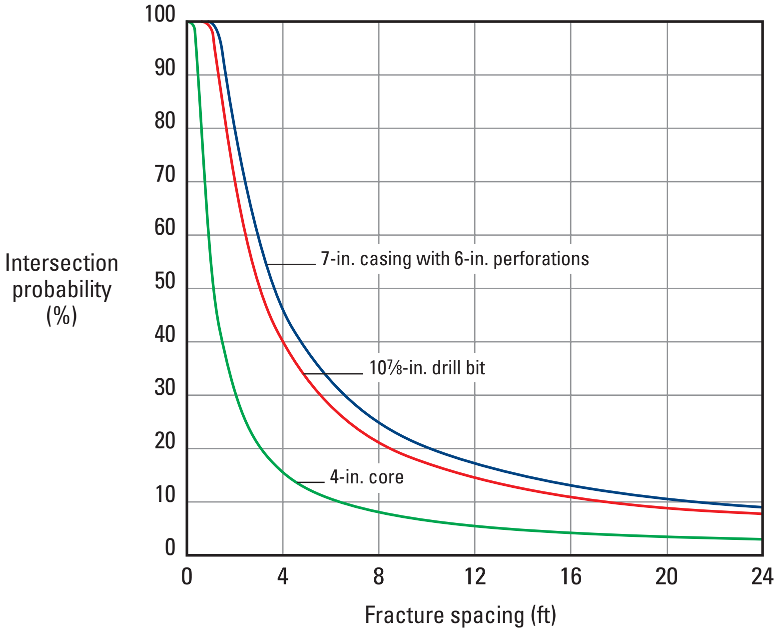

Figure 44. Probability of intersection of perforations with a fracture.

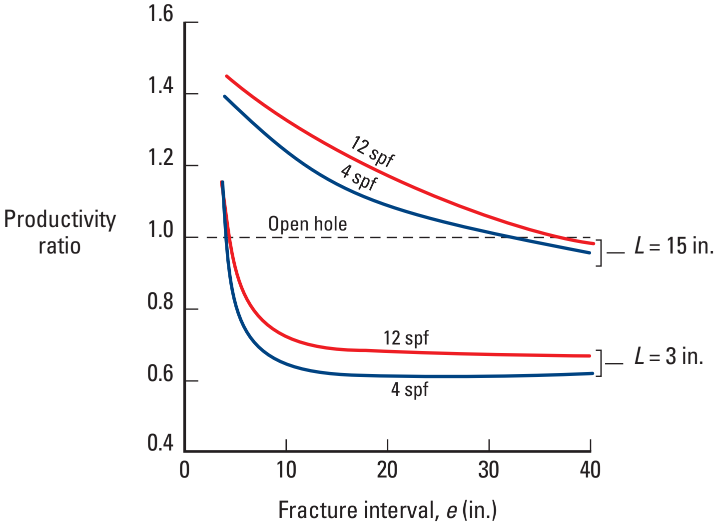

Figure 45. Relative performance of perforated and openhole completions in fractured reservoirs.

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Conclusions

Table 8 outlines the relative importance of the four main perforation parameters for various conditions of reservoir heterogeneity. A rating of 1 represents the most important parameter, and a rating of 4 represents the least important parameter.

Table 8. Relative Importance of Four Main Perforation Parameters

Perforation Parameter	Isotropic Permeability	Anisotropic Permeability	Shale Laminations	Natural Fractures	Hard Rock
Effective shot density	2	1	1	3	2
Perforation diameter	4	3	4	4	4
Perforating phasing	3–4†	4	3–4†	2, 4†	3†
Perforation length	1	2	2	1	1

† The importance of phasing declines to 4 for phasing greater than 0°.

Combined effects

All the groups of variables (perforation geometry, formation damage, and formation characteristics) have a combined effect on productivity. SPAN Schlumberger perforating analysis is needed to model the combined effect because modeling individual variables assumes the ideal condition for the other variables. (SPAN analysis is discussed in the “Reservoir Completion Types” chapter.) In addition to modeling the PR and associated skin effect for perforated completions, SPAN analysis also models further effects on productivity loss that are caused by not removing the perforation skin effect.

Negative skin effect

A negative value of skin effect is associated with PR > 1 (see Eq. 5). In effect, this means that the productivity exceeds that of a corresponding open hole. Although a negative skin effect is usually associated with stimulation, it is clear from the results shown in Figs. 31, 32, 34, 36, and 39 that it can also be achieved in naturally perforated completions if the penetration and shot density are high enough.

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Perforation Damage and Cleanup

Sources of perforation damage

Perforation damage refers to the reduced permeability of fluid flow through the perforation in comparison with an ideal perforation in an undisturbed formation with no effect on the rock permeability. Perforation damage represents the additional pressure loss sustained by the reservoir fluid as it travels through the perforation into the wellbore.

Perforation damage must be minimized and can even be totally removed. The primary objective of modeling and engineering underbalanced perforating operations is the removal of perforation damage.

Perforation damage consists of one or more of the following factors:

- zone of reduced permeability (i.e., crushed zone) around the perforation cavity in the rock
- pulverized sand particles and perforation debris inside the perforation cavity
- possible formation failure in weak rocks and collapse of the perforation cavity upon itself
- possible interference between perforations and formation failure between adjacent cavities
- production of sand and fines left unevacuated from the perforation cavity
- possible transient invasion of the newly created perforation by wellbore fluids (may occur even in underbalance conditions and before the start of perforation cleanup surge flow).

As used in this catalog, the consolidation and strength of rocks are categorized as listed in Table 9.

Table 9. Consolidation and Strength Categorization of Rocks for Perforating

Rock Category	Uniaxial Compressive Strength (UCS) (psi)	Perforation Characteristics
Unconsolidated	~1	No perforation cavity No typical perforation damage Fractured sand grains along perforation track
Weakly consolidated	<500	No perforation cavity Perforation permeability damage along perforation track
Weak consolidated	>500	Perforation cavity Typical crushed damage zone Cavity may fail because of compressive stress
Strongly consolidated	>2,500	Perforation cavity Typical crushed damage zone Cavity failure only under extreme compressive stress

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There are two distinct approaches to managing perforation damage:

- minimize the damage (e.g., when perforating in weak rocks)
- remove the damage, usually with the underbalance or by acid washing, swabbing, or other forms of postshot flow.

The removal of perforation damage is closely related to the underbalance applied. Underbalance criteria are discussed in this chapter along with approaches to managing perforation damage in hard rocks and weak rocks and considerations for perforation cleanup.

Consolidated hard rocks

Crushed zone

The shock wave generated by the jet passing through rock creates the crushed zone. The shock wave fractures sand grains within its range of action, decreasing the size of the pore throats and correspondingly reducing permeability around the perforation cavity. Because material does not transfer out of the crushed zone, the porosity of sandstones is essentially unaffected but the porosity of carbonates is reduced within the crushed zone. Perforation jet formation and its interaction with rock are low-heat-generation processes; thus, no vitrification or liquefaction of rock occurs.

Figures 46 and 47 are thin sections of sandstone rock samples taken outside and inside, respectively, of the crushed zone around a perforation. The sand-grain fracturing effect is evident, as is the lack of an effect on porosity (apparent from the equal occurrence of blue epoxy resin filling the areas not occupied by grains on the two thin sections). Figure 48 quantifies the crushed zone, depicting fracture density for two different shaped charges as a function of the distance from the perforation cavity.

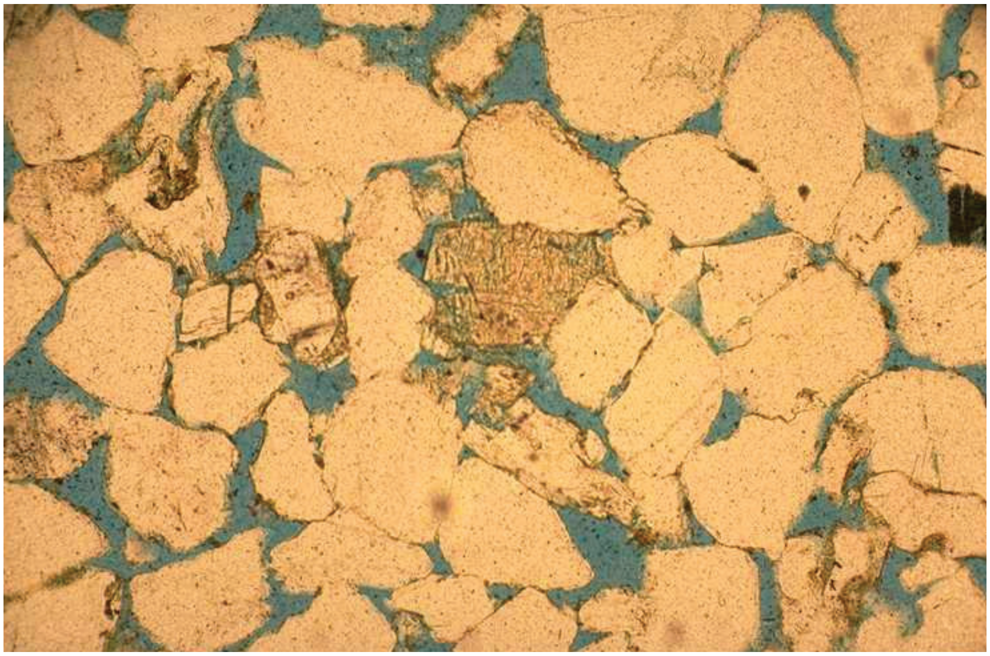

Figure 46. Thin section of perforated rock sample outside the crushed zone.

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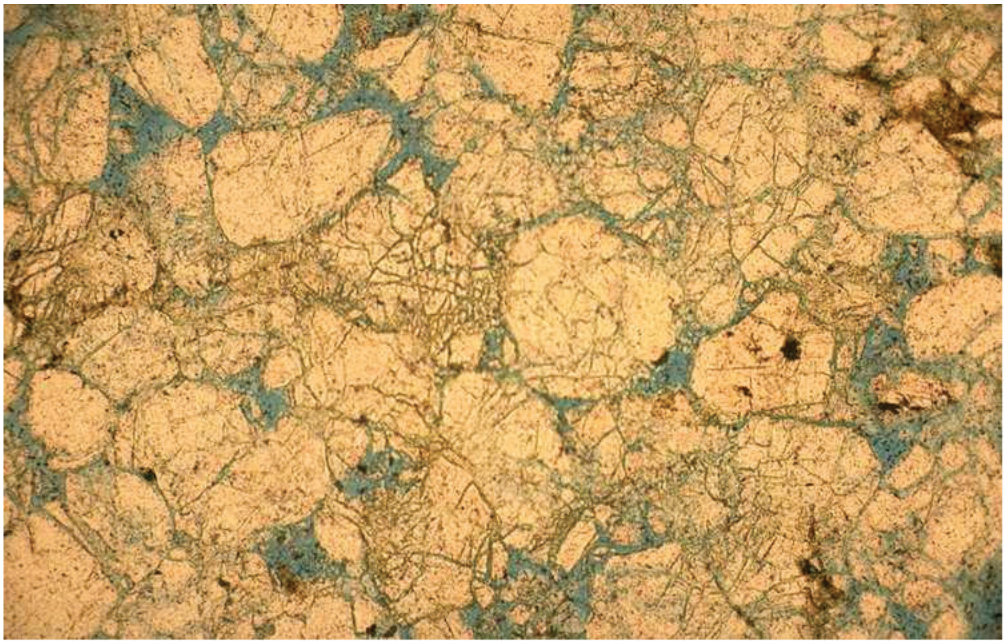

Figure 47. Thin section of perforated rock sample inside the crushed zone.

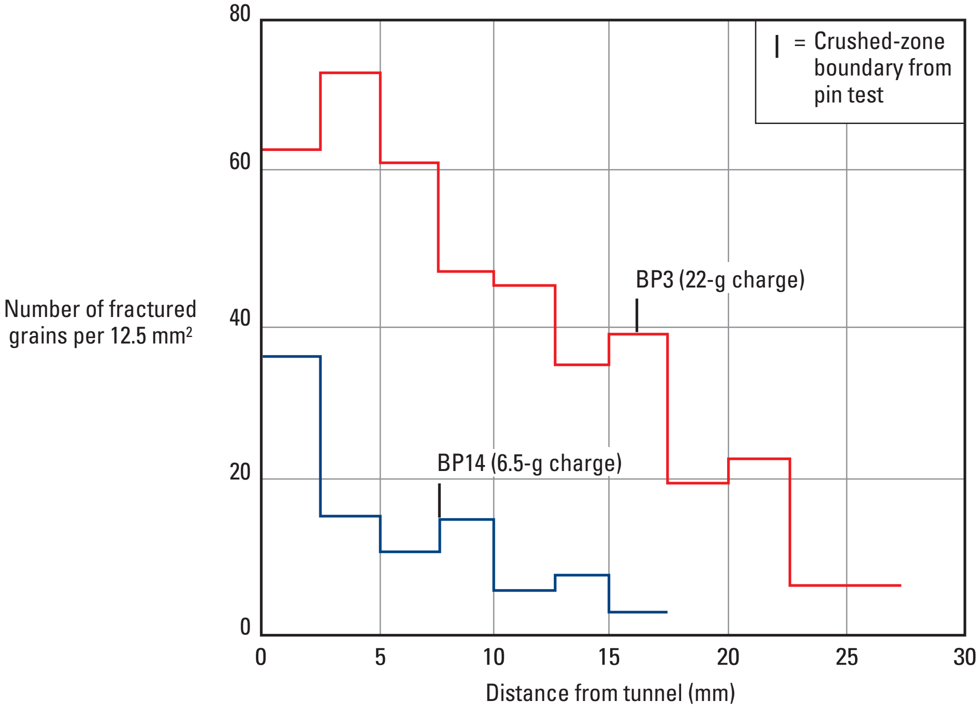

Figure 48. Fracture density in the crushed zone.

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Material in the crushed zone is loosely consolidated and is not necessarily easily removed, depending on the rock properties and perforation process. It can be completely removed from the perforation by applying sufficient underbalance during the perforation process, although there is obviously a limit depending on the rock permeability, pressure, and pore fluid.

Single-shot experiments to measure the additional skin effect caused by perforation damage (Behrmann et al., 1991) show an apparently random variation in the perforation skin effect with the other environmental parameters held constant (Table 10). This condition results from the rock's natural heterogeneity, which always prevails, even in the same bedding plane. The randomness of the skin effect probably helps to explain why many perforations in the same perforated interval do not seem to produce at all, as revealed by production logs. Another finding of Behrmann et al.'s study is that formation stress does not seem to influence the skin effect caused by perforation damage in consolidated rocks.

Table 10. Random Variation in Perforation Skin Effect

Test No.	Permeability (mD)	Penetration (in.)	Debris Free?	Skin Effect
BP26	215	5.1	Yes	5.9
BP29	218	4.1	No	3.1
BP29a	218	5.1	No	14.3
BP30	224	6.8	No	8.9
BP31	196	6.1	Yes	1.7

Pulverized material

Some or all of the crushed-zone material is removed from the walls of the perforation cavity during underbalanced perforating. If not evacuated by the underbalance, fractured formation particles remain in the perforation cavity as pulverized material that may include shaped charge debris (mostly liner debris).

Pulverized material typically has high permeability and porosity, and its presence does not always adversely affect productivity. This material can affect injectivity, however, and can even act as a flapper valve that nearly blocks injection (Behrmann and McDonald, 1996). Thus, removing pulverized material is crucial when injecting to avoid extremely high injection pressures (as discussed in the next chapter). Table 11 lists production and injection index values measured for two perforations flowed under alternating positive and negative pressure differentials. As the data show, the production index remains high throughout the experiment, whereas the injection index is at best much lower, declining sharply to almost zero as the experiment proceeds.

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Table 11. Production and Injection Data from Flow into an Unevacuated Perforation

Time (min)	Differential Pressure (psi)	Production Index (cm^3/s/psi)	Injection Index (cm^3/s/psi)
0	142	0.255	–
41	148	0.243	–
0	142	–	0.165
10	150	–	0.095
0	148	0.307	–
5	146	0.296	–
10	299	0.275	–
20	300	0.267	–
0	143	–	0.146
6	148	–	0.091
12	313	–	0.08
16	280	–	0.057
20	464	–	0.053
28	436	–	0.038
33	589	–	0.04
41	617	–	0.03
0	295	0.257	–
8	309	0.25	–

The effect of perforation damage is more important in highly deviated and horizontal wells, where gravity makes it difficult to remove pulverized material from the bottom perforations. For this reason, “downside” perforating is not recommended for deviated and horizontal wells, and the orientation of the perforations is important (see the “Completion Perforating Equipment” chapter for a discussion of oriented perforating).

Removing pulverized material is also of importance in gravel-packed completions. The unevacuated material interacts with the packing material, resulting in a reduction in permeability, and thus very high skin factors, as discussed in “Specific perforating requirements” in the next chapter.

Other damaging effects

Other damaging effects include

- debonding of clay particles and production of fines
- transient injection of completion fluid into the perforation (discussed in “Perforation cleanup” in this chapter)
- creation of a *stress cage* around the perforation.

The stress cage results from the crushed-zone material returning unevenly to a plastic state after fracturing by the jet shock wave. Residual stress may contribute to cracking of the rock, formation failure around the perforation tunnel, and local generation of fines.

Perforation damage in high-strength sandstone

Microfractures may be created in very hard rock to provide a fluid conduit that bypasses the perforation damage. Negative perforation damage skin effects have been obtained in cores of high-strength reservoir and outcrop rocks with 3,000-psi underbalance (Blosser, 1995).

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Weak rocks and sand production

Experimental studies

Perforating experiments in weak rocks have been conducted to address numerous field problems, including

- characterization of perforation damage
- selection of underbalance
- dynamics of perforation cleanup
- characterization of the sand production process
- engineering of gravel packs
- prevention of sanding.

The first laboratory experiments were performed jointly by BP and Schlumberger in the early 1990s. Outcrop cores from the Castlegate formation (a weak sandstone with ~1,400-psi UCS) were perforated under two values of confining stress and various values of underbalance (Behrmann et al., 1992). The rock around the perforation failed under all sets of conditions. At a low effective confining stress, the failed rock was expelled into the wellbore, creating a large, asymmetrical cavity. At higher values of confining stress, however, the failed rock stayed in the perforation, filling the cavity. As shown in Fig. 49, the borders of the initial (filled) perforation cavity are distinguishable, as well as the failed rock around the initial cavity. The experiments also indicated that perforation productivity seems to decrease as underbalance increases.

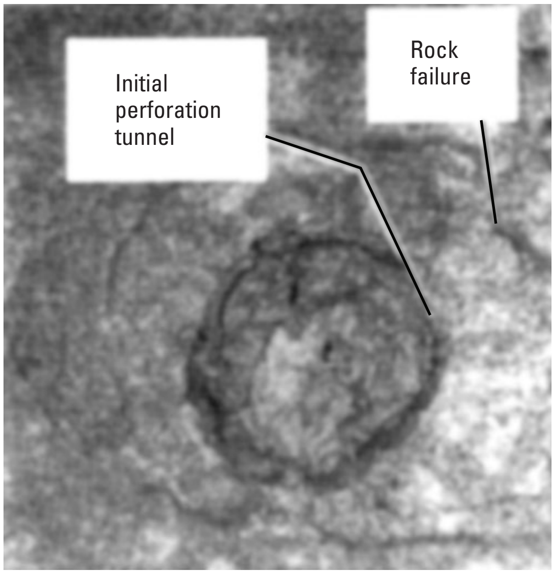

Figure 49. Perforation experiment in weak-rock sample with no perforation tunnel. (© 1992 Society of Petroleum Engineers, Inc., Behrmann et al.)

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In 1992 and 1993, BP, Elf, Shell, and Schlumberger performed multiple-shot experiments on large blocks of Castlegate sandstone. The results (Behrmann et al., 1997b) were crucial because they provided the basis for fully understanding perforation damage in weak rocks and the mechanisms of sand production and managing these issues in practical terms. The conclusions of the experiments are summarized in the next section of this chapter.

In 1996, van den Hoek et al.'s experiments on weak but consolidated rock samples showed that the perforation cavities fail in compression, not tension. The primary role of fluid flow in sand production is to transport loose sand resulting from failed material from the perforation. Nevertheless, fluid flow may also cause the tensile failure of failed sandstone within failed perforations or in unconsolidated sand.

Kooijman et al. (1996) experimented on large blocks of weak artificial sandstone to simulate sand production behind a horizontal liner under different conditions of stress, drawdown, and water-cut. They concluded that sand production under rock failure may lead to a stable completion with only minor effects on productivity. The study recognizes the significant influence of the onset of water-cut on sand production.

Blok et al. (1996) and Venkitaraman et al. (1997) experimented on gravel packs performed in perforated Castlegate sandstone cores. These key studies led to the recognition of permeability impairment from gravel packing poorly cleaned perforations and the efficiency of both the surge flow and postperforation flow in cleaning out the perforations (see "Perforation cleanup" in this chapter).

Perforation damage in weak rocks

The main conclusions of experimental studies of perforation damage in weak rocks can be summarized as follows:

- In weak but consolidated sands, the rock around the perforation may fail in compression, especially at high underbalances and high stresses.
- In unconsolidated formations, there are no open perforation cavities.
- Under specific conditions of shot density, depending on the perforation spacing, the formation between perforations may also fail, potentially contributing to sand production.
- Removing pulverized sand debris from the perforation cavity is difficult using typical oilfield flow rates before the onset of water production. This was independently recognized by Snider et al. (1997), although they recommended minimum penetration in weak rock, which is contrary to modern sand prevention practices.
- Multiple perforations exhibit different levels of damage and productivity.

Sand production processes

Experimental studies on sand production processes have produced the following major conclusions:

- Sand production can be viewed as a multistep, decoupled process for typical oilfield rates:
    1. transient production of pulverized material from the perforation cavity
    2. production of sand generated by failure of the perforation cavity under stress
    3. sand production from failure of the reservoir rock under stress, resulting from depletion or excessive drawdown
    4. sand production at the onset of water-cut
    5. massive sand production that ensues in water-wet unconsolidated reservoirs results from the decrease of high oil surface tension that enables the sand particles to separate from the loose matrix.

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- Stable hemispherical arches may form at the wellbore/cavity interface and reduce sand production. However, the stable arches are usually destroyed by the debonding of sand grains at the onset of water production, which further aggravates the sand production problem.
- Perforations oriented parallel to the maximum horizontal stress direction usually produce a minimum amount of sand (dependent on the vertical stress conditions and well deviation).
- Sand production from erosion in open perforations is not significant at typical oilfield production rates.
- Multiple perforations exhibit different sanding rates.

Gravel packs

Experimental studies on gravel packs offer these major conclusions:

- Produced sand fills all the volume it can around a slotted liner. A stable configuration may eventually occur, in which no more sand is extracted from the reservoir rock. This stable configuration can be destroyed only by massive sand production resulting from the initiation of water-cut (Kooijman et al., 1996).
- Formation fines and the remaining pulverized sand in packed unclean perforations invade the gravel, which greatly impairs the permeability (skin effect and associated pressure losses). The permeability impairment results in very high skin effect values calculated from pressure transient tests conducted to evaluate gravel-packed wells.
- Acidizing may reverse impaired permeability; however, acid treatment to remove fines is seldom effective over the long term. After acidizing, more formation fines move from the undisturbed rock toward the perforation cavity.
- Effective perforation cleanup is essential to avoid perforation-induced gravel-pack impairment.
- The frac-and-pack technique brings the benefits of hydraulic fracturing to gravel-pack completions. A key study of high-rate sanded-off wells (Welling, 1998) shows that cavity flow impairment and poor communication with the fractures reduce productivity in frac-packed wells. Thus, adequate perforation phasing is an important factor to improve the effective perforation AOF in communication with the fracture.

Perforation cleanup

Experimental work

Many of the previously cited experimental studies include conclusions about perforation cleanup. The experimental work summarized here focuses specifically on enhancing the understanding of perforation cleanup.

- Experiments conducted by Halleck and Deo (1988) suggested that a sequential combination of an initial, transient surge flow and subsequent postshot flow are responsible for perforation cleanup. The researchers postulated that damaged rock is loosened during the early transient and then flushed out by the postshot flow. The level of underbalance determines how much the material is loosened.
- Experiments at SRC (Bartusiak et al., 1993) measured surge flow, postshot flow, and core-flow efficiency (CFE) in four tests on Berea sandstone. CFE, a measure of the degree of cleanup, increased sharply during the surge flow, as long as sufficient underbalance was applied, but increased only marginally during the postshot flow. The surge flow volume had only limited impact on CFE. A similar picture emerged at lower values of underbalance, with the CFE correspondingly lower.

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- Further experiments at SRC used fast quartz gauge technology to acquire pressure data soon after perforating (Behrmann et al., 1997a). A surprising result is that during the first 10 ms after the perforation is created, borehole pressure oscillations generated by shock waves induce a negative pressure differential (i.e., wellbore pressure greater than core pressure) in spite of the underbalance (Fig. 50). Thus, some borehole fluid invades the perforation even before the surge flow starts, possibly contributing to additional perforation damage if the subsequent perforation cleanup is insufficient.

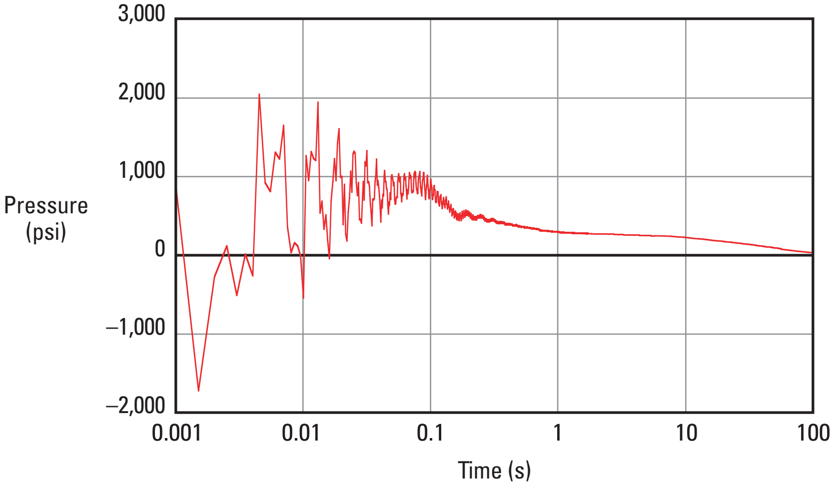

Figure 50. Pressure differential during an underbalanced perforating test.

Dynamics of perforation cleanup

Perforation cleanup results from the underbalance. Underbalance generates stresses in the crushed zone, progressively removing the damaged material. Turbulent flow is not necessarily required to clean perforations.

The first cleanup period (called *surge flow*) is a transient flow. If the underbalance during this period is sufficiently high, the dynamic surge of reservoir fluid into the perforation cavity sweeps pulverized perforation material into the wellbore. It also induces stresses in the crushed zone that cause the rock to fail and spall off. The transient flow is high rate and extremely brief (tens of milliseconds). Only a small amount of fluid and a small volume of formation are involved. The transient flow is independent of neighboring perforations, as long as the perforation-to-perforation spacing is at least 3 to 4 in. The reservoir properties and underbalance determine the effectiveness of the transient flow in cleaning the perforation. For total cleanup to occur, it must happen during the high-rate transient flow.

The second cleanup period (called *postshot flow*) is a semisteady-state flow. It lasts longer and involves greater volumes of fluid than the first cleanup period. The effects depend on neighboring perforations (their number, shot density, and phasing) and the reservoir's deliverability, in such terms as permeability, porosity, and drawdown. Postshot flow has limited effectiveness in cleaning the perforation but may help remove pulverized sand remaining after the surge flow and secondary damage (e.g., invasion of formation fines into the perforation tunnel).

The efficiency of perforation cleanup does not depend on surge volume. Designing completions to maximize surge flow volume is not an important priority for removing crushed-zone material. Perforation cleanup depends only weakly on fluid viscosity, up to about 100 cp.

Regardless of the underbalance, a brief (transient) invasion of completion fluid into the perforation occurs. Therefore, the nature of the completion fluid, (e.g., brine, solvent, oil, acid, or damaging fluids) may affect perforation cleanup.

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As previously discussed, gravity affects downside perforations. Damaging material removed from one perforation is likely to flow into the next perforation with the well fluid. In addition, the presence of the gun in the well during surge flow prevents the cleanup of downside perforations. Downside perforating is not recommended in highly deviated or horizontal wells unless absolutely required for other reasons.

Underbalance criteria

Overview

The term *underbalance* refers to the pressure differential (assumed to be negative) between the wellbore pressure and reservoir pressure. Thus, a well is perforated underbalance when the wellbore pressure is less than the reservoir pressure at the time of perforating. When the pressure differential is positive at the time of perforating (i.e., wellbore pressure is greater than reservoir pressure), the well is perforated *overbalance*.

Historically the perforating process was performed overbalance, sometimes with very high-density fluids and even drilling mud to avoid the risk of blowout. In the 1960s, almost by chance, underbalanced perforating was found to improve perforation productivity. Numerous field and laboratory experiments followed this discovery, with a focus on improving productivity by optimizing the underbalance. The potential benefits of overbalance, including extreme overbalance, were also studied. Overbalance is discussed in the next chapter.

As previously discussed, underbalance is the only factor that contributes significantly to removing perforation damage. As previously mentioned, this cleanup occurs only in the first milliseconds after perforation. The subsequent postshot flow is an insignificant factor, because flow rates and the ensuing drag forces necessary to remove perforation damage are much less than during the surge flow. Assessing and then applying the optimum underbalance are therefore critical in completion engineering. The optimum underbalance to achieve clean perforations is a function of permeability, porosity, reservoir strength, and charge type and size.

This section provides a timeline of the evolution of underbalance criteria, leading to the current best criterion. The best criterion—meaning that considered valid—for conventional underbalanced perforating in most reservoirs for a wide range of environmental conditions is the formula developed by Behrmann (1996), which is subsequently described in this chapter and "Specific perforating requirements" in the next chapter.

The historical criteria reviewed here are not recommendations for choosing underbalance. Rather, the purpose of this discussion is to provide an understanding of how the current best criterion was developed over the past few decades.

Bell (1984)

In the 1960s the industry recognized that underbalanced perforations increase productivity and that the amount of underbalance depends on both the type of reservoir pore fluid and the formation's permeability. In 1972, Bell et al. observed an increase in perforation flow efficiency with increased underbalance. He subsequently determined that postshot flow is the driving force behind perforation cleanup and offered the first criterion for selecting underbalance:

- $k > 100$ mD: Use 200 to 250 psi in oil and 1,000 to 2,000 psi in gas.
- $k < 100$ mD: Use 1,000 to 2,000 psi in oil and 2,000 to 5,000 psi in gas.

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King et al. (1986)

King et al. based their well-known study on a set of 90 wells perforated underbalanced with the TCP technique and acidized after perforating. The wells were tested after perforating and after acidizing. For wells in which acidizing improved the productivity of the completions, King et al. postulated that the underbalance was insufficient to remove most perforation damage and that a higher underbalance before acidizing would have improved productivity. Conversely, the underbalance was assumed sufficient to remove most perforation damage in completions for which acidizing did not improve productivity.

Tariq (1990) integrated all of King et al.'s field data, as shown in Fig. 51 graphed as the underbalance pressure as a function of permeability. The solid dots (oil) and squares (gas) correspond to wells in which acidizing improved productivity; acidizing did not improve the productivity of wells represented by open symbols. The lines separating the two groups of points describe criteria for selecting the minimum underbalance pressure as a function of the permeability. Tariq presented two formulas, one for oil wells and one for gas wells:

Oil:

$$\Delta p = \frac{3{,}100}{k^{0.37}}, \tag{7}$$

Gas:

$$\Delta p = \frac{3{,}000}{k^{0.40}}. \tag{8}$$

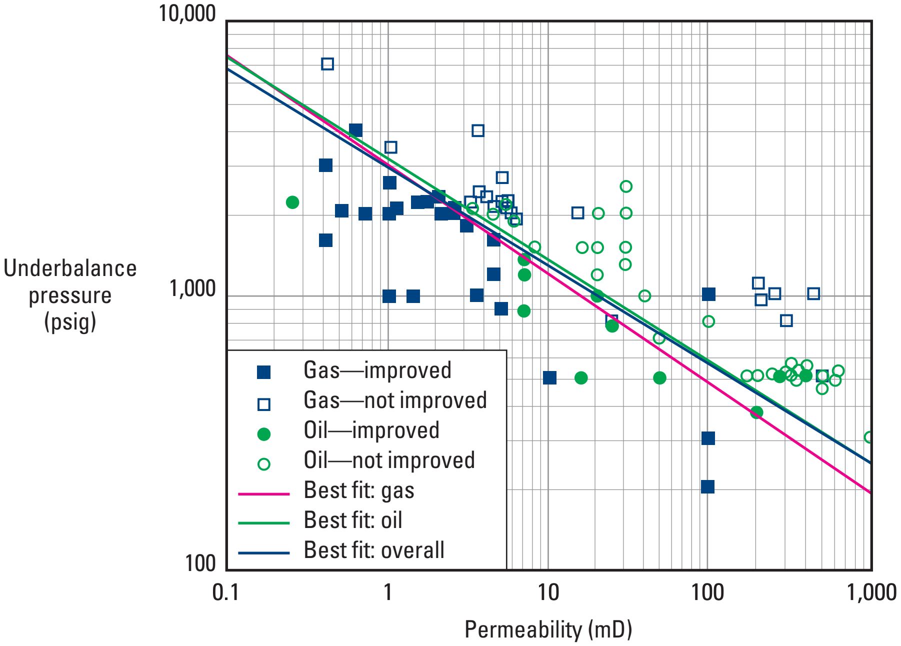

Figure 51. Underbalance field data of King et al. (1986) with best statistical fits for oil wells, gas wells, and all wells. (© 1990 Society of Petroleum Engineers, Inc., Tariq.)

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Crawford (1989)

Crawford (1989) expanded on King's data by proposing minimum and maximum values of underbalance pressure for gas wells. The values are derived from sonic velocity calculations based on sand production potential.

Hsia and Behrmann (1991)

Hsia and Behrmann's work represents the first attempt to directly measure the perforation damage skin effect as a function of rock permeability and underbalance at controlled simulated downhole conditions. The experimental study involved perforating targets of Berea and Gold sandstones with a 3.2-g shaped charge and various values of underbalance pressure. Hsia and Behrmann concluded that zero-skin perforations could be created during the transient surge flow (i.e., without postshot perforation flow) by applying sufficient underbalance as determined by calculating the minimum underbalance for the conditions of the experiments.

Plotted in Fig. 52 are the results of measured single-perforation skin effect as a function of underbalance. Cutoffs of 200 mD and 100 mD are suggested for the Berea and Gold formations, respectively, including the applicable minimum underbalance for zero skin effect.

Figure 53 superimposes Hsia and Behrmann's formulation over King et al.'s (1986) data for different values of a parameter governing the Reynolds number of the perforation flow. Hsia and Behrmann's proposed formula suggests that the minimum values of underbalance pressure necessary to obtain zero-skin perforations are much greater than those proposed by King et al., especially at low permeability. This lack of agreement implies that King et al.'s acid jobs did not actually result in zero-skin perforations and that perforation cleanup was incomplete.

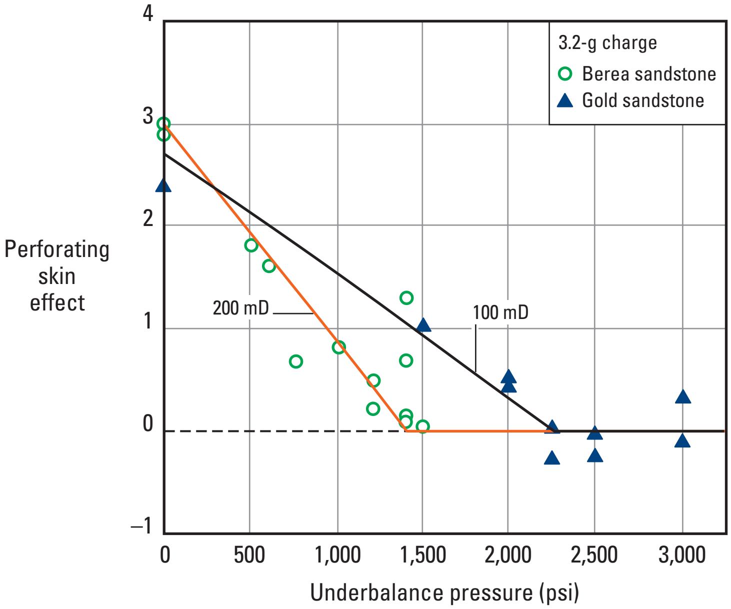

Figure 52. Single-shot perforation skin effect versus initial underbalance. (© 1991 Society of Petroleum Engineers, Inc., Hsia and Behrmann.)

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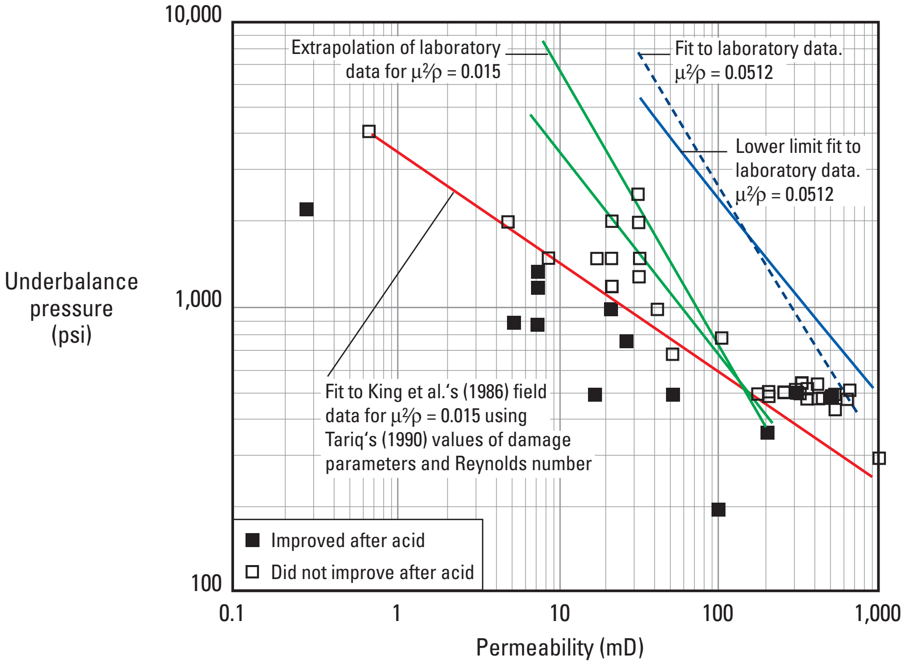

Figure 53. Comparison of required initial underbalance for laboratory data with field data from King et al. (1986). μ = fluid viscosity (cp) and ρ = density (g/cm³). (© 1991 Society of Petroleum Engineers Inc., Hsia and Behrmann.)

Behrmann (1996)

Behrmann (1996) proposed that the surge flow may be laminar, if not turbulent, in the crushed zone at some distance from the axis of the perforation cavity. Thus, removing the crushed zone under the influence of the surge flow may be modeled using laminar and viscous drag forces. Behrmann reinterpreted data from the previous study (Hsia and Behrmann, 1991) in terms of single-shot perforation skin effect as a function of the modeled drag force. Because underbalance governs drag force, extrapolating the data to a zero-skin condition provides a means for calculating the minimum required underbalance. On the basis of certain assumptions, the data are correlated to a formula in which porosity, permeability, and the perforation cavity diameter are the only variables. The perforation cavity diameter is derived from the casing entrance hole (i.e., the charge liner diameter) and the unconfined compressive strength of the rock.

Two correlations are used, depending on the permeability, to calculate the minimum underbalance necessary to yield zero-skin perforations:

For $k > 100$ mD:

$$\Delta p = \frac{1{,}480\,\phi\, d^{0.3}}{k^{0.5}}, \tag{9}$$

For $k < 100$ mD:

$$\Delta p = \frac{630\,\phi\, d^{0.3}}{k^{0.33}}, \tag{10}$$

where

d = perforation cavity diameter

ϕ = porosity.

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This approach also enables calculation of the perforation skin effect for underbalance pressure less than the minimum required for zero skin effect:

For $k > 100$ mD:

$$s_s = \left(\frac{d_{CD}}{20}\right)^2 \frac{2.64 - 0.00183 \Delta p k^{0.5}}{\phi d^{0.3}}, \tag{11}$$

For $k < 100$ mD:

$$s_s = \left(\frac{d_{CD}}{20}\right)^2 \frac{2.64 - 0.00395 \Delta p k^{0.333}}{\phi d^{0.3}}, \tag{12}$$

where

s_s = single-shot skin effect (also referred to as perforation damage skin effect s_{pd})

d_{CD} = shaped charge liner diameter.

SPAN Schlumberger perforating analysis uses this same approach to calculate the perforation skin effect when perforation cleanup is incomplete. SPAN analysis first calculates the minimum underbalance required for zero skin effect. For actual underbalance less than the calculated minimum, the ratio of the permeability of the (remnant) crushed zone to the permeability of the undisturbed formation is determined.

Behrmann and McDonald (1996)

Behrmann and McDonald (1996) presented an interesting application of Behrmann's (1996) derivations with relevance to several aspects of perforating requirements. The findings were applied to a large population of rock samples from Alaska and the North Sea. Extensive core measurement had previously established the permeability-porosity relationship for these rocks (Fig. 54). The results are presented in the form of minimum underbalance pressure as a function of permeability, expressed in these formulas normalized to a formation perforation cavity diameter of 1 in.:

For Alaska and North Sea Brent cores:

$$\Delta p^{0.5} = 90.37 - 7.86 \ln k. \tag{13}$$

For quartz arenite cores:

$$\Delta p^{0.5} = 50.58 - 3.442 \ln k. \tag{14}$$

Figure 55 shows the correlation between the Alaska and North Sea Brent cores. Once again, the suggested values for the minimum underbalance are much higher than those proposed by King et al. (1986).

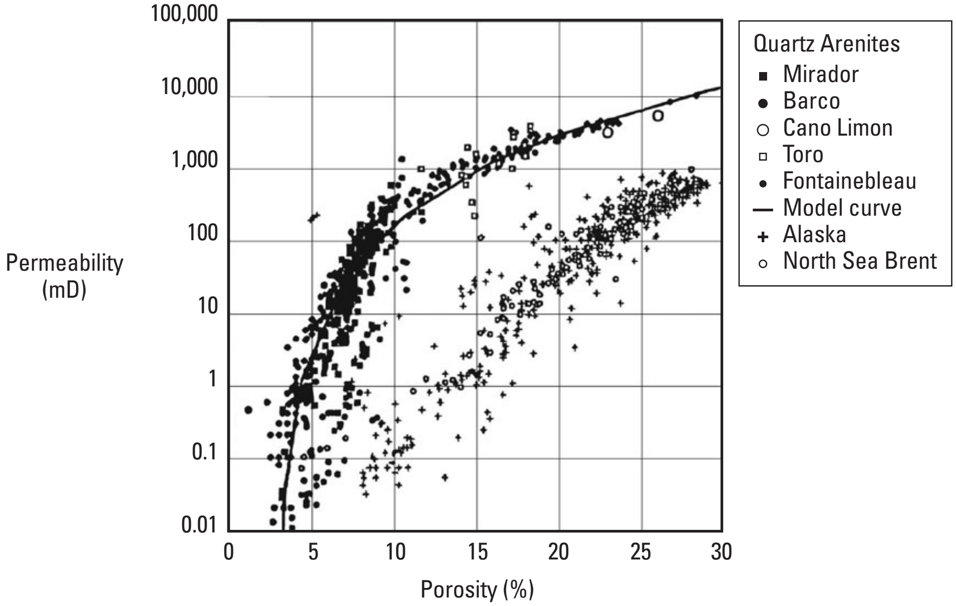

Figure 54. Permeability-porosity relationships. (© 1996 Society of Petroleum Engineers Inc., Behrmann and McDonald.)

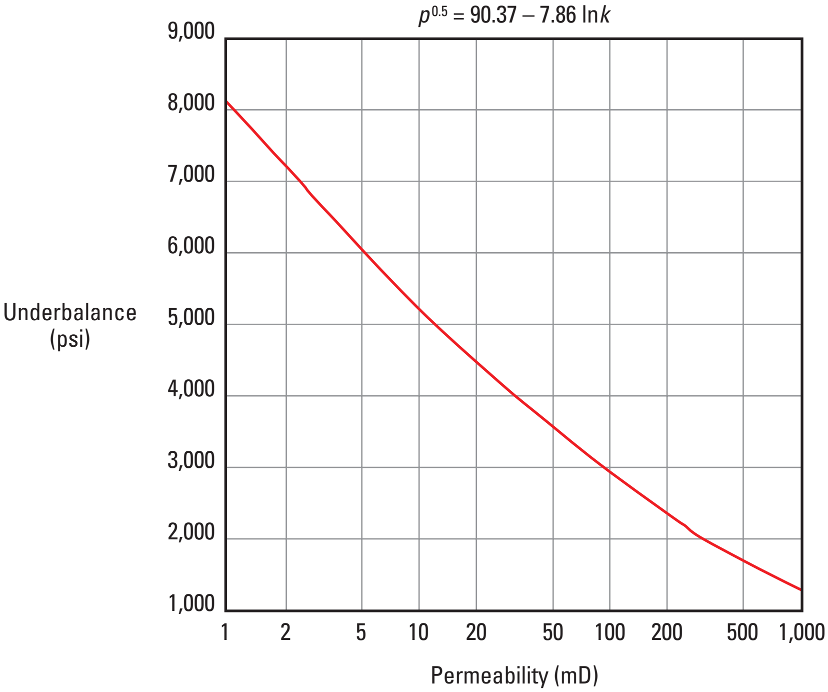

Figure 55. Optimum underbalance versus permeability for Alaska and North Sea Brent cores. (© 1996 Society of Petroleum Engineers Inc., Behrman and McDonald.)

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Walton (2000)

Walton identified three possible damage removal mechanisms: erosion, tensile failure, and shear failure. All the previously discussed damage removal models are essentially erosion models; the required underbalance depends on the rock permeability. Walton developed tensile and shear failure models in which the required underbalance depends on the rock strength. He demonstrated that erosion is too weak to be an important factor in perforation cleanup. The new models are currently being evaluated against laboratory and field data.

PURE Perforating System for Clean Perforations

The PURE* perforating system optimizes the well dynamic underbalance (i.e., the transient underbalance that occurs just after creation of the perforation cavity) by basing the job design on the properties of the reservoir, wellbore, and gun string. This novel technique consistently obtains the maximum effective transient underbalance to eliminate or minimize perforation damage.

Background

As previously discussed, underbalanced perforating is the technique of choice for removing perforation damage and producing productive perforations. The degree of underbalance required depends primarily on the rock properties, such as permeability and strength. For example, hard, low-permeability rocks need a large underbalance, sometimes as much as 8,000 psi. However, the conventional design approach of setting the wellbore pressure below the reservoir pressure before the guns are fired does not always produce the expected level of productivity. Additionally, low reservoir pressures limit the magnitude of the initial underbalance.

Recent single-shot perforating experiments at the Schlumberger Productivity Enhancement Research Facility (PERF) at SRC in Rosharon, Texas, USA, demonstrate that the wellbore pressure varies considerably during the first half-second after the charges are detonated (Walton et al., 2001). This variation in wellbore pressure is reflected in relation to the transient underbalance, and it is the maximum dynamic underbalance—not the initial underbalance—that governs perforation cleanup.

Figure 56 shows the results of Tests 1 through 4 with the same charge and starting at an initial underbalance of 1,000 psi. The maximum dynamic underbalance varied from 400 to 1,300 psi. The corresponding CFEs were 0.70, 0.69, 0.61, and 0.21 (CFE = 1 denotes a perfectly clean perforation). Two similar Tests 5 and 6 (Fig. 57) started with a initial overbalance of 500 psi. The maximum dynamic underbalance ranged from –300 to 2,400 psi with CFEs of 0.92 and 0.41, respectively. Although both sets of tests used identical charges and outcrop cores, their CFEs were substantially different.

The essence of the PURE technique is to generate a dynamic underbalance situation similar to that produced in Test 5, which results in a sharp reduction in wellbore pressure.

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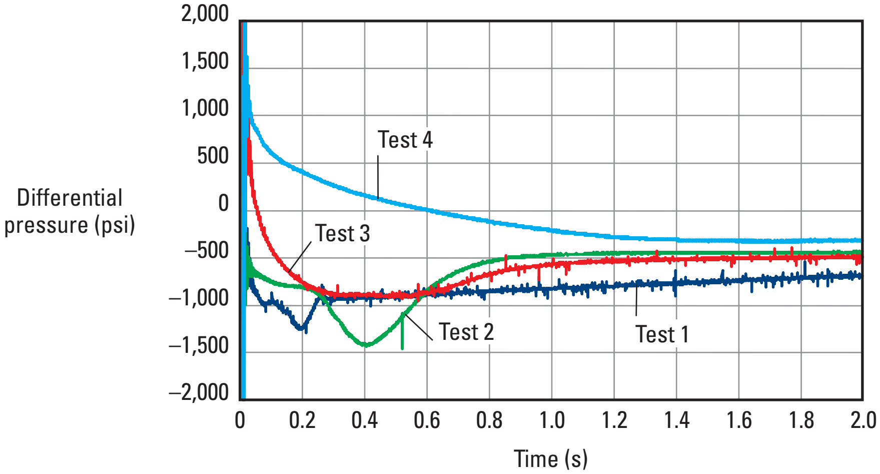

Figure 56. Differential pressure (between the simulated wellbore pressure and the pore pressure) for Tests 1 through 4 shows that the maximum dynamic underbalance varied from 400 to 1,300 psi.

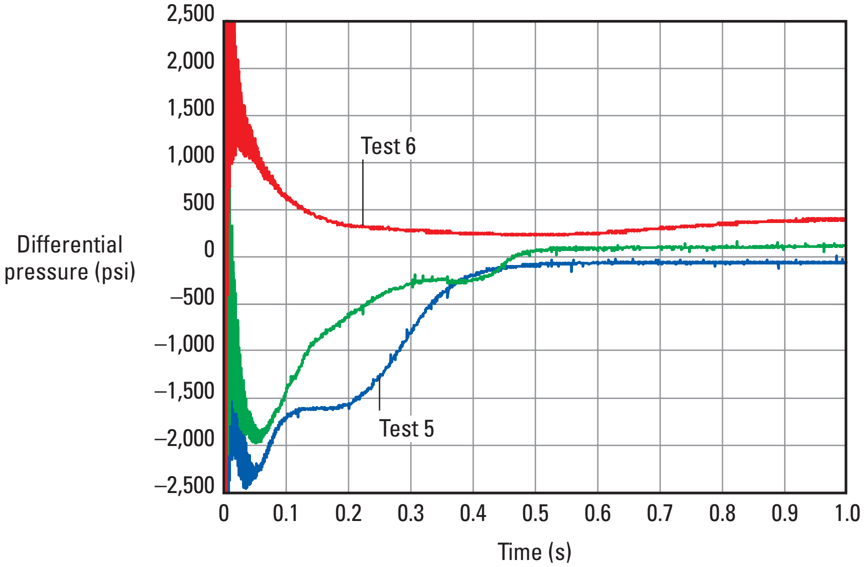

Figure 57. Tests 5 and 6 have a range of –300 to 2,400 psi for the maximum dynamic underbalance.

Field application

Careful control of the wellbore dynamics is critical to the success of the perforated completion. The PERF experiments conclusively showed that previously neglected variations in wellbore parameters have a profound effect on the performance of the completion. Significant improvement in perforation and reservoir performance can be achieved through integrated design and control of the completion geometry, fluids, and perforating hardware. For each job a unique perforating system must be designed to create and control the dynamic underbalance. Design software has been developed specifically to customize the perforating system and optimize the completion process.

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Case studies

The PURE technique has been successfully performed in hard- and soft-rock formations, oil and gas reservoirs, sandstones and carbonates, and producers and injectors.

- Horizontal completions for Chevron Texaco in the Rocky Mountains region of the United States were perforated with moderate underbalance up to 600 psi but would not flow without an acid wash of 15% hydrochloric acid (HCl) applied via coiled tubing. This was usually followed by a full-scale matrix mud acid job using foam as a diverter. The PURE system was used to overcome the perforation damage (Behrmann et al., 2002), and four of five completions then flowed immediately upon perforating at post-stimulation rates. This successful application of the PURE technique resulted in savings of USD 600,000, just by eliminating the acid stimulations.
- Oil production from the PDVSA SIN-75 well in Venezuela is almost double what was expected following PURE perforating. Instead of the expected 250 B/D, 400 B/D of oil is artificially lifted from a zone at 9,100 ft and about 3,500-psi reservoir pressure. Total production is 800 bbl with 50% water cut. A 35-ft net (48-ft gross) interval was perforated using 3⅜-in. guns loaded at shot densities of 6, 5.5, and 4 spf. The well was shot at an initial static overbalance of 800 psi contained below a packer and drop-bar-activated tubing- or rathole-pressure-operated valve (DTRV). A hydraulic delay firing (HDF) head was used to fire the guns. After the tubing was swabbed down, the DTRV was opened and the well surged by dropping a bar.

  Previously, the wells in this area were perforated (TCP) with static underbalance. The fluid level in the wells after perforating would be at 6,000 to 7,000 ft. After shooting with the PURE technique, the postperforating fluid level was at 500 ft and never went deeper than 1,400 ft during swabbing, which confirmed the creation of clean perforations. The wells had been typically treated with a perforation acid wash, but no acid was required after the PURE technique was used.
- Three water injector wells in the same reservoir in North America were perforated using the PURE method, either wireline or coiled tubing, and CIRP* Completion Insertion and Removal under Pressure equipment. The 1- to 2-D sandstone, at about 4,000 psi, was perforated with the PURE technique at balanced conditions with either 4½- or 3⅜-in. guns. Injection rates in the three PURE wells are up to 5 times higher than the rates achieved in the same reservoir by using traditional perforating techniques. The operator plans to use the PURE technique on all future water injection wells.
- In South America five producer wells were perforated by using TCP and the PURE closed-chamber technique. The producing zones are sandstone at a depth of 8,000 ft with 15% porosity, 1- to 2-D permeability, and 2,200-psi reservoir pressure. Test results from all five wells showed skin factors ranging from 0 to –1 whereas the previous average skin effect in almost 20 wells was 12 (14 of which are shown in Fig. 58). The improvement in skin effect achieved with the PURE technique resulted in a productivity improvement in these pumped wells of more than double, from 3 to 7 BFPD/psi.
- Typically gas-producing wells in the Morrow formation in West Texas in the United States require postperforation cleanup treatments. The producing formation is a tight (16% porosity), 1-mD sandstone. Perforating using the PURE technique and permanent TCP have produced results much better than expected.
- Anadarko used the PURE technique to perforate two wells in Wyoming. The design featured 3⅜-in. guns and closed-chamber TCP with an automatic production valve (SXPV) in a tight, 0.5- to 1.5-mD sandstone in a depleted reservoir at approximately 2,500 psi. The wells were shot with a static overbalance of approximately 3,500 psi. As documented by Stutz and Behrmann (2004), the PURE method produced results far beyond expectations and without the typically required acid job.

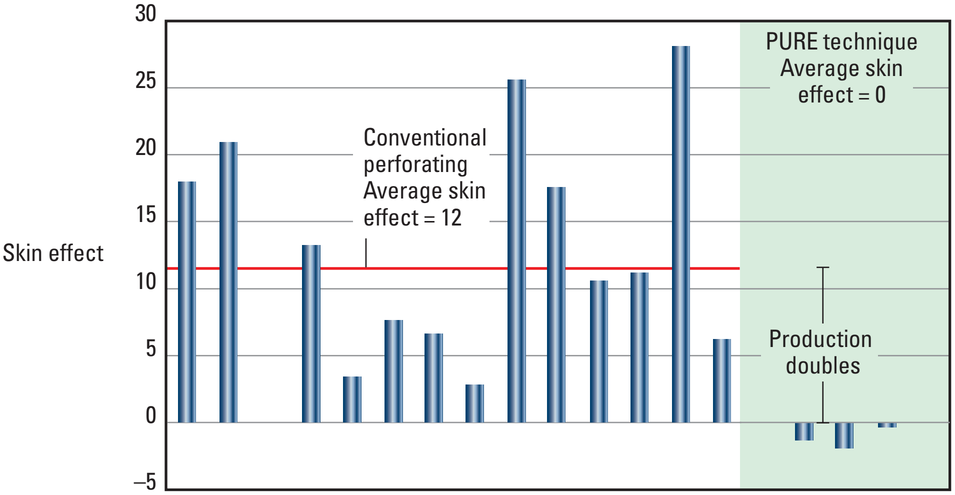

Figure 58. Use of the PURE technique in five South American wells more than doubled production with an average skin effect of 0, down from the previous average skin effect of 12 in 14 wells perforated with conventional techniques.

- In South America multiple runs of the PURE technique with 2½-in. guns on wireline at balance were used to perforate a gas-bearing sandstone with 2.2-mD permeability, 27% porosity, and 4,000-psi pressure. The 3½-in. monobore completions were then produced immediately after shooting. Typically wells in this area require fracturing because of high near-wellbore skin after perforating. With the PURE technique no fracturing was necessary and the well produces much better than expected.
- In Asia multiple runs of the PURE technique with 2-in. guns on wireline were used in a 2⅞-in. monobore completion to perforate a 10-mD gas zone. Production results have been stellar.
- A 90-ft zone in a water injector well in Alaska, United States, was initially conventionally perforated with several runs of 4½-in. guns on wireline. A fall-off test indicated significant skin effect for an injection rate of 17,500 BWPD. Perforating an additional 20 ft at balance with a PURE design using 3⅜-in. guns and PowerJet deep penetrating shaped charges resulted in an increase in the injection rate to 25,000 B/D. Production logging indicated that 97% of the injected fluid was going into the new zone perforated with the PURE method. This represents a 6-fold improvement in injectivity per foot of PURE perforation.
- A very low-pressure (900- to 1,100-psi reservoir pressure, 40- to 50-mD permeability) sandstone in the United States was successfully perforated using a staged, multizone shoot and test campaign based on the PURE technique. After a zone was conventionally perforated, tested, and plugged, a PURE design that effectively used the well pressure was used on the subsequent interval. The PURE method reduced the skin effect and negated the need for a costly nitrogen surge to clean up before testing. The improved completion efficiency has decreased the total well completion cost by 30% to 40% for the operator.

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- In the Middle East the Khuff-C and Khuff-B carbonate formations were perforated using a PURE design for 2⅞-in. guns on wireline. The Khuff-B typically requires a postperforation cleanup acid wash before producing, and the Khuff-C requires both an acid wash and acid matrix treatment. The Khuff-C was perforated first and produced 8 MMcf gas at 1,900 psi, much above the expected rate at and without the usual acid wash treatment. The Khuff-C was then isolated and the upper zone in the Khuff-B was perforated. Again, an acid wash was not needed to inject 5 bbl/min of brine at 8,900 psi. Once the injection rate was established, acid was bullheaded from surface to further increase the injection rate to 5 bbl/min at 3,000 psi, which was sufficient to perform the acid matrix stimulation. The success of the PURE perforating job made the overall operation considerably more efficient and less costly for the operator.
- A horizontal well in a weak-rock formation has double the production of offset wells after the PURE technique was used with an initial overbalance (Stenhaug et al., 2003). The PURE design was incorporated into the OrientXact* tubing-conveyed oriented perforating system for sand prevention, and PowerJet deep penetrating shaped charges were used for debris control.

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Reservoir Completion Types

Completion types

Shaped charge perforating is the most common method used to achieve communication between the formation and the wellbore. The character of the communication path through the cement and casing is critical to the completion and well performance. Perforating ideally makes many large, uniform holes for gravel-pack completions or provides uniform entry points through the casing and cement for hydraulic fracturing fluids and proppants, and it can enhance well productivity by creating clear channels through the portion of the formation damaged during the drilling process. Perforating can even be used in specific applications to reduce sand production. Perforating is the most cost-effective means to achieve formation-to-wellbore communication objectives. Furthermore, the technique is flexible and reliable.

The main factors affecting well performance are the completion, formation and fluid properties, and reservoir geometry (Fig. 59). Of these, factors such as hydrocarbon saturation, porosity, permeability, fluid properties, and geometry can be measured or inferred from measurements. However, they cannot usually be controlled. By contrast, the completion is a controlled operation, and as such its design affects well performance. Because perforations are a critical part of the completion, careful consideration should be given to the type, size, number, and orientation

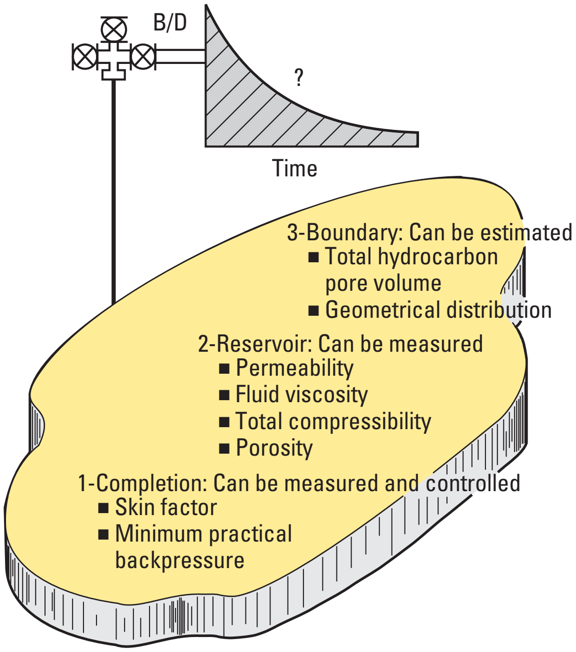

Figure 59. Factors affecting well performance.

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of the perforations in addition to the conditions in the well during perforating. This section discusses the relationship between perforating and well performance and thus the role perforating plays in the completion optimization strategy (Fig. 60) (Venkitaraman et al., 2001).

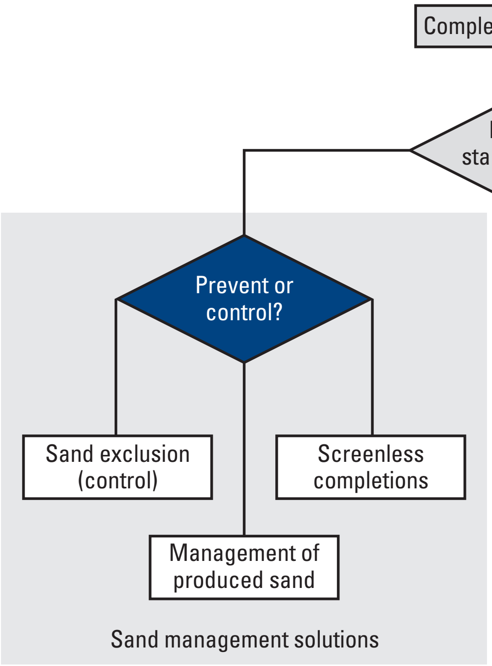

Figure 60. Completion optimization decision tree.

Completion objective

Perforated completions can be divided into three types—natural, stimulated, and sand management (i.e., sand production is a concern). (Perforated completions in horizontal wells, which are discussed separately, typically combine features from the three completion types.) In all completion types, the objective is to maximize production through the enhancement of some aspect of reservoir performance modeled by the radial flow equation (Eq. 4 in the "Productivity and Skin Effect" chapter and Fig. 61).

Radial flow Eq. 5 (in the "Productivity and Skin Effect" chapter) is used to derive the productivity index to evaluate both the performance of a well over time and the effects of any production enhancement.

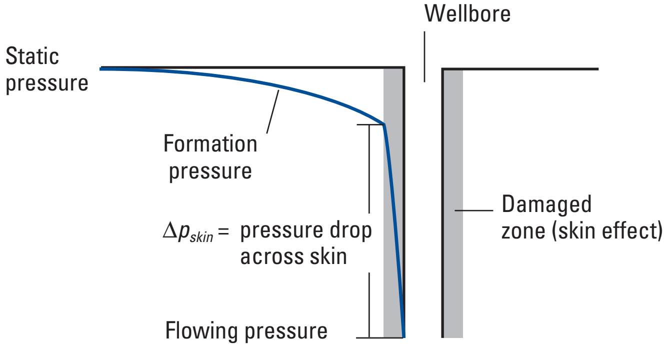

Figure 61. Pressure distribution in a reservoir with skin effect.

Natural completions

Natural completion is usually selected for sandstone reservoirs with permeabilities greater than 10 mD and porosities greater than 9 p.u. However, gas reservoirs with permeabilities as low as 0.7 mD have been successfully completed without stimulation (Stutz and Behrmann, 2004). Candidate reservoirs for natural completion typically have small skin values, good transmissibility, and stable rock mechanics. Although production may be enhanced through fracture stimulation or the application of enhanced recovery methods (artificial lift, thermal, chemical, or waterflood), natural completions do not require stimulation or sand management during the primary completion.

Effects of perforation

In the natural completion, the primary perforation factors are perforation damage, penetration length, and effective shot density. The perforation diameter in the reservoir is generally of secondary importance; however, the deepest penetration with the greatest phase distribution is desirable to enhance production (see “Productivity and Skin Effect” chapter).

In the overbalanced completion, well fluids and pressures are selected to create a hydrostatic head greater than the reservoir pressure. This provides pressure containment for a well completed with large-diameter casing guns or HSD High Shot Density guns without the presence of well completion hardware. Although efficient, this method has the disadvantages of damaging the formation as a result of fluid invasion and plugging perforations with no perforation cleanup, leading to larger positive skin values.

In the underbalanced completion, reservoir pressure is greater than the wellbore pressure, creating a negative differential across the formation during perforation. The underbalanced completion offers a significant benefit: Because the completion assembly may be in place at the time of perforation, maximum perforation cleanup can be accomplished through the surge effect from the underbalance, with no fluid invasion into the reservoir.

The PURE perforating system for clean perforations combines the advantages of perforating underbalanced without requiring an initial underbalance (see the preceding chapter for more information). With optimized perforating equipment, clean perforations can be obtained even with an initial overbalance.

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Natural completions in consolidated hard-rock reservoirs

For natural completions in consolidated hard-rock reservoirs, the PURE technique is used with deep penetrating shaped charges. Maximum shot density in shots per foot is determined by the PURE design. If PURE perforating cannot be used, very high shot density guns can be used to minimize the skin effect caused by perforation damage. However, the trade-off between high density and deep penetration should be evaluated through SPAN perforating analysis. Perforation diameter and phasing are of secondary importance, as long as the phasing is nonzero. Perforation length is the most important parameter if the formation is heavily damaged by the invasion of drilling fluids. If no information on formation damage is available, the shaped charges that provide the greatest possible penetration length should be used.

The relative priority of perforation parameters for natural completions in consolidated hard-rock reservoirs under several typical formation conditions is presented in Table 12.

Table 12. Relative Importance of Perforation Parameters in Hard-Rock Natural Completions

Perforation Parameter	Isotropic Permeability	Anisotropic Permeability	Shale Laminations	Wellbore Damage	Hard Rock
Clean perforations	1	1	1	1	1
Effective shot density	1	1	1	2	2
Perforation diameter in rock	3	3	3	3	3
Perforating phasing	4†	1‡	1‡	4†	4†
Perforation length	1	2	2	1	1

Note: 1 = highest priority; 4 = lowest priority

† For phasing greater than 0°

‡ For oriented guns with optimum phasing

Natural completions in naturally fractured reservoirs

In naturally fractured reservoirs, optimizing the perforation length and perforation phasing are important to intersect as many fractures as possible. Deep penetrating charges are preferred. The "Productivity and Skin Effect" chapter discusses this preference in more detail.

Another consideration is whether to complete and perforate in open hole or cased hole. As mentioned in "Productivity and Skin Effect," perforating with deep penetrators is more effective unless large fracture spacing makes the fracture intersection probability unacceptably small. In openhole completions, mud or mud filtrate may plug the fractures. Further, Halleck and Dogulu (1996) noted that

- Jet metal (liner fragments) may invade the fracture, reducing its hydraulic conductivity.
- Shock stresses may deform the surrounding rock, closing the fracture where it intersects the perforation.

On the basis of these considerations, recommendations are as follows for completions in open holes:

- Perforate balanced or at a modest underbalance with the PURE technique if the average fracture width is large enough to accommodate whole mud invasion.
- Perforate overbalanced (potentially with the PURE technique), including acidizing, if the mudcake has built to a thickness that could impair acid leakoff. The acid removes plugging material at the fracture-to-perforation junction.

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Stimulated completions

Stimulated completions are divided into two broad categories: hydraulic fracturing and acidizing. Occasionally the two are combined in an “acid frac” job. Fracturing applications for sand management are discussed subsequently in this chapter.

Perforating for hydraulic fracturing

Hydraulic fracturing is performed to enhance the effective wellbore radius r_w' (Fig. 62) and is usually indicated for reservoirs with low values of permeability ($k < 1$ mD). Perforating is one of the most critical elements in the success of this type of stimulated completion. The perforation is the origin of the fracturing pressure, the opening for injecting fracturing fluid and proppant, and the conduit for reservoir fluids to flow into the wellbore.

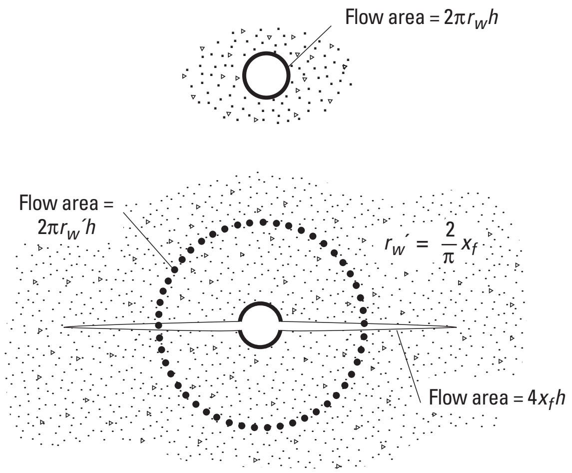

Figure 62. The effective wellbore radius r_w' is used to describe how the fracture essentially enlarges the wellbore exposure to the formation. In equations for pseudoradial flow (Prats, 1961), h is the fracture height and x_f is the effective fracture length. The fracture typically propagates away from the wellbore in two fracture “wings” (called a biwing configuration) 180° apart along the preferred fracture plane.

Limited-entry technique

Historically, hydraulic fracturing has been performed using the *limited-entry technique*. Limited entry involves placing low-density shots (1 spf or less) across reservoir intervals, which are sequentially fractured and propped open. This technique primarily ensures very high casing pressure to fracture high-stress intervals. The limited-entry technique can also be used to penetrate lower permeability zones.

The perforation diameter and uniformity are the most important factors. If not optimized, they can create pressure restrictions in the flowing fracturing fluid and proppant. The objective is to maximize the percentage of perforations open to the fracture, which limits the differential pressure across the perforations and minimizes erosion. The result is improved proppant or acid placement and better stimulation treatment.

The limited-entry technique is also used with plastic balls to seal off a set of perforations so that fluid is diverted to another perforated interval for fracturing or treatment. Perforating requirements for the “ballout” technique include the creation of uniform entrance holes, which can be sealed evenly and completely by the ball sealers.

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Bullet guns were the first perforators that could produce the required uniform perforation diameter. (The bullet left at the end of the perforation was not a factor in creating and propagating the fracture.) Bullet guns were replaced by small shaped charges. Currently several different types of guns, including Frac Gun* perforating system for wells requiring fracture stimulation and ASFS* addressable-switch firing system guns, can deliver the same effect of a homogeneous entrance hole when the gun is well centered inside the casing.

Perforation screenout

Another consideration is the creation of perforations that avoid premature screenout in or near the perforation. *Screenout* is the bridging of proppant sand along its path toward the edges of the fracture. It limits fracture propagation and prevents the advance of more sand to prop the fracture open.

The occurrence of premature screenout depends on the flow geometry and concentration of proppant. Gruesbeck and Collins (1982) identified a relationship between the concentration of proppant sand and the ratio of perforation diameter over the sand particle diameter necessary to prevent perforation screenout. Figure 63 shows that the perforation diameter must be at least 6 times the average diameter of the proppant sand particles at moderate to high proppant concentrations. In fact, the preferred ratio is from 8 to 10 to allow for variations in shaped charge performance and gun positioning in the wellbore. Ideally SPAN analysis should be run to find the minimum casing entrance hole for a given combination of gun, shaped charge, and casing.

Premature screenout can occur anywhere along the proppant flow path, not only at the perforation. Avoiding premature fracture screenout is a major objective of stimulation design because screenout limits the effective dimensions of the fracture and the amount of proppant sand that can be injected.

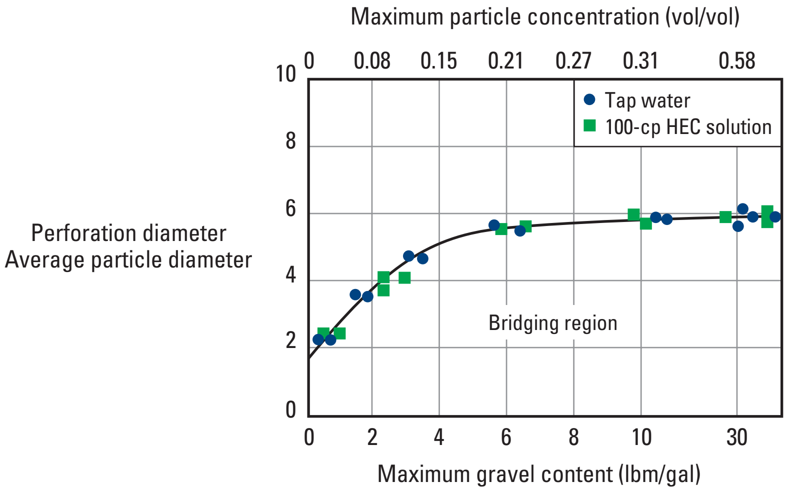

Figure 63. Bridging of particles in perforations (after Gruesbeck and Collins, 1982). HEC = hydroxyethyl cellulose.

Fracture initiation in hard rocks

Laboratory experiments in 1973 by Daneshy showed that higher fracture initiation pressure was required when the fracture orientation along the *preferred fracture plane* (PFP) was at a high angle (90°) in relation to the perforation. The PFP is the plane normal to the minimum far-field stress direction that contains the wellbore and the wellbore surface.

Warpinsky (1983) reported that hydraulically induced fractures may not be in the same plane as the perforation. These investigations also indicated that the fracture may initiate on a plane different from the perforation plane if the perforations and the PFP differ by more than 30°.

More recently, Nolte (1988) pointed out that the fluid and proppant must travel along an annular path around the casing to communicate with the fracture when the fracture does not initiate at the perforations. This condition may cause higher treating pressures, premature screenout, and asymmetric penetration of the fracture wings.

Behrmann and Elbel (1991) conducted experiments on fracture initiation through real perforations. These full-scale laboratory tests produced many implications for the dynamics and geometry of hydraulic fracturing, as well as for field procedures. Major findings concerning fracture generation related to placement of the perforations are as follows:

- There are only two generic fracture initiation sites: at the base of the perforations (not at the tip) and at the intersection of the wellbore with the PFP.
- Fracture initiation depends on the orientation of the perforations with respect to the PFP. If the angle is greater than 30°, a fracture generally initiates where no perforation exists. Fracture initiation may require much higher wellbore pressure and possible premature screenout may occur because the pressure must be transmitted (and proppant must travel) through the cement–sandface annulus. Therefore, perforation phasing is extremely important for optimizing fracture initiation.
- The rate of fracturing fluid injection directly affects both the fracturing pressure and fracture initiation sites. High rates promote high fracturing pressures and fewer fracture initiation sites. Lower rates result in much lower fracturing pressures that remain constant throughout the injection and more initiation sites created from both perforations and discrete points around the cement–sandface annulus. Table 13 compares high-pressure Test 7 and three low-pressure tests in the Torrey Buff formation, a modest-strength sandstone. Test 7 had only three initiation sites; multiple fractures were initiated in Tests 8, 9, and 10.
- Perforation length is relatively unimportant.

Table 13. Injection Pressure Rates for Fracturing Torrey Bluff Sandstone Cores

Test (No.)	Breakdown Pressure (psi)	dp_i/dt (psi/s)	dp_p/dt (psi/s)	Ratio of Injection to Pore Pressure Rates
7	7.6	560	120	4.7
8	6.0	69	23	3
9	6.6	69	23	3
10	6.4	59	17	3.5

Notes: dp_i/dt = average injection pressure rate, dp_p/dt = average in situ pore pressure rate.

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Further work by Behrmann and Nolte (1998) analyzed the effect of the perforating gun system on fracture initiation and propagation under the following conditions:

- Possible presence of a microannulus between the cement and sandface—influence of both the cementing parameters and selected perforating strategy on the presence of a microannulus
- Fracture tortuosity resulting from the curvature of the fracture path—the direct effect of misalignment between gun phasing and the PFP
- Possible generation of multiple, competing fractures—the direct effect of gun phasing because multiple fractures can propagate from many perforations with multiple phasings favoring multiple fractures
- Fracture initiation pressure.

Optimizing these parameters for a fractured completion requires comparing the advantages and drawbacks of different perforating strategies. “Specific perforating requirements” subsequently discusses options for various circumstances. The same section describes other implications of Behrmann et al.’s (1998) experimental work related to the selection of gun and charge type, phasing, and shot density.

A primary design concern in perforating is avoiding creation of or further propagating a cement–sandface microannulus. Many factors can result in the creation of a microannulus, including the dynamics of cementing and testing the casing, displacing fluids, and generating the underbalance. Table 14 lists parameters related to perforating that significantly affect microannulus creation.

Table 14. Perforating Parameters that Affect Cement–Sandface Microannulus Creation

Parameter	Promotes Microannulus?
Capsule gun	Yes
Hollow carrier gun	To some extent
Small gun-to-casing clearance	Yes
Liquid in wellbore	Yes
Low shot density	No
Gas in wellbore	No

Except when gas is the wellbore fluid, perforating debonds a portion of the cement–sandface hydraulic bond. Debonding results from gun swell (or charge-explosive coupling for capsule charges), passage of the perforating jet through the wellbore fluid, and expulsion of explosive detonation gases into the wellbore fluid. With hollow carrier guns, debonding may be a function of the gun phasing.

Two factors require careful balancing in selecting a shaped charge for deep penetrating or big hole applications—the trade-off between the minimum perforation penetration of 6 in. and the minimum entrance hole size, which is related to the mean proppant particle size. Perforation penetration beyond 6 in. into the formation is not considered important. The perforation is oriented with respect to the PFP but does not lie within the PFP when the fracture begins at the base of the perforation, not at its tip. However, the perforations must have a casing entrance hole diameter at least 8 to 10 times the diameter of the proppant sand to prevent bridging that results in a perforation screenout.

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Three parameters determine the minimum shot density: perforation casing diameter, desired injection rate per perforation, and pressure loss through the casing and cement tunnel. These parameters are interrelated as

$$p_{pf} = 0.237\rho\left[\frac{Q}{C_d d^2}\right], \tag{15}$$

where

p_{pf} = perforation friction pressure loss for noncrosslinked fluids

ρ = fluid density

Q = injection rate

C_d = dimensionless discharge coefficient of the fracturing fluid (available from correlations such as Lord et al., 1994)

d = perforation diameter.

Figure 64 illustrates the relationship between the injection rate and casing hole diameter at different values of injection pressure drop in water-base systems (Behrmann et al., 1998).

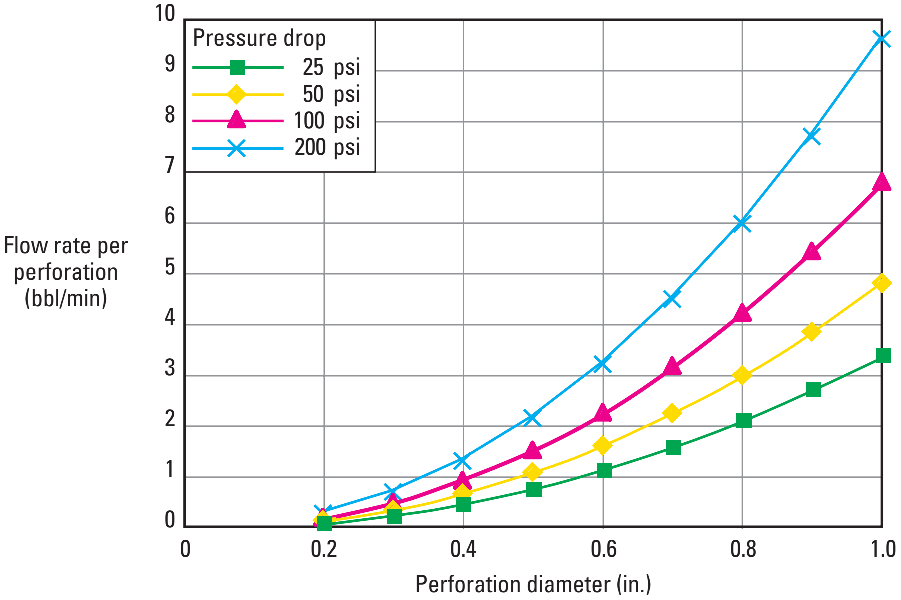

Figure 64. Injection rate versus casing hole diameter and pressure drop in water-base systems.

Best practice: Oriented perforating

Oriented perforating is a best practice for fracturing because the aligned perforations maximize the number of holes open to a hydraulic fracture and enable fluids to flow directly into the PFP. Near-wellbore pressure losses are minimized or eliminated.

A gun system with 180° phasing is ideal for orienting the perforations in the direction of the PFP. If not indicated on local geological studies, the location of the geographical azimuth of the PFP can be inferred from openhole logs such as the DSI* Dipole Shear Sonic Imager, FMI*

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Fullbore Formation MicroImager, and UBI* Ultrasonic Borehole Imager or their logging-while-drilling (LWD) equivalents, such as the RAB* Resistivity-at-the-Bit tool. Oriented perforating provides numerous benefits:

- removes the influence of microannulus pinch points
- removes the near-wellbore tortuosity of fluid flow paths
- increases the number of holes open to the fracture, thus increasing the effective AOF with the fracture
- maximizes the near-wellbore fracture width
- enhances the use of low-viscosity fluids for fracturing.

If the gun cannot be oriented, the advantages and drawbacks must be considered for the different gun systems described in Behrmann et al. (1998) in relation to the fracture initiation pressure, cement bond integrity, presence of microannulus pinch points, possible creation of multiple competing fractures, and tortuosity of the flow paths.

The following tables compare the parameters in two cases: without a microannulus (Table 15) and with a microannulus (Table 16).

Table 15. Perforating Gun Performance: Not Oriented, Vertical Well, No Microannulus

Gun Phasing (°)	Fracture Initiation Pressure	Multiple Fracture Creation	Low Tortuosity	Preservation of Cement Bond
0	3	1	3	1
180	3	1	3	1
120	2	2	2	2
60	1	3	1	3

Note: 1 = best; 3 = worst

Table 16. Perforating Gun Performance: Not Oriented, Vertical Well, Microannulus

Gun Phasing (°)	Fracture Initiation Pressure	Multiple Fracture Creation	Reduced Influence of Microannulus Pinch Points
0	3	1	4
180	3	2	3
120	2	3	3
60	1	4	1

Note: 1 = best; 4 = worst

For highly deviated and horizontal wells where the angle between the wellbore and the PFP is greater than 30°, the recommended approach is to cluster the perforations over shorter intervals (a few feet per interval) at maximum shot density and phasing. This technique maximizes perforation communication with one dominant fracture per interval.

Extreme overbalance (EOB) perforating may be an option if the objective is to enhance communication between the perforations and the reservoir, rather than to create deep fractures in the formation. EOB perforating can also be performed in preparation for standard hydraulic fracturing. For more details, see “Extreme overbalance” in this chapter.

Acidizing

Acidizing is a stimulation process used to

- provide fluid-conducting paths in carbonates
- repair formation damage caused by drilling
- clean damaged perforations.

Figure 65 shows the areas of interest in an acidized well.

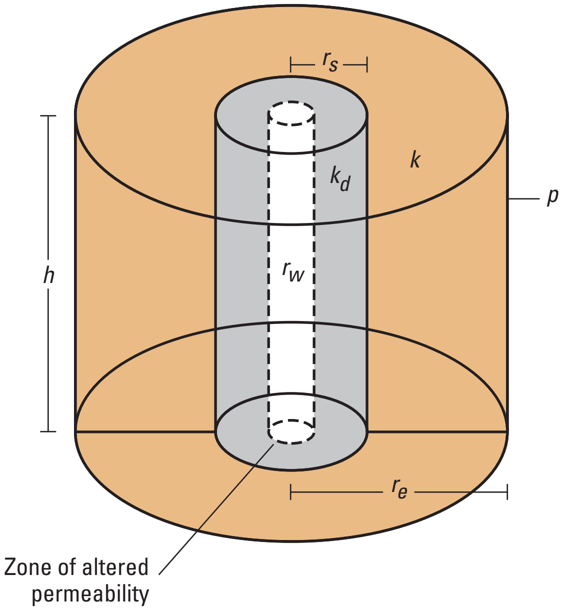

Figure 65. Well and zone of permeability altered by damage.

Acidizing objectives include improving the permeability of the near-wellbore damaged zone k_d and improving the skin effect within the radius of the damaged zone r_s. By convention, $s = 0$ denotes no damage in comparison with a clean, unperforated openhole completion (i.e., $k_d = k$). If $k_d < k$, then $s > 0$ indicates damage. If $k_d > k$, then $s < 0$ indicates stimulation. The only damage (and its related skin effect) affected by acidizing is damage to the formation. Acidizing has no effect on pressure drops (i.e., skin effect) that result from the mechanical design of the completion.

An *acid frac* job is used to etch the surface of the hydraulically induced fracture. After the fracture closes, the etched surface significantly improves the effective wellbore radius r_w'. Acid frac jobs are operationally less complicated than full-scale hydraulic fracturing or propped fracturing operations because no proppant is used; this eliminates the potential for premature fracture termination caused by screenout or proppant flowback problems. The principal disadvantages of this technique are the expense of the acid fluids, nonuniform leakoff resulting in "wormholes," and limited life of the fracture caused by fracture closure. Acid frac jobs are usually performed on carbonate reservoirs, as subsequently discussed in "Perforating in carbonates."

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Extreme overbalance

First developed by Oryx Energy and Arco in two slightly different versions, EOB is defined as the application of a very high overbalance pressure, either during perforating or during surging of existing perforations. The overbalance, which is significantly above the formation breakdown pressure, creates short fractures in the formation, a few meters in length. Although short, the fractures go beyond the skin damage zone and should improve the productivity of the well.

Initial field experience indicated that the pressure gradient in the well should be in the range of 1.4 to 3.0 psi/ft for successful operations. Currently, absolute pressure, rather than the gradient, is thought to be the key design parameter.

To perform EOB, a few hundred feet of tubing is filled with fracturing fluid (usually brine). The fluid is forced into the formation under the effect of the overbalance by using large volumes (typically more than 50,000 ft^3) of compressed nitrogen supplied by a surface pumping unit. The operation typically lasts less than 1 min.

The basic technique lends itself to several interesting variations. Perforating guns may be conveyed by tubing or wireline. Liquids in the well can include clear brines, acid, fracturing gels, gels with suspended proppant, and resin for sand management. Alternatively, the wellbore can be filled with gas.

EOB fracture mechanics

As previously mentioned, Behrmann and Elbel's (1991) initial experiments with real perforations indicated that there are only two generic fracture initiation sites in conventional hydraulic fracturing. These sites are the base of the perforations (not the tip) and the intersection of the PFP with the axis of the wellbore. At which site initiation occurs depends mostly on the selected phasing and orientation of the gun.

Full-scale EOB experiments and field tests (Behrmann and McDonald, 1996; Hovem et al., 1995; Snider et al., 1996) confirm that when perforations are closely aligned with the PFP, the fracture is a single biwing fracture propagated from the perforations closest to the PFP. These tests reveal no evidence of the initiation of parallel multiple fractures. All fractures initiate from the base of the perforations.

Another effect of EOB is a greater angular difference between the PFP and a perforation for fracture initiation—if the perforation is aligned beyond this angle, the fracture initiates at the sandface in the PFP. In other words, the sensitivity of EOB operations to shot phasing is less critical than in conventional hydraulic fracturing. Figures 66 and 67 show EOB and hydraulic fracturing patterns, respectively, with the shot orientations along and outside of the PFP.

The dynamics of EOB enhance the creation of multiple fractures from the phased perforations while limiting fracture length and width. EOB fracture initiation pressures are usually higher than the initiation pressures of fractures created by conventional hydraulic fracturing. This effect may be caused by an increase in the dynamic fracture toughness and unwashed perforation debris, which acts as a filtercake to impede the injection of the fracturing fluid (Behrmann and McDonald, 1996).

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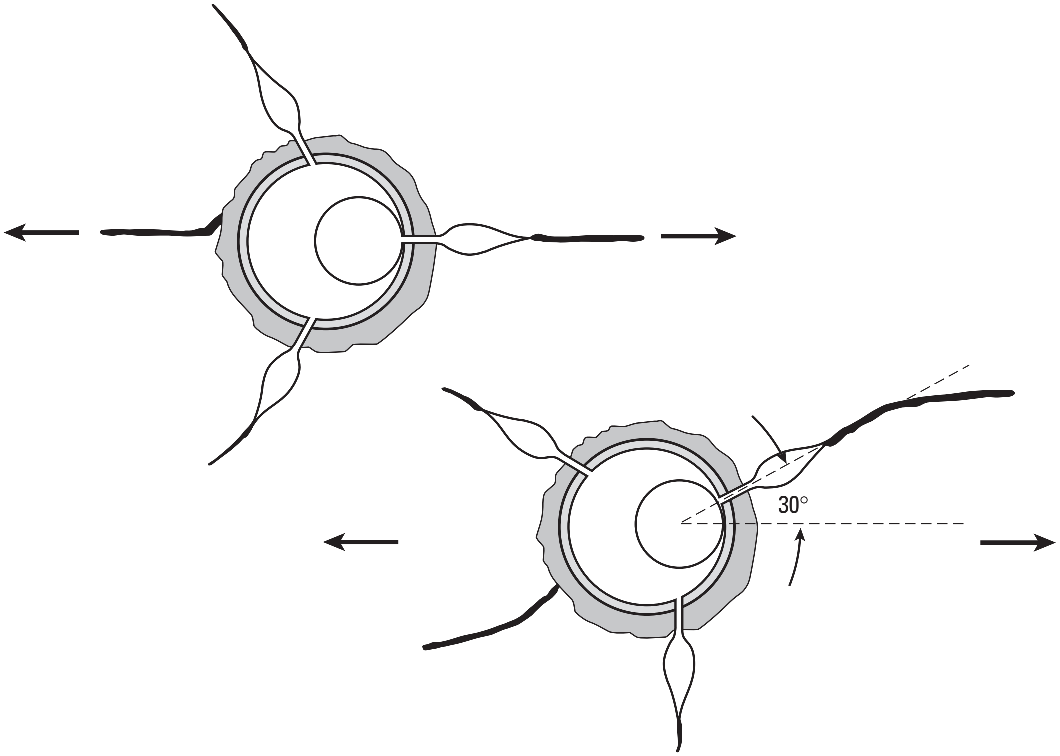

Figure 66. EOB multiple initiation for 120° shot phasing for two different gun alignments with the PFP (direction indicated by arrows). (© 1996 Society of Petroleum Engineers Inc., Behrmann and McDonald.)

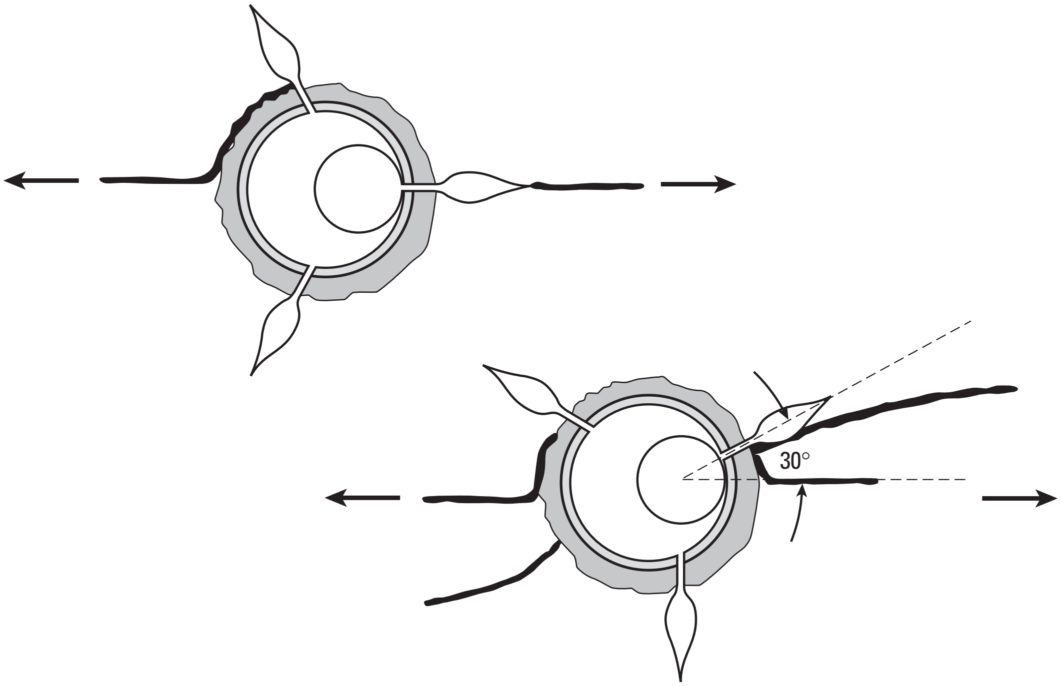

Figure 67. Hydraulic fracturing multiple initiation for 120° shot phasing for two different gun alignments with the PFP (direction indicated by arrows). (© 1996 Society of Petroleum Engineers Inc., Behrmann and McDonald.)

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EOB perforating applications

EOB perforating is not an inexpensive substitute for conventional hydraulic fracturing. The *half-length* of the fracture, which is the radial distance from the wellbore to the outer tip of the propagated fracture, is usually much longer in conventional fracturing than in EOB perforating. In addition, conventional fractures are propped open by proppant sand, whereas EOB fractures immediately close in on themselves upon the release of wellbore pressure. Rather, EOB perforating can be effective in situations that take advantage of its distinct characteristics:

- EOB perforating enhances wellbore communication with the formation, beyond the skin-damaged zone and past the perforations. Wells tested for production immediately after an EOB perforating operation typically show increased productivity. This benefit is typically short-lived, however, because of the immediate fracture closure.
- EOB perforating may be used as the primer for a subsequent conventional hydraulic fracturing operation. A biwing fracture must be created for this application, which limits the choice of gun phasing to 180° with orientation into the PFP or possibly 60° with random orientation.
- If acid is used as the fracturing fluid in carbonate reservoirs, EOB perforating may enhance the dynamic diversion of the acid.
- In naturally fractured reservoirs, EOB perforating may create multiple fractures that intersect the natural reservoir fractures. HSD High Shot Density gun systems with many shot phasings are recommended for this application.
- EOB perforating may be used to stimulate injection wells where the fractures do not need to be propped open for improved injectivity.

In addition to these applications for EOB perforating, the use of propellants as fracturing energy provides good results in heavy tar sands. The propellant gas seems to liquefy the sand and oil, which are subsequently produced together.

In conclusion, EOB perforating may be applied best in reservoirs of low to moderate permeability. In more favorable permeability conditions, using the PURE system for underbalanced perforating is the preferred method to prevent damage during perforating.

Sand management completions

Oil and gas reservoirs producing through sandstones that are not structurally competent often produce sand along with the formation fluids. Fluid movement through sandstone reservoirs applies tensile force on the sand grains because of fluid pressure differences. Production drawdown and in situ stresses induce compressive stresses on the perforation. If these stresses exceed the formation restraining forces, sand is produced, and the near-wellbore permeability is significantly altered.

The consequences of sand production include

- sand plugging of casing, tubing, or surface facilities
- casing collapse
- destruction of downhole and surface equipment
- costly disposal of produced sand.

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Completion strategies in weak rocks

Two possible conditions must be considered in designing a perforated completion for a weak-rock reservoir:

- Very weak and unconsolidated reservoirs—Because the well will definitely produce sand, the objective is to control sand production. Perforating requirements include removing perforation damage, optimizing gravel placement, and avoiding skin effect. This type of reservoir has no perforation cavity within the formation but may have a region of a lower sand density, as if a cavity were filled in the formation. The effects of the saturating fluid (oil or gas, oil viscosity) are important.
- Weak but consolidated reservoirs—The well may produce sand; therefore, an alternative strategy is to perforate for sand prevention. This perforation produces a cavity in the formation that is usually filled with comminuted sand and failed formation material. Perforation permeability damage is a certainty.

Determining whether the reservoir is very weak (less than 300-psi UCS), unconsolidated, or consolidated is a necessary step in selecting an effective perforation strategy. Effective stress is also important because sand production is due to a combination of rock strength and stress. Schlumberger Sand Management Advisor software can be used to predict if a perforated formation is going to produce sand. Unconsolidated wells produce sand, and perforating must address how best to maximize gravel-pack efficiency (see “Perforating for gravel packs” subsequently in this chapter).

Various perforating strategies may be applicable in consolidated formations. Either sand management or perforating for sand prevention is possible (see “Perforating for screenless sand management completions” for a detailed discussion).

A new strategy involves building a decision tree based on whether a perforation cavity definitely exists in the formation (Venkitaraman et al., 2000a). This decision process requires knowledge of several parameters:

- rock properties, such as UCS
- environmental parameters, such as in situ stress
- perforating parameters, such as charge type, phasing, shot density, and applied underbalance.

Additional single-shot experiments on cores are recommended for determining whether a perforation cavity is present.

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Sand management completion strategies

Sand management completions are techniques that enable the optimum production of hydrocarbons without inducing the negative effects of sand production along with the flowing fluid. They can be classified into three broad categories (Fig. 68): sand exclusion methods, screenless completions, and management of produced sand at the surface.

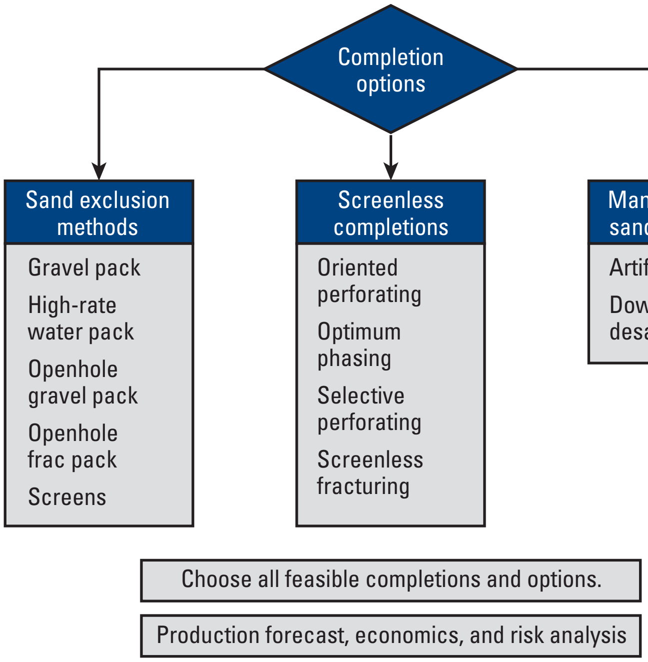

Figure 68. Three categories of sand management completions.

- Sand exclusion methods use a medium, usually a screen, to stop or filter the sand at the sandface. Cased hole techniques in this category that incorporate perforations are gravel packing and frac packing.
  - Gravel packing is the oldest technique for controlling sand production. It consists of placing a sand pack between the formation and a wire screen to prevent the migration of formation fines into the wellbore (Fig. 69). Gravel packing may be accomplished externally in open hole or internally in cased hole.
  - Frac packing is one of the most popular methods of sand control in cased and cemented wells. The proppant fracturing of high-permeability unconsolidated or weakly consolidated reservoirs with screens creates short propped fractures that may result in a zero or negative skin effect.
- Screenless completions are methods that do not rely on screens but on completion techniques that avoid producing sand. The successful application of screenless techniques is greatly dependent on the perforating strategy.
  - Oriented perforating uses the stress anisotropy in the formation to selectively orient the perforations in the direction of maximum stability in the 3D stress space.
  - Optimum phasing of perforations maximizes perforation-to-perforation spacing.
  - Selective perforating utilizes inherent strength inhomogeneties to avoid perforating in sections of the formation that are weak.

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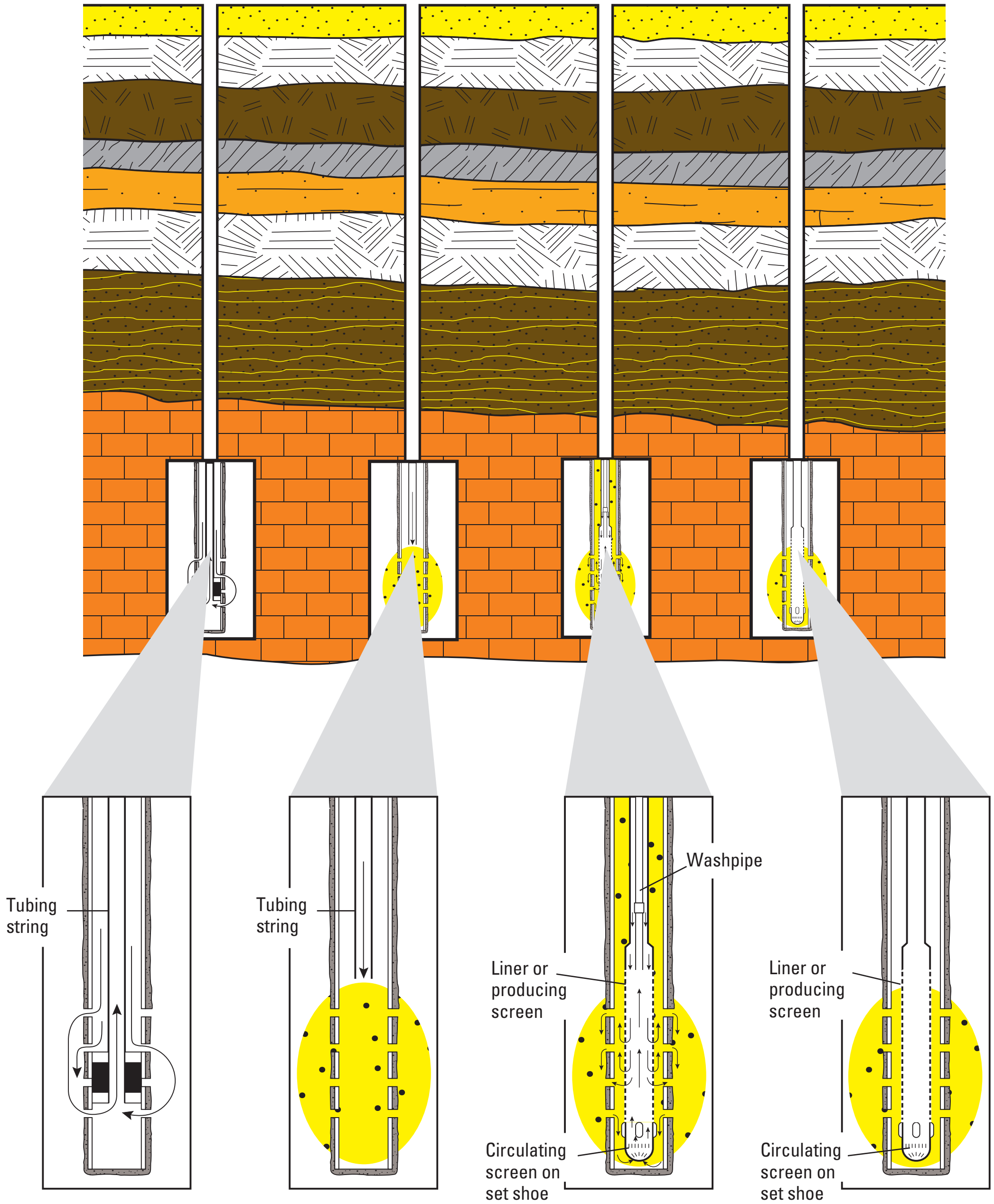

After perforation the perforations are washed with a wash tool.

The zone is squeeze packed.

The liner is gravel packed.

The gravel pack is completed.

Figure 69. Gravel-packing process.

These first three techniques can be used separately or in combination (e.g., selective oriented perforating or optimum-phased oriented perforating).

– Screenless fracturing, as the name implies, uses the fracture to stop the sand.

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- Management of produced sand at the surface is a less-frequently used category of techniques. One example is restricting the production rate to minimize sand transport. Sand production can sometimes be prevented by restricting the flow of the fluids through the formation to a rate that avoids collapse of the stable arch that forms around the perforation (Fig. 70). This method can be enhanced by the use of high shot density, uniform perforations, and controlled cleanup.

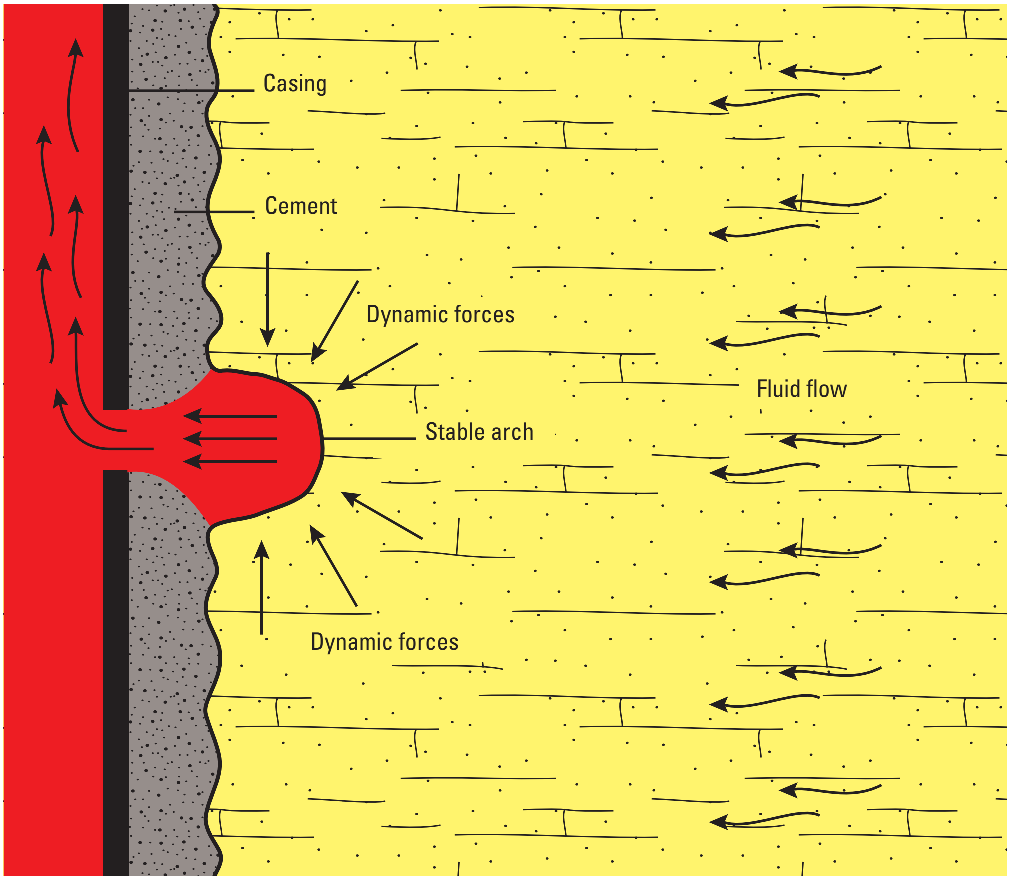

Figure 70. Stable arch and forces formed around a perforation in an unconsolidated formation.

Perforating for sand exclusion

In general, the success of sand exclusion treatments in cased holes is affected by the perforation density, perforation hole diameter, and amount of damage. If the perforation density is too low or the hole diameter is too small, a large pressure drop occurs across the pack, which introduces a large skin effect, reduces well performance, and damages the pack. Perforation-generated fines mixed with gravel in either the tunnel through the casing and cement or the perforation cavity reduces the permeability of the gravel, which results in pack failure and reduced well productivity as measured by the PI.

The greater the perforation density and hole diameter, the smaller the pressure drop through each perforation and the slower the fluid velocity. This promotes creation of a stable arch around the perforation and reduces the influx of formation fines, which in turn reduces screen erosion and increases the life of the sand management treatment.

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Perforating for gravel packs

Perforation phasing is an important factor for reducing pressure gradients around the wellbore. Reduced pressure gradients provide increased production. Except where required for special completion objectives, 0° phased perforations are not recommended because they introduce a large geometric skin effect as the flow converges on the one side of the wellbore.

In addition to the requirement to minimize the pressure drop through the casing–cement tunnel, perforating for a gravel pack has four objectives:

- Minimize or remove permeability damage, which impairs the placement of gravel inside the perforation cavity, damages the permeability of the gravel pack, and creates an excessively high skin factor.
- Avoid exposing the formation to lost circulation material (LCM), chemicals injected during well killing operations, or other potentially damaging completion fluids.
- Be aware of and manage unavoidable initial (transient) sand production.
- Avoid producing excessive volumes of sand, which may affect gun removal.

Permeability damage may be formation damage, perforation crushed-zone damage, or both. In unconsolidated sands, crushed-zone damage is removed through the development of a dilated region at the sandface. The comminuted material (typically fractured sand grains) within the cavity is unconsolidated sand and must be removed.

Precompletion procedures

Drilling and precompletion procedures that minimize sand production are necessary steps. Decreasing the surface tension between the formation fluid and the sand grains and using low-viscosity completion fluids help to produce the damaging fines and comminuted sand grains from the perforation cavity. Thus, the following recommendations apply:

- Drill with water-base mud and let brine invade about 1 ft into the formation.
- Use brine as the completion fluid if the reservoir fluid is gas or low-viscosity oil.
- Use diesel or universal solvent as the completion fluid if the reservoir fluid is high-viscosity oil.

No defined perforation cavity in the formation

If there is not a defined perforation cavity in the formation, the recommended strategy is to minimize the pressure drop in the casing–cement tunnel portion of the perforation:

- Use big hole charges to maximize the AOF.
- Give priority to the highest shot density for gun systems that produce the same AOF.

Defined perforation cavity in the formation

If a defined perforation cavity is created in the formation, the strategy to follow is to minimize the pressure drop both in the formation and across the casing–cement tunnel. Deep penetrating charges are preferred because they reduce the impact of near-wellbore formation damage and the extent of perforation damage in comparison with big hole charges. In some cases, however, minimizing damage may be less important than maximizing AOF. Big hole charges at high shot density are recommended to maximize the AOF. Regardless, the diameter of the perforation tunnel through the casing and cement should be at least 8 to 10 times the mean gravel diameter to avoid bridging of the sand during packing operations. The trade-off between big hole charges and deep penetrating charges can be examined in detail using SPAN perforating analysis (see "SPAN perforating analysis").

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Additional considerations

- Use brine or other nondamaging fluids as completion fluids.
- Apply sufficient underbalance to remove the fractured sand grains.
- Perforate with an open choke to sustain the postshot flow of the well.
- Drop the guns while perforating to avoid sanding the guns in place in the well. Explosive gun drop subassemblies, such as the wireline X-Tools* automatic release (WXAR), automatic gun release (SXAR) (TCP or drillstem test [DST]), and automatic release anchor (MAXR) (monobore), can be used for this purpose. See the “Completion Perforating Equipment” and “Completion Perforating Without Killing the Well” chapters for a description of this hardware.
- Run gun systems and gravel-pack hardware at the same time, such as the one-trip PERFPAC* sand control method, to avoid having to kill the well and thus expose the formation to damaging fluids. This approach is described in “Completion Perforating Without Killing the Well.” Flowing the well after perforation also assists with perforation cleanout.
- Use nondamaging fluids if the well must be killed.

Frac packs and high-rate water packs

Perforating requirements for standard frac-pack and high-rate water pack completions are identical to those for internal gravel packs. Minimizing the pressure drop through the pack and controlling sand production are of greater importance than placing a fracture through the formation.

Several sand management recommendations apply (Behrmann et al., 1998):

- Maximize the AOF.
- Use big hole charges with a phasing of 60° (for frac packs or high-rate water packs) or 45°(for high-rate water packs only). The shot density should be 12, 16, 18, or 21 spf. The minimum diameter of the entrance hole should be 8 to 10 times the proppant sand diameter.
- Maximize sand placement to fill any microannuli with proppant sand and create an artificial external pack.

Perforating for screenless sand management completions

Screenless fracturing with proppant placement

Screenless fracturing completions are based on placing proppant in a fracture that contacts, or covers, all the perforations to manage sand production. The formation may be treated with resin or another consolidating agent to improve the near-wellbore strength before fracturing. Proppant material (usually resin-coated proppant with fibers for flowback control) is injected into the fracture to keep formation sand from being produced into the wellbore.

The perforating requirements differ from those for other types of gravel-pack completions because the fracture and proppant placed inside it should cover all the perforations. The key to achieving complete perforation coverage is limiting the perforated interval and orienting the perforations in the PFP. The following sand management recommendations apply (Behrmann et al., 1998):

- Create a minimum-diameter entrance hole of 8 to 10 times the proppant sand diameter.
- Do not allow the diameter of the perforations (or entrance hole in casing) to exceed the predicted fracture width in the formation close to the wellbore. Ideally the perforation diameter of the casing–cement tunnel is less than 0.5 in.

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- Limit the perforated interval to no more than 30 ft in vertical wells and less (e.g., a 5- to 10-ft interval) as well deviation increases. Care must be taken in applying this technique in deviated wells (especially wells with 30° to 60° deviation) where the direction of fracture propagation is not known or predictable with certainty.
- Orient the perforations to within 10° of the PFP.
- Use a 0° or 180° phased gun.
- Create an external pack in any microannuli that formed to control formation sand.

Perforation-only screenless techniques

A perforated completion program designed to prevent or minimize sand production has four completion objectives:

- Avoid or minimize failure of the perforation cavity in the formation (e.g., caused by excessive underbalance, drawdown, or pressure depletion).
- Minimize the perforation damage.
- Avoid perforation-to-perforation failure.
- Minimize shot density.

The perforating strategy for sand prevention implies that sanding is limited or does not occur. Because of this assumption, the strategy does not consider sand control measures. The approach is quite different from the sand control measures previously discussed; thus, the requirements are also different. Nevertheless, massive sand production may still occur at the onset of water production, at high drawdown, or from pressure depletion. Deciding which completion to use (i.e., screenless or sand exclusion) should account for potential field management of sand and hydrocarbon production over the life of the well. The analysis of the economics and risks should also include the cost for any intervention that could be required prior to implementing a completion option.

Perforating requirements

The following recommendations are based on experimental work and field tests described in the “Perforation Damage and Cleanup” chapter in this book.

- Minimize the risk of perforation failure by using deep penetrating charges and a gun system phased to maximize charge-to-charge spacing. The use of deep penetrating charges reduces the pressure drop across the sandface, which reduces the stress on a perforation. This also minimizes the risk of perforation cavity collapse. Deep penetrating charges are also used because the diameter of the perforation cavity in the formation is small compared with that of big hole charges. A small-diameter cavity is more stable than a large-diameter cavity.
- Limit the underbalance during perforating to avoid causing formation failure around the perforation cavities and between neighboring perforations.
- Keep the flow rate per perforation below a critical level to reduce the likelihood of transporting produced sand.

On the basis of these recommendations, selecting the shot density requires balancing the risk of perforation failure with the likelihood of sand transport. A shot density that is too high produces perforations that are too close to one another, thus increasing the probability of perforation-to-perforation failure occurring. A shot density that is too low produces high fluid velocity in and around the perforations, which increases the likelihood of sand transport.

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Optimized perforation spacing

The perforation-to-perforation spacing should be optimized for the specific shot density (Venkitaraman et al., 2000b). In turn, gun systems must be designed with nonstandard shot-to-shot distances and phasing angles. The lines labeled L_1, L_2, and L_3 on Fig. 71 are the shot-to-shot distances on the sandface for a phasing of 60°.

Ideally, the three distances should be equal. However, because equal distances are not possible, the optimum solution for maximum perforation-to-perforation spacing for a given shot density is shown in Fig. 72. The sensitivity parameter can be calculated as the product of the shot density and the wellbore radius (the latter representing the distance from the center of the gun to the sandface). The minimum shot-to-shot spacing measured on the gun increases from 4.88 to 7.61 in. when the angular phasing is changed from 60° to 99° on a 3⅜-in. gun at 6 spf. This optimized relation led to the construction of a 99° phased gun system that was used to successfully minimize sand production in the Magnus field, UK North Sea (Venkitaraman et al., 2000b).

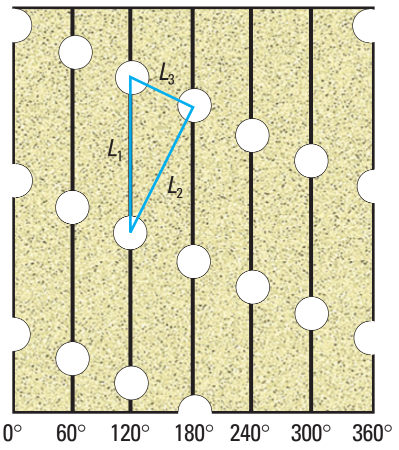

Figure 71. Shot-to-shot spacing for 60° phasing.

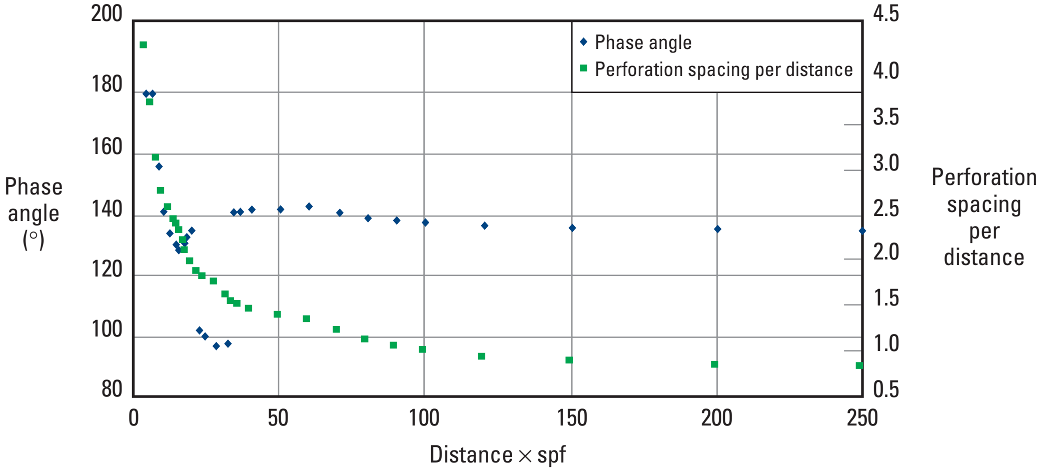

Figure 72. Optimum phasing and perforation spacing. The distance is from the jet origin to the sandface.

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Mechanical stability of the perforation tunnel

Another design requirement stems from the need to maintain the mechanical stability of the perforation tunnel (Sulbaran et al., 1999). Formations that require protection from sand production also have borderline mechanical integrity related to perforating. Perforations should be oriented in the direction of maximum stability to prevent sand production in geological environments where there are large contrasts between the three components of the stress tensor.

For a known stress tensor orientation, a tolerance angle can be calculated to describe the area where the perforations should be stable. Concentrating the perforations along the direction of maximum stability reduces the occurrence of perforation failure. The direction of maximum stability can be determined with Sand Management Advisor software. This 3D model for sand prediction uses information from a variety of sources, including a mechanical earth model (MEM) of a field's geomechanics and the analytical output of SPAN perforating analysis and ProCADE* well analysis software. Stress calculations are conducted for various values of perforation orientation and phasing to determine the critical drawdown pressure at which shear failure of the formation occurs (Fig. 73). The perforation orientation with the largest sand-free production window for drawdown conditions is in the direction of maximum stability. Sand

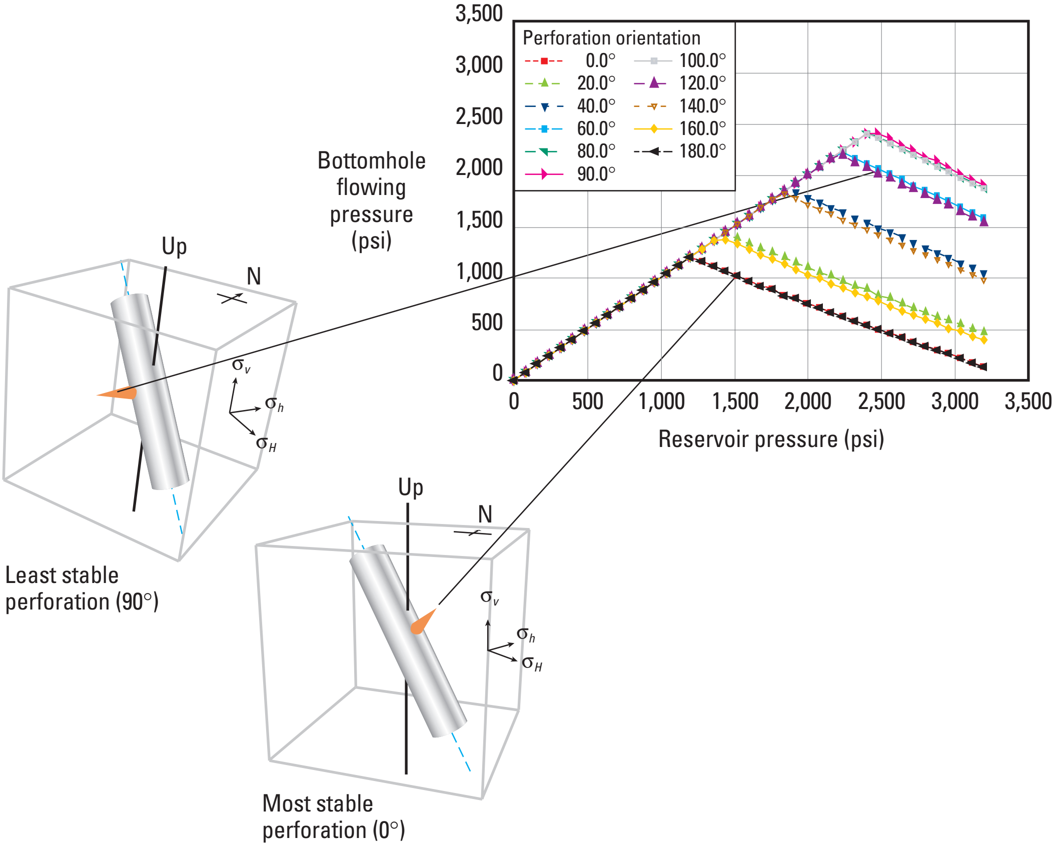

Figure 73. Critical drawdown pressures calculated with Sand Management Advisor software show that the perforation oriented at 0° is the most stable (i.e., fails last), with the largest sand-free window. The perforation oriented at 90° fails first, most likely in association with the vertical stress orientation. The components of the stress tensor are σ_v = vertical stress, σ_H = maximum horizontal stress, and σ_h = minimum horizontal stress.

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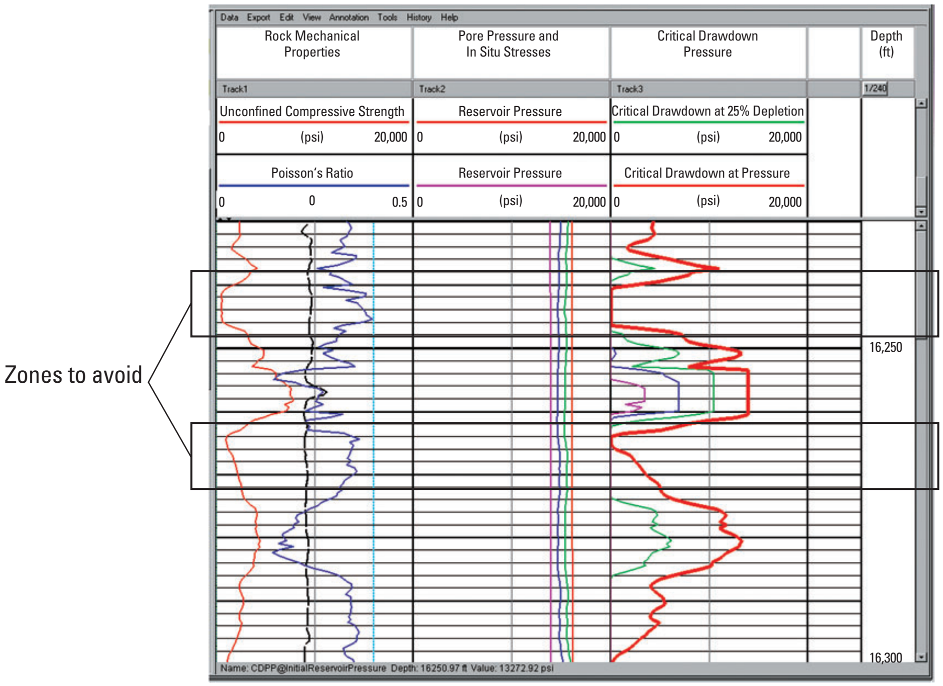
Management Advisor also conducts critical drawdown analysis to identify the weakest zones to avoid perforating them. The weakest zones will fail and produce sand regardless of the perforation orientation (Fig. 74).

The next step is to design a specific gun system to fit the required orientation. Figure 75 shows the shot distribution on a two-dimensional plane, with the shots concentrated at an angle ±ϕ from the system's axis of symmetry. The value of ϕ is chosen within the tolerance angle to maximize the shot-to-shot spacing.



Name: CDPP@InitialReservoirPressure Depth: 16250.97 ft Value: 13272.92 psi

Figure 74. Sand Management Advisor identifies zones to avoid perforating because they will produce sand at any perforation orientation or completion design.

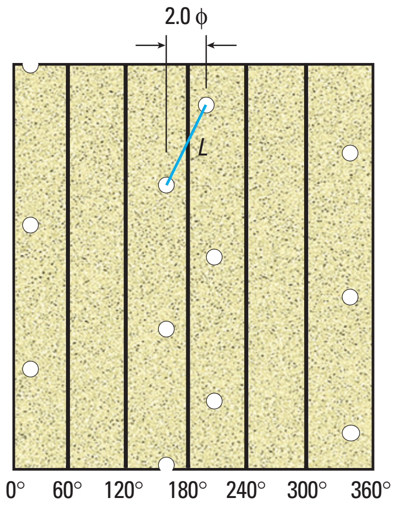


Figure 75. Shot distribution to ensure mechanical stability of the perforation tunnel.

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In the well, the gun must be oriented to match the system's axis of symmetry with the predetermined direction of maximum horizontal stress. Oriented perforating is discussed in the "Wireline Perforating Techniques" and "Completion Perforating Equipment" chapters.

Field examples

Sulbaran et al. (1999) reported four field examples in which all the described requirements were considered to successfully design and execute perforating programs for sand prevention in a sand-prone formation in Venezuela.

Perforating in carbonates

Background

The data on perforation optimization in carbonates is limited. All laboratory tests have been made in tight, very strong rocks and using deep penetrating charges. Productivity was always enhanced by using the deepest penetrating charge, followed by acidization.

Decision tree for perforating in carbonates

Several scenarios for perforating in carbonates are possible.

- Recommendations for high formation strength
  - Low permeability—Use overbalance or potentially the PURE perforating system for clean perforations. Maximize penetration and shot density with optimum phasing for acidization. Perforate with acid in the wellbore.
  - High permeability—Use underbalance. Maximize penetration and shot density with optimum phasing for productivity. Perforate with or without acid in the wellbore.
- Recommendations for low formation strength
  - High permeability—Use underbalance. Maximize penetration and shot density. Optimize the phasing (Fig. 72) of oriented guns to minimize the production of formation rock. Perforate with or without acid in the wellbore.
  - Low permeability—Use overbalance. Maximize penetration and shot density. Optimize the phasing (Fig. 72) of oriented guns to minimize the production of formation rock. Perforate with or without acid in the wellbore.
- Horizontal wells—Stand off or orient the guns.

Completion applications

Completions are divided into three basic categories of application: temporary, permanent, and workover.

Temporary completions

A temporary completion is typically used during the initial testing of a new exploration or appraisal well to assess the well's delivery capacity and determine the presence of a skin factor that could undermine production rates. Temporary completions have more varied objectives in development wells:

- DSTs for reservoir parameters
- hydraulic fracturing
- acidizing

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- squeeze cementing
- multizone production
- long perforation intervals
- gravel-pack operations.

Permanent completions

A permanent completion is performed with a packer, tubulars, and surface wellhead and facilities in place. It typically consists of both the *upper completion*, which is the surface system of Christmas tree, valves, tubing hanger, and subsurface safety valve, and the *lower completion*, which includes the packer, liner hanger, and other downhole components. This type of completion maximizes well control and personnel safety at the surface.

In the past, permanent completions were used for naturally flowing wells, gas lift wells, and hostile environment wells. Today, more wells of all types are perforated for an initial permanent completion. Recently developed hardware has made these types of permanent completions possible. For example, hardware is available to perforate a well without killing it and to run and then retrieve long gun strings under pressure.

The "Completion Perforating Without Killing the Well" chapter discusses the equipment in more detail.

Workover completions

The workover environment provides opportunities for both temporary and permanent completion techniques. Unlike other completion objectives, a workover usually is conducted to correct a well production problem, repair downhole equipment, or recomplete the well for another objective.

Design of perforated completions

Perforated completion design focuses on maximizing PI and thus reducing the reservoir-to-wellbore pressure drop. The pressure drop must be modeled at design stage. After job execution, the actual performance of the completion must be compared with the predicted results. A good match confirms that the design parameters were correct and job execution was successful. A poor match reveals problems that must be corrected to improve and optimize the completion.

Two computer programs are essential during the design stage and for evaluating the productivity of the completion:

- NODAL* production system analysis is used to comprehensively analyze the total pressure drop from reservoir to stock tank by optimizing each component.
- SPAN Schlumberger perforating analysis focuses on the reservoir-to-wellbore pressure drop in perforated completions.

NODAL production system analysis

NODAL analysis is a performance design and diagnostic tool for the reservoir, well, and surface facilities. The flow of fluids is modeled from the reservoir's outer boundary to the sandface; across the perforations and downhole completion; through the tubing string, including any restrictions and safety valves; to the surface choke, the separator, and eventually the flowlines or stock tank.

The objective of NODAL analysis is to optimize the pressure drop at a number of nodes (e.g., at the sandface, choke, and tubing end). Figure 76 describes the nodes in a basic system, and Fig. 77 shows the associated pressure drops. A key consideration is the pressure drop corresponding to the flow through the perforations.

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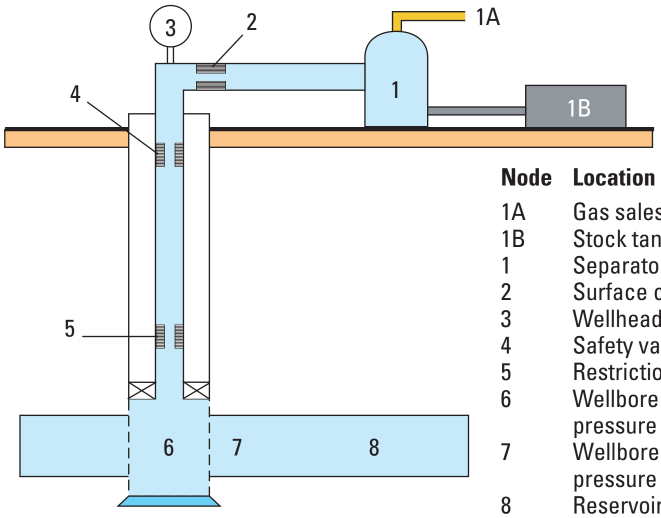
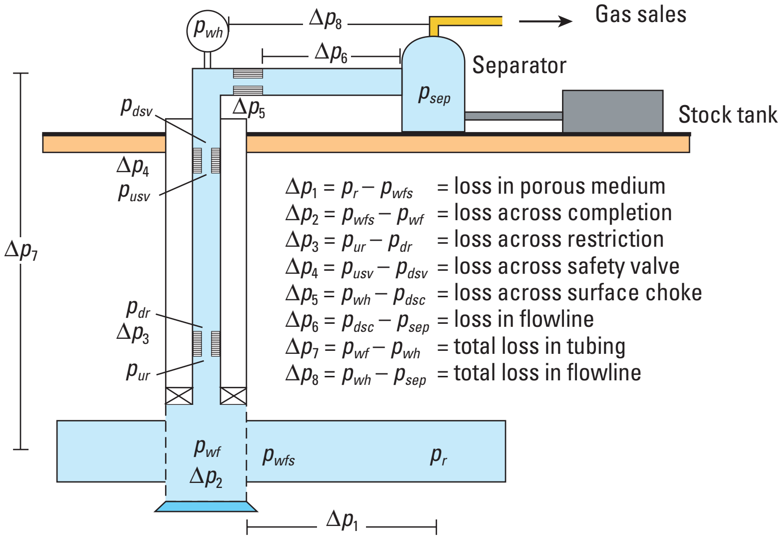


Node	Location	Remarks
1A	Gas sales	
1B	Stock tank	
1	Separator	
2	Surface choke	Functional
3	Wellhead	
4	Safety valve	Functional
5	Restriction	Functional
6	Wellbore flowing pressure (p_{wf})	
7	Wellbore sandface pressure (p_{wfs})	
8	Reservoir pressure (p_r)	

Figure 76. Description of nodes in a basic system for NODAL analysis.



$\Delta p_1 = p_r - p_{wfs}$ = loss in porous medium
$\Delta p_2 = p_{wfs} - p_{wf}$ = loss across completion
$\Delta p_3 = p_{ur} - p_{dr}$ = loss across restriction
$\Delta p_4 = p_{usv} - p_{dsv}$ = loss across safety valve
$\Delta p_5 = p_{wh} - p_{dsc}$ = loss across surface choke
$\Delta p_6 = p_{dsc} - p_{sep}$ = loss in flowline
$\Delta p_7 = p_{wf} - p_{wh}$ = total loss in tubing
$\Delta p_8 = p_{wh} - p_{sep}$ = total loss in flowline

Figure 77. Components of the pressure drop in the system in Fig. 76. p_{dr} = downstream restriction pressure, p_{dsc} = pressure downstream of the surface choke, p_{dsv} = pressure downstream of the safety valve, p_r = reservoir pressure, p_{sep} = separator pressure, p_{ur} = upstream restriction pressure, p_{usv} = pressure upstream of the safety valve, p_{wf} = wellbore pressure, p_{wfs} = wellbore sandface pressure, p_{wh} = wellhead flowing pressure.

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Downstream system performance is compared with upstream system performance at each node. The node's operating point occurs at the intersection of the downstream and upstream performance characteristics. The performance characteristics are plotted as the operating pressure versus flow rate (Fig. 78), with the operating point representing the operating pressure and flow rate at a node. Performance analysis can be conducted based on assumptions (during the design phase) or in diagnosis mode (for remedial work). In either case, the objective is to shift the node's operating point on the plot to the right, which is the direction of increase for the flow rate.

For the sandface node as an example, performance analysis is conducted to minimize the reservoir-to-wellbore pressure drop, which maximizes the sandface flow rate. Figure 78 shows the sandface pressure as a function of the sandface flow rate. The operating point of the sandface node is determined by matching the following characteristics:

- *Inflow performance relationship* (IPR) of the reservoir represents the performance of the upstream system (i.e., the reservoir). At first glance, the IPR (green line on Fig. 78) appears to be a straight line, with a slope that is the inverse of the PI. As discussed in the "Productivity and Skin Effect" chapter, the PI includes both reservoir performance and total skin effect. In turn, the total skin effect includes all skin effect components associated with perforation damage, the perforated completion, and the penetration depth related to the depth of any formation damage. Thus, the slope of the IPR characteristics partly reflects skin effect that must be minimized.
- *Vertical lift performance* (VLP) represents the lift characteristics of downstream system components, such as tubing. In other words, VLP is the flow rate the downstream system can sustain for a particular sandface pressure. VLP is the blue curve on Fig. 78.

As shown on Fig. 78, the operating point is at the intersection of the IPR and VLP for the sandface pressure and flow rate of the system.

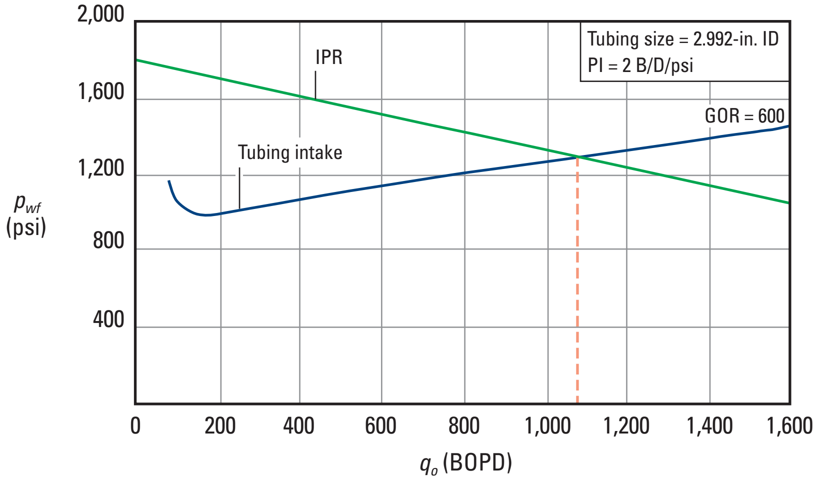

Figure 78. Operating point determination from IPR and VLP characteristics.

Two basic methods can be used to shift the sandface operating point to the right on the plot to increase the sandface flow rate that the well can lift to the surface:

- Improve the lift characteristics by reducing the slope of the VLP line on the graph—Increasing the size of the tubing is one of the most efficient ways to improve lift characteristics; however, this approach is not always possible because of geometric constraints, potential generation of two-phase flow conditions, limitations on performance of the choke and other surface equipment, and other factors.
- Improve the PI (i.e., reduce the slope of the IPR line on the graph)—Any reduction in the total skin effect clearly improves the PI and possibly increases the sandface flow rate. Completion engineers attempt to minimize skin effect primarily for this reason. PI can also be improved by using other methods, such as reservoir stimulation.

NODAL analysis calculates the pressure drop at each defined node in a producing well by repeating the previously described method. Actions taken to improve the performance of a node, whether during the design or diagnostic phase, affect the global system performance related to the surface production rate only if the remainder of the system operates under optimized conditions. For example, reperforating a zone to reduce the effect of perforation damage by increasing shot density would not work under the following conditions:

- The tubing is too small to lift more fluid than it did before reperforating.
- Flowline pressure conditions at the surface prevent the downstream collecting system from accepting more fluid from the well.

In short, the potential for improving well performance is global and tied to the economics of the optimization process.

SPAN perforating analysis

SPAN perforating analysis predicts the efficiency of a completion for a specific gun system in a specific environment. SPAN analysis is best applied during the design phase to help select a gun system that fits the geometry, fluids, and underbalance parameters of the planned completion.

SPAN calculations are rigorous and intended to replicate actual perforating conditions. If the calculations cannot be made algorithmically (e.g., when correcting the penetration algorithm for formations under stress), the data are extrapolated from a database of experiment results to the current conditions.

Depth of formation damage

SPAN analysis cannot provide reliable information to characterize formation damage because such information is seldom quantifiable. Several well-established methods are available for estimating the depth of formation damage.

The interpretation output of openhole logs is the diameter of invasion d_i. Array induction tools, especially the AIT* Array Induction Imager Tool, calculate the volume of filtrate, and this parameter can yield a reasonably accurate value of d_i. However, d_i is not equivalent to the depth of damage obtained in perforating studies. To obtain an equivalent depth value, the wellbore diameter must be subtracted from d_i and the result divided by 2 because the depth of formation damage is a radius measured from the sandface as the origin.

If openhole log interpretation methods are used to estimate the depth of damage for perforating design, d_i and the depth of damage may not represent the same physical phenomenon. Deep filtrate invasion may not create significant formation damage. Conversely, shallow invasion may. Accurate correlation must take into account the invasion profile, saturation, and relative permeability and wetting capability of each fluid involved. This issue is complex, and satisfactory answers are rarely easily determined.

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Comparing LWD and wireline logs run at different times in the same well may provide information on the filtrate invasion rate and whether significant amounts of filtrate may still be present in the near-wellbore region at the time of perforating.

Fluid samples obtained with wireline formation testers are always contaminated by filtrate. Recent sophisticated wireline formation testers, such as the MDT* Modular Formation Dynamics Tester, include a pumpout system that makes it possible to collect uncontaminated samples of reservoir fluids. The determination of when the sample is uncontaminated is based on real-time measurements, such as the sample fluid's resistance and optical properties (refraction index). Testing therefore provides an indication of filtrate invasion at the depth of the tested interval before the well is completed.

The magnitude and depth of formation damage can have a profound effect on productivity and perforating strategy. Because of the difficulty in obtaining reliable data, a sensitivity analysis on these parameters is recommended when SPAN analysis is conducted.

SPAN analysis for productivity enhancement

SPAN analysis is also used to model the charge performance and productivity of perforated completions. It can be used to help the analyst select the optimal perforation system and make productivity predictions for the perforated completion. The SPAN results can be used directly or as inputs to NODAL analysis or reservoir modeling software.

SPAN functions

SPAN analysis consists of three modules: penetration, productivity, and underbalance.

- Penetration module calculates the shot penetration and entrance hole diameter based on the SPAN database (Berea slabs, API, and other tests and shootouts) and current perforating theory. The analyst selects one or more gun systems from the list of Schlumberger perforating systems. The penetration for each gun system is corrected for in situ environmental conditions, including charge clearance, rock strength, and effective formation stress. The SPAN analysis then creates a cross-section plot for each gun system, showing the gun's position in the completion and the perforations in relation to the position of the gun charges and extent of the damaged zone. This plot helps users evaluate the efficiency of the selected gun system for the completion geometry and depth of formation damage. Figure 79 is a SPAN cross-section plot for a hypothetical Well Alpha 1. The input data for the well are on the penetration report in Fig. 80.

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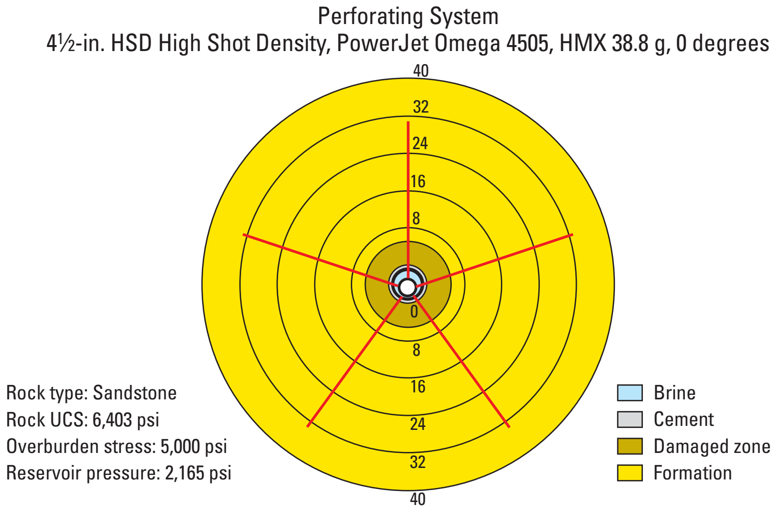
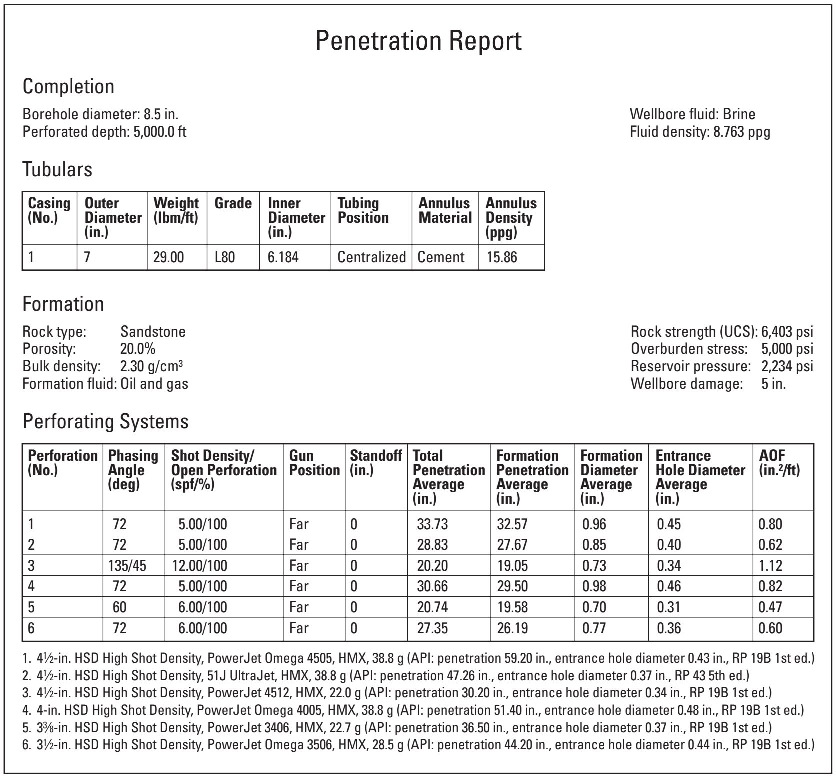


Angle (deg)	Clearance (in.)	Total Penetration (in.)	Formation Penetration (in.)	Formation Diameter (in.)	Casing Entrance Hole (in.)	
0	1.88	31.78	30.62	0.90	0.42	
72	1.00	33.84	32.69	1.01	0.47	
144	0.12	34.25	33.09	0.94	0.44	
216	0.12	34.25	33.09	0.94	0.44	
288	1.00	33.84	32.69	1.01	0.47	
Average	0.78	33.59	32.43	0.96	0.45	
				AOF (in.^{2}/ft)	0.80	at 5.00 spf

Figure 79. SPAN cross-section plot.



Penetration Report

Completion

Borehole diameter: 8.5 in.
Perforated depth: 5,000.0 ft

Wellbore fluid: Brine
Fluid density: 8.763 ppg

Tubulars

Casing (No.)	Outer Diameter (in.)	Weight (lbm/ft)	Grade	Inner Diameter (in.)	Tubing Position	Annulus Material	Annulus Density (ppg)
1	7	29.00	L80	6.184	Centralized	Cement	15.86

Formation

Rock type:	Sandstone
Porosity:	20.0%
Bulk density:	2.30 g/cm^3
Formation fluid:	Oil and gas

Rock strength (UCS):	6,403 psi
Overburden stress:	5,000 psi
Reservoir pressure:	2,234 psi
Wellbore damage:	5 in.

Perforating Systems

Perforation (No.)	Phasing Angle (deg)	Shot Density/ Open Perforation (spf/%)	Gun Position	Standoff (in.)	Total Penetration Average (in.)	Formation Penetration Average (in.)	Formation Diameter Average (in.)	Entrance Hole Diameter Average (in.)	AOF (in.^{2}/ft)
1	72	5.00/100	Far	0	33.73	32.57	0.96	0.45	0.80
2	72	5.00/100	Far	0	28.83	27.67	0.85	0.40	0.62
3	135/45	12.00/100	Far	0	20.20	19.05	0.73	0.34	1.12
4	72	5.00/100	Far	0	30.66	29.50	0.98	0.46	0.82
5	60	6.00/100	Far	0	20.74	19.58	0.70	0.31	0.47
6	72	6.00/100	Far	0	27.35	26.19	0.77	0.36	0.60

1. 4½-in. HSD High Shot Density, PowerJet Omega 4505, HMX, 38.8 g (API: penetration 59.20 in., entrance hole diameter 0.43 in., RP 19B 1st ed.)
2. 4½-in. HSD High Shot Density, 51J UltraJet, HMX, 38.8 g (API: penetration 47.26 in., entrance hole diameter 0.37 in., RP 43 5th ed.)
3. 4½-in. HSD High Shot Density, PowerJet 4512, HMX, 22.0 g (API: penetration 30.20 in., entrance hole diameter 0.34 in., RP 19B 1st ed.)
4. 4-in. HSD High Shot Density, PowerJet Omega 4005, HMX, 38.8 g (API: penetration 51.40 in., entrance hole diameter 0.48 in., RP 19B 1st ed.)
5. 3⅜-in. HSD High Shot Density, PowerJet 3406, HMX, 22.7 g (API: penetration 36.50 in., entrance hole diameter 0.37 in., RP 19B 1st ed.)
6. 3½-in. HSD High Shot Density, PowerJet Omega 3506, HMX, 28.5 g (API: penetration 44.20 in., entrance hole diameter 0.44 in., RP 19B 1st ed.)

Figure 80. SPAN penetration report.

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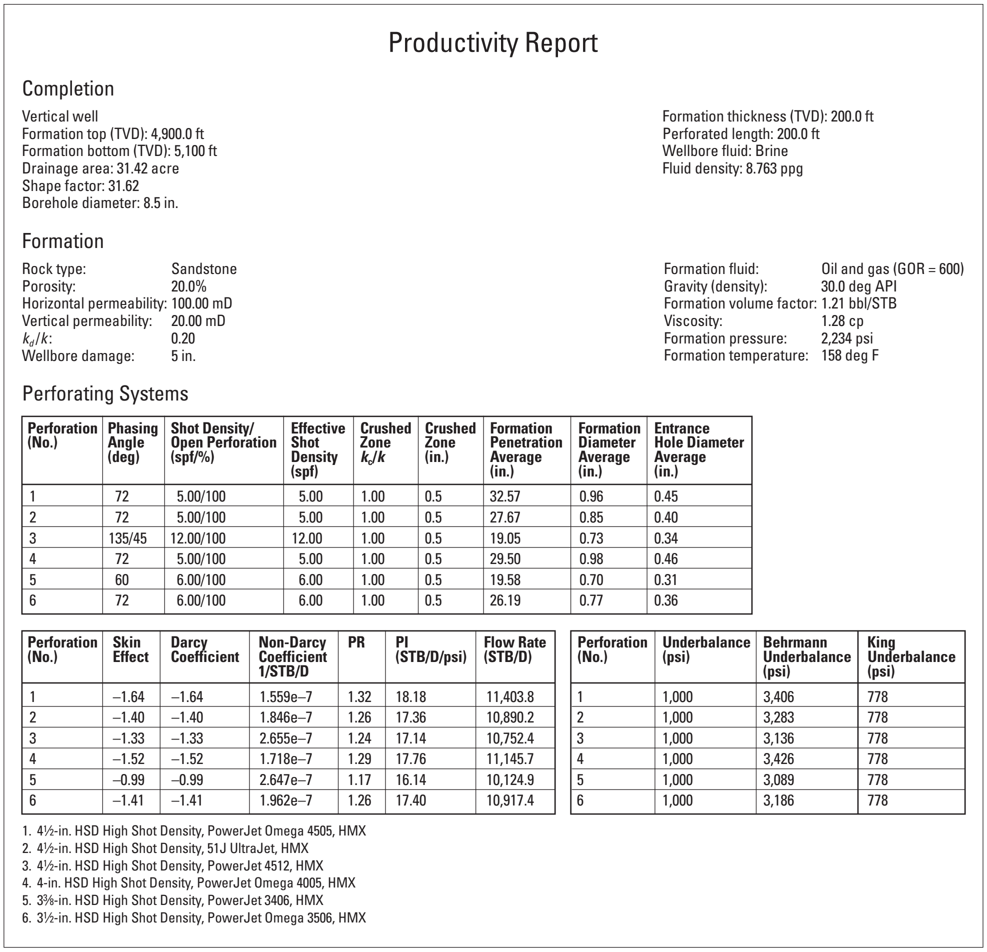
- Productivity module calculates the productivity of perforated completions (Fig. 81). Productivity can be calculated for up to six gun systems for variables such as damaged zone thickness, anisotropy ratio, and shot density, along with various sensitivity parameters, including gun choice, ratio of crushed-zone permeability (k_c/k), and shot density. Figure 82 is a plot of the PR versus shot density, and Fig. 83 is a plot of PR versus damaged zone thickness.

  In addition to open perforations, the productivity of intact and collapsed gravel-pack configurations can be modeled. Productivity can be displayed as a skin factor (Darcy and non-Darcy), productivity ratio, or productivity index. The non-Darcy (rate-dependent) productivity option includes the turbulent pressure drops in the reservoir, perforations, and casing–cement tunnel. The pressure drop components from turbulence can be large in high-rate production gas wells



Productivity Report

Completion

Vertical well
Formation top (TVD): 4,900.0 ft
Formation bottom (TVD): 5,100 ft
Drainage area: 31.42 acre
Shape factor: 31.62
Borehole diameter: 8.5 in.

Formation thickness (TVD): 200.0 ft
Perforated length: 200.0 ft
Wellbore fluid: Brine
Fluid density: 8.763 ppg

Formation

Rock type:	Sandstone
Porosity:	20.0%
Horizontal permeability:	100.00 mD
Vertical permeability:	20.00 mD
k_d/k:	0.20
Wellbore damage:	5 in.

Formation fluid:	Oil and gas (GOR = 600)
Gravity (density):	30.0 deg API
Formation volume factor:	1.21 bbl/STB
Viscosity:	1.28 cp
Formation pressure:	2,234 psi
Formation temperature:	158 deg F

Perforating Systems

Perforation (No.)	Phasing Angle (deg)	Shot Density/ Open Perforation (spf/%)	Effective Shot Density (spf)	Crushed Zone k_c/k	Crushed Zone (in.)	Formation Penetration Average (in.)	Formation Diameter Average (in.)	Entrance Hole Diameter Average (in.)
1	72	5.00/100	5.00	1.00	0.5	32.57	0.96	0.45
2	72	5.00/100	5.00	1.00	0.5	27.67	0.85	0.40
3	135/45	12.00/100	12.00	1.00	0.5	19.05	0.73	0.34
4	72	5.00/100	5.00	1.00	0.5	29.50	0.98	0.46
5	60	6.00/100	6.00	1.00	0.5	19.58	0.70	0.31
6	72	6.00/100	6.00	1.00	0.5	26.19	0.77	0.36

Perforation (No.)	Skin Effect	Darcy Coefficient	Non-Darcy Coefficient 1/STB/D	PR	PI (STB/D/psi)	Flow Rate (STB/D)
1	–1.64	–1.64	1.559e–7	1.32	18.18	11,403.8
2	–1.40	–1.40	1.846e–7	1.26	17.36	10,890.2
3	–1.33	–1.33	2.655e–7	1.24	17.14	10,752.4
4	–1.52	–1.52	1.718e–7	1.29	17.76	11,145.7
5	–0.99	–0.99	2.647e–7	1.17	16.14	10,124.9
6	–1.41	–1.41	1.962e–7	1.26	17.40	10,917.4

Perforation (No.)	Underbalance (psi)	Behrmann Underbalance (psi)	King Underbalance (psi)
1	1,000	3,406	778
2	1,000	3,283	778
3	1,000	3,136	778
4	1,000	3,426	778
5	1,000	3,089	778
6	1,000	3,186	778

1. 4½-in. HSD High Shot Density, PowerJet Omega 4505, HMX
2. 4½-in. HSD High Shot Density, 51J UltraJet, HMX
3. 4½-in. HSD High Shot Density, PowerJet 4512, HMX
4. 4-in. HSD High Shot Density, PowerJet Omega 4005, HMX
5. 3⅜-in. HSD High Shot Density, PowerJet 3406, HMX
6. 3½-in. HSD High Shot Density, PowerJet Omega 3506, HMX

Figure 81. SPAN productivity report.

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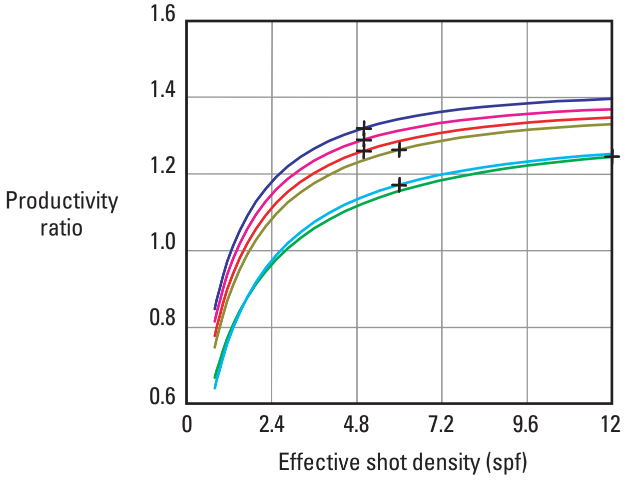


Formation

k_h: 100.00 mD
k_h/k_v: 5.00
Bulk density: 2.30 g/cm³
Rock UCS: 6,403 psi
Overburden: 5,000 psi
Reservoir: 2,234 psi
k_d/k: 0.20
Well damage: 5 in.

Completion

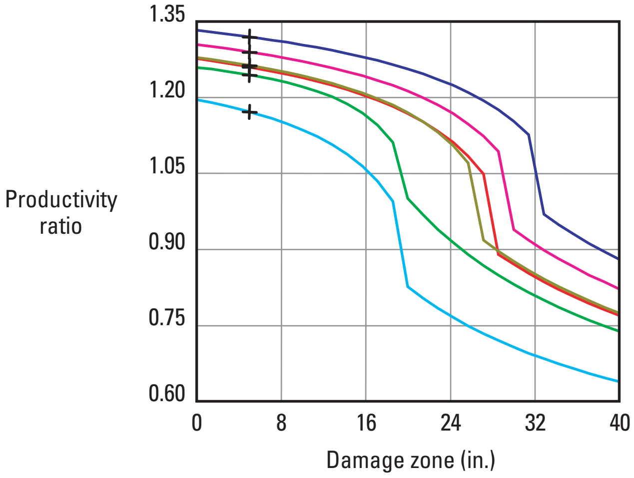
Vertical well
Formation thickness (TVD): 200.0 ft
Perforated length: 200.0 ft
Drainage area: 31.42 acre
Shape factor: 31.62

Perforating systems

- 4½-in. HSD High Shot Density, PowerJet Omega 4505, HMX
- 4½-in. HSD High Shot Density, 51J UltraJet, HMX
- 4½-in. HSD High Shot Density, PowerJet 4512, HMX
- 4-in. HSD High Shot Density, PowerJet Omega 4005, HMX
- 3⅜-in. HSD High Shot Density, PowerJet 3406, HMX
- 3½-in. HSD High Shot Density, PowerJet Omega 3506, HMX

Phasing	Shots (spf)	Offset (deg)	k_c/k	Crush (in.)	Formation Penetration/ Diameter Avg. (in.)
72	5	0	1.00	0.5	32.57/0.964
72	5	0	1.00	0.5	27.67/0.8524
135/45	12	0	1.00	0.5	19.05/0.7318
72	5	0	1.00	0.5	29.5/0.9827
60	6	0	1.00	0.5	19.58/0.6963
72	6	0	1.00	0.5	26.19/0.7719

Figure 82. SPAN plot of PR versus shot density.



Formation

k_h: 100.00 mD
k_h/k_v: 5.00
Bulk density: 2.30 g/cm³
Rock UCS: 6,403 psi
Overburden: 5,000 psi
Reservoir: 2,234 psi
k_d/k: 0.20
Well damage: 5 in.

Completion

Vertical well
Formation thickness (TVD): 200.0 ft
Perforated length: 200.0 ft
Drainage area: 31.42 acre
Shape factor: 31.62

Perforating systems

- 4½-in. HSD High Shot Density, PowerJet Omega 4505, HMX
- 4½-in. HSD High Shot Density, 51J UltraJet, HMX
- 4½-in. HSD High Shot Density, PowerJet 4512, HMX
- 4-in. HSD High Shot Density, PowerJet Omega 4005, HMX
- 3⅜-in. HSD High Shot Density, PowerJet 3406, HMX
- 3½-in. HSD High Shot Density, PowerJet Omega 3506, HMX

Phasing	Shots (spf)	Offset (deg)	k_c/k	Crush (in.)	Formation Penetration/ Diameter Avg. (in.)
72	5	0	1.00	0.5	32.57/0.964
72	5	0	1.00	0.5	27.67/0.8524
135/45	12	0	1.00	0.5	19.05/0.7318
72	5	0	1.00	0.5	29.5/0.9827
60	6	0	1.00	0.5	19.58/0.6963
72	6	0	1.00	0.5	26.19/0.7719

Figure 83. SPAN plot of PR versus damaged zone thickness.

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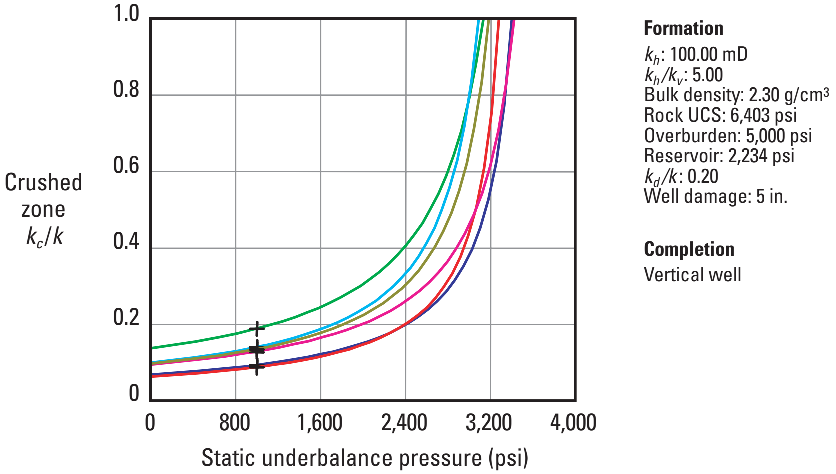
- Underbalance module calculates the minimum static underbalance necessary for zero-skin perforations based on algorithms for two popular static underbalance models (Behrmann, 1996; King et al., 1986). If the actual value of the static underbalance is less than the minimum required for zero skin effect, SPAN analysis uses the Behrmann (1996) equations to calculate the skin effect caused by residual perforation damage in the form of values of k_c/k. Figure 84 shows the effect calculated using Behrmann's static underbalance correlation on the crushed-zone permeability ratio as a function of static underbalance pressure. As previously discussed, recent research and field results indicate that static underbalance alone is insufficient to achieve clean perforations. Typically, a value of k_c/k from 0.1 to 0.3 is obtainable with a traditional static underbalance job design whereas a value of k_c/k from 0.8 to 1.0 is obtainable with a job design from the PURE perforating system for clean perforations.



Perforating systems

- — 4½-in. HSD High Shot Density, PowerJet Omega 4505, HMX
- — 4½-in. HSD High Shot Density, 51J UltraJet, HMX
- — 4½-in. HSD High Shot Density, PowerJet 4512, HMX
- — 4-in. HSD High Shot Density, PowerJet Omega 4005, HMX
- — 3⅜-in. HSD High Shot Density, PowerJet 3406, HMX
- — 3½-in. HSD High Shot Density, PowerJet Omega 3506, HMX

Charge Diameter (mm)	k_c/k	Crush Avg. (in.)	Formation Penetration Avg. (in.)	Formation Diameter Avg. (in.)
48.00	0.09	0.5	32.57	0.96
51.00	0.09	0.5	27.67	0.85
34.00	0.19	0.5	19.05	0.73
40.00	0.13	0.5	29.50	0.98
41.00	0.14	0.5	19.58	0.70
41.00	0.14	0.5	26.19	0.77

Note: k_c/k calculated from base underbalance

Figure 84. SPAN plot of k_c/k versus underbalance pressure.

Specific perforating requirements

The perforating requirements discussed here are based on the results of experiments and field tests described in subsequent chapters. The requirements are presented as recommendations, with summaries of the experiment and test results. The detailed rationales behind these recommendations are also in later chapters.

Perforating techniques

Three basic perforating techniques are available to the completion design engineer:

- Through-tubing perforating—The guns are lowered into the well through the production string or in a monobore. Gun conveyance can be by wireline, coiled tubing, tractor, or slickline.

- Casing gun perforating—Large-diameter guns are lowered into a cased well before the production string is run. Gun conveyance can be by wireline, slickline, tractor, drillstring, coiled tubing, or the tubing string.
- Completion perforating—Large-diameter guns are run with the completion and left in the hole. The guns may possibly be run and left in the well before the completion and then fired and left in the hole after the completion is run.

Through-tubing perforating

Schlumberger provides four basic types of through-tubing perforators: steel hollow carrier HSD guns, guns used with the PURE method, expendable or semiexpendable Enerjet and PowerSpiral* strip guns, and Pivot Gun* systems.

These through-tubing perforating gun systems have the following features:

- Wellhead and completion string are in place and tested before the casing is perforated.
- Underbalanced differential from the reservoir into the wellbore provides perforation cleanup.
- Perforations may be made as required over the life of the well, with or without a rig on site.
- Using the PURE method to increase production is especially effective in wells where formation communication is already present for establishing underbalanced conditions.
- Operating time is short, resulting in good job efficiency and use of rig time. The maximum perforated interval per run is limited by the surface setup and is typically 30 ft.

Casing gun perforating

Schlumberger provides four types of casing guns: Port Plug guns, HEGS* High-Efficiency Gun Systems, PURE gun systems, and HSD guns. These guns have the following features:

- Gun size is limited only by the casing inside diameter (ID), which enables use of the highest-performance deep penetrating or big hole charges at optimal shot density and perforation phasing.
- With wireline-conveyed guns, the overbalanced differential from the wellbore into the formation allows the use of longer guns than with through-tubing perforating. Typically 60 ft or more, depending on the method of deployment, can be readily achieved. Only simple wellhead control equipment is needed.
- Compared with expendable through-tubing guns, carrier-type guns significantly reduce the amount of perforating debris introduced into the wellbore during the perforating process.
- Gun systems used with the PURE method can achieve better cleanup and less formation damage.

Wireline- and tubing-conveyed perforating

Perforating guns are conveyed into the well on either wireline (electric or slickline) or tubing (production tubing, drillpipe, or coiled tubing). The choice between wireline- and tubing-conveyed perforating should be made based on the completion objectives and operational considerations.

From an operational viewpoint, wireline perforating operations are usually faster for a few short intervals to perforate. TCP operations are more efficient for long, multizone perforation intervals. The higher operating speed of wireline perforating is an important consideration for high-temperature wells because it reduces the exposure of explosives and seals to high downhole temperatures compared with TCP operations.

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TCP provides a number of benefits in completing wells:

- The advantages of through-tubing gun systems are combined with those of casing gun systems.
- Large guns may be fired in an underbalanced condition with well control equipment and the production string in place.
- Long intervals may be efficiently perforated in one run with a kill string in place, if required.
- The programmed underbalance is applied to all perforated intervals evenly and in a controlled fashion.
- The variety of firing systems and accessories accommodates a wide range of well conditions and completion techniques.
- After firing, expended guns may be dropped to the bottom of the well, which allows future through-tubing operations.

With TCP, well intervention may be eliminated along with having to kill the well.

Conveyance method selection

Perforating gun systems initially were deployed on wireline (casing and through-tubing perforating guns) and later on tubing (TCP). Historically, gun systems were classified in three groups related to the conveyance method:

- Through-tubing perforating enables the use of underbalance but restricts the gun system options.
- Casing gun perforating provides a full range of options but restricts the use of underbalance.
- TCP allows using both underbalance and a full range of gun system options.

Perforating technology has evolved considerably to make a wide variety of deployment methods possible. Each method has specific applications, as well as advantages and drawbacks. The major deployment methods are

- wireline
- tubing (or drillpipe in DST operations)
- coiled tubing, with or without an electric line
- wireline tractor
- slickline
- snubbing.

Achieving an optimal design requires comparing the advantages and disadvantages of the various conveyance methods and weighing them against each other and against the gun systems being considered for the specific completion. The following major perforating issues require consideration:

- gun length
- mechanical strength
- high-angle wells
- pressure control
- depth control
- underbalance
- rigless completions
- gun options (size, firing head, connections)
- selectivity
- debris
- duration of operations.

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Gun length

Using wireline traditionally restricts the length of the gun assembly because of the total weight on the rope socket and the need to lubricate the guns into and out of the hole. Slickline conveyance limits the length of the gun assembly even more.

The GunStack* stackable perforating gun system can solve the lubrication problem because the gun assembly can be run, built, and retrieved in sections. The CIRP Completion Insertion and Removal under Pressure system also allows insertion and removal of long gun sections into and out of live wells. A third option is the WXAR assembly.

With the WXAR, long gun sections are run in the hole overbalanced with wireline or coiled tubing. Underbalance is established before the guns are fired. The WXAR drops the guns at the time of detonation, and if the well has pressure after perforating, only the firing head must be lubricated out of the well.

The "Completion Perforating Without Killing the Well" chapter describes GunStack, CIRP, WXAR, and other hardware options that minimize formation damage.

Tubing- and coiled tubing–conveyed operations (and, to some extent, tractor-conveyed operations) place no limitations on gun length, providing that provisions are made to either drop the guns and retrieve them after killing the well or use specific techniques for perforating without killing the well, such as the CIRP system or multiple WXAR assemblies.

Mechanical strength

Flexibility is a consideration if mechanical strength is required to pull or push the gun. The conveyance methods rank as follows for flexibility:

1. snubbing, TCP, and coiled tubing—highest
2. tractor—limited (same as wireline unless in combination with coiled tubing)
3. wireline—limited
4. slickline—limited (same as wireline).

Tractor conveyance has some limitations concerning the weight of the guns. High-strength adaptors must be used for tapered gun strings, such as the long strings of up to 8,500 ft that have been run in horizontal wells. Gun bending must also be considered in terms of alignment, weight, and amount of snubbing force required. The "Operating Environment and Engineering of Perforating Operations" chapter discusses gun bending in more detail.

High-angle wells

Wireline may not allow guns to descend in high-angle and horizontal wells unless a tractor, rollers, or a combination of the two is used. Coiled tubing is the preferred conveyance method, unless the length of the horizontal section causes the coiled tubing to lock up before the guns reach the interval to be perforated.

Pressure control

Difficulty in controlling wellhead pressure is related to the cross-sectional area of the conveyance element. Thus, surface pressure control is easier with small-diameter slickline than with larger diameter electric wireline when perforating with a cable. Controlling wellhead pressure when perforating with a cable must also take into consideration the generation of friction by flowing fluids on the cable, which can result in sufficiently large forces to blow the guns up the hole.

Wellhead pressure control is easier to maintain in coiled tubing operations in which the weight of the string, a snubbing unit, or both the string and snubbing unit easily overcome the surface pressure. Coiled tubing operations typically are limited to a maximum of 10,000 psi at the surface because of safety and equipment considerations.

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For initial pressure surges, the wireline perforating anchoring tool (WPAT) can be used to overcome gun movement resulting from an undesirable pressure surge after perforating. The guns are positively anchored at the time of perforating with a time-delay action that keeps them in place (see the "Wireline Perforating Techniques" chapter for details).

Depth control

Depth control is crucial to perforating operations. Using an electric line (e.g., wireline, conductor slickline, or coiled tubing equipped with a conductor line) is ideal because it allows running correlation logs while deploying the guns.

A separate wireline descent is often necessary in TCP operations to run a correlation log and reposition the tubing string before perforating. When slickline is employed, a dummy tagging run is required to position the guns on depth.

Horizontal and very high-angle wells pose additional depth control concerns. Line slack (tractors) and helical buckling (coiled tubing) result in measured depths that are different from the actual depths along the well.

The DepthLOG* depth correlation tool determines depth by using a traditional casing collar locator (CCL) with flow-through capabilities, which provides the effect of open-ended, unobstructed coiled tubing. The use of fluid pulse telemetry to transmit data to the surface eliminates the need for an electric line in coiled tubing operations. The resulting real-time CCL correlation log, which meets API standards at surface, enables operators to accurately correlate depth in reference to the baseline log.

Underbalance

One of the most important criteria for optimizing performance is creating an underbalance at the time of perforation.

In an underbalanced completion, the reservoir pressure is greater than the wellbore pressure at the time of perforating. The resulting negative pressure differential aids perforation cleanout through the surge effect from the underbalance, which also prevents the invasion of completion fluid into the reservoir.

Achieving underbalance is almost always possible, regardless of the conveyance method. Through-tubing underbalanced completions usually limit the gun size, perforation density, and phasing. Very high underbalance, which is sometimes preferred to clean out the perforations and generate high post-perforation flow, is not possible with wireline-conveyed guns in the well unless anchoring devices, such as the WPAT, are used. Anchoring devices are also recommended when the underbalance is unknown (e.g., perforating new intervals in a column of differentially depleted producing intervals). In extreme cases, the negative differential pressure may cause friction to pull the gun down after perforating, resulting in a broken wireline if the gun is not anchored.

Rigless completions

Many recompletions and workovers can be performed without a rig, which helps to lower operational costs and simplify logistics. Because hoisting facilities are generally limited in rigless work, conveyance options for rigless perforating and reperforating are limited mainly to the following three methods (listed from highest to lowest cost):

- guns on the wireline or slickline, possibly involving tractors
- coiled tubing–conveyed guns
- guns run on the tubing, such as in TCP, during snubbing operations with a light workover performed.

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CIRP and GunStack systems can be used to run long gun strings into and out of a well without a rig and under pressure. These systems incorporate gun construction and disassembly equipment that can provide gun retrieval under wellhead pressure. Both systems require assembly under pressure, with the CIRP system assembled at the surface and the GunStack system assembled downhole.

Gun diameter, density, and phasing

The ideal perforation completion option is to use the maximum-diameter gun system that can run into the well and through existing restrictions. Limiting factors for the practical gun diameter include gun swell after perforating and the height of burrs created by the perforation jet on the gun wall and inside of the casing. The likely occurrence of sanding in a well also imposes limits on the choice of gun diameter.

Regardless of the conveyance method, the largest diameter gun that fits into the casing usually provides the best performance except when the gun is run through tubing into a larger diameter casing. Monobore completions overcome this limitation because there are no restrictions.

Phasing and shot density are selected on the basis of the results of the design program. The only restriction these two parameters place on the gun conveyance method is that phasing options are limited when running capsule-type guns through the tubing.

Selectivity

Shooting guns on an electric wireline using diode switches provides selectivity in perforating. If pressure-actuated firing heads are used in TCP operations, selectivity depends on the tubing pressure settings for gun detonation. The operating windows for the different firing heads must be adequately spaced to avoid potential overlap.

The ProFire* programmable firing head provides selectivity with greater flexibility for handling pressure windows in TCP operations. See the “Tubing-Conveyed Perforating Completion Techniques” chapter for more information on the ProFire hydraulic firing system.

Debris

Gun and shaped-charge debris left in the well can lead to problems owing to

- accumulation of fill at the bottom of the well
- debris not falling to the bottom of deviated wells
- debris that reaches the surface and damages equipment
- possible sticking of completion equipment.

Debris mainly comes from expendable through-tubing guns. If debris is a concern, carrier guns are preferred because they generally contain the debris inside the hollow carrier, other than debris from the shaped charge (i.e., case, liner, and jacket) that may come out of the gun.

Duration of operations

The conveyance method has a direct impact on the duration of operations. Running in, shooting, and pulling out a casing gun in an overbalanced condition may take only an hour using wireline. In shallow (about 5,000 ft) land wells in Bakersfield, California, a typical HEGS High Efficiency Gun System can be run in, shot, and run out in 20 minutes. At the other extreme, a TCP operation may take days to run in and position a DST string, set the packer, operate the valves, pressure test the equipment, establish underbalance, fire the guns with a time delay, and, finally, drop the guns.

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Operations that use wireline or slickline to convey the gun are the fastest. The slowest operations are TCP and drillpipe conveyed. Operation time varies for coiled tubing operations, especially in horizontal wells and tractor operations, depending on the complexity of the job.

Controlling the duration of operations may be necessary for other than economic reasons because high-temperature downhole environments limit operation time. Explosives and seals experience thermal and chemical decomposition; therefore their ratings are important factors for review concerning possible completion redesigns, exceeding time estimates, and job flexibility. See the “Operating Environment and Engineering of Perforating Operations” chapter for a more detailed discussion.

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Operating Environment and Engineering of Perforating Operations

Operating environment

Schlumberger perforating equipment is designed for a wide range of downhole environments. Equipment selection depends on the requirements of the particular completion. For operations in hostile environments, advanced planning with your Schlumberger representative is strongly recommended.

The effects of temperature, pressure, and fluid properties are briefly presented in this chapter with information about various completion techniques and approaches to optimizing well productivity.

Time and temperature guidelines

A successful perforating job is the result of thorough preparation, selection, and execution of the complete perforating system. The perforating system integrates explosives, firing head and detonator, gun system, seals, lubricants, quality control and conformance, cleanliness, assembly procedures, and training. Each of these factors affects the rating of the system.

High temperature is one of the most important factors in selecting the explosive type and carrier design and in performing the wellsite operation. Both the maximum temperature value and the length of time the explosives are exposed to a particular temperature are important (see "Perforating Fundamentals" chapter in this book for more information on explosives and other detonation components). The time factor is crucial if more than a few hours separate the time between exposure to the temperature and actual detonation. In some cases, the guns are positioned in the well (e.g., anchored) for months before detonation.

Schlumberger time and temperature ratings ensure that there is no degradation in perforator performance (penetration and entrance hole) up to the maximum rating. For higher temperature or longer duration perforating operations, HNS charges are recommended.

Table 17. Temperature Guidelines for Explosives in Hollow Carrier Guns†

	Temperature Rating‡			
Explosive Type	**1 hr**	**100 hr**	**200 hr**	**400 hr**
RDX	340°F [171°C]	240°F [115°C]	225°F [107°C]	210°F [99°C]
HMX	400°F [204°C]	300°F [149°C]	285°F [141°C]	270°F [132°C]
HNS	500°F [260°C]	460°F [238°C]	440°F [227°C]	420°F [216°C]

† Ratings for strip guns and other exposed applications vary.

‡ Temperature ratings are set at the highest temperature that retains 100% of the explosive performance. Above these temperatures, explosives show reduced performance and some may autodetonate.

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Completions that plot above the HMX line in Fig. 85 are considered high risk (i.e., high temperature, high pressure, long duration) and require special preparation. Systems that require the use of HNS explosives to meet the time and temperature guidelines for explosive charges also have the following components:

- HNS detonating cord and NONA boosters should be used.
- High-temperature detonator and firing heads are required for TCP operations.
- Seals and perforating gun systems have their own time and temperature characteristics, separate from those of the explosives components. The gun system must be selected to also match the required time and temperature exposure of the operation.
- Specialized field preparation and assembly procedures must be followed.
- Clients may specify additional quality control procedures that can be performed only at the time of manufacture.

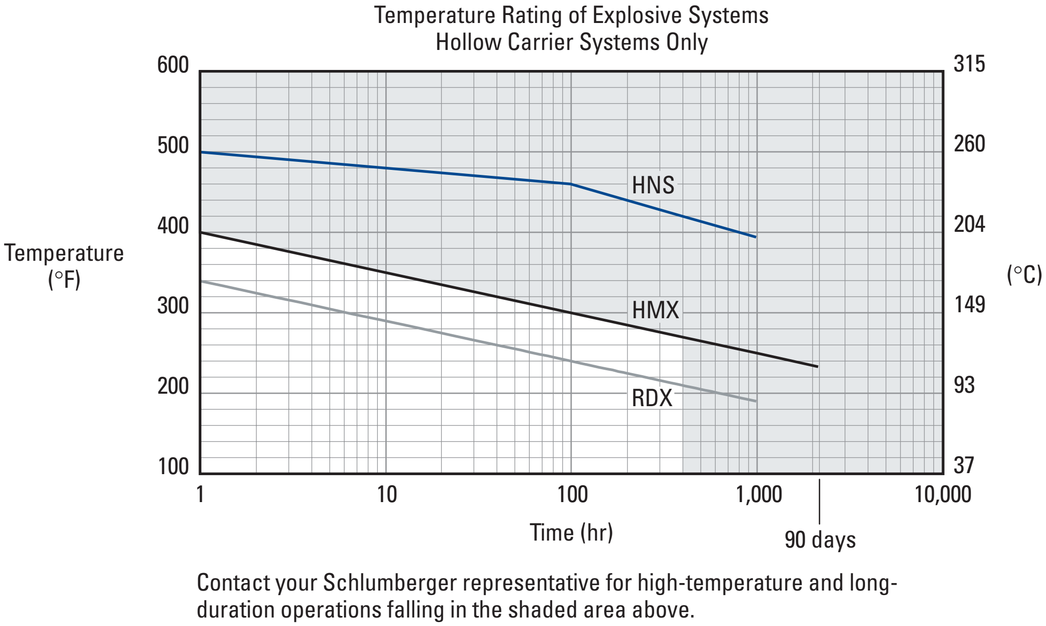

Figure 85. Time and temperature guidelines for selection of explosives in hollow carrier guns. Exceeding the temperature rating leads to reduced performance followed by burning (all explosives) and possible autodetonation (RDX and HMX explosives).

The temperature rating of a perforating system is that of the lowest rated component of the system. Additional hardware changes may be required if conditions may exceed any one of the following:

- temperature > 330°F
- pressure > 15,000 psi
- time > 100 hr.

Reusing explosives that were previously exposed to temperature cycles increases the likelihood that failure or misfires will occur and should be considered only as a last resort. If the time and temperature exposure of the explosive is exceeded, typically the failure mode is reduced performance or no performance and low-order detonation. However, the failure of RDX and HMX systems may result in high-order detonation with potentially catastrophic results for the well completion.

Special care must be taken because of trapped pressure in retrieving unfired explosives devices that have exceeded time and temperature limits. A specific procedure must be followed for retrieving HMX explosives once 330°F has been exceeded or if 300°F has been exceeded for more than 100 hr because of the increased sensitivity of the explosive to shock.

Numerous accessories are used in perforating operations, such as weights, adapters, and positioning devices. Table 18 details accessories for high-temperature operations.

Table 18. High-Temperature Accessories

Temperature Rating (°F)	Tool	Description	Length (in.)	Weight (lbm)
500	EQF-53[†]	$1\frac{11}{16}$-in. weight (H_2S)	72	61
500	EQF-54[†]	$2\frac{1}{8}$-in. weight (H_2S)	72	105
400[‡]	MH-22	$1\frac{3}{8}$-in. monocable head (H_2S)	18.9	5.1
400[‡]	MH-32	Monocable head for –22, –23, and –25 cables	12.4	–
500	AH-106[†]	$1\frac{3}{8}$- to $1\frac{11}{16}$-in. monocable adapter	3.36	1
500	CCL-AG	$1\frac{11}{16}$-in. high-temperature casing collar locator	18	12
500	CCL-AT[†]	$1\frac{11}{16}$-in. high-temperature casing collar locator (high-pressure version of CCL-AG)	18	12
500	MPD-NB	$1\frac{3}{8}$-in. magnetic positioning device	19.4	12
500	MPD-LB[†]	$1\frac{11}{16}$-in. magnetic positioning device	19.4	14
500	MPD-MB[†]	2-in. magnetic positioning device	19.4	22
500	SPD-AB	$1\frac{11}{16}$-in. spring positioning device	31.7	–

[†] Program to Evaluate Gun Systems (PEGS) verified

[‡] Optional upgrade to 500°F

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Pressure

Other important considerations are the hydrostatic pressure and type of fluid surrounding the perforating gun. Exceeding a carrier's pressure rating may flood the guns or crush the carrier, in turn causing a low-order detonation and bomb-like effect that could damage the well and stick the gun. The surrounding environment (i.e., liquid or gas) determines the carrier's ability to withstand the forces that occur during perforating. The rating of the gun for the well environment must be confirmed.

Perforating guns are designed and built to downhole pressure specifications. As such, they meet downhole safety margins and should not be exposed to any more pressure at surface than is necessary to enter the well. Pressure control equipment must not be pressure tested while a loaded perforating gun is in the lubricator. New pressure control equipment includes subs that enable opening a pressure control string to take in a perforating gun and pressure testing the disconnected joint without applying pressure to the perforating gun.

High-pressure, high-temperature (HPHT) conditions also influence the selection of elastomers for the pressure seals. In HPHT operations seals should be changed between runs into the well to avoid failure. Capsule charges should not be reused after HPHT exposure.

Wellbore fluid chemical properties

Completion operations planning must take into account the chemical properties of the wellbore fluid, such as the concentration of hydrogen sulfide (H_2S), carbon dioxide (CO_2), and acid in the well during and immediately after perforating. H_2S, CO_2, and acid attack perforating guns, causing general corrosion and possible hydrogen embrittlement that may lead to material failure. Factors affecting the severity of the hydrogen embrittlement include pressure, aggressiveness of the environment, type of material, stress the material is under, and length of time the material is exposed.

Operations in the presence of H_2S or acid require special precautions for the perforating guns and their associated hardware. Perforating guns are not H_2S-proof according to NACE International (formerly the National Association of Corrosion Engineers) guidelines. Associated equipment (e.g., completion accessories, TCP firing heads, wireline cable) may be made H_2S-proof, either routinely or by special arrangement.

Perforating guns are generally resistant to the effects of hydrogen embrittlement, depending on the factors previously discussed (environment, material type, etc.). Additional considerations are as follows:

- Fluids such as cesium formate and potassium formate brines require using compatible elastomers for the seals in perforating equipment.
- Inhibitors used should be selected to not affect the sealing performance of the elastomers used in perforating equipment.
- Hollow carrier guns are generally preferred to exposed guns for operations in environments with a high H_2S concentration and when acid is used.

Perforating in gas or liquid

Some perforating gun assemblies can survive a shot in gas or air whereas some can be shot only when surrounded by liquid.

Potential hazards

Perforating in wells filled with gas or when a fluid with a high gas to liquid volume ratio is used can be hazardous to both personnel and equipment unless proper procedures are followed. The following effects can occur in predominantly gas environments:

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- Gas may enter high-pressure elastomer seals and migrate to unexpected areas, creating trapped high pressure in tools brought back to the surface.
- The shaped charges of a leaking hollow carrier gun do not operate properly, possibly leading to low-order detonation or an uncontrolled detonation (i.e., bomb effect).

Gun swell

During gun system development, tests are performed in both water and air to determine the maximum outside diameter (OD) of the carriers after they are shot.

The guns are loaded with charges that are heavier than normal and several are shot in both air and water, all at atmospheric pressure. Each gun carrier is then mounted and turned on a lathe where the OD surface anomalies are automatically and continuously measured with a laser. The data are processed to determine the maximum cylindrical swell diameter for the gun, charge, and environment combination. This measurement is important for determining the clearance for long gun strings in a particular wellbore. The primary consideration is the ability to fish the guns with washover pipe if they become stuck.

A different measurement is taken for through-tubing applications or other jobs where the guns must pass through a nipple or similar restriction. For guns loaded and shot as previously described, 18-in. precision ID gauge tubes are passed over each carrier to determine the go and no-go gauge ID or carrier OD. This measurement is typically smaller than the maximum cylindrical swell diameter. The measurement is conservative because nipples are very short and the gauges are 18 in. long.

Gun swell data are in the perforating gun systems chapters. This information is also on the current Schlumberger SRC perforating calendar poster.

Burr height

The passage of the jet through the gun and through the casing leaves burrs on the outside of the gun carrier and on the inside surface of the casing. Burrs are also produced on the outside of the casing, but these do not affect the maximum diameter tolerances for shot guns. The maximum diameters specified for shot HSD guns include the burrs. In most cases, the specified maximum diameter is the same as that without burrs. Sporadically burrs exceed the maximum swell diameter.

In fishing operations with washover pipe, burrs that exceed the gun carrier OD (i.e., from the scallop surface to beyond the swollen carrier OD) are easy to knock off and should pose no problem. Burrs can be a problem in through-tubing applications if the burrs exceed the carrier OD. This situation is rare; a burr typically poses no problem unless the gun carrier has no scallops or recesses to contain the burr.

Casing wall burrs are smaller but still may bind firmly to the casing wall. They do not break away as easily as those from a gun carrier. The size of internal casing wall burrs is included in the official API Section I data for each gun and charge combination. The minimum casing ID after perforating is determined by subtracting twice the burr height from the casing drift diameter. The resulting number is compared with the maximum diameter for shot guns.

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Gun-specific characteristics for perforating in gas

Specific hardware must be used for perforating in gas, and planning a perforating job in gas or air requires verifying the gun rating for gas applications. Gun-specific technical data applicable to perforating in gas and high gas-to-liquid ratio wells can be summarized as follows:

- Enerjet guns shot in gas may cause excessive strip deformation. Special procedures include using short guns and two magnetic positioning devices. No weights should be run below the strip.
- Pivot Gun systems can be shot in gas if the void volumes in the gun are filled with grease. The grease improves cord-to-charge transfer and reduces friction when the gun is deploying.
- HSD guns are available in various ratings. Most gun, charge, and shot density combinations can be shot in air or gas at zero pressure. Some combinations must be shot in liquid.
- HEGS and Port Plug guns can be shot in air or gas, but a special dry-hole port plug must be used with Port Plug guns.

Perforating-associated shock

Shaped charge detonation can create intense shock loading on the guns, tubing, cables, packers, and other downhole tools. The principal mechanisms that may lead to damage are as follows:

- Recoil, as the shaped charge jets are propelled toward the casing and formation—This lateral force may cause the gun to strike the wellbore wall, but it is typically a concern only if the guns are loaded asymmetrically (e.g., at 0° phasing).
- Shock pressure pulse in the gun carrier steel, well fluid, casing, cement, and formation—The amplitude of the pressure pulse diminishes as it travels farther from the source (i.e., the boundary of the perforated interval) and depends on the geometry of the downhole assembly and compressibility of the media in which the gun is shot. Shock is more likely to damage sensor packages than it is to generate gun movement.
- Wellbore pressure pulse that results as wellbore fluid is pushed into the gun (as in PURE jobs) or as detonation gas exits the gun.

As the pressure pulse travels along the wellbore at the local speed of sound (approximately 4,900 ft/s in liquid), it creates an upward or a downward force on the end of a gun string. An end occurs at the termination of the gun, where it changes in diameter, or where it connects to a tubing string of a different diameter in TCP assemblies. Whether the force is oriented upward or downward depends on the local geometry (i.e., gun length, perforated interval length, completion string configuration).

Another upward force can be created if the distance from the lowermost shot to the bottom of the well is small enough that the shock wave does not die out through attenuation in the wellbore fluid. The pressure pulse reverberates on the well bottom and is reflected upward.

An additional effect results from

- Surge flow induced by underbalanced perforating—The shear stresses created on the gun, cable, or other downhole components may lead to gun movement or loss of tension in the cable.

The following factors enhance the effects of the perforating shock wave:

- low-compressibility wellbore fluids (e.g., water)
- big hole and zinc case charges
- high hydrostatic pressure

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- tight clearance between gun and casing
- short guns
- small-volume rathole
- short distance between topmost shot and packer.

Conversely, these factors reduce the effects of the perforating shock wave:

- high-compressibility wellbore fluids (e.g., gas)
- deep penetrating charges
- low hydrostatic pressure
- loose clearance between gun and casing
- long guns
- large-volume rathole
- long distance between topmost shot and packer.

Mud weight

In addition to the effects of hydrostatic pressure on the perforating guns, mud weight may affect the operation of TCP firing systems. High-density muds tend to segregate over time, which affects both pressure-activated and mechanical drop bar firing systems. Pressure-activated firing heads are preferred to other firing systems for use with higher-density muds because the ability of high-density mud to transmit pressure is greater than the ability of a drop bar to reach the firing head. Fluid isolation equipment is used to ensure that mud solids do not affect firing head operation.

Well deviation

Well deviation beyond 45° may cause a problem for wireline-conveyed perforating guns because of increased frictional forces on the cable, lower gravitational force along the wellbore, and smaller clearance between the ends of the gun assembly and the casing ID at doglegs. One key factor is that descending guns on the move are subject to less friction than they are when static. Generating downward movement of a still gun is more difficult (because of the high static friction) than keeping it on the move once descent has begun (because of the comparatively lower dynamic friction). Friction forces must be kept in perspective with the absolute well deviation and the well profile (doglegs and torsion). For example, friction forces can be greatly reduced by fitting a round-bottom nose onto the gun.

Negotiating sharp doglegs with long guns is another issue. The “rigid” gun approach is misleading because long guns bend. This flexibility greatly improves the descent performance of long gun strings. The maximum gun length that can be run depends on many variables in addition to dogleg severity, such as friction, wellbore deviation, and method of conveyance. Tool planners and coiled tubing modeling should be used to calculate the maximum gun length as a function of all input variables.

In the past, well deviation beyond 45° made it extremely difficult to drop guns from a tubing-conveyed system. The SXAR automatic gun release solves this problem. Gun systems have been successfully dropped at deviations greater 80° (see the “Completion Perforating Equipment” chapter).

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At deviations between 45° and 65°, wireline perforating operations can be successfully completed using weights. Table 19 lists commonly available weights for wireline perforating, and Table 20 lists special slant hole equipment.

At deviations greater than 65°, TCP perforating (drillpipe-conveyed or coiled tubing–conveyed perforating) is the most common technique. Roller adapters and orienting equipment may be used for TCP operations in highly deviated or horizontal wells. See the "Completion Perforating Equipment" chapter for a discussion of TCP orienting techniques and equipment. Alternatively, guns may be conveyed with a wireline tractor.

Table 19. Typical Weights for Wireline Perforating

Weight	OD (in.)	Type	Service	Length (in.)	Weight (lbm)	Pressure Rating (psi)	Temperature Rating (F°)
EQF-33	3⅜	Steel	Standard	60	150	20,000	450
EQF-38	$1\frac{11}{16}$	Steel	Standard	48.4	30.4	20,000	450
EQF-39	2	Steel	Standard	48.4	42.7	20,000	450
EQF-41	1⅜	Steel	Standard	45.8	19	20,000	450
EQF-43	$1\frac{11}{16}$	Tungsten	Standard	72	74	20,000	450
EQF-46	2⅛	Tungsten	Standard	72	104	25,000	450
EQF-47	1⅜	Tungsten	H_2S	72	48.5	20,000	450
EQF-53	$1\frac{11}{16}$	High density	H_2S	72	61	25,000	500
EQF-54	2⅛	High density	H_2S	72	105	25,000	500

Table 20. Types and Specifications of Special Slant Hole Equipment

Device	Makeup Length (in.)	Weight (lbm)	OD (in.)	Hole Size (in.)		Temperature Rating (°F)	Pressure Rating (psi)
				Min.	Max.		
Rollered pivot joint (AH-86)	17	35	3.7	4.2	na	340	20,000
Rollered flex joint (AH-88)	36	32	1.71, 2.18	2.25	na	350	15,000
Rollered spring positioning device (SPD-G)	54	21	1.71, 2.18	2.25	6	350	15,000
Rollered flex joint (AH-90)	27	14.5	1.41	1.5	na	350	15,000
Rollered spring positioning device (SPD-H)	52.4	14	1.41	1.5	6	350	15,000
Adjustable roller assembly (CME-AL)	na	34	5.7	5.7	9	na	na
Adjustable roller assembly (CME-AK)	na	40	5.7	5.7	9	na	na

na = not applicable

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Perforating Research

Objectives

Perforating, like other technological fields, requires research for advancement and innovation. Schlumberger Perforating Research is located at SRC, alongside the perforating engineering departments and InTouchSupport.com* perforating helpdesk. This collocation is unique among the many Schlumberger research entities and confers many advantages from close working relationships with both engineers and clients, leading to better focus of the research effort.

The major objectives of perforating research are to

- investigate the physics of perforating, including development of the perforator and its interaction with the wellbore and reservoir
- support development of new perforating technology
- address specific perforating requests from oil and gas operators.

Perforating research covers the entire spectrum, from explosives through shaped charge and gun material design, to interaction of the shaped charge jet with the wellbore fluid and with the reservoir. In a nutshell, Perforating Research seeks to develop perforating techniques that maximize hydrocarbon productivity while minimizing the risk of sand production under the safest and most economic conditions. To this end, a combination of mathematical analysis, numerical simulation, and laboratory experiments is employed.

Materials research

The energetic materials program supports the research, development, and manufacturing of all explosive components used in perforating—detonators, boosters, detonating cords, and shaped charges. New explosive materials are developed. Research focuses primarily on

- HPHT environments
- performance improvement
- increased safety
- cost reduction.

SRC also maintains a fully equipped metallurgical laboratory for materials research. In addition to supporting shaped charge and explosives research, the metallurgy laboratory performs failure analysis on gun carriers and other components and conducts perforating sustaining efforts concerning metals.

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Shaped charge research

Shaped charge research addresses performance, design, materials, and manufacturing issues in addition to investigating new concepts for perforating shaped charges and gun systems. Research focuses on two major areas:

- fundamentals of perforator performance and target interaction
- performance and quality improvement of existing charges.

Achieving these goals requires a thorough understanding of charge detonation, jet formation, and interaction of the jet with the formation. Third-party software is used to simulate the shaped charge detonation and jet formation processes, which facilitates shaped charge design. Experiments in the shaped charge laboratory measure jet characteristics such as velocity and density, and experiments in the PERF laboratory at SRC (discussed later in this chapter) provide penetration data from real rocks under downhole stress conditions. Together with mathematical models of the penetration process, the data enable addressing the effect of the target material on perforator performance. In situ performance of existing charges is also calculated and embedded in SPAN Schlumberger perforating analysis software.

The results of these rigorous research efforts include the high-performance deep penetrating PowerJet and PowerJet Omega* shaped charges.

Perforation productivity enhancement

A major concern of Perforating Research is the development of techniques for maximizing productivity in a wide range of downhole conditions and environments. Central to these investigations is the fact that the very act of creating the perforation cavity damages the rock matrix around the perforation, thereby reducing productivity. Techniques to reduce or remove the damage require first understanding of the damage mechanism, then predictions of the extent of the damage, and finally methods of removing it.

The principal removal mechanism is by perforating underbalanced. Experiments in the PERF laboratory show that perforation cleanup id controlled not so much by the initial underbalance as the effective transient underbalance experienced by the perforation as the wellbore pressure varies during the first few tenths of a second after perforating. Investigation of the physics of the interactions of the gun, wellbore, and reservoir enabled first being able to predict and then control the pressure variations. These developments led in turn to the technique now known as the PURE perforating system for clean perforations (see “Perforation Damage and Cleanup” chapter).

Other investigations include perforating in gas-saturated rocks and in weak rocks. In this context Perforating Research works with Schlumberger Sand Management Solutions to understand the physics of sand production from perforated completions and to develop methods of mitigating or at least reducing the risk of sand production. Some projects are funded entirely internally whereas others are at least partially supported by clients. A recent client-supported project investigated the optimum strategy for a shoot-and-pull operation, in which the well is killed while the guns are removed and completion hardware is installed. Most client-supported tests are tightly focused. Typically the performance of specific charges is evaluated in operator-supplied reservoir cores under typical downhole conditions. These tests help to define the optimum charge and perforating conditions for a particular reservoir. Typical objectives are to determine penetration depth, optimum underbalance, and the sand-producing propensity of the rock after depletion, high rate, or water cut.

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Productivity Enhancement Research Facility

The PERF facility at SRC is a state-of-the-art perforating laboratory (Fig. 86). Tests are performed using single-shot pressure vessels (PV-93 and PV-20) similar to API RP 19B Section 4 test vessels and the new polyaxial stress frame, in which multishot experiments are conducted in more realistic downhole geometry conditions.

Both testing vessels and the stress frame duplicate the three major in situ conditions:

- rock stress (confining or overburden for the pressure vessels and true triaxial for the stress frame)
- pore pressure
- wellbore pressure.

Single- and mixed-phase (oil, water, gas) tests can be conducted. Computerized data acquisition and measurement capabilities are available to perform constant-pressure or constant-rate measurements. Single-shot perforation and flow measurements can also be made with different charges. Core samples for all tests can be consolidated in situ (with resin) for thin-section scanning electron microscope (SEM) analysis.

Figure 86. Advances in perforating research are made at the Schlumberger PERF laboratory.

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Pressure vessel PV-93

In addition to its basic capabilities, PV-93 (Fig. 87) can be rotated to orient the perforation in any direction. This enables the simulation of perforation in vertical, deviated, and horizontal wells to study the effect of gravity. For a typical perforation and flow test, the core sample (for which porosity and permeability have been measured) is mounted inside the confining chamber. The core sample is enclosed in a rubber sleeve to prevent communication with the confining fluid in the chamber. An end attachment to the core sample is used to conduct the desired pore fluid into the core.

The pore fluid is stored in a bank of three 10-gal accumulators that are precharged to reservoir pressure. The accumulators supply the core with the necessary reservoir fluid for the underbalance surge.

The shaped charge is placed inside a modified perforating gun in the simulated wellbore at a known standoff from the casing, which is simulated by a 1.125-in.-thick shooting plate (cement with 0.375 in. of steel). Electrical shooting conductors from the gun are routed through pressure-tight connectors to the shooting box.

The simulated wellbore contains wellbore fluid and is attached to precharged accumulators (up to 11 gal). A custom-designed transfer-barrier accumulator system can be used to flow the core at elevated pressure immediately after perforating, removing the detonation gases in solution. Fast gauges mounted on the wellbore and confining chamber record the pressure fluctuations at the time of detonation. The wellbore part of the pressure vessel can also be heated to test reactive wellbore fluids at more realistic conditions and reaction rates.

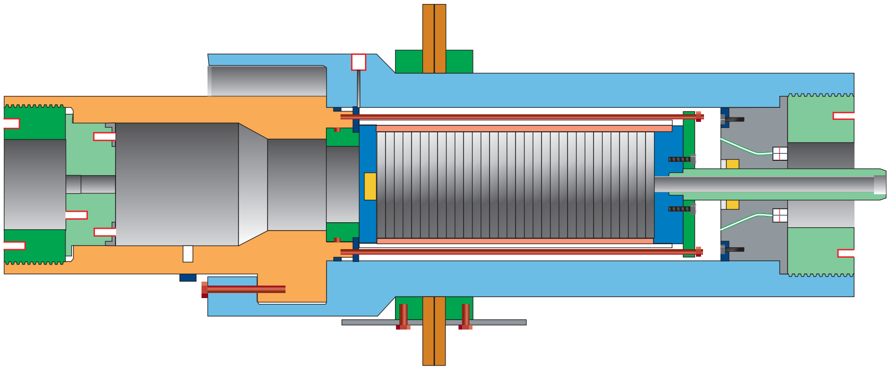

Figure 87. PV-93 experimental pressure vessel.

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After perforating, a flow tube is connected to the perforation to allow fluid to flow out of the core sample during the simulation of production flow. A small video probe can be inserted into the cavity to observe and record cleanout or monitor sand production while the core sample is still under the confining stress. Sand production can be monitored at different flow rates, for increasing depletion conditions, and at the onset of water cut. Six constant-flow-rate pumps (including two syringe pumps controlled by programmable logic controllers [PLCs]) are available to flow the sample with a water phase, oil phase, or mixed phase while flow meters and pressure gauges are used to measure the postperforation productivity. The flow path can be reversed to simulate injection flow. A gravel-pack head assembly can be installed in the simulated wellbore, against the shooting plate at a known standoff, to circulate gravel inside the perforation.

To simulate openhole completions, a cross section of the core is exposed to the wellbore. A special apparatus circulates mud across the face of the core at a fixed differential pressure. Leakoff through the core and decline in productivity are monitored to determine the extent of formation damage caused by the invasion of mud filtrate.

In addition to these tests, PV-93 is used to study the effects of specific acid formulations for treating near-wellbore formation damage.

Pressure vessel PV-20

Pressure vessel PV-20 (Fig. 88) operates similarly to PV-93. Although it accommodates larger diameter, longer cores, perforation orientation is limited to vertical geometries (up or down). Perforations can be simultaneously created in two outcrop core samples (one up, one down) to compare the effect of dirrerent rock types or permeabilities on productivity. The core sample cannot be kept under stress to examine the perforation, and unlike the PV-93 vessel, neither gravel packing nor sand production monitoring is possible.

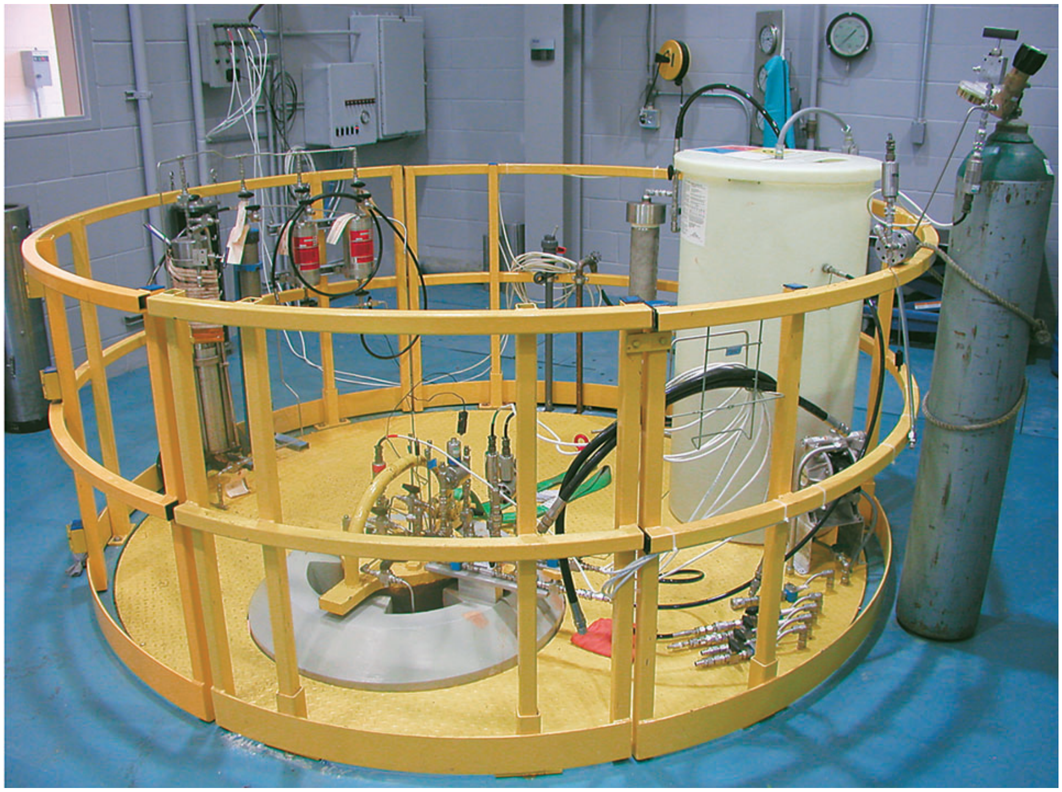

Figure 88. PV-20 experimental pressure vessel.

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Polyaxial stress frame

The polyaxial stress frame (Figs. 89 and 90) enables the application of true triaxial stress on a block of rock measuring 30 in. × 30 in. × 54 in. in height. In addition to simulating independent triaxial stresses, the frame can be arranged for controlled pore pressure and wellbore pressure on a block size of 27 in. × 27 in. × 50 in. in height. This produces a highly realistic simulation of the downhole environment.

Each block can accommodate from one to three casings, which can be placed at various locations in the block. A centrally located casing in the block can be used to shoot an actual field gun at downhole conditions with up to 36 shots at 12 spf. With three casings, three different guns can be used to perforate, with each gun containing up to 13 shots at 4 spf and 0° phasing. This capability allows different charges to be tested into the same rock or the same charge to be tested at different stress conditions. In tests with controlled pore pressure, postperforating flow testing can be conducted using the various pumping systems at PERF. If higher volumes of flow are required, a field pumping unit can be connected to a high-volume flow loop to provide fluid to the test block.

In addition to perforating tests, the polyaxial stress frame can be used for experiments concerning hydraulic fracturing, openhole tool performance, borehole deformation, wellbore fluid damage, kill pill effectiveness, propellant research, and novel stimulation technique evaluation, among others.

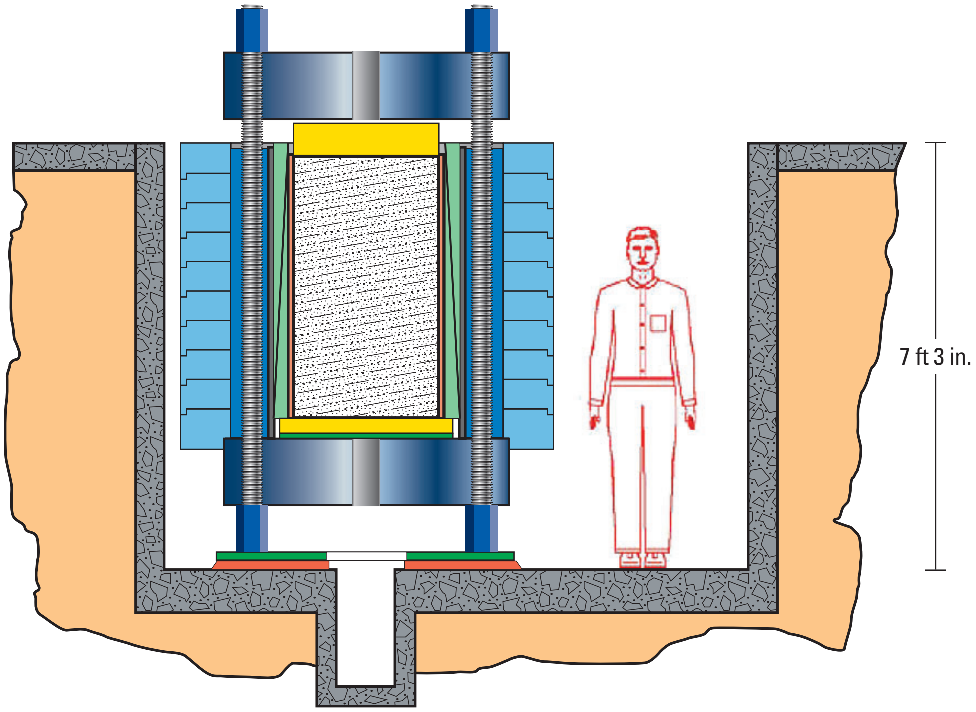

Figure 89. Polyaxial stress frame.

Figure 90. Installation of the top steel platen onto the 12 tie rods of the assembled polyaxial stress frame.

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Perforating Gun Systems

Introduction

There are two major types of perforating gun systems:

- Capsule guns are exposed gun systems, with the individual shaped charges in pressure-tight capsules that, along with the other gun components, are exposed to the well environment.
- Hollow carrier guns use shaped charges that are positioned inside pressure-tight steel tubes.

Other perforating guns are for special applications, such as tubing punchers, or customized systems. Regardless of the type of gun or perforating application, gun performance depends on design and manufacturing quality control (QC), as verified by testing.

Perforating gun design

Successful perforating gun system design incorporates a multitude of topics, including physics, mechanics, chemistry, metallurgy, and explosives principles. It utilizes peaceful applications of the best efforts of both weapons and armor technologies and incorporates rock mechanics, fluid flow in porous media, wellbore completion constraints, operational constraints, logistics, and economics considerations.

The performance goal of perforating gun design is the optimization of features:

- Maximized external collapse pressure resistance—Both the mechanical strength and wall thickness must be sufficient to withstand pressures between 4,000 and 27,500 psi, depending on the application.
- Maximized shaped charge performance—Internal space must be available for the largest possible shaped charge package. This in turn requires a thinner walled hollow carrier, which must have a higher strength to withstand the external pressure.
- Survivability of the hollow carrier from detonation of the shaped charges—Both high toughness and high strength are required of the hollow carrier material. Therefore, the metallurgy (chemistry, cleanliness, and heat treatment) of the steel must be carefully designed and manufactured to provide the necessary toughness properties and strength level.
- Optimal shaped charge design—Three aspects should be addressed.
  - Performance in the target reservoir—For competent rock, the primary function of the shaped charge is to create the deepest possible perforation cavity in the reservoir for the size of the shaped charge that can be used in the gun. For very weak and unconsolidated rock where sand control is required, the primary function of the shaped charge is to create the largest possible hole size in the wellbore casing for the size of the shaped charge that can be used in the gun. Regardless of the rock type, minimizing formation damage while achieving maximum performance is the desired goal.
  - Interior of the hollow carrier—The shaped charge must be designed and distributed within the hollow carrier to minimize mechanical and explosive damage to the hollow carrier while also minimizing charge-to-charge interactions within the gun that could reduce

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  performance and consistency. Because of the various geometries of the charge case, explosive, and liner, the charge-to-charge interactions vary as does the resulting damage to the gun. An optimal configuration maximizes the system performance compared with single-shot performance and causes only minimal damage to the hollow carrier.
  - Shaped charge design—Notwithstanding the other requirements, the shaped charge has to function in and of itself. It must detonate when initiated by the detonating cord. The liner must collapse to the centerline at velocities of about 4 to 5 miles/s. The liner must form into a jet with the desired mass and velocity profile for the intended application. Maximizing shaped charge performance requires careful and extensive design, modeling, manufacturing, testing, and review.

- Maximized reservoir productivity—Deep penetrating charges are used in a gun system to produce the deepest possible perforation cavities in the optimum distribution around the wellbore. A productivity-maximizing distribution of perforations can be modeled within the shot density and phasing constraints of the gun system. However, interactions between the detonating shaped charges and the shaped charge jets they form, wellbore fluids between the gun and casing, and the target reservoir can have individual or combined adverse effects on performance. These interactions must also be optimized to maximize performance.
- Minimized harmful debris from the perforating process—Shaped charges are akin to hand grenades in that they produce metal shrapnel when detonated. Whereas the objective of a hand grenade is to maximize shrapnel quantity and velocity, it is the opposite for a shaped charge: Shrapnel is bad. It creates debris that gets in the way of everything else to be done in the well. Therefore, the amount of shrapnel, or debris, that can exit the gun must be minimized.
- Minimized mechanical damage to the wellbore and completion equipment—Tall buildings are demolished with explosives in a controlled fashion to minimize damage to their surroundings. Perforating guns use explosives with the objectives of maximizing performance while creating minimum damage to their surroundings as well, but without any demolition.
- Operate as designed over long periods of time at elevated temperatures and pressures—More and more well completions require that the perforating gun string remain downhole for long periods of time before the guns are detonated, often at elevated temperatures and pressures. The explosives that are used must be stable at elevated temperatures over time, and the internal gun environment must be chemically clean.
- Effective seal design—Shaped charges require air space in front of them to function properly. If wellbore fluid leaks into a hollow carrier, the shaped charges function instead as many small bombs. Bombs do not produce jets, and all the explosive energy is transmitted to the wall of the hollow carrier, potentially causing serious damage to both the gun and wellbore. A reliable seal design and elastomers appropriate for the wellbore fluids are required.
- Fishable if the guns become stuck in the well—Things sometimes go wrong. The gun string must be fishable if the guns become stuck because of sanding, wellbore gun debris, or some other failure or operational problem. This performance requirement often limits the maximum diameter of the guns to ensure that they can be easily retrieved. This in turn limits the size of all components that would otherwise be larger toward the objective of maximizing performance.
- Mechanically sound to withstand the rigors of transportation and handling—Perforating gun components may be dropped or otherwise mishandled and therefore must be able to survive these accidents safely.
- Facilitate transportation, storage, loading, and operation—Assembly must be straightforward, robust, and account for safety issues. The completed gun assembly must also be mechanically sound to withstand the rigors of transportation, handling, and subsequent operations.
- Comply with government regulations worldwide—Schlumberger operates in more than 100 countries worldwide and must comply with all transportation, storage, and safety regulations.

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Quality control

Design and engineering procedures

Product Lifecycle Management Process

The Product Lifecycle Management Process (PLMP) consists of two distinct activities: the development of a product or service through a project, followed by support of the commercial product or service until its eventual obsolescence. The PLMP employs a framework of phases, checkpoints, and deliverables to

- ensure the timely and appropriate participation of various Schlumberger communities in the product development process
- ensure the completeness of the process, without critical errors of omission or missing steps
- provide a basis for monitoring and management through the use of a common process
- manage challenges and risks by dividing projects into incremental steps.

RapidResponse client-driven product development

To meet client needs that fall outside of the normal research and development (R&D) process, the Schlumberger RapidResponse client-driven product development system is in place for modifying existing equipment or designing new products. Although RapidResponse efforts are project specific and typically in response to an urgent request, the same high levels of engineering excellence and attention to quality are employed as on the development of other products.

Schlumberger field locations interact directly with the RapidResponse perforating and other product teams online. A product search first identifies whether an item is available, and therefore can be ordered, or if it is in the following categories:

- A similar item is available that requires minor modification.
- The product exists but requires substantial modification, or the product is nonexistant.

In either case, a comprehensive quotation is returned for use by Schlumberger operations personnel and the client to make a suitable decision.

Benefits

The RapidResponse process provides multiple benefits:

- tailor-made solutions for specific perforating needs
- fast and cost effective
- fully supported by extensive Schlumberger engineering and manufacturing expertise
- easily accessible by field personnel
- client kept fully informed.

Ballistic chain

The four components of the ballistic chain are the detonator (and optional supplemental booster), detonating cord, charge primer, and shaped charge (for more information on these components, see the “Perforating Fundamentals” chapter). To prevent a misfire, ballistic transfer must be properly performed at all component junctions of the ballistic chain.

Several aspects of hardware design address ballistic transfer concerns:

- Thick, round, grain-heavy detonating cords are used for increased reliability instead of lead-jacketed cords, such as those formerly used in the HyperDome through-tubing hollow carrier gun.

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- The manufacturing process for shaped charges includes manual placement of the primer in each shaped charge. See "Shaped charge manufacturing" in this chapter for more details.
- Ballistic transfer on long guns must be made across to adjacent guns, creating additional transfer challenges. Modern ballistic transfer subassemblies include positive-contact make-ups for adjoining strings of detonating cord equipped with boosters.
- Ballistic transfer in the trigger charge firing (TCF) head uses a small shaped charge fired by the TCF head into the booster, which terminates the detonating cord of the gun.

Field procedures also ensure the integrity of the ballistic chain:

- Specially designed detonating cord cutter—The cord cut is especially important because a poor-quality cord termination (e.g., slanted, jagged, or with loose or lost explosive powder) may fail to transmit the explosive shock wave.
- Special detonator-to-cord crimping tools and procedures—The crimp must be tight enough to resist cord shrinkage under temperature but loose enough to prevent restricting the cross-sectional area of travel for the explosive shock wave.
- Use of qualified boosters only—Boosters are critical components at high temperatures. HMX and HNS explosives for well perforating are less sensitive than RDX.
- Strict adherence to procedures—Recommended procedures must be followed in building guns, fastening the cords, avoiding unnecessary cord loops, and ensuring a clean environment.
- Recommended combinations of explosives—Recommendations must be followed to ensure that no incompatible explosives are used at any junction of the ballistic chain.

Shaped charge manufacturing

The shaped charge is the most critical gun system component to manufacture with maximum quality consistency. Shaped charges are made by assembling four components: case, main explosive pellet, primer, and liner. Each component must be manufactured to exact tolerances to ensure that the liner collapses to form the jet according to the design of the charge. For routine manufacturing production runs, each charge must perform to a minimum target penetration standard related to API RP 19B Section 1 (see "American Petroleum Institute testing of gun systems" for a detailed discussion).

Tooling

The cone dies used to press the charge liner are the most critical tooling components. Each die is made from hardened tool steel. The tools are then shaped using diamond-faced grinders, and the working surfaces are finished with diamond-impregnated compounds. The tools are heat-treated in-house for consistency.

All tools are fully traceable to support QC tracking of the day-to-day production of shaped charges. For example, manufacturing procedures put into place for PowerJet deep penetrating shaped charges have resulted in significant performance improvement in all charges.

Quality control of raw materials

Materials used in the manufacturing of shaped charges must meet stringent QC requirements:

- Steel and plastic components are cross checked directly with suppliers according to product specifications.
- A fully equipped chemistry laboratory measures each batch of explosives for purity, thermal stability, melting temperature, granulation, and bulk density.
- Each batch of liner powder is assessed for moisture content, granulation, particle size and shape, and bulk density.
- Complete entries are made in the manufacturing database to ensure that raw materials are also fully traceable. Samples of all raw materials are stored for replicating a field problem.

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Manufacturing

Schlumberger manufactures all parts of the shaped charges except the cases.

The liners are manufactured from powdered or solid metal. Powdered metal liners are made from a blended mixture of components, including a weighted mixture of several metal powders, lubricants (to help the powder flow around the shaped tools during pressing), and corrosion inhibitors. The mixture is pressed in a die body at very high loads to form a shaped cone. Solid liners are made by drawing a metal sheet over the tool and pressing it to form a shaped cone.

Shaped charges are manufactured by assembling the case (typically made of steel), primer, explosive pellet, and liner. The primer is deposited into the case and the level consistency verified. The main explosive is then poured into the case and leveled manually as a total quality measure to further ensure consistency. The explosive is pressed into the case under a very high load designed to produce a pellet of optimum density. During this operation, the liner is also pressed onto the explosive to form the finished shaped charge.

Quality control testing of shaped charges

Repeated performance measurement of manufactured shaped charges is integral to ensuring the quality of the finished product. The performance measures are total target penetration and hole size.

At the beginning of a new production run (associated with a new date-shift code), at least two charges are shot into a concrete QC target (Fig. 91). Each target is built to Schlumberger standards, including a real gun section. A water standoff is placed on the target to simulate an actual downhole shot. Targets are aged to achieve a specified compressive strength. Expected penetration in the QC target relates to API RP 19B Section 1 penetration specifications. The minimum penetration requirement for the production run is set to guarantee 90% of the Section 1 penetration specifications. Production can begin when the results of the startup shots indicate that the minimum requirement has been surpassed.

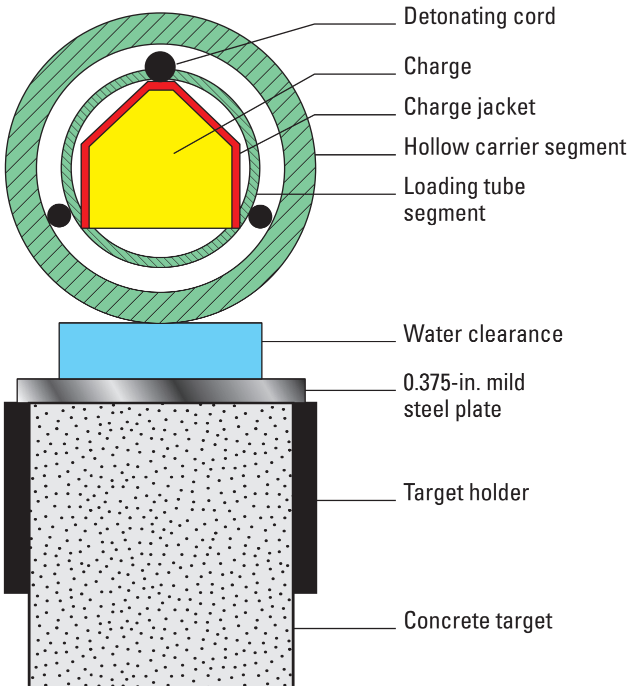

Figure 91. QC testing setup for deep penetrating and big hole charges.

Samples are selected and shot at regular intervals throughout production. Shots are conducted every 240 charges or every 120 charges for high-temperature charges. If the sample shots do not match the performance of the startup shots, the entire batch is discarded.

Additional tests are performed during manufacturing. A drop test ensures the integrity of the charge and liner. A Bruceton test verifies the sensitivity of initiation of the shaped charge versus the thickness of any potential gap between the cord and the charge. Random batches of charges are pulled from storage bunkers at set intervals and shot to determine aging effects.

Manufacturing and qualification for critical wells

Critical wells

Schlumberger has a procedure for manufacturing, qualifying, assembling, and operating equipment for use in "critical" wells. When the operator and field organization identify a critical well, SRC provides engineering support as well as full QC and traceability of the perforating components.

Examples of critical wells are as follows:

- wells with one or more of these conditions: high pressure, high temperature, long explosive exposure time prior to perforating
- wells in an environmentally sensitive area
- wells where replacing failed equipment would take considerable time
- wells being drilled and completed at an exceptional cost to the operator
- special requests by Schlumberger clients.

Quality verification and consignment

All perforating gun and firing head hardware, explosives, and components required for the critical well are listed and quantities are determined.

To verify hardware quality, all components are traced to the raw materials, and the raw materials are checked against specifications. A critical well quality file is opened for the specific well to record dimensions that typically include the following measured parameters:

- verification of critical dimensions, measured on the manufactured equipment, to ensure that they are completely within tolerance
- sealbore ends of hollow carriers
- diameters of all O-ring grooves
- diameters of all extrusion-resistant edges of O-rings
- important, but noncritical, reference dimensions.

To verify the quality of explosives, all explosive components are traced to the raw materials. The raw material certifications are compared with the specifications and verified, and then recorded in the critical well file along with inspection and performance datasheets. The following items are specific concerns in quality verification:

- Detonating cord—Cords are X-rayed to certify that they are free of flaws, and the films are kept on record.
- Boosters—Each booster in a designated lot is individually numbered, measured, and recorded. Sample boosters of varying dimensions are test fired to ensure adequate ballistic transfer for the selected boosters in all density categories. Only if a selected lot passes all tests is it qualified for the critical well.
- Shaped charges—Production datasheets (which include QC testing) are reviewed. A small quantity of charges may be stored for future reference at the client's request.
- Detonators—All detonators undergo review, inspection, traceability, and qualification testing.

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Firing head components are inspected completely. Functional tests can also be performed (e.g., to measure the delay time of firing head orifices under actual environmental conditions).

Quality verification of elastomers and plastic components is performed at the expected environmental and operating conditions.

Failure to meet requirements for dimensions, specifications, or testing is the criterion for rejecting a component. SRC allows exceptions only when they are approved by the operator's representative as required.

Both the operator and SRC audit the quality verification steps described here. When the quality verification is approved, consignment of the equipment can take place. The equipment is consigned with the documentation gathered in the critical well file during the quality verification phase.

Preparation and assembly at location

Both the local Schlumberger manager and the designated operator's representative supervise the following steps:

1. Clear all critical well work areas of components not associated with the well.
2. Identify all critical well components and verify against the quality file and other relevant documentation.
3. Jointly qualify field personnel.
4. Perform all assemblies according to instructions in the field operations manuals, under SRC supervision, or both.
5. Repackage and seal leftover explosives for future reference.

American Petroleum Institute testing of gun systems

In September 2006, the API published the 2nd Edition of API RP 19B, *Recommended Practices for Evaluation of Well Perforators*. Since 1962, API RPs have been the industry standard for testing and evaluating perforating systems. API publications remain in effect for a maximum of 7 years, so the previous standard, RP 43 (5th Edition), which was published in January 1991, ceased to be in effect as an operative API standard in January 1997. RP 19B 1st Edition was published in November 2000, and the 2nd Edition provides necessary updates and several improvements to allow its continued use into the future.

In addition, on April 1, 2001, the API instituted its significant new API Perforator System Registration Program. The program establishes a procedure by which an API representative, trained by the manufacturers of shaped charges, is present to witness all critical phases of the RP 19B Section 1 test. The API maintains a list of all registered tests as well as copies of the witness reports for the tests. Schlumberger was instrumental in getting the witness program implemented toward the goal of reestablishing much of the credibility of the Section 1 test.

RP 19B 2nd Edition has four sections, each describing a specific test procedure:

- Section 1—Evaluation of Perforating Systems Under Surface Conditions, Concrete Targets
- Section 2—Evaluation of Perforators Under Stress Conditions, Berea Targets
- Section 3—Evaluation of Perforator Systems at Elevated Temperature Conditions, Steel Targets
- Section 4—Evaluation of Perforation Flow Performance Under Simulated Downhole Conditions
- Section 5—Debris Collection Procedure for Perforating Guns.

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Section 1—Evaluation of Perforating Systems Under Surface Conditions, Concrete Targets

The Section 1 test is a system test of the complete gun in an actual downhole configuration, including the charges at the shot density and phasing specified for the gun system. The changes in RP 19B from RP 43 are in this section. As before, the target is concrete of 5,000-psi compressive strength. However, the aggregate used in the concrete was changed from ASTM International (formerly the American Society for Testing and Materials) C-33 sand to API 16–30 frac sand. This change provides much tighter control on the aggregate size, shape, and mineralogy, which results in a more repeatable target.

Other changes include increasing the water/cement ratio from 0.50 to 0.52 (owing to the required "dry" nature of API frac sand) and more specific procedures on how the compressive strength specimens (briquettes) are prepared and tested. Total penetration depth, casing hole diameter, and burr height are measured and recorded. Figure 92 shows the API Section 1 test setup and target.

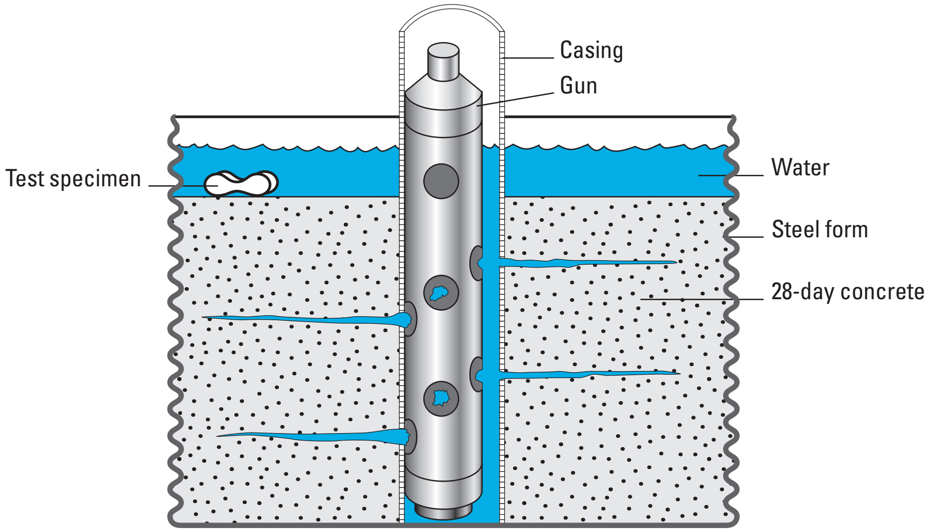

Figure 92. Setup for Section 1 test (RP 19B).

The Section 1 test is performed at surface temperature and pressure using standard field equipment. The gun is shot positioned in the casing as it would be in an actual well to best evaluate performance variations resulting from the gun-to-casing clearance. The minimum quantity production run for the charge is 1,000 (300 for high-temperature explosives). At least 12 charges or 1 ft fully loaded at the specified shot density, whichever provides more shots, is tested. The charges must have been aged 28 days to test for possible aging effects.

The Perforator System Registration Program requires the representative witness to observe and record the following items for registration of an RP 19B Section 1 test with the API:

1. Charge selection from the required minimum lot size
2. Gun loading, including gun description and verification of its status as standard field equipment
3. Gun firing and data collection, including samples of the target concrete and the casing used in the target and concrete slurry information
4. Review of production QC data and QC shots of witness-selected charges

Optional activities to witness are target pouring and briquette preparation and testing.

Section 2—Evaluation of Perforators Under Stress Conditions, Berea Targets

The purpose of the Section 2 test is to simulate actual downhole conditions by testing charges in a target of Berea sandstone stressed at 3,000 psi with simulated wellbore pressure applied. The setup for the test is shown in Fig. 93.

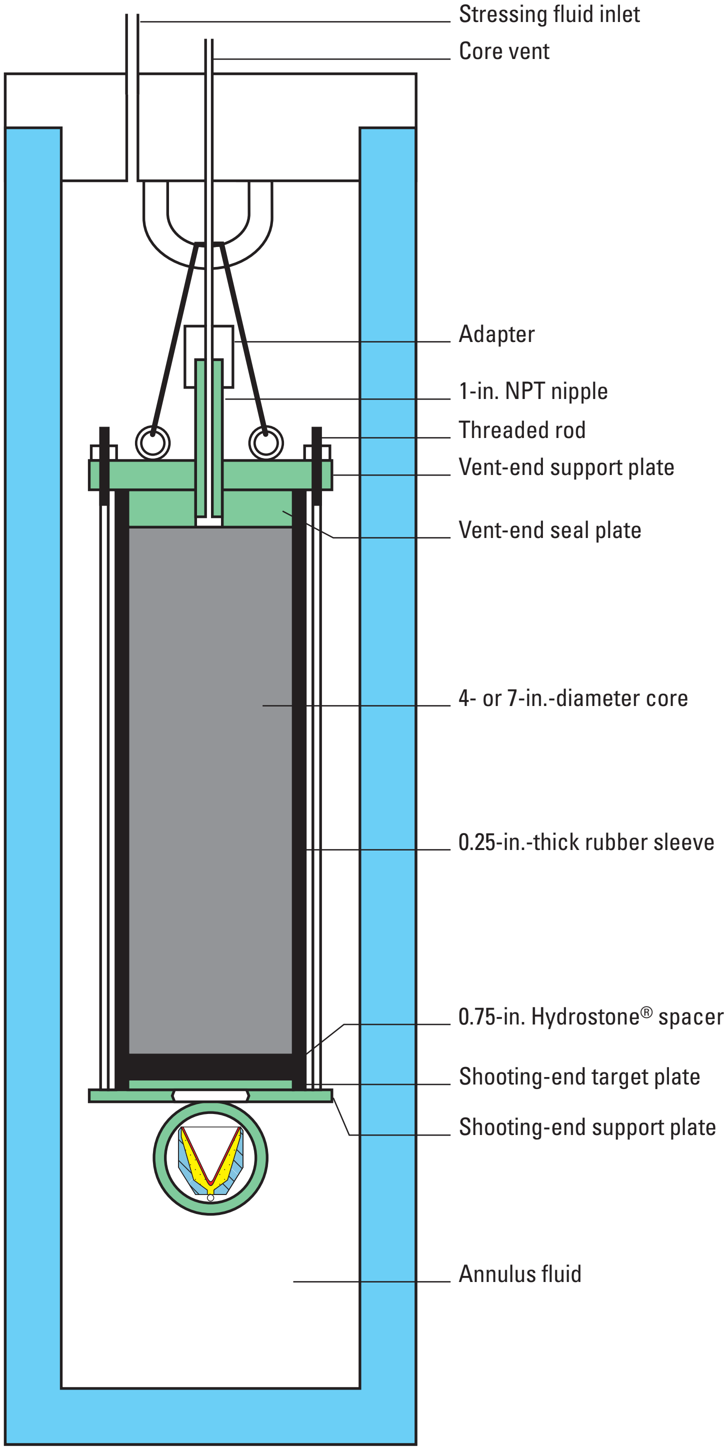

Figure 93. Setup for Section 2 test (RP 19B).

The Berea core diameter is 4 in. for charges of 15 g or less and 7 in. for charges exceeding 15 g. Only deep penetrating charges of less than 600 grains [38.9 g] of explosive are allowed. The core is dried and then vacuum-saturated with a 3% brine solution. The target and single-shot perforating gun section are placed in a pressure vessel that simulates the 3,000-psi confining stress. A minimum of three shots are fired at ambient temperature. Penetration and entrance hole size are measured and recorded.

There are no provisions for the registration of Section 2 tests.

Section 3—Evaluation of Perforator Systems at Elevated Temperature Conditions, Steel Targets

The Section 3 high-temperature test is a separate verification of the pressure integrity of the entire gun system at the rated pressure, temperature, and time. No explosives are required for the pressure test. At least six charges are loaded in the gun and ASTM International A-36 steel targets are mounted around the gun. The entire gun system, including any associated hardware to be included in the rated system, is heated to and maintained at the rated temperature for a specified time and then fired at temperature. Penetration and entrance hole performance are compared with the performance of an identically loaded gun tested at ambient temperature using similar targets. For TCP systems, at least one detonation transfer must be demonstrated. The setup for this test is shown in Fig. 94.

There are no provisions for the registration of Section 3 tests.

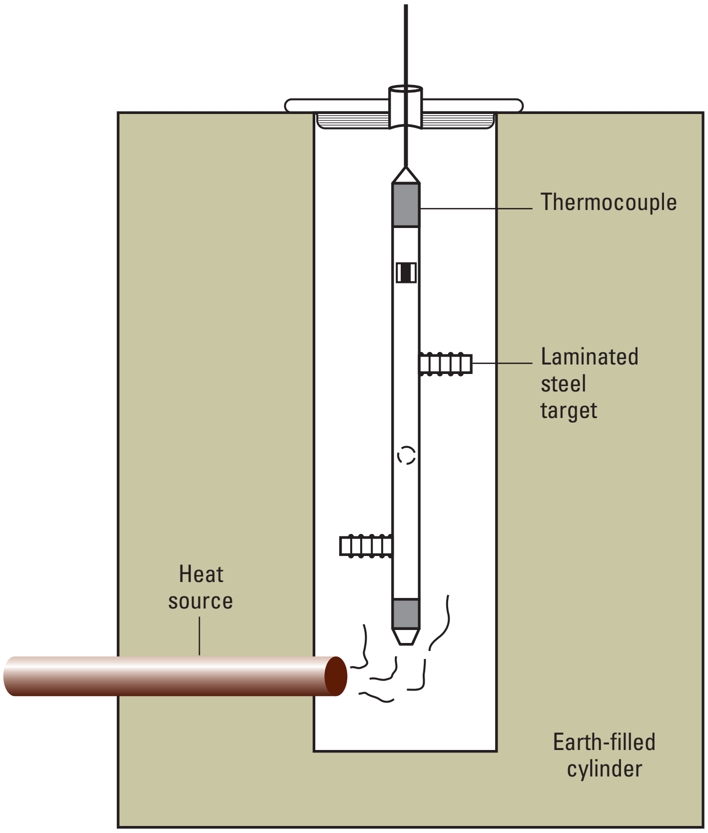

Figure 94. Setup for Section 3 test (RP 19B).

Section 4—Evaluation of Perforation Flow Performance Under Simulated Downhole Conditions

The Section 4 tests are optional for determining perforation flow performance based on flow rate data and characteristics of the perforation and core. Figure 95 illustrates the setup for a Section 4 test.

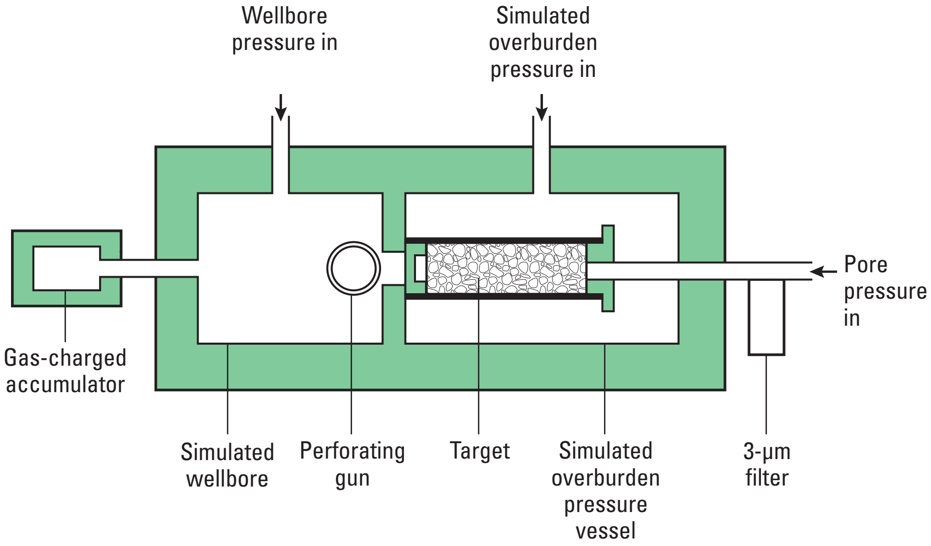

Figure 95. Setup for Section 4 test (RP 19B).

Several tests are performed on single-shot perforations fired in a confining pressure vessel that contains a cylindrical quarry sample or well core equipped with the following elements:

- face plate to simulate the casing
- flexible jacket to transmit the simulated overburden stress to the core
- provisions to apply pore fluid pressure to the core boundaries (the flow system).

Pore fluid pressure may be applied to the cylindrical sides of the core (radial flow), unperforated end of the core (axial flow), or both the sides and end in a manner simulating in situ pore pressure fields. A second pressure vessel simulating the wellbore contains the single-shot gun system.

There are no provisions for the registration of Section 4 tests.

Section 5—Debris Collection Procedure for Perforating Guns

The Section 5 test for hollow carrier and capsule guns was introduced in the 2nd Edition of RP 19B. The test quantifies the debris that comes out of a perforating gun upon detonation. It also identifies any debris that remains in a hollow carrier gun and could come out of the gun as it is retrieved from the well. The test is only for comparing gun systems and is not to be used to determine the amount of debris that will be left in a wellbore.

Standard field equipment is used for the test, with the entire gun fully loaded to maximum shot density, including a minimum continuous linear 2.5 ft of perforations. The Section 1 test setup is used with hollow carrier guns restrained to stay inside and in a vertical position in the water-filled casing. For testing capsule guns, a closed pressure vessel pressurized to 5,000 psi is used. The produced solid debris is collected and characterized for weight, volume, sieve size, and type of material.

There are no provisions for the registration of Section 5 tests.

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Perforator performance

Perforator performance in downhole environments is critical to successful well completion. Although the API tests provide a basis for comparing the performance of perforators in downhole conditions, no analytical criteria are available to translate the performance data into in situ conditions at the wellbore. Thus, using API test results requires caution and careful consideration. For example, API tests are supposed to be conducted using standard manufacturing batches of charges. However, tests performed on charges that are specially manufactured for API testing may not represent average charge performance. Section 1 tests, often the only ones available, are performed in concrete. The penetration depths, therefore, do not necessarily represent downhole penetration depths in actual formations. Finally, environmental parameters affect a perforator's penetration in downhole conditions (e.g., rock strength, formation stress, temperature, pressure, and gun position at the time of perforating).

API makes decisions in consultation with the oil and gas industry. It does not function as a detached group of experts that issues directives, but takes advice and input from service companies, oil and gas operators, and scientific and technical organizations. For this reason, the established API procedures balance industry objectives, state-of-the-art technology, and the influence of service providers.

The new Registration Program undoubtedly improves the credibility of the Section 1 test. Operators know that registered tests were conducted following proper procedures and that an API-assigned representative witnessed and verified the reported data. Further development of the quality programs associated with the engineering and manufacturing of perforating systems is next. The Registration Program provides a credible "snapshot" in time for a system and a particular lot of charges. Confidence in the quality of ongoing production remains an important objective.

The following three chapters list perforating gun performance and specification summaries including current API RP 19B and RP 43 test data.

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Capsule Gun Perforating Systems

Introduction to exposed guns

Capsule guns—also called “capsule-charge guns”—are exposed gun systems, with the individual shaped charges sealed in pressure-tight capsules mounted on a carrier strip or links that are exposed to the well environment.

Capsule guns are typically used in through-tubing perforation applications and generate superior performance compared with hollow carrier guns of the same diameter. Schlumberger capsule guns are developed through an extensive engineering and manufacturing program. They are holistically designed as a system, comprising the carrier strips or links, charges, and detonating cords, to provide maximum perforator performance. The entire capsule gun system is then manufactured following rigorous Schlumberger quality assurance (QA) standards.

The capsule guns described in this chapter are designed for use on an electric wireline cable, although some of the systems can also be run on slickline. There are two designs of capsule guns: *expendable* (the charges and mounting assembly are left as debris after firing) and *retrievable* (debris is left, but the mounting is recovered). The latter design is also called *semiexpendable*. Some of the capsule gun systems have a selectivity option that allows shooting more than one zone per run.

The capsule charges are designed to withstand extreme downhole pressures and temperatures and hostile fluids. Every charge is manufactured through a rigorous QC program to ensure the highest mechanical reliability possible. Multiple checks of each charge verify that there is no pressure leakage. Because the capsule is exposed to the well environment, its rugged packaging is made to withstand continuous vibration and mechanical impact so that charges can perform as designed when the bottom of the well is reached.

The retrievable carrier strips, which convey the charges, are also a major engineering challenge. The carrier strips must withstand the explosion and stay relatively straight so that they can reenter the tubing after the gun is shot. They must also be able to handle the mechanical impact that occurs when conveying the guns downhole.

The entire carrier strip and capsule-charge design is optimized to maximize performance, yet maintain reliability. Increasing the thickness of the carrier strip enhances its mechanical integrity but reduces the size of the charge, which limits the performance of the charge. Schlumberger engineers have optimized the design of the carrier strips and capsule charges so that the charges provide the best performance in the industry and are the most reliable system available.

Because loaded capsule guns contain only secondary high explosives (detonating cord, boosters, and charges), they are safe to transport and handle following standard Schlumberger safety procedures.

Figure 96 illustrates capsule gun terminology. Capsule gun specifications are defined as follows:

- gun size—nominal OD (in.)
- gun phasing—azimuthal distance between charges (°)
- shot density—number of charges per unit length (1 ft) of gun
- shot spacing—longitudinal distance (in.) between shots.

Following the introductory material in this chapter are gun selection guidelines, gun datasheets, and a summary listing of capsule gun performance and mechanical data.

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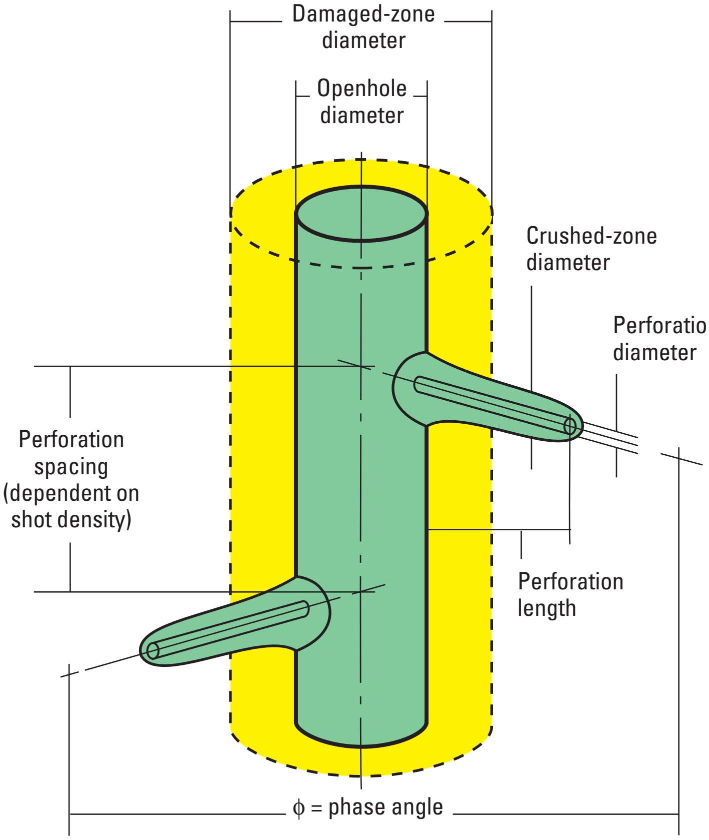

Phased Enerjet Gun

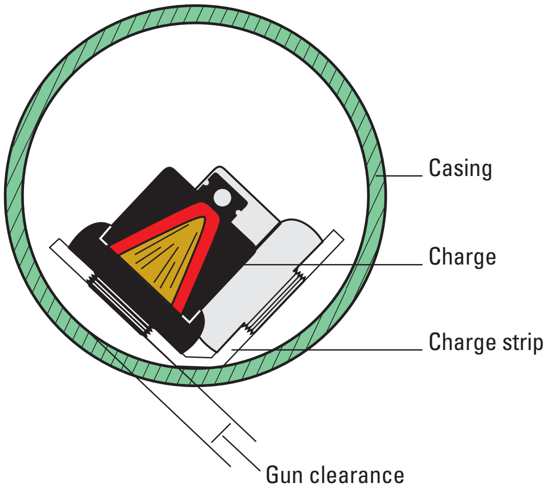

Figure 96. Capsule gun system terminology.

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Capsule gun selection

Selecting the most appropriate capsule gun depends on numerous factors:

- productivity ratio
- ID of nipples and valves in the downhole assembly
- bottomhole pressure and temperature
- sensitivity to perforating debris
- borehole fluid
- shot phasing and density
- deviation and doglegs.

Because productivity is a function of penetration, entrance hole, phasing, and shot density, it may not be a straightforward procedure to determine which capsule gun system will perform best. SPAN Schlumberger perforating analysis is a useful computer simulation program for comparing the well productivity of various systems (see “SPAN perforating analysis” in the “Reservoir Completion Types” chapter).

The PowerSpiral capsule perforating system is the Enerjet expendable-strip gun system of choice. As subsequently discussed in the PowerSpiral datasheet, the PowerSpiral system features the technological breakthrough of shock-absorbing material between the charges. The material attenuates shock waves generated during detonation, which reduces charge-to-charge interference as well as minimizes shock waves in the wellbore (Figs. 97 and 98). This significantly increases the performance of cross-wellbore shots. With its multiple phasing, high shot densities, and use of Power Enerjet* charges, the PowerSpiral Enerjet system is capable of achieving the highest well productivity in the industry. In addition, the shock-absorbing material virtually disappears after the detonation, leaving a negligible amount of environmentally friendly debris in the well.

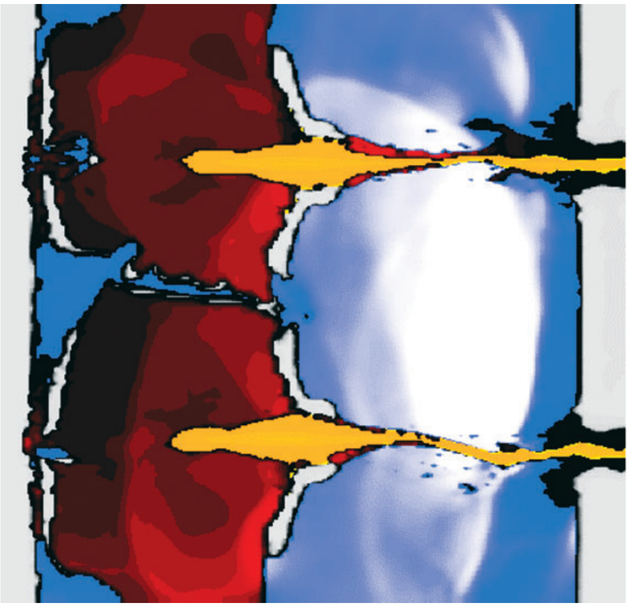

Figure 97. A computer simulation of two capsule shaped charges shot in a liquid-filled borehole demonstrates the decrease in performance that typically occurs from the complex shock effects resulting from interference between the pressure waves formed by the jets. The white area between the two jets is a region of high pressure. At 45 μs after detonation (the top charge was detonated first), the pressure front has collapsed the cavities, partially interrupted the top jet, and severely damaged the bottom jet.

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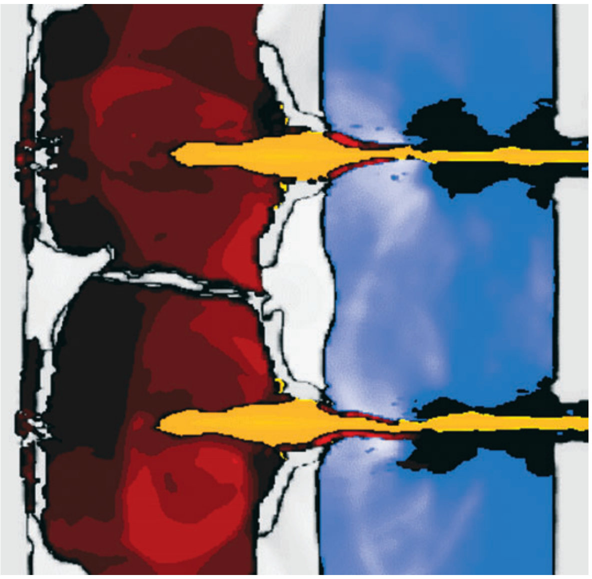

Figure 98. The same computer simulation as in Fig. 97 conducted with PowerSpiral shock-absorbing material between the capsule shaped charges. With the reduction of charge-to-charge interference both jets remain straight at 45 μs after detonation and the liquid has no noticeable effect on the jets.

Table 21 is a productivity comparison of the 2⅛-in. Enerjet systems.

The minimum restriction of the downhole assembly is usually the primary limiting factor. In general, the largest gun that can be accommodated by restrictions in the well should be used. Penetration depth and entrance hole size usually increase with gun size. Big hole charges are also available for some capsule gun systems.

The next factor to consider in choosing a capsule gun is the bottomhole pressure. If a gun is run beyond its pressure rating, the capsule may collapse, causing autodetonation and possible damage to the well.

Bottomhole temperature is a similarly critical consideration. Capsule guns using carrier strips with RDX explosives are rated at 330°F [165°C] for 1 hr. However, for high-temperature operations, all guns are available with HMX explosives, and some have optional HNS explosives for very high temperature wells.

Table 21. Enerjet Systems Productivity Comparison[†]

2⅛-in. Enerjet System	Productivity Ratio	
	No-Damage Zone	Moderate-Damage Zone
PowerSpiral, 6 spf	1.096	0.818
0°-phased retrievable Enerjet, 6 spf	1.009	0.803
Biphased (±45°) retrievable Enerjet, 6 spf	1.094	0.795
Spiral-phased expendable Enerjet, 4 spf	1.032	0.715

[†] Based on SPAN calculation for 5½-in. 17-lbm/ft casing

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Capsule guns generate debris that remains in the well, and the sensitivity of the completion to this debris should be considered. Schlumberger capsule guns are available in partially retrievable and nonretrievable (expendable) versions. With a retrievable Enerjet gun system, the carrier strip is retrieved, although charge case debris remains in the well. The PowerSpiral system also has a retrievable carrier strip. Table 22 compares the capsule gun systems by debris (amount of fill left downhole) and robustness (ability to withstand buckling); although capsule guns carry high-performance charges and substantially outperform hollow carrier guns of the same size, they are not as rugged as hollow carrier guns because the charges, detonating cord, and detonators are exposed to the well environment. For details on the debris fill generated, see summary Table 39 at the end of this chapter.

Table 22. Capsule Gun System Comparison by Debris and Robustness

	Retrievable or Expendable	Debris	Robustness
PowerSpiral	Retrievable	Very good	Good
0°-phased Enerjet	Retrievable	Excellent	Very good
Biphased Enerjet	Retrievable	Very good	Good
Spiral Enerjet	Expendable	Good	Fair
Pivot Gun	Expendable	Fair	Fair

The Pivot Gun system is a high-performance nonretrievable capsule gun. Its penetration performance is equal to or better than that of most hollow carrier guns, yet it is small enough to run through 2⅜-in. tubing. Upon firing, the entire gun (except the deployment head) breaks into small pieces and falls to the bottom of the well.

Hostile chemicals such as H_2S, acids, and bromides can attack capsule guns and make them inoperable. Special precautions that can be taken are coating the gun with insulating varnish and using selected detonating cord and detonators. For hostile chemicals with concentrations of 30% or more in the borehole fluid, using hollow carrier gun systems is recommended.

Phasing and shot density are parameters that affect productivity. Retrievable Enerjet systems are available with 0°, biphase (±45°), and spiral (45°) phasing. Expendable Enerjet systems are available with 0°, triphase (0°, ±45°), and continuous spiral (45° or 60°) phasing. Increasing the phase angle from 0° to 60°, 90°, or 180° increases productivity according to various studies and field practice (see the “Productivity and Skin Effect” chapter for details). When small capsule guns are shot in large casings, the effect of the gun-to-casing clearance may reduce penetration and negate the productivity improvement of phasing. In such cases, 0° (or for the Pivot Gun system, 180°) phasing is preferred. Increasing the shot density also improves productivity, as described in “Reservoir Completion Types.”

Well deviation is another consideration. Guidelines on maximum lengths and diameters for different dogleg angles are in the “Operating Environment and Engineering of Perforating Operations” chapter. For deviations beyond 60° to 70°, coiled tubing, tractor conveyance, or a TCP technique with a hollow carrier gun system should be used.

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Precautions and considerations

Wireline capsule guns are often run with wellhead pressure control equipment. The lubricator must never be pressure tested with an armed perforating gun inside. A pressure leak in the gun or detonator could result in gun detonation.

Additional considerations in selecting these exposed gun systems are as follows:

- The casing or tubing where the capsule gun is being shot should be fully supported. Unsupported or poorly cemented casing may split when the gun is detonated. This is more likely to occur in liquid-filled casing. In dry gas environments, the risk of splitting is reduced.
- If debris generation is a problem, the retrievable Enerjet gun systems (PowerSpiral and 0°-phased and biphased retrievable guns) leave less debris in the well compared with the expendable systems. Generally, the debris fill of a given Enerjet gun is larger when it is shot in liquid compared with in dry gas.
- Casing diameter is also a consideration. As a general rule, the casing diameter should be at least twice the size of the capsule gun. If perforating operations are in supported tubing or a liner that is less than twice the diameter of the gun, either the expendable Enerjet system or a drop-off system with a retrievable Enerjet system should be used with no expectation of retrieving the gun. In either case, the toolstring can be retrieved, but the problem of bridging the pipe may be an issue. The 0°-phased systems are the best option in large-diameter casing such as 9⅝ in. because shots across casing have significantly reduced performance.

Capsule gun datasheets

The following datasheets provide a succinct summary of Schlumberger capsule guns. For special applications, contact your Schlumberger representative about other phasings and shot densities that can be made on request.

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PowerSpiral Gun System

The PowerSpiral gun system (available in 1¹¹⁄₁₆-, 2⅛-, and 2½-in. sizes) is a retrievable capsule perforating gun designed for through-tubing wireline operations (Fig. 99 and Table 23). This spiral-phased (Fig. 100) system incorporates the technological breakthrough of shock-absorbing material located between the charges. The material attenuates shock waves during the detonation, which reduces charge-to-charge interference as well as minimizes shock waves in the wellbore. The result is significantly increased performance of shots across the wellbore (Table 24). PowerSpiral features such as multiple phasing, high shot density, and use of PowerJet charges enable the PowerSpiral system to generate perforations capable of the highest well productivity for its size.

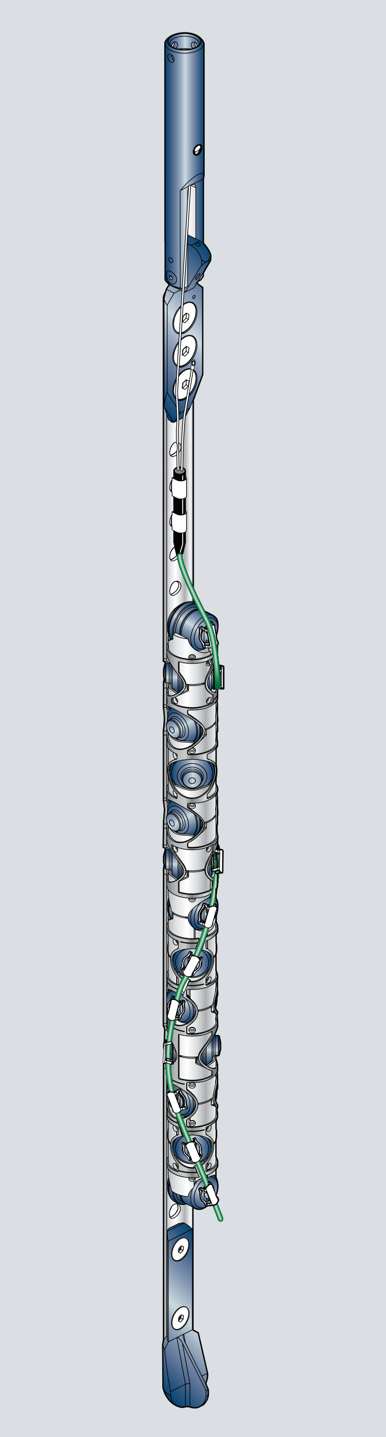

Figure 99. PowerSpiral gun system.

Applications

- Through tubing
- Deep penetration
- Rigless perforation or reperforation

Table 23. PowerSpiral Mechanical Specifications

Outside diameter (in.)	1¹¹⁄₁₆	2⅛	2½
Shot density (spf)	7.5	6	5
Phasing† (°)	45	45	45
Temperature rating, 1 hr (°F [°C])	HMX: 365 [185]	HMX: 365 [185]	HMX: 365 [185]
Pressure rating (psi)	20,000	15,000	15,000
Min. casing size (in.)	4	4½	4½
Min. restriction (in.)	1.78	2.25	2.62
Max. gun length (ft)	30	30	30
Debris fill per charge (in./ft)			
4½-in. casing	0.14	0.08	0.88
5½-in. casing	0.09	0.12	0.59
7-in. casing	0.06	0.07	0.38
Max. tensile strength‡ (lbf)	8,000	12,000	18,000

† Spiral phasing
‡ Pull strength of the gun strip

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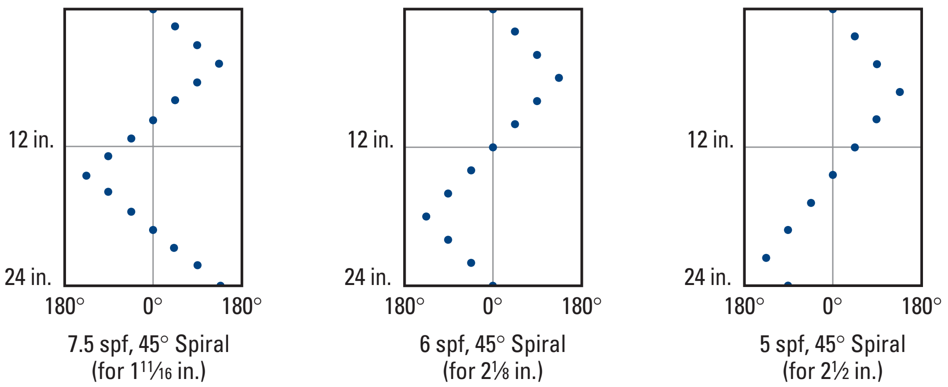

Figure 100. PowerSpiral shot patterns in 5½-in. casing.

Table 24. PowerSpiral Performance Summary[†]

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
1¹¹⁄₁₆-in. PowerSpiral	7.5, 45	PowerSpiral, HMX	19.5	0.22	0.06/0.10	4½, 11.6
2⅛-in. PowerSpiral	6, 45	PowerSpiral, HMX	27.2	0.32	0.08/0.11	5½, 17.0
2½-in. PowerSpiral	5, 45	PowerSpiral, HMX	36.6	0.39	0.07/0.11	5½, 17.0

[†] Blue type identifies API 19B Registered Perforation Systems.

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1.63-in. Retrievable Enerjet Gun

The 1.63-in. retrievable Enerjet gun, designed for a 1.71-in. nipple, is a high-performance exposed capsule gun suitable for through-tubing operations (Figs. 101 and 102 and Tables 25 and 26). Rig-up is easy with the articulated head. When the gun is fired, the charge cases shatter to leave the carrier strip, charge caps, head, and other accessories intact for retrieval. The retained caps are useful for individual shot verification.

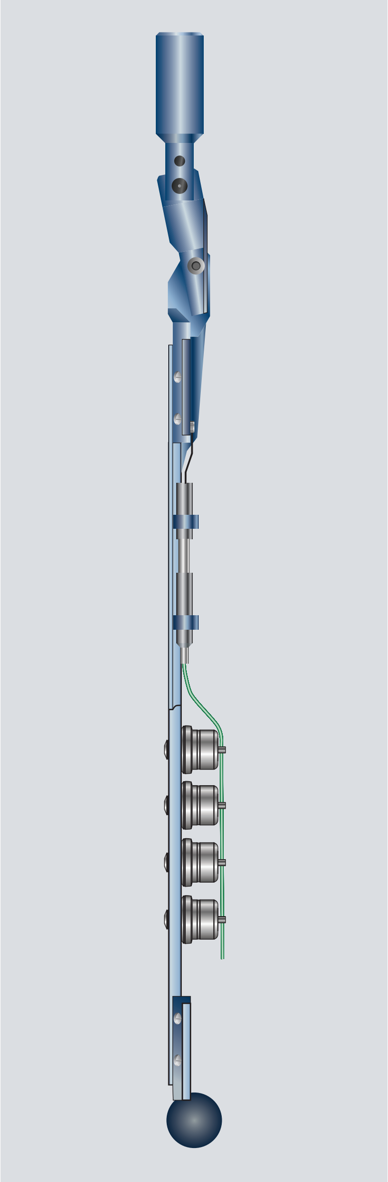

Figure 101. 1.63-in. retrievable Enerjet gun.

Applications

- Through tubing
- Deep penetration
- Rigless perforation or reperforation

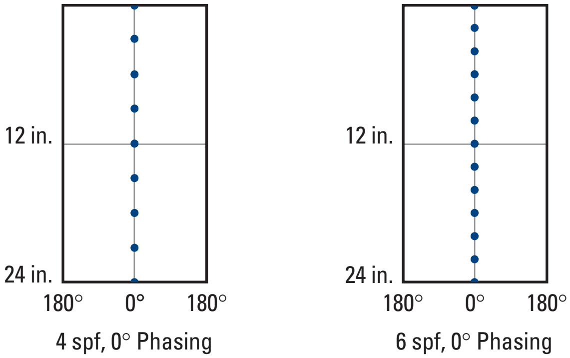

Figure 102. 1.63-in. retrievable Enerjet shot patterns in 4½-in. casing.

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Table 25. 1.63-in. Retrievable Enerjet Mechanical Specifications

Outside diameter (in.)	1.63
Shot density (spf)	4 or 6
Phasing (°)	0
Temperature rating, 1 hr (°F [°C])	RDX: 330 [165] HMX: 365 [185]
Pressure rating (psi)	20,000
Min. casing size (in.)	4
Min. restriction (in.)	1.71
Max. gun length (ft)	50
Debris fill per charge (in./ft)	
4½-in. casing	0.13
5½-in. casing	0.08
7-in. casing	0.06
Max. tensile strength† (lbf)	10,000

† Pull strength of the gun strip

Table 26. 1.63-in. Retrievable Enerjet Performance Summary†

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
1.63-in. retrievable Enerjet	4, 0	Enerjet, RDX	18.0	0.28	0.03/0.05	4½, 11.6
1.63-in. retrievable Enerjet	4, 0	Enerjet, HMX	17.8	0.29	0.03/0.06	4½, 11.6

† API RP 43 5th edition or API 19B Section 1

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1¹¹⁄₁₆-in. Retrievable Enerjet Gun

The 1¹¹⁄₁₆-in. retrievable Enerjet gun is a high-performance exposed capsule gun suitable for through-tubing operations (Figs. 103 and 104). Continuous spiral phasing is available (Tables 27 and 28). When the gun is fired, the charge cases shatter to leave the carrier strip, charge caps, head, and other accessories intact for retrieval. The retained caps facilitate individual shot verification.

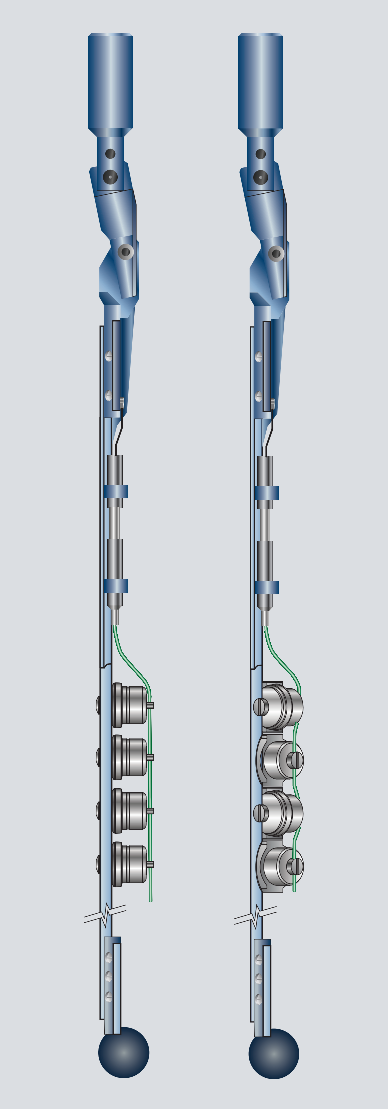

Figure 103. 1¹¹⁄₁₆-in. retrievable Enerjet gun.

Applications

- Through tubing
- Deep penetration
- Rigless perforation or reperforation

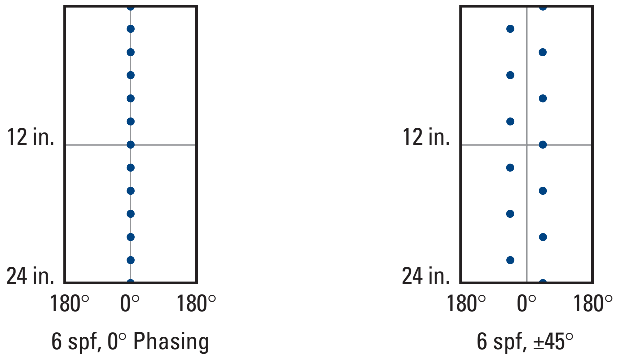

Figure 104. 1¹¹⁄₁₆-in. retrievable Enerjet shot patterns in 4½-in. casing.

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Table 27. 1¹¹⁄₁₆-in. Retrievable Enerjet Mechanical Specifications

	0° Phased	High-Temperature 0° Phased	Biphased
Outside diameter (in.)	1¹¹⁄₁₆	1¹¹⁄₁₆	1¹¹⁄₁₆
Shot density (spf)	6	6	6
Phasing (°)	0	0	±45
Temperature rating, 1 hr (°F [°C])	HMX: 365 [185]	HNS: 450 [232]	HMX: 365 [185]
Pressure rating (psi)	20,000	20,000	20,000
Min. casing size (in.)	4	4	4
Min. restriction (in.)	1.78	1.78	1.78
Max. gun length (ft)	50	20	35
Debris fill per charge (in./ft)			
4½-in. casing	0.13	0.13	0.16
5½-in. casing	0.08	0.08	0.10
7-in. casing	0.06	0.06	0.07
Max. tensile strength[†] (lbf)	10,000	10,000	9,000

[†] Pull strength of the gun strip

Table 28. 1¹¹⁄₁₆-in. Retrievable Enerjet Performance Summary[†]

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
1¹¹⁄₁₆-in. retrievable Power Enerjet	6, 0	Power Enerjet, HMX	21.6	0.20	0.01/0.03	4½, 11.6
1¹¹⁄₁₆-in. biphased retrievable Power Enerjet	6, ±45	Phased Power Enerjet, HMX	14.6	0.26	0.05/0.08	4½, 11.6

[†] API RP 43 5th edition or API 19B Section 1

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2⅛-in. Retrievable Enerjet Gun

The 2⅛-in. retrievable Enerjet gun is a high-performance exposed capsule gun suitable for through-tubing operations (Figs. 105 and 106 and Tables 29 and 30). When the gun is fired, the charge cases shatter to leave the carrier strip, charge caps, head, and other accessories intact for retrieval. The retained caps facilitate individual shot verification.

Applications

- Through tubing
- Deep penetration
- Rigless perforation or reperforation

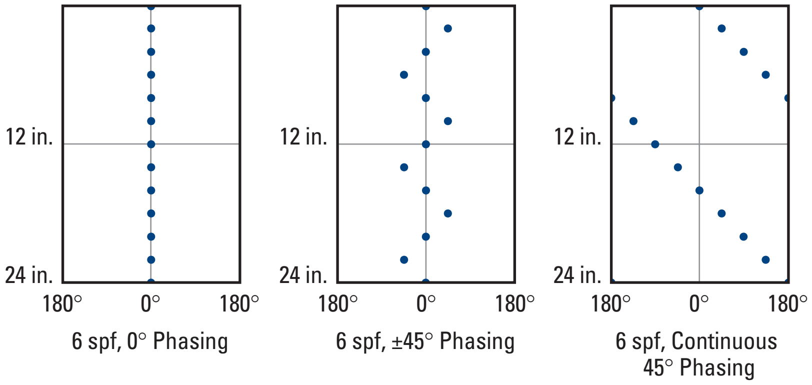

Figure 106. 2⅛-in. retrievable Enerjet shot patterns in 5½-in. casing.

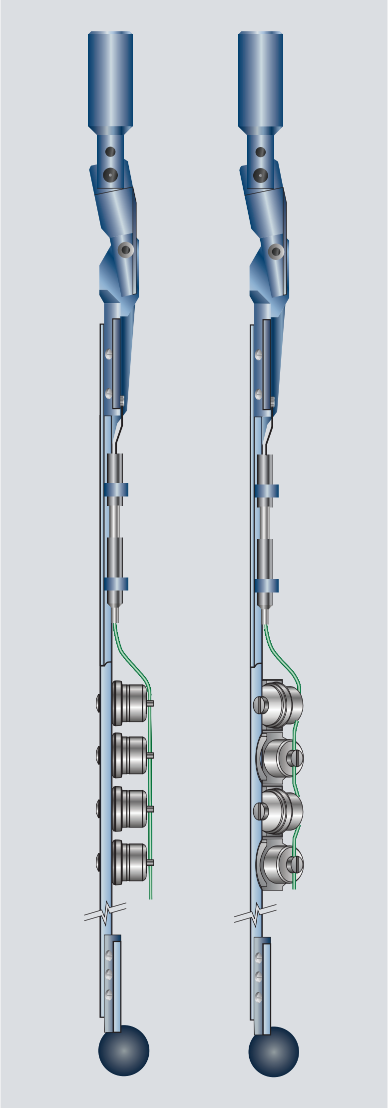

Figure 105. 2⅛-in. retrievable Enerjet gun.

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Table 29. 2⅛-in. Retrievable Enerjet Mechanical Specifications

	0° Phased	High-Temperature 0° Phased	Biphased
Outside diameter (in.)	2⅛	2⅛	2⅛
Shot density (spf)	4	4	6
Phasing (°)	0	0	±45
Temperature rating, 1 hr (°F [°C])	RDX: 330 [165] HMX: 365 [185]	HNS: 450 [232]	RDX: 330 [165] HMX: 365 [185]
Pressure rating (psi)	20,000	20,000	15,000
Min. casing size (in.)	4½	4½	4½
Min. restriction (in.)	2.25	2.25	2.25
Max. gun length (ft)	50	20	35
Debris fill per charge (in./ft)			
4½-in. casing	0.16	0.16	0.19
5½-in. casing	0.10	0.10	0.13
7-in. casing	0.07	0.07	0.08
Max. tensile strength† (lbf)	15,000	15,000	15,000

† Pull strength of the gun strip

Table 30. 2⅛-in. Retrievable Enerjet Performance Summary†

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^{2}/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
2⅛-in. retrievable Enerjet	4, 0	Enerjet, RDX	21.9	0.31	–	0.02/0.03	5½, 17.0
2⅛-in. retrievable EnerjetExpress*	6, 0	EnerjetExpress, RDX	21.2	0.34	–	0.05/0.07	5½, 17.0
2⅛-in. retrievable EnerjetExpress	6, 0	EnerjetExpress, HMX	23.5	0.34	–	0.05/0.07	5½, 17.0
2⅛-in. retrievable Power Enerjet	6, 0	Power Enerjet, HMX	30.4	0.32	–	0.06/0.08	5½, 17.0
2⅛-in. retrievable big hole Enerjet	4, 0	Enerjet Big Hole, RDX	10.0	0.57	1.02	0.08/0/10	5½, 17.0
2⅛-in. retrievable big hole Enerjet	4, 0	Enerjet Big Hole, HMX	10.5	0.51	0.82	0.05/0/07	5½, 17.0
2⅛-in. retrievable big hole Enerjet	6, ±45	Enerjet Big Hole, HMX	7.9	0.49	1.13	0.04/0/07	4½, 11.6

† API RP 43 5th edition or API 19B Section 1; blue type identifies API 19B Registered Perforation Systems.

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1¹¹⁄₁₆-in. Expendable Enerjet Gun

The 1¹¹⁄₁₆-in. expendable Enerjet gun is a high-performance exposed capsule gun suitable for through-tubing operations (Fig. 107 and Tables 31 and 32). Zero phase, triphase, and continuous spiral options are available (Fig. 108). When the gun is fired, the charge cases, charge caps, and carrier strip shatter to reduce the risk of getting stuck after perforating. The head and other accessories remain intact for retrieval.

Applications

- Through tubing
- Deep penetration
- Rigless perforation or reperforation
- Debris-insensitive operations

Table 31. 1¹¹⁄₁₆-in. Expendable Enerjet Mechanical Specifications

Outside diameter	1¹¹⁄₁₆ in.
Shot density (spf)	6
Phasing (°)	0, 45, 0 ± 45
Temperature rating, 1 hr (°F [°C])	HMX: 365 [185]
Pressure rating (psi)	20,000
Min. casing size (in.)	4
Min. restriction (in.)	1.78
Max. gun length (ft)	30
Debris fill per charge (in./ft)	
4½-in. casing	0.18
5½-in. casing	0.12
7-in. casing	0.08
Max. tensile strength† (lbf)	9,000

† Pull strength of the gun strip

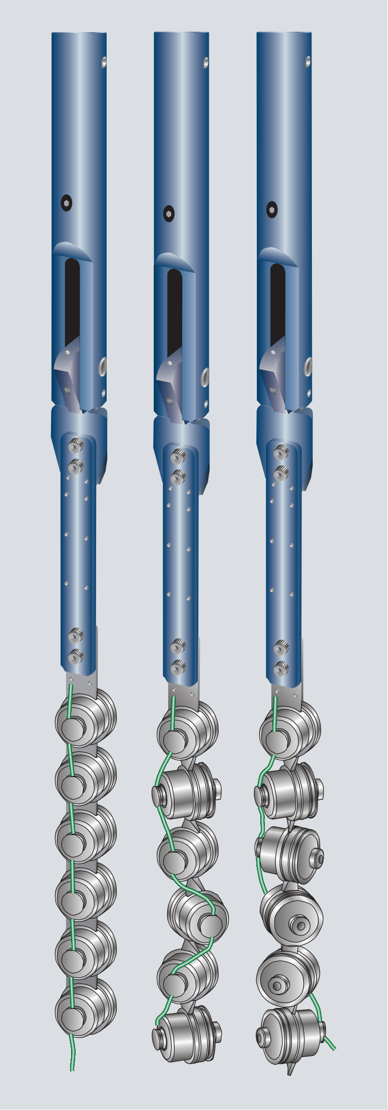

Figure 107. 1¹¹⁄₁₆-in. expendable Enerjet gun.

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Table 32. 1 11⁄16-in. Expendable Enerjet Performance Summary[†]

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
1 11⁄16-in. triphased expendable Enerjet	6, 0 ± 45	Phased Enerjet, HMX	13.9	0.23	0.05/0.08	4½ in., 11.6
1 11⁄16-in. expendable Enerjet	6, 45	Phased Enerjet, HMX	13.5	0.23	0.05/0.08	4½ in., 11.6

[†] Unofficial API RP 43 5th edition

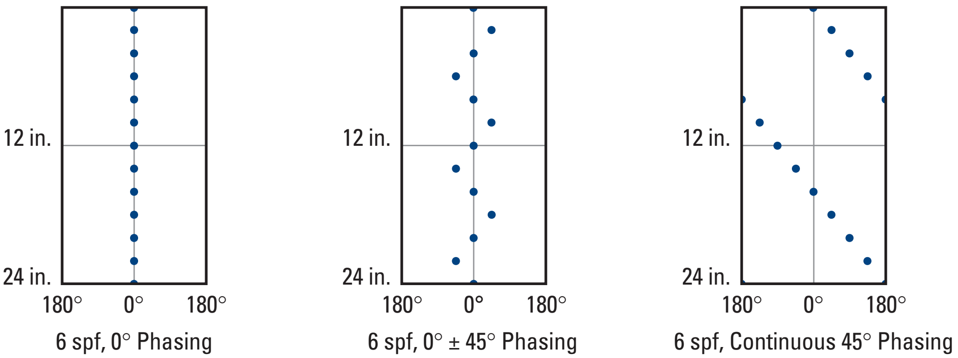

Figure 108. 1 11⁄16-in. expendable Enerjet shot patterns in 4½-in. casing.

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2⅛-in. Expendable Enerjet Gun

The 2⅛-in. expendable Enerjet gun is a high-performance exposed capsule gun suitable for through-tubing operations (Fig. 109 and Tables 33 and 34). Zero phase, triphase, and continuous spiral options are available (Fig. 110). When the gun is fired, the charge cases, charge caps, and carrier strip shatter to reduce the risk of getting stuck after perforating. The head and other accessories remain intact for retrieval, with an OD of only 1¹¹⁄₁₆ in.

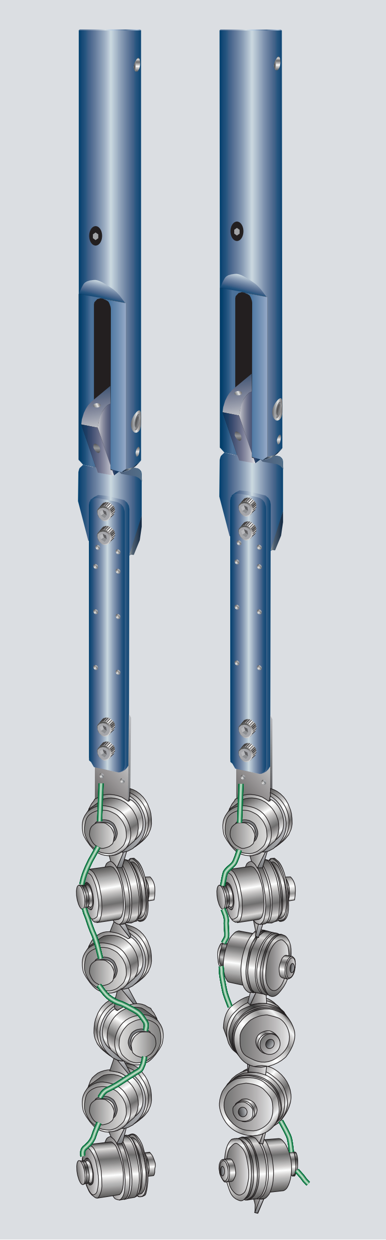

Figure 109. 2⅛-in. expendable Enerjet gun.

Applications

- Through tubing
- Deep penetration
- Rigless perforation or reperforation
- Debris-insensitive operations

Table 33. 2⅛-in. Expendable Enerjet Mechanical Specifications

Outside diameter (in.)	Running in and deployed: 2⅛ Retrieval: 1¹¹⁄₁₆
Shot density (spf)	4, 6
Phasing (°)	0, 45, 0 ± 45
Temperature rating, 1 hr (°F [°C])	HMX: 365 [185]
Pressure rating (psi)	15,000
Min. casing size (in.)	4½
Min. restriction (in.)	2.25 in.
Max. gun length (ft)	30
Debris fill per charge (in./ft)	
4½-in. casing	0.23
5½-in. casing	0.15
7-in. casing	0.10
Max. tensile strength[†] (lbf)	15,000

[†] Pull strength of the gun strip

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Table 34. 2⅛-in. Expendable Enerjet Performance Summary†

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.²/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
2⅛-in. expendable Enerjet	4, 45	Power Enerjet, HMX	27.3	0.25	–	0.06/0.09	4½ in., 11.6
2⅛-in. triphased expendable big hole Enerjet	6, 0 ± 45	Enerjet big hole, HMX	8.1	0.47	1.04	0.07/0.10	5½ in., 17.0

† API RP 43 5th edition or API 19B Section 1

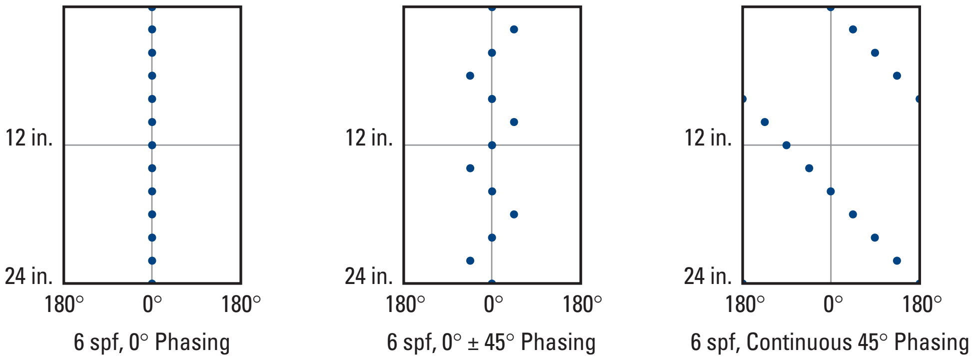

Figure 110. 2⅛-in. expendable Enerjet shot patterns in 5½-in. casing.

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2½-in. Expendable Enerjet Gun

The 2½-in. expendable Enerjet gun is a high-performance exposed capsule gun suitable for through-tubing operations (Figs. 111 and Tables 35 and 36). Zero phase, triphase, and continuous spiral options are available (Fig. 112). When the gun is fired, the charge cases, charge caps, and carrier strip shatter to reduce the risk of getting stuck after perforating. The head and other accessories remain intact for retrieval.

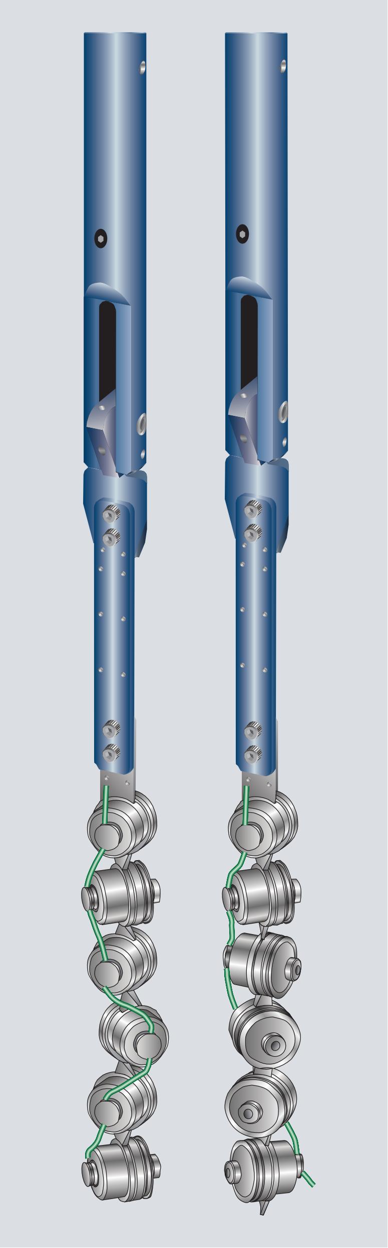

Figure 111. 2½-in. expendable Enerjet gun.

Applications

- Through tubing
- Deep penetration
- Rigless perforation or reperforation
- Debris-sensitive operations

Table 35. 2½-in. Expendable Enerjet Mechanical Specifications

Outside diameter (in.)	2½
Shot density (spf)	4 or 5
Phasing (°)	0, 0 ± 45, continuous 45 or 60
Temperature rating, 1 hr (°F [°C])	HMX: 365 [185]
Pressure rating (psi)	15,000
Min. casing size (in.)	4½
Min. restriction (in.)	2.62
Max. gun length (ft)	30
Debris fill per charge (in./ft)	
4½-in. casing	0.44
5½-in. casing	0.30
7-in. casing	0.21
Max. tensile strength† (lbf)	4,000

† Pull strength of the gun strip

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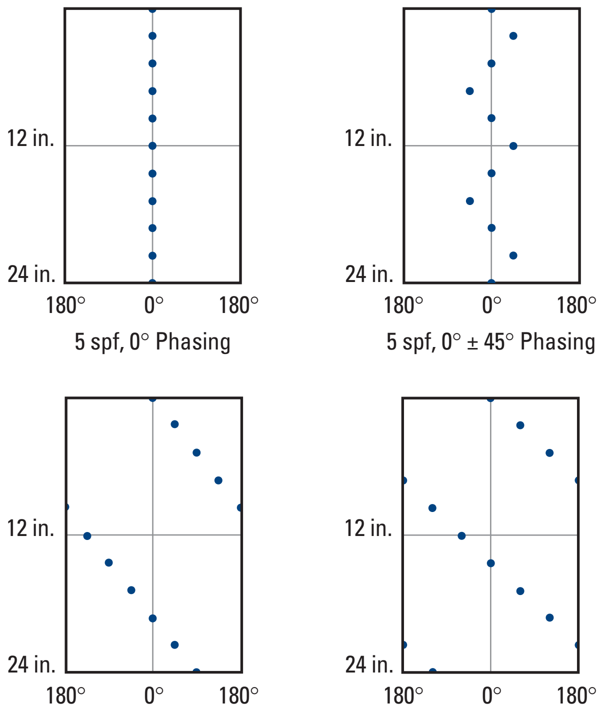
Table 36. 2½-in. Expendable Enerjet Performance Summary[†]

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
2½-in. expendable Power Enerjet	4, 0	Power Enerjet, HMX	34.8	0.28	0.04/0.06	7 in., 32.0
2½-in. expendable Enerjet	4, 0 ± 45	Power Enerjet, HMX	31.1[‡]	0.27[‡]	0.10/0.15	7 in., 32.0
2½-in. expendable Enerjet	4, 45	Power Enerjet, HMX	26.6[‡]	0.33[‡]	0.06/0.09	5½ in., 17.0

[†] API RP 43 5th edition or API 19B Section 1
[‡] Unofficial API



5 spf, 0° Phasing

5 spf, 0° ± 45° Phasing

5 spf, Continuous 45° Phasing

5 spf, Continuous 60° Phasing

Figure 112. 2½-in. expendable Enerjet shot patterns in 5½-in. casing.

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Pivot Gun System

The Pivot Gun system is a wireline capsule gun with excellent performance for through-tubing operations (Tables 37 and 38). It is ideal for workover reperforating or shooting past deep formation damage. Gun diameter running-in-hole is only 1¹¹⁄₁₆ in., but once the gun is below the tubing, the charges are rotated outward to produce an effective diameter of 3.786 in. (Fig. 113). Penetration produced by the Pivot Gun system is deeper than that of other similar-sized guns. The carrier strip and charges break up after detonation, and the CCL and deployment head are retrieved.

Operational safety is enhanced with the gun's safe arming/deployment verification circuit, which prevents the gun from being armed and fired until the charges are fully rotated outward from the gun carrier by the deployment head and rods. The unique parallel deployment of the Pivot gun system means that a stuck charge does not prevent the other charges from properly deploying. An unfired deployed gun can still be retrieved because the charges rotate back into the carrier as the gun enters the tubing reentry guide.

Applications

- Through tubing
- Deep penetration
- Rigless perforation or reperforation

Table 37. Pivot Gun Mechanical Specifications

Outside diameter (in.)	Running in: 1¹¹⁄₁₆ Deployed: 3.786
Shot density (spf)	4
Phasing (°)	180
Temperature rating, 1 hr (°F [°C])	RDX: 330 [166] HMX: 365 [185]
Pressure rating (psi)	12,000
Min. casing size (in.)	Deployed: 4½
Min. restriction (in.)	1.78
Max. gun length (ft)	15
Debris fill per charge (in./ft)	
4½-in. casing	0.85
5½-in. casing	0.48
7-in. casing	0.33
Max. tensile strength[†] (lbf)	2,000

[†] Pull strength of the gun strip

Table 38. Pivot Gun Performance Summary[†]

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
1¹¹⁄₁₆-in. Pivot Gun	4, 180	Ultracap*, RDX	27.8	0.38	0.05/0.08	4½, 11.6
1¹¹⁄₁₆-in. PowerPivot* Gun	4, 180	PowerPivot, HMX	28.4	0.35	0.06/0.09	4½, 11.6

[†] API RP 43 5th edition or API 19B Section 1; blue type identifies API 19B Registered Perforation Systems.

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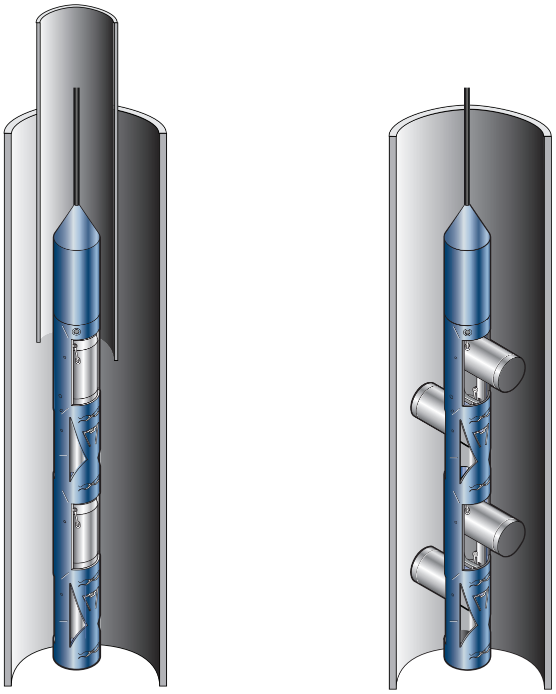

Figure 113. Pivot Gun system.

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Capsule gun performance and mechanical data summary

Table 39 summarizes the performance and mechanical data for the individual capsule guns.

Table 39. Capsule Gun Performance and Mechanical Data Summary

Perforating System Designation	Shot Density, spf	Phasing, °	Charge	API RP 43 Fifth Edition Section 1 or API 19B Section 1					Temperature Rating for 1 h, degF	Maximum Explosive Load, g	Maximum Pressure Rating, psi	Minimum Restriction, in	Debris Fill per Charge in 4½-, 5-, and 7-in Casing, in	Maximum Gun Length, ft
				Penetration, in	Entrance Hole, in	Area Open to Flow, in^2/ft	Burr Height Avg/Max., in	Casing Size, in	Casing Weight, lbm/ft					
1¹¹⁄₁₆-in Pivot Gun*	4	180	1¹¹⁄₁₆-in Ultracap*, RDX	27.8	0.38	–	0.05/0.08	4½	11.6	330	22.0	12,000	1.78	0.85/0.48/0.33	15
1¹¹⁄₁₆-in PowerPivot* Gun	4	180	1¹¹⁄₁₆-in PP, HMX	28.4	0.35	–	0.06/0.09	4½	11.6	365	22.0	12,000	1.78	0.85/0.48/0.33	15
1.63-in Retrievable Enerjet*	4	0	1.63-in EJ, RDX	18.0	0.28	–	0.03/0.05	4½	11.6	330	8.0	20,000	1.71	0.13/0.08/0.06	50
1.63-in Retrievable Enerjet	4	0	1.63-in EJ, HMX	17.8	0.29	–	0.03/0.06	4½	11.6	365	8.0	20,000	1.71	0.13/0.08/0.06	50
1¹¹⁄₁₆-in Retrievable Power Enerjet*	6	0	1¹¹⁄₁₆-in PE, HMX	21.6	0.20	–	0.01/0.03	4½	11.6	365	8.0	20,000	1.78	0.13/0.08/0.06	50
1¹¹⁄₁₆-in Biphased Retrievable Power Enerjet	6	±45	1¹¹⁄₁₆-in Ph PE, HMX	14.6	0.26	–	0.05/0.08	4½	11.6	365	8.0	20,000	1.78	0.16/0.10/0.07	35
1¹¹⁄₁₆-in PowerSpiral* Enerjet	7.5	45	1¹¹⁄₁₆-in PowerSpiral EJ, HMX	19.5	0.22	–	0.06/0.10	4½	11.6	365	8.0	20,000	1.78	0.15/0.09/0.07	30
2⅛-in Retrievable Enerjet	4	0	2⅛-in EJ, RDX	21.9	0.31	–	0.02/0.03	5½	17.0	330	14.0	20,000	2.25	0.16/0.10/0.07	50
2⅛-in Retrievable EnerjetExpress*	6	0	2⅛-in EJ Express, RDX	21.2	0.34	–	0.05/0.07	5½	17.0	330	13.8	20,000	2.25	0.16/0.10/0.07	50
2⅛-in Retrievable EnerjetExpress	6	0	2⅛-in EJ Express, HMX	23.5	0.34	–	0.05/0.07	5½	17.0	365	13.8	20,000	2.25	0.16/0.10/0.07	50
2⅛-in Retrievable Power Enerjet	6	0	2⅛-in PE, HMX	30.4	0.32	–	0.06/0.08	5½	17.0	365	14.3	20,000	2.25	0.16/0.10/0.07	50
2⅛-in PowerSpiral Enerjet	6	45	2⅛-in PowerSpiral EJ, HMX	27.2	0.32	–	0.08/0.11	5½	17.0	365	14.5	15,000	2.25	0.22/0.14/0.09	30
2⅛-in Retrievable Big Hole	4	0	2⅛-in EJ BH, RDX	10.0	0.57	1.02	0.08/0.10	5½	17.0	330	17.0	20,000	2.25	0.16/0.10/0.07	50
2⅛-in Retrievable Big Hole	4	0	2⅛-in EJ BH, HMX	10.5	0.51	0.82	0.05/0.07	5½	17.0	365	17.0	20,000	2.25	0.16/0.10/0.08	50
2⅛-in Retrievable Big Hole	6	±45	2⅛-in PE BH, HMX	7.9	0.49	1.13	0.04/0.07	4½	11.6	365	14.0	20,000	2.25	0.23/0.15/0.10	50
2⅛-in Triphased Expendable Big Hole	6	0, ±45	2⅛-in EJ BH, HMX	8.1	0.47	1.04	0.07/0.10	5½	17.0	330	15.0	15,000	2.25	0.23/0.15/0.10	30
2½-in Expendable Power Enerjet	4	0	2½-in PE, HMX	34.8	0.28	–	0.04/0.06	7	32.0	365	27.0	15,000	2.62	0.44/0.37/0.21	30
2½-in PowerSpiral Enerjet	5	45	2½-in PowerSpiral EJ, HMX	36.6	0.39	–	0.07/0.11	5½	17.0	365	25.6	15,000	2.62	0.653/0.469/0.284	30

Notes: Every attempt has been made to verify the accuracy of the data tabulated; contact your Schlumberger representative for further information.

Other shot densities and phasings are available; Schlumberger also custom designs perforation systems to meet specific needs.

Blue type identifies API 19B Registered Perforation Systems.

na = not available

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Hollow Carrier Gun Perforating Systems

Introduction to hollow carrier guns

Hollow carrier guns are pressure-tight steel tubes in which shaped charges are positioned. For gun ODs of 2⅞ in. and larger, hollow carrier guns perform better than exposed guns because they use larger charges, optimized phasing, and increased shot density. Hollow carrier guns are also used when debris is unacceptable and in hostile conditions that preclude using exposed guns.

Schlumberger hollow carrier guns are designed as systems, comprising specific carriers, charges, detonating cords, and boosters, to provide maximum perforator performance. All Schlumberger gun systems are manufactured to our rigorous QA standards. There are six main types of hollow carrier guns:

- HSD High Shot Density guns feature a high shot density of 4 spf or higher with optimum phasing patterns and the largest high-performance charges available for natural, stimulated, and sand control completions. For applications that require a large AOF, the Bigshot 21* gun system provides a shot density of 21 spf.
- PURE perforating system for clean perforations optimizes the well dynamic underbalance to consistently eliminate or minimize perforation damage.
- OrientXact tubing-conveyed oriented perforating system sets new standards for alignment accuracy and verification of charge orientation, making it ideally suited for long and high-deviation wells.
- Frac Gun perforating systems are engineered for fracture stimulation of wells, with additional applications in slimhole wells, sand control operations, and coalbed methane (CBM) wells.
- Port Plug guns shoot the charges through replaceable plugs in a reusable gun carrier and feature highly flexible multiple-gun selectivity for remote operations, enabling the perforation of large intervals with minimal hardware.
- HEGS High-Efficiency Gun Systems are similar to Port Plug guns, with longer, expendable hollow carriers that are faster to load and run.

This chapter is organized in sections for each gun type consisting of introductory material, gun selection guidelines, and concise gun datasheets with specifications and performance data. At the end of the chapter is a summary listing of hollow carrier gun performance and performance data.

Hollow carrier gun selection

Once the decision has been made to use hollow carrier guns in the completion, selection of the most appropriate gun depends on several factors:

- casing ID and required gun-to-casing clearance
- packer sealbore diameter (for TCP “sting-through” applications)
- bottomhole pressure and temperature
- deep penetrator or big hole application
- perforator performance
- shot density, phasing pattern, and orientation.

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The casing ID must be considered to achieve the best perforator performance compatible with the casing size. Penetration depth and entrance hole size and uniformity usually improve with increasing gun size because the space available for charges increases and gun-to-casing clearance decreases.

Table 40 lists the recommended hollow carrier guns for different casing sizes. In general, the largest gun that can be accommodated by the casing ID should be used, but washover requirements must also be considered. For example, in sand control completions the guns may become sanded-in when perforations are surged with high underbalance. Thus, adequate clearance must be left between the guns and the casing for potential washover operations. Because of the wide variety of guns, charges, and hardware configurations within the larger context of wellbore conditions and perforating techniques, it is not possible to define with certainty a fixed gun-to-casing clearance. Schlumberger assists operators with gun selection to ensure optimum perforating performance and successful job execution.

Table 40. Casing Size and Hollow Carrier Gun Selection

Casing or Tubing Size (in.)	Gun size (in.)
2⅞	HSD gun: 1.56
2⅞ and 3½	HSD gun: 2
3½ and 4½	HSD gun: 2¼
3½	HSD gun: 2½
4½	HSD gun: 2⅞
	Port plug gun: 3⅛
	HEGS gun: 3⅛
	Port plug gun: 3⅜
4½ and 5	HSD gun: 3⅛
4½, 5, and 5½	HSD gun: 3⅜
5	HSD gun: 3½
	Port plug gun: 3⅜
	HSD gun: 3.67
5½	HSD gun: 4
	Port plug gun: 4
	HEGS gun: 4
7	HSD gun: 4½
	Port plug gun: 4
	HEGS gun: 4
	HSD gun: 4⅝
	HSD gun: 4.72
7 and 7⅝	HSD gun: 5
	Port plug gun: 4
	HEGS gun: 4
9⅝	HSD gun: 7
	Port plug gun: 4
	HEGS gun: 4

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The next factor to consider in choosing a hollow carrier gun is the bottomhole pressure. Shooting a hollow carrier gun below its minimum pressure rating may result in excessive swell or gun splitting or loss of the port plugs, possibly requiring a fishing job. If a gun is run beyond its pressure rating, the carrier may collapse, causing autodetonation and possible damage to the well.

Bottomhole temperature is a similarly critical consideration. Figure 114 is a guide to the maximum allowable temperature and exposure time for HSD guns. The standard 1-hr temperature rating for Port Plug guns is 340°F [171°C]; for high-temperature operations, HMX explosives that raise the rating to 400°F [204°C] are available. HEGS guns are rated up to 340°F [171°C] (1 hr), depending on the gun and charge combination used.

The maximum static temperature expected during the completion process is typically estimated from the final temperature recorded during openhole logging. Care must be taken, however, because the actual temperature can exceed openhole logging temperatures by 40°F [22°C] or more. Bottomhole temperature can also be estimated from the geothermal gradient and depth, as shown in Fig. 115.

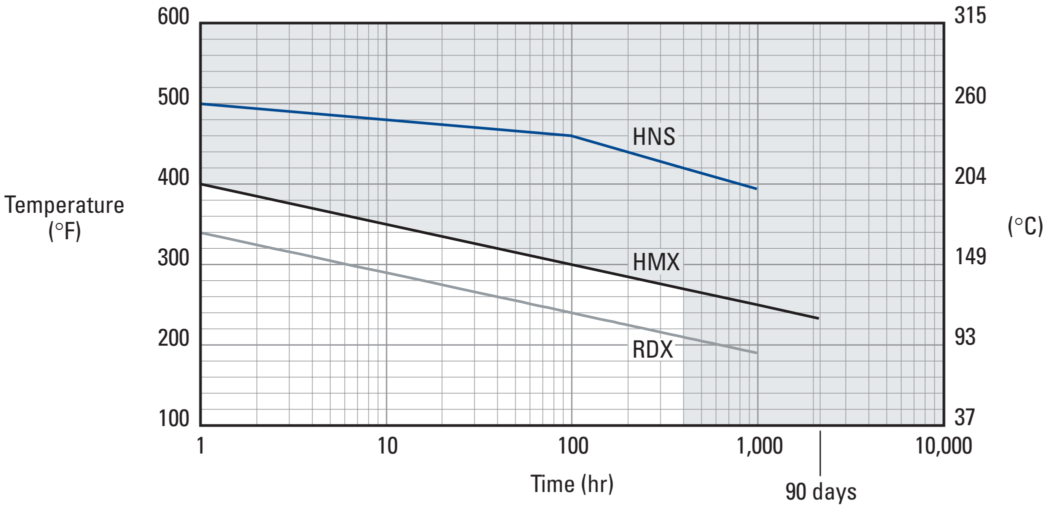
Time and temperature effects on explosives are cumulative. If a gun string must be removed from the well without firing, the explosives should not be used for subsequent runs unless the total time and temperature rating (Fig. 114) will not be exceeded. Special safety procedures are required for retrieving HMX charges run above 300°F [149°C] upon their return to the surface.

Higher rated explosives (HMX or HNS) are recommended if there is uncertainty about the bottomhole temperature or if there may be unplanned delays before firing the guns.

More information on perforating safety is in the “Safety,” “Operating Environment and Engineering of Perforating Operations,” and “Wireline Perforating” chapters.

The type of completion dictates the choice of perforator charge—either deep penetrating or big hole charges. The Frac Gun system uses the charges for HSD guns because these charges combine the best features of the deep penetrating and big hole charges.

Deep penetrating charges are the usual choice for natural and stimulated completions. Deep penetrating charges that penetrate beyond the damaged zone next to the borehole produce the best well productivity. If the formation is deeply damaged during the drilling or completion process or is washed out or if there are multiple casing strings, deep penetrating charges such as PowerJet charges are recommended.



Contact your Schlumberger representative for high-temperature and long-duration operations falling in the shaded area.

Figure 114. Temperature and time guidelines for selection of explosives in hollow carrier guns. Exceeding the temperature rating leads to reduced performance followed by burning (all explosives) and possible autodetonation (RDX and HMX explosives).

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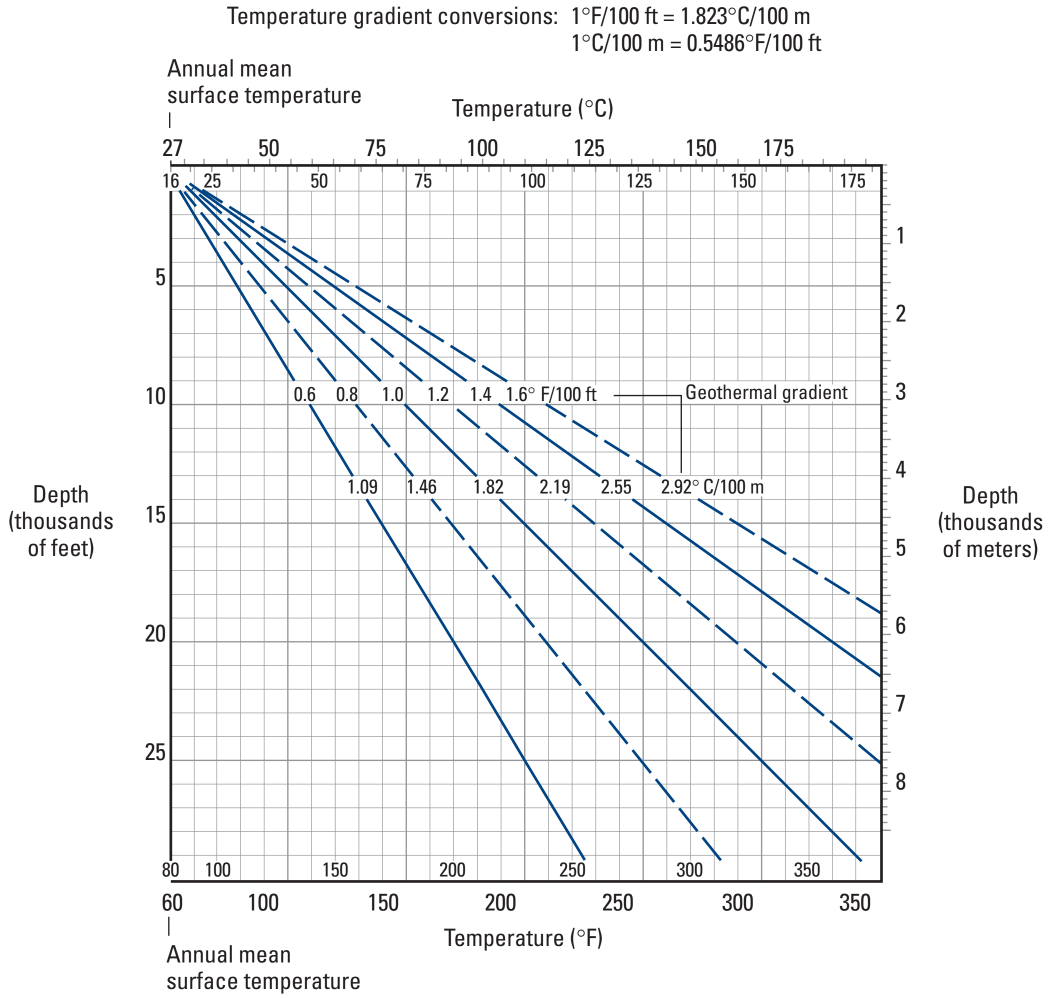

Figure 115. Estimation of formation temperature (linear gradient assumed).

Big hole charges are normally used in gravel-packed completions. Big hole charges open up larger diameter holes in the casing with shallower penetration than deep penetrating charges of equivalent size. The largest, most symmetric holes promote the development of a stable arch in the formation around the perforation, which reduces pressure drop across the perforation and usually results in the best-quality gravel-pack completions. Although HSD guns with big hole charges are often run slick—without centralizers or standoffs—a standoff between the gun and casing improves the consistency of the entrance hole diameters. Refer to the “Perforation Fundamentals” chapter.

In cases such as horizontal wells, perforation debris may cause problems during completion or with other tools run into the well for stimulation or monitoring purposes. For these reasons, low- or controlled-debris perforators such as PowerFlow or PowerJet charges are recommended.

The next step is to pick the gun system that provides the required penetration depth and entrance hole diameter. Because shot density, phasing, and orientation are parameters that affect productivity, Schlumberger hollow carrier guns are designed in consideration of these features. For example, higher shot densities result in improved productivity, especially in zones with thin vertical permeability barriers, as described in the “Reservoir Completion Types” chapter. High shot densities, along with large entrance holes, are also important for the effectiveness of gravel-pack completions.

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Schlumberger HSD guns feature improved phasing for better productivity, more efficient gravel packing, and retention of casing strength. In highly deviated and horizontal wells, the orientation of the perforations can prevent sand production and affect hydraulic fracturing efficiency. The challenges of accurate orientation are adeptly managed by the innovative OrientXact perforating system, as subsequently discussed in this chapter.

HSD High Shot Density guns

HSD High Shot Density guns feature increased shot density, optimum phasing patterns, and the largest high-performance charges available for natural, stimulated, and sand control completions. HSD guns use expendable, retrievable carriers, which means that once the gun system has been used, it is retrieved and disposed of. Deployment is run primarily on either wireline cable or tubing. Tractor conveyance can be used in deviated wells.

Running HSD guns on wireline cable has the following advantages:

- precision depth control with positioning by casing collar locator, gamma ray correlation, or both methods
- fast trip times
- selectivity for all gun sizes to enable perforating more than one interval per run into the well
- application as either casing guns before the completion is in place or as through-tubing guns after running the completion, depending on the gun size and restrictions.

Conveying HSD guns on tubing (TCP or coiled tubing) has the following advantages:

- perforating underbalanced with large casing guns, which has been shown to improve well productivity
- conveying gun strings in highly deviated or horizontal wells
- perforating long intervals in one run in the well
- precise orientation for optimum perforating performance
- flexibility of numerous completion possibilities without the need to kill the well.

Slickline perforating with the eFire-Slickline* electronic firing head system is a relatively new technology that provides advantages in speed and reliability (see the “Firing Systems” chapter).

Features

- Gun system—Schlumberger HSD guns are designed as systems, comprising specific carriers, charges, detonating cords, and boosters, to provide maximum perforator performance. To ensure that performance meets design specifications, charges are QC tested during production in actual gun carriers.
- Expendable carriers—All HSD guns are expendable, which eliminates the need for separate porthole plugs. The standard range of carrier sizes is 1-, 5-, 10-, 20-, and 30-ft lengths.
- Shot density—High shot densities range from a minimum of 4 spf for the 1.56-in. size to 21 spf for the Bigshot 21 system and up to 27 spf for the 7-in. size.
- Helical shot pattern—The helical shot pattern available in all gun sizes provides the smallest vertical spacing between shots and the optimum phasing pattern for productivity and remaining casing strength. Shot spacing can be varied on request.
- Automatic ballistic connection—Schlumberger HSD guns feature self-aligning detonation-transfer modules between guns and spacers for automatic ballistic connection during makeup.
- Firing modes—Both bottom-up and top-down firing modes are available: top-down for TCP, which allows installation of the firing head last, and bottom-up for wireline applications, which provides fluid desensitization.

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- Mechanical connections—For TCP, Schlumberger HSD guns have drillpipe connections with API tapered thread modified to incorporate high-pressure O-ring seals. These connections provide fast, safer vertical makeup on the rig floor.
- Exclusive use of secondary explosives—Loaded HSD guns contain only secondary high explosives (detonating cord, boosters, and charges) for safer transport and handling following standard Schlumberger safety procedures.
- All HSD guns are combinable with the S.A.F.E. Slapper-Actuated Firing Equipment and Secure detonator systems.

Figure 116 illustrates the configuration of the HSD gun system.

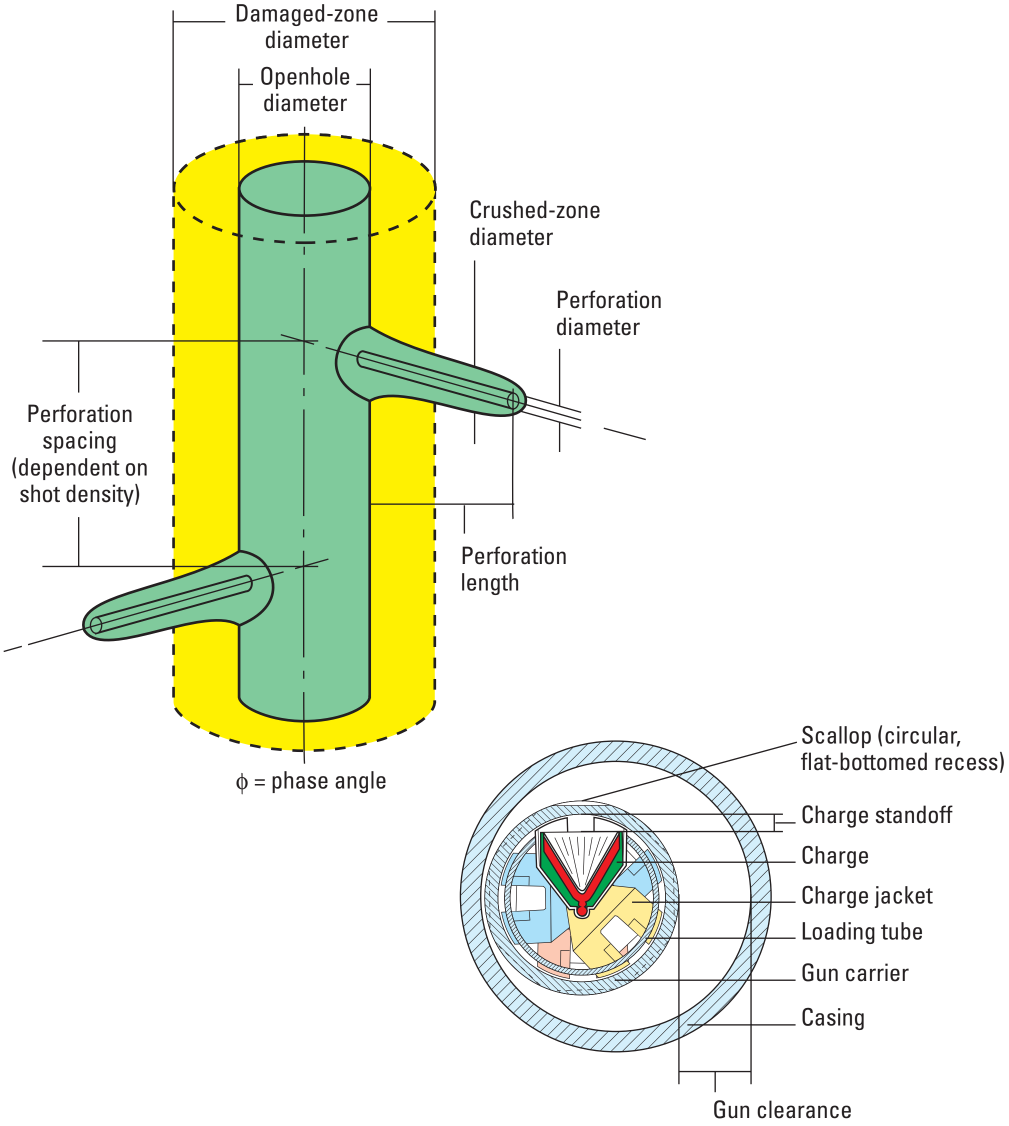

Figure 116. HSD gun system.

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1.56-in. HSD Perforating Gun

The 1.56-in. HSD guns are for operations in slimhole casing but have applications in any completion where downhole restrictions limit gun size, including through-tubing, dual-completion, monobore, and extended-reach operations (Figs. 117 and 118 and Tables 41 and 42).

Guns can be conveyed using wireline, slickline, tubing, or coiled tubing. The intercarriers screw together TCP style for fast rig-up and rig-down. More than 5,000 ft of guns can be run to perforate long intervals in one run, with the guns aligned by using the locks built in to the Acme-threaded intercarriers.

Applications

- Natural, stimulated, and sand control completions
- Slim holes or completion restrictions
- Deep penetration
- Multiple-interval perforating

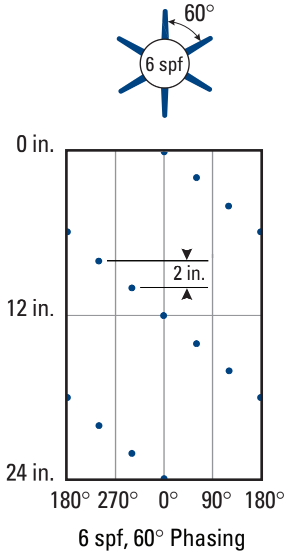

Figure 118. 1.56-in. HSD shot pattern for 4½-in. casing.

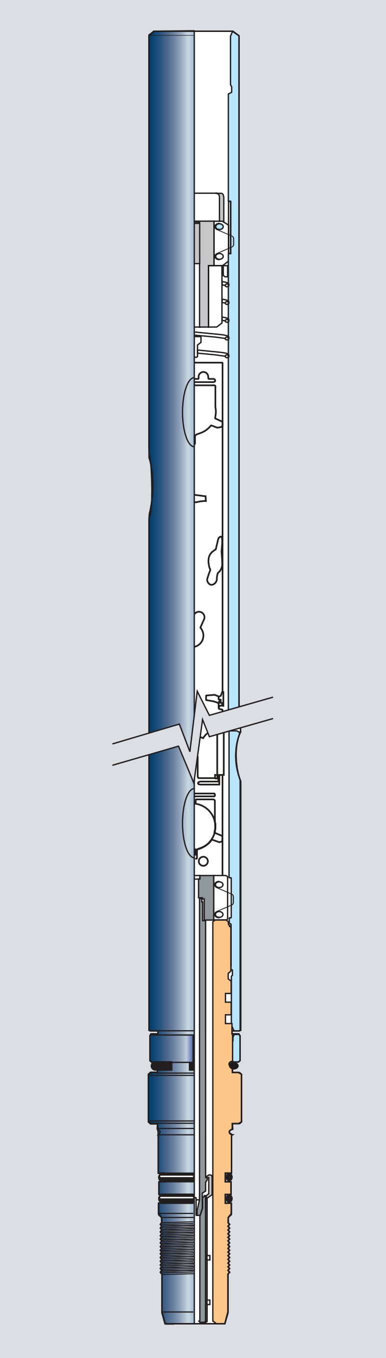

Figure 117. 1.56-in. HSD gun, 6 spf, 60° phasing.

Table 41. 1.56-in. HSD Mechanical Specifications

Outside diameter (in.)	1.56
Shot density (spf), phasing (°)	4, 0; 4, 60; 4, 90
	6, 0; 6, 60; 6, 135; 6, 180
	8, 120
Shot spacing (in.)	4 spf: 3
	6 spf: 2
	8 spf: 1.5
Temperature rating (°F [°C])	500 [260]†
Pressure rating (psi)	20,000
Min. casing size (in.)	2⅜
Max. diameter including burrs, shot in liquid/gas (in.)	1.72/1.75
Max. gun length (ft)	5, 10, 20, 30
Interval missed between guns (in.)	13
Weight of loaded 20-ft gun in air (lbm)	74
Max. explosive load (g)	3.5
Tensile load (lbf)	
Recommended	35,000
Min.	57,000
Max.	86,000

† With high-temperature explosives and seals

Table 42. 1.56-in. HSD Performance Summary†

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^{2}/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
1.56-in. HSD	6, 60	PowerJet 1606, HMX	11.3	0.17	–	0.04/0.08	2⅞, 6.4

† API RP 43 5th edition or API 19B Section 1; blue type identifies API 19B Registered Perforation Systems.

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2-in. HSD
Perforating Gun

The 2-in. HSD guns are for operations in slimhole casing but have applications in completions where downhole restrictions limit gun size, including through-tubing, dual-completion, monobore, and extended-reach operations (Fig. 119 and Tables 43 and 44).

Shot densities with PowerJet charges are available up to 6 spf (Fig. 120). The standard phasing is 60°, with 120° and 180° phasings and a 135° spiral-phased version available.

Guns can be conveyed using wireline, slickline, tubing, or coiled tubing. The intercarriers screw together TCP style for fast rig-up and rig-down. More than 4,500 ft of guns can be run to perforate long intervals in one run, with the guns aligned by using the locks built into the Acme-threaded intercarriers.

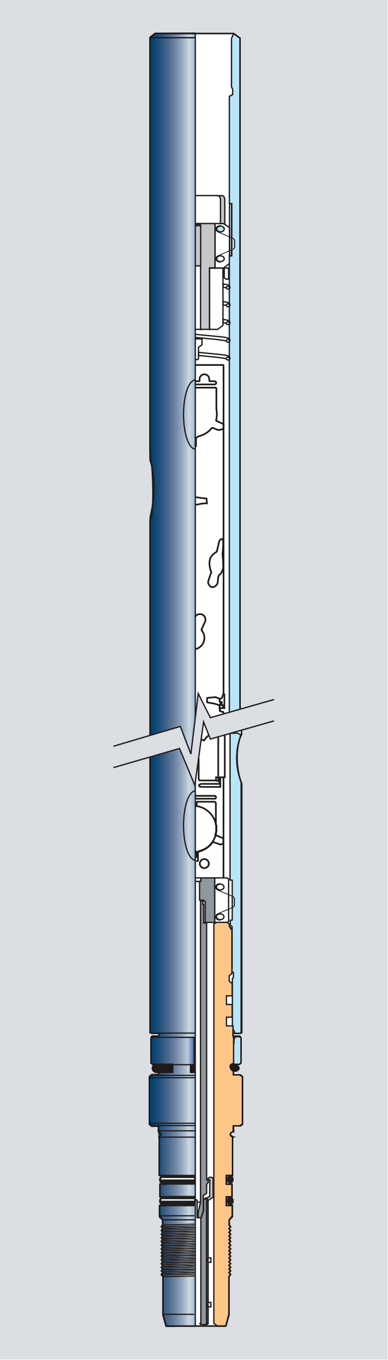

Figure 119. 2-in. HSD gun, 4 spf, 60° spiral.

Applications

- Natural, stimulated, and sand control completions
- Slim holes or completion restrictions
- Deep penetration
- Multiple-interval perforating

Table 43. 2-in. HSD Mechanical Specifications

Outside diameter (in.)	2
Shot density (spf), phasing (°)	4, 0; 4, 60; 4, 120; 4, 180
	6, 0; 6, 60; 6, 135
Shot spacing (in.)	4 spf: 3
	6 spf: 2
Temperature rating (°F [°C])	500 [260][†]
Pressure rating (psi)	20,000
Min. casing size (in.)	2⅞
Max. diameter including burrs, shot in liquid/gas[‡] (in.)	2.16–2.29/2.21
Max. gun length (ft)	5, 10, 20
Interval missed between guns (in.)	13
Weight of loaded 20-ft gun in air (lbm)	119
Tensile load (lbf)	
Recommended	57,000
Min.	91,000
Max.	134,000

[†] With high-temperature explosives and seals

[‡] Depends on gun configuration and charge type

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Table 44. 2-in. HSD Performance Summary[†]

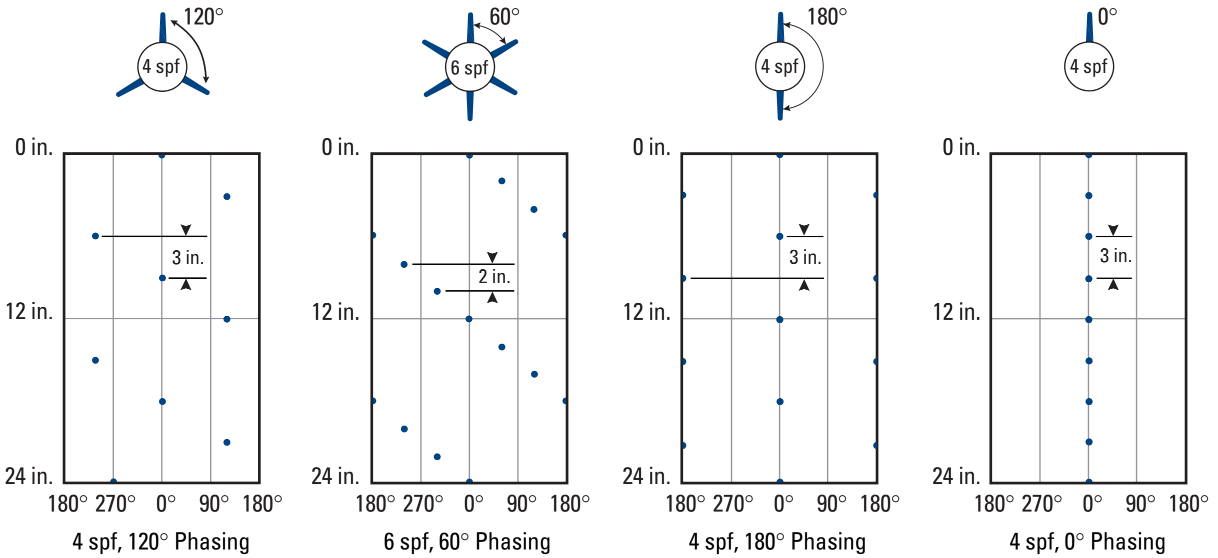
Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^{2}/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
2-in. HSD	6, 60	PowerJet Omega* 2006, HMX	21.8	0.22	–	0.05/0.08	3½, 9.2
2-in. HSD[‡]	6, 60	PowerJet 2006, HNS	15.3	0.22	–	0.03/0.05	2⅞, 6.4
2-in. HSD	6, 60	PowerJet 2006, HMX	18.6	0.2	–	na	2⅞, 6.4
2-in. HSD	6, 0/180	PowerJet 2006, HMX	17.9[§]	0.20[§]	–	na	2⅞, 6.4
2-in. HSD	6, 60	HyperJet 2006, RDX	9.6	0.33	–	0.05/0.08	3½, 9.2
2-in. HSD	6, 60	UltraJet 2006, HMX	16.6	0.23	–	0.04/0.05	3½, 9.2

na = not available

[†] API RP 43 5th edition or API 19B Section 1; blue type identifies API 19B Registered Perforation Systems.

[‡] Nonswell version available

[§] Unofficial API data



4 spf, 120° Phasing

6 spf, 60° Phasing

4 spf, 180° Phasing

4 spf, 0° Phasing

Figure 120. 2-in. HSD shot patterns for 2⅞-in. casing.

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2¼-in. HSD Perforating Gun

The 2¼-in. HSD guns are for operations in slimhole casing but have applications in completions where downhole restrictions limit gun size, including through-tubing, dual-completion, monobore, and extended-reach operations (Figs. 121 and 122 and Tables 45 and 46).

Guns can be conveyed using wireline, slickline, tubing, or coiled tubing. The intercarriers screw together TCP style for fast rig-up and rig-down. More than 5,000 ft of guns can be run to perforate long intervals in one run, with the guns aligned by using the locks built in to the Acme-threaded intercarriers.

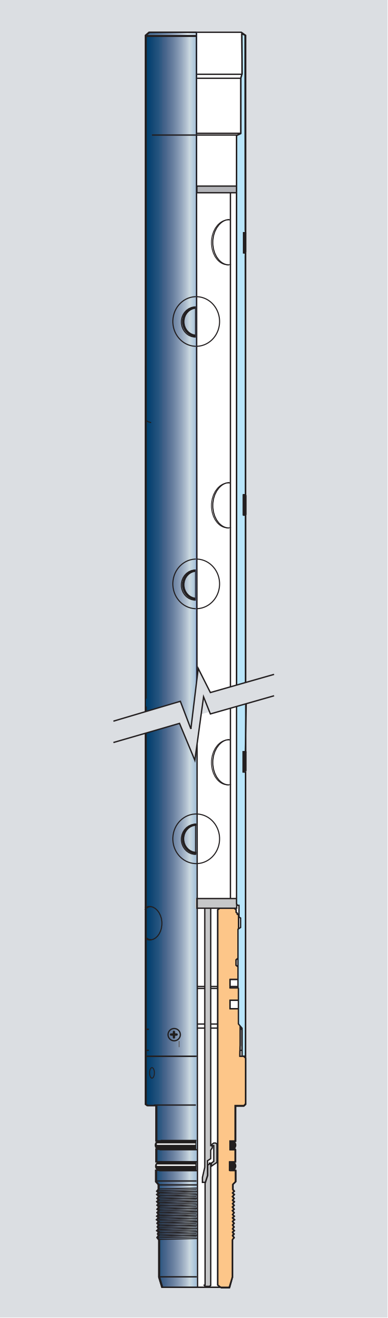

Figure 121. 2¼-in. HSD gun.

Applications

- Natural, stimulated, and sand control completions
- Slim holes or completion restrictions
- Deep penetration
- Multiple-interval perforating

Table 45. 2¼-in. HSD Mechanical Specifications

Outside diameter (in.)	2.25
Shot density (spf), phasing (°)	4, 120; 4, 180
	6, 60
Shot spacing (in.)	4 spf: 3
	6 spf: 2
Temperature rating (°F [°C])	500 [260]†
Pressure rating (psi)	20,000
Min. casing size (in.)	3½
Max. diameter including burrs, shot in liquid/gas (in.)	2.46/2.48
Max. gun length (ft)	5, 10, 20
Interval missed between guns (in.)	13
Weight of loaded gun in air (lbm)	136
Tensile load (lbf)	
Recommended	63,000
Min.	101,000
Max.	155,000

† With high-temperature explosives and seals

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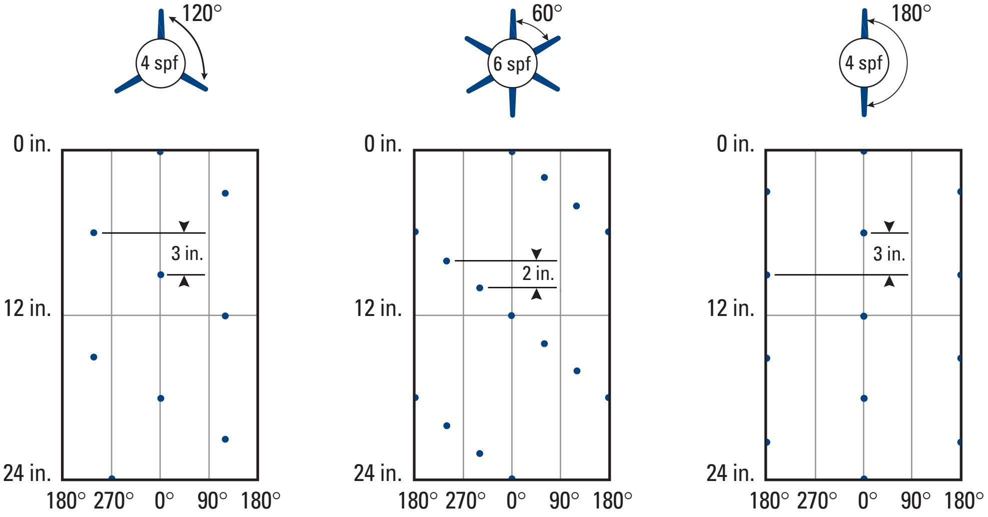

4 spf, 120° Phasing

6 spf, 60° Phasing

4 spf, 180° Phasing

Figure 122. 2¼-in. HSD shot patterns for 4½-in. casing.

Table 46. 2¼-in. HSD Performance Summary†

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^{2}/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
2¼-in. HSD	6, 60	PowerJet 2306, HMX	17.7	0.30	–	0.08/0.10	3½, 9.2
2¼-in. HSD	6, 60	PowerJet 2306, HNS	15.7	0.27	–	0.06/0.09	3½, 9.2

† API RP 43 5th edition or API 19B Section 1; blue type identifies API 19B Registered Perforation Systems.

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2½-in. HSD Perforating Gun

The 2½-in. HSD guns are for slimhole casing operations but have applications in completions where downhole restrictions limit gun size, including through-tubing, dual-completion, monobore, and extended-reach operations (Fig. 123 and Tables 47 and 48).

The standard 2½-in. gun has a 60° spiral hole pattern and can be loaded with big hole or deep penetrating charges up to 6 spf (Fig. 124). Also available is a gun with 4 spf and 180° phasing. For special applications other phasings and shot densities can be made upon request.

Guns can be conveyed using wireline, slickline, tubing, or coiled tubing. Multiple guns are aligned with standard Acme-threaded intercarriers.

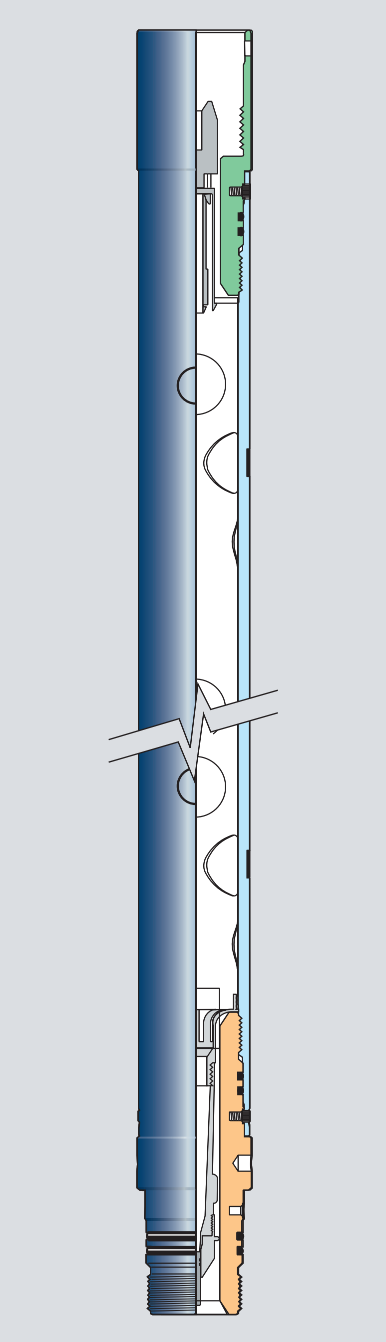

Figure 123. 2½-in. HSD gun, 6 spf, 60° spiral.

Applications

- Natural, stimulated, and sand control completions
- Slim holes or completion restrictions
- Deep penetration
- Multiple-interval perforating

Table 47. 2½-in. HSD Mechanical Specifications

Outside diameter (in.)	2½
Shot density (spf), phasing (°)	4, 180
	6, 60
Shot spacing (in.)	4 spf: 3
	6 spf: 2
Temperature rating (°F [°C])	500 [260]†
Pressure rating (psi)	25,000
Min. casing size (in.)	3½
Max. diameter including burrs, shot in liquid/gas‡ (in.)	2.59–2.78/2.75
Max. gun length (ft)	5, 10, 20, 30
Interval missed between guns (in.)	12.5
Weight of loaded 20-ft gun in air‡ (lbm)	177–179
Tensile load (lbf)	
Recommended	68,000
Min.	109,000
Max.	164,000

† With high-temperature explosives and seals
‡ Depends on gun configuration and charge type

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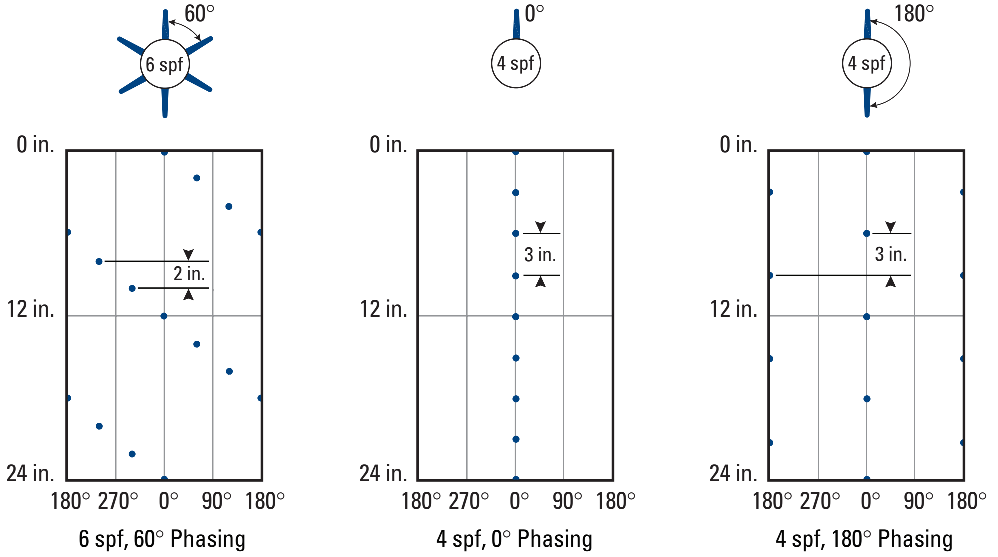
Table 48. 2½-in. HSD Performance Summary†

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^{2}/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
2½-in. HSD	6, 60	PowerJet Omega 2506, HMX	30.6	0.32	–	0.04/0.07	3½, 9.2
2½-in. HSD	6, 60	PowerJet 2506, HNS	16.7	0.30	–	0.07/0.09	3½, 9.2
2½-in. HSD	6, 60	PowerJet 2506, HMX	18.7	0.34	–	0.07/0.11	3½, 9.2
2½-in. HSD	6, 60	UltraJet 2506, HMX	16.6	0.32	–	0.07/0.11	3½, 9.2
2½-in. HSD	6, 60	HyperJet 2506, RDX	13.1	0.43	–	0.07/0.11	3½, 9.2
2½-in. HSD	6, 60	31 CleanSHOT*, HMX	19.2	0.30	–	0.06/0.07	3½, 9.3

† API RP 43 5th edition or API 19B Section 1; blue type identifies API 19B Registered Perforation Systems.



6 spf, 60° Phasing

4 spf, 0° Phasing

4 spf, 180° Phasing

Figure 124. 2½-in. HSD shot patterns for 3½-in. casing.

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2⅞-in. HSD Perforating Gun

The 2⅞-in. HSD guns are for slimhole operations in 4½- to 5½-in. casing but have applications in completions where downhole restrictions limit gun size, including through-tubing, dual-completion, monobore, and extended-reach operations (Fig. 125 and Tables 49 and 50).

The standard 2⅞-in. gun has a 60° spiral hole pattern and can be loaded with big hole or deep penetrating charges up to 6 spf (Fig. 126), with a HPHT version also available. The 4-spf gun has 180° phasing and is available in a liquid-only version. Other phasings and shot densities can be made upon request.

Guns can be conveyed using wireline, slickline, tubing, or coiled tubing. Multiple guns are aligned with intercarriers.

Applications

- Natural, stimulated, and sand control completions
- Slim holes or completion restrictions
- Deep penetration
- Multiple-interval perforating
- HPHT environments or liquid only

Table 49. 2⅞-in. HSD Mechanical Specifications

Outside diameter (in.)	2⅞
Shot density (spf), phasing (°)	4, 180; 4, 180 for liquid 6, 60; 6, 60 for HPHT
Shot spacing (in.)	4 spf: 3 6 spf: 2
Temperature rating (°F [°C])	500 [260]†, ‡
Pressure rating (psi)	25,000‡
Min. casing size (in.)	4½
Max. diameter including burrs, shot in liquid/gas§ (in.)	2.96–3.16/3.08–3.22
Max. gun length (ft)	5, 10, 20, 30
Interval missed between guns (in.)	12
Weight of loaded 20-ft gun in air§ (lbm)	232–237
Tensile load (lbf)	
Recommended	84,000
Min.	135,000
Max.	216,000

† With high-temperature explosives and seals
‡ PEGS verified
§ Depends on gun configuration and charge type

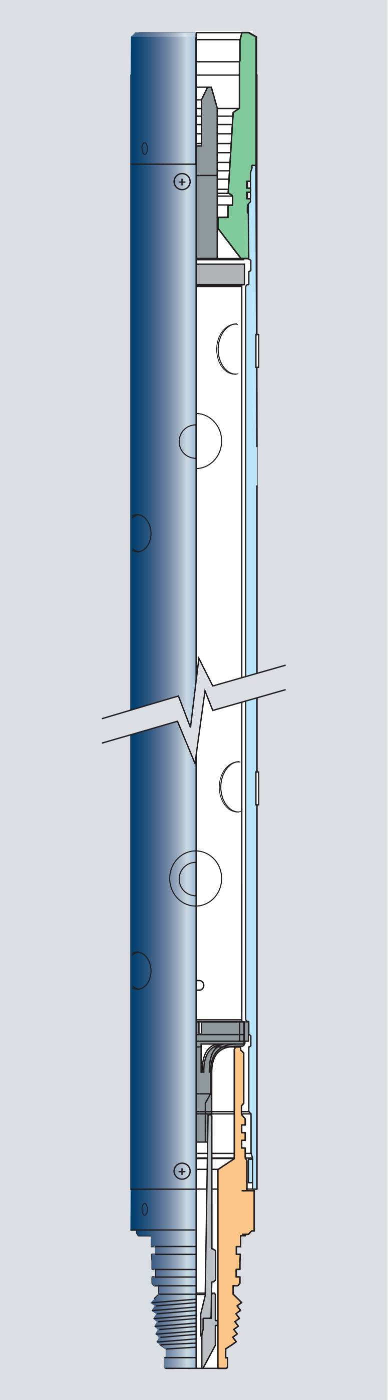

Figure 125. 2⅞-in. HSD gun, 6 spf, 60° spiral.

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Table 50. 2⅞-in. HSD Performance Summary†

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^{2}/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
2⅞-in. HSD	6, 60	PowerJet Omega 2906, HMX	36.0	0.34	–	0.05/0.08	4½, 11.6
2⅞-in. HSD	6, 60	PowerJet 2906, HMX	25.3	0.38	–	0.06/0.08	4½, 11.6
2⅞-in. HSD	6, 60	PowerJet 2906, HNS	21.0	0.31	–	0.06/0.09	4½, 11.6
2⅞-in. HSD	6, 60	UltraJet 2906, HMX	22.1	0.36	–	0.07/0.09	4½, 11.6
2⅞-in. HSD	6, 60	HyperJet 2906, RDX	15.0	0.39	–	0.06/0.09	4½, 11.6
2⅞-in. HSD	4, 0/180	PowerJet 2906, HMX	27.7	0.36	–	na	4½, 11.6
2⅞-in. HSD	6, 60	34 CleanSHOT, RDX	17.7	0.27	–	na	4½, 11.6

na = not available

† API RP 43 5th edition or API 19B Section 1; blue type identifies API 19B Registered Perforation Systems.

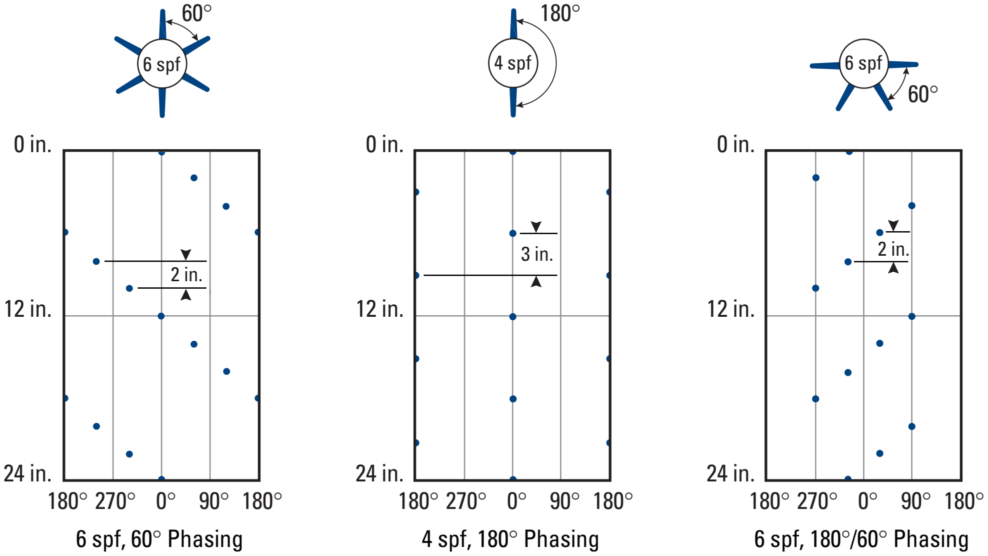

Figure 126. 2⅞-in. HSD shot patterns for 4½-in. casing.

3⅛-in. HSD Perforating Gun

The 3⅛-in. HSD guns are for operations in 4½- to 5½-in. casing but have applications in other completions where downhole restrictions limit gun size, including through-tubing, dual-completion, monobore, and extended-reach operations (Fig. 127 and Tables 51 and 52).

The 3⅛-in. HSD gun is ideal for sand control, which relies on phasing in combination with high shot density and big hole charges to maximize the AOF. The 3⅛-in. gun features 10 spf with 135°/45° phasing and uses PowerFlow charges, which do not produce the carrot associated with copper-lined big hole charges (Fig. 128). The gun's fin standoffs ensure that hole sizes are consistent on all sides of the casing. For special applications, other phasings and shot densities can be made upon request.

Guns can be conveyed using wireline, slickline, tubing, or coiled tubing. Multiple guns are aligned with intercarriers.

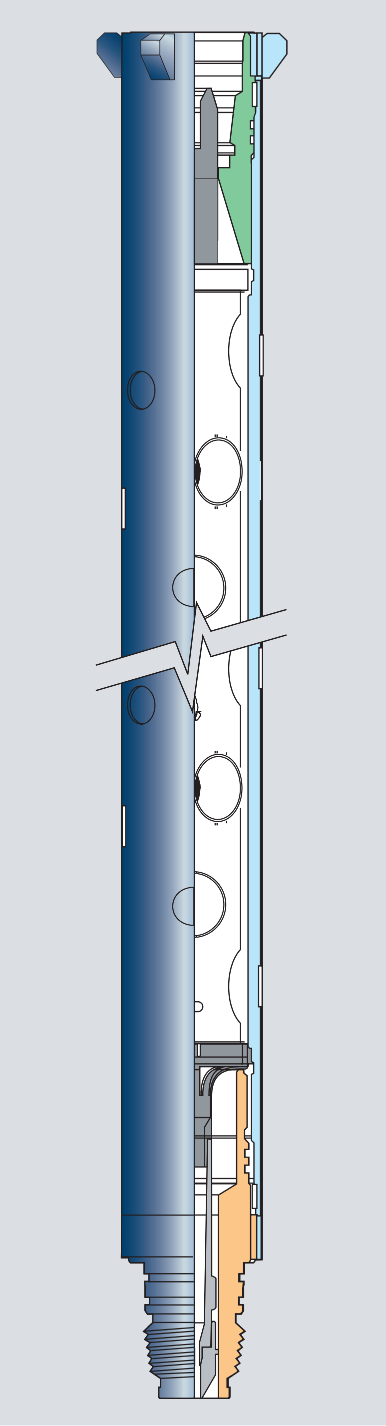

Figure 127. 3⅛-in. HSD gun, 10 spf, 135°/45° phasing.

Applications

- Natural, stimulated, and sand control completions
- Completion restrictions
- Deep penetration
- Multiple-interval perforating

Table 51. 3⅛-in. HSD Mechanical Specifications

Outside diameter (in.)	Nominal: 3⅛
	Across standoffs: 3.96
Shot density (spf), phasing (°)	5, 180; 6, 60; 10, 135/45
Shot spacing (in.)	5 spf: 2.4; 6 spf: 2; 10 spf: 1.2
Temperature rating (°F [°C])	400 [204]
Pressure rating (psi)	20,000
Min. casing size (in.)	4½
Max. diameter including burrs, shot in liquid[†] (in.)	3.45–3.57
Max. gun length (ft)	5, 10, 20
Interval missed between guns (in.)	12
Weight of loaded gun in air[†] (lbm)	272–292
Tensile load (lbf)	
Recommended	96,000
Min.	153,000
Max.	252,000

[†] Depends on gun configuration and charge type

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Table 52. 3⅛-in. HSD Performance Summary†

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.²/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
3⅛-in. HSD	6, 60	PowerJet Omega 3106, HMX	36.9	0.34	–	0.06/0.10	4½, 11.6
3⅛-in. HSD	6, 60	34JL UltraJet, HMX	24.0	0.41	–	0.07/0.11	4½, 11.6
3⅛-in. HSD	5, 0/180	34JL UltraJet, HMX	23.8	0.42	–	0.07/0.11	4½, 11.6

† API RP 43 5th edition or API 19B Section 1; blue type identifies API 19B Registered Perforation Systems.

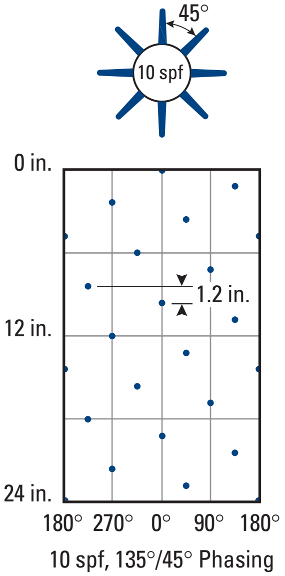

Figure 128. 3⅛-in. HSD shot pattern for 5-in. casing.

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3⅜-in. HSD Perforating Gun

The 3⅜-in. HSD guns are for operations in 4½- to 5½-in. casing but have applications in other completions where downhole restrictions limit gun size, including through-tubing, dual-completion, monobore, and extended-reach operations (Fig. 129 and Tables 53 and 54).

The standard 3⅜-in. gun has a 60° spiral hole pattern and can be loaded with a choice of charges up to 6 spf (Fig. 130). Also available is a 4-spf 180°-phased gun. For sand control, the 3⅜-in. gun can be used at 12 spf with 135°/45° phasing and PowerFlow charges. Shot density of 6 spf and 99° phasing or the ±25°-phased gun for horizontal wells is ideal for sand prevention.

Guns can be conveyed using wireline, slickline, tubing, or coiled tubing. Multiple guns are aligned with intercarriers.

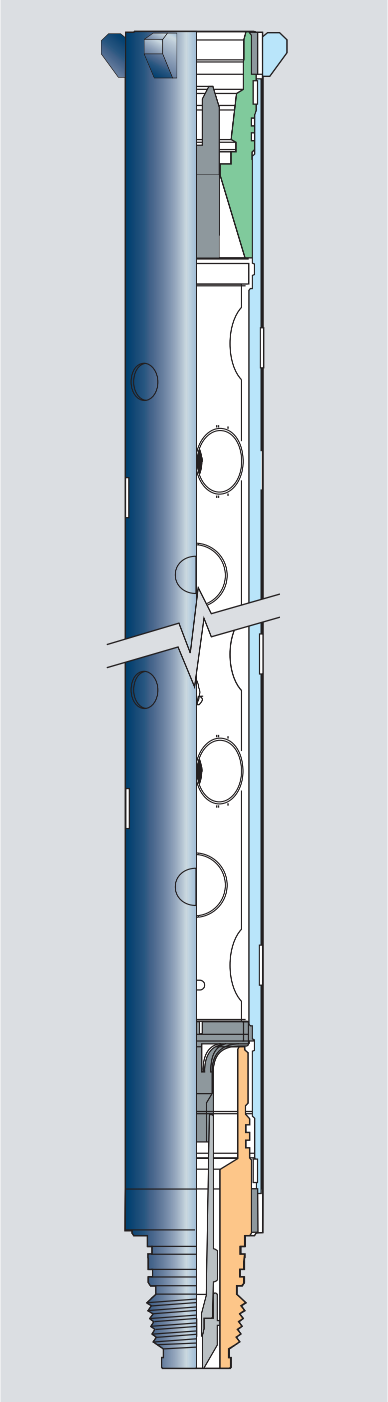

Figure 129. 3⅜-in. HSD gun, 12 spf, 135°/45° phasing.

Applications

- Natural, stimulated, and sand control completions
- Completion restrictions
- Deep penetration
- Multiple-interval perforating

Table 53. 3⅜-in. HSD Mechanical Specifications

Outside diameter (in.)	Nominal: 3⅜ Across standoffs: 4.40
Shot density (spf), phasing (°)	4, 60; 4, 180; 4, 50/25; 5, 180; 6, 60; 6, 99; 12, 135/45
Shot spacing (in.)	4 spf: 3; 5 spf: 2.4; 6 spf: 2; 12 spf: 1
Temperature rating (°F [°C])	500 [260]†, ‡
Pressure rating (psi)	20,000‡
Min. casing size (in.)	4½
Max. diameter including burrs, shot in liquid/gas§ (in.)	3.56–3.66/3.76–3.77
Max. gun length (ft)	5, 10, 20, 30
Interval missed between guns (in.)	12
Weight of loaded 20-ft gun in air§ (lbm)	327–332
Tensile load (lbf)	
Recommended	103,000
Min.	165,000
Max.	274,000

† With high-temperature explosives and seals
‡ PEGS verified
§ Depends on gun configuration and charge type

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Table 54. 3⅜-in. HSD Performance Summary[†]

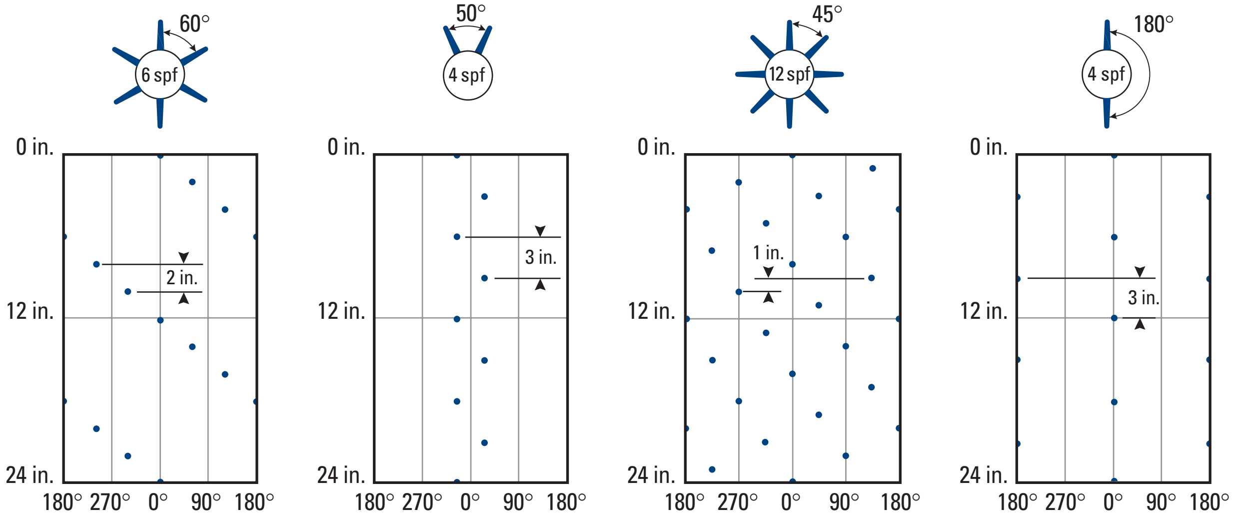
Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^{2}/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
3⅜-in. HSD[‡]	6, 60	PowerJet 3406, HMX	36.5	0.37	–	0.06/0.09	4½, 11.6
3⅜-in. HSD[‡]	6, 60	PowerJet 3406, HNS	26.8	0.31	–	0.05/0.10	4½, 11.6
3⅜-in. HSD[‡]	6, 60	UltraJet 3406, HMX	31.4	0.44	–	0.06/0.13	4½, 11.6
3⅜-in. HSD[‡]	6, 60	HyperJet 3406, RDX	23.5	0.49	–	0.05/0.12	4½, 11.6
3⅜-in. HSD[‡, §]	21, 120/60	PowerJet 2006, HMX	16.2	0.18	–	na	5½, 17.0
3⅜-in. HSD[‡]	6, 60	34B CleanSHOT, RDX	18.5	0.31	–	0.04/0.08	4½, 11.6
3⅜-in. HSD[‡]	6, 60	34B HyperJet II, RDX	21.9	0.40	–	0.05/0.09	4½, 11.6
3⅜-in. HSD[‡, §]	6, 99	34B HyperJet II, RDX	20.2	0.38	–	na	5½, 17.0
3⅜-in. HSD[‡]	6, 60	34JL UltraJet, HMX	28.9	0.37	–	0.06/0.09	4½, 11.6

na = not available

[†] API RP 43 5th edition or API 19B Section 1; blue type identifies API 19B Registered Perforation Systems.

[‡] Also available in 3½- and 3.67-in. perforating systems

[§] Unofficial API data



6 spf, 60° Phasing

4 spf, U50

12 spf, 135°/45° Phasing, 5½-in. casing

4 spf, 180° Phasing

Figure 130. 3⅜-in. HSD shot patterns for 4½- and 5½-in. casing.

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3½-in. HSD Perforating Gun

The 3½-in. HSD guns are for operations in 5- to 5½-in. casing but have applications in other completions where downhole restrictions limit gun size, including through-tubing, dual-completion, monobore, and extended-reach operations (Fig. 131 and Tables 55 and 56).

The standard 3½-in. gun has a 60° spiral hole pattern and can be loaded with a choice of charges at 4, 5, or 6 spf according to the job design (Fig. 132). Other phasings and shot densities can be made upon request.

Guns can be conveyed using wireline, slickline, tubing, or coiled tubing. Multiple guns are aligned with intercarriers.

Applications

- Natural, stimulated, and sand control completions
- Completion restrictions
- Deep penetration
- Multiple-interval perforating

Table 55. 3½-in. HSD Mechanical Specifications

Outside diameter (in)	3½
Shot density (spf), phasing (°)	4, 60; 4, 180
	6, 60; 6, 72
Shot spacing (in.)	4 spf: 3
	6 spf: 2
Temperature rating (°F [°C])	500 [204][†]
Pressure rating (psi)	25,000
Min. casing size (in.)	5
Max. diameter including burrs, shot in liquid (in.)	3.72
Max. gun length (ft)	5, 10, 20, 30
Interval missed between guns (in.)	4 spf, 60° and 6 spf, 180°: 15
	6 spf, 60°: 12
Weight of loaded 20-ft gun (lbm)	378
Tensile load (lbf)	
Recommended	144,000
Min.	230,000
Max.	334,000

[†] With high-temperature explosives and seals

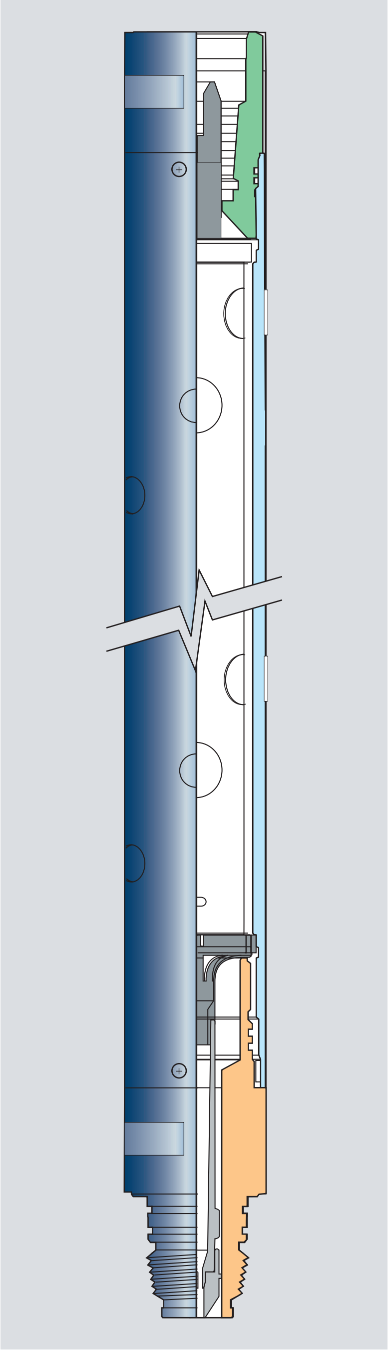

Figure 131. 3½-in. HSD gun, 4 spf, 60° phasing.

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Table 56. 3½-in. HSD Performance Summary[†, ‡]

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF ($in.^2/ft$)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
3½-in. HSD	6, 72	PowerJet Omega 3506, HMX	44.2	0.44	–	0.06/0.14	5, 15.0

[†] Blue type identifies API 19B Registered Perforation System.

[‡] See Table 54 for 3⅜-in. HSD gun systems that are also available as 3½- and 3.67-in. systems.

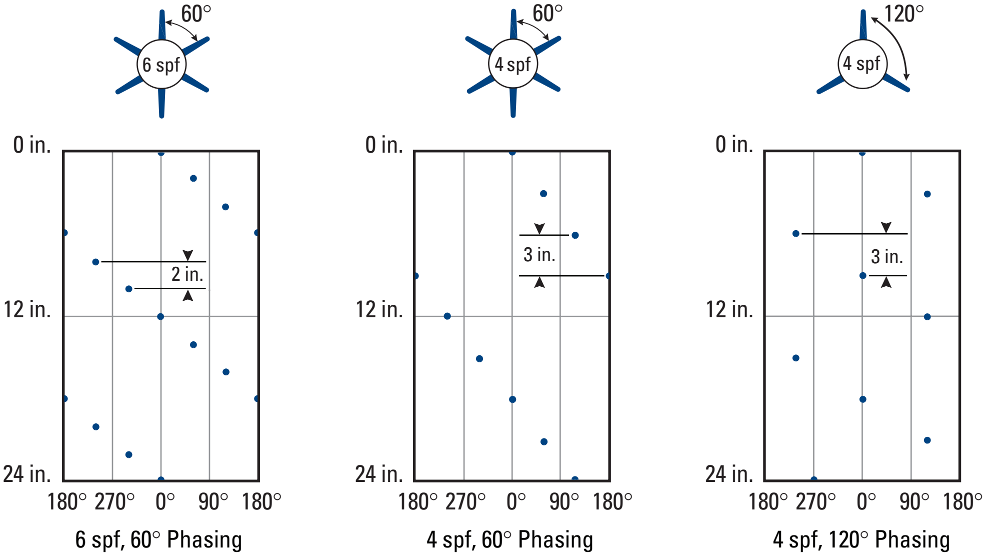

Figure 132. 3½-in. HSD shot patterns for 5-in. casing.

3.67-in. HSD Perforating Gun

The 3.67-in. HSD guns are for operations in 5- to 5½-in. casing but have applications in other completions where downhole restrictions limit gun size, including through-tubing, dual-completion, monobore, and extended-reach operations (Fig. 133 and Tables 57 and 58).

The standard 3.67-in. gun has a 60° spiral hole pattern and can be loaded with a choice of charges up to 5 spf (Fig. 134). Other phasings and shot densities can be made upon request.

Guns can be conveyed using wireline, slickline, tubing, or coiled tubing. Multiple guns are aligned with intercarriers.

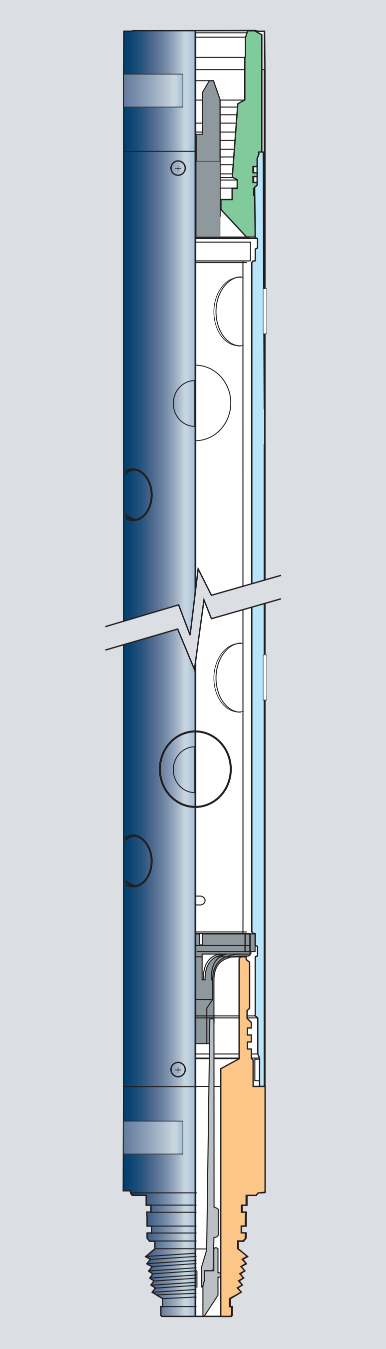

Figure 133. 3.67-in. HSD gun, 6 spf, 60° phasing.

Applications

- Natural, stimulated, and sand control completions
- Completion restrictions
- Deep penetration
- Multiple-interval perforating

Table 57. 3.67-in. HSD Mechanical Specifications

Outside diameter (in.)	3.67
Shot density (spf), phasing (°)	5, 60
	6, 60
Shot spacing (in.)	5 spf: 2.4
	6 spf: 2
Temperature rating (°F [°C])	500 [260]†
Pressure rating (psi)	25,000
Min. casing size (in.)	5
Max. diameter including burrs, shot in liquid/gas (in.)	3.96/4.01
Max. gun length (ft)	5, 10, 20, 30
Interval missed between guns (in.)	16.4
Weight of loaded 20-ft gun in air (lbm)	443
Tensile load (lbf)	
Recommended	219,000
Min.	351,000
Max.	437,000

† With high-temperature explosives and seals

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Table 58. 3.67-in. HSD Performance Summary[†, ‡]

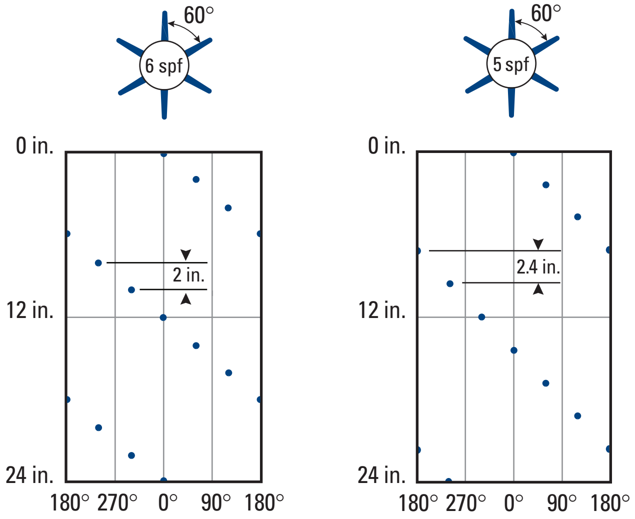
Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^{2}/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
3.67-in. HSD	5, 60	37J CleanSHOT, RDX	31.2	0.36	–	0.05/0.08	5, 15.0
3.67-in. HSD[§]	5, 60	37J CleanSHOT, HMX	32.7	0.38	–	na	5, 15.0

na = not available

[†] API RP 43 5th edition or API 19B Section 1

[‡] See Table 54 for 3⅜-in. HSD gun systems that are also available as 3½- and 3.67-in. systems.

[§] Unofficial API data



6 spf, 60° Phasing

5 spf, 60° Phasing

Figure 134. 3.67-in. HSD shot patterns for 5-in. casing.

Schlumberger

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4-in. HSD Perforating Gun

The 4-in. HSD guns are for operations in 5½-in. casing but have applications in larger completions where downhole restrictions limit gun size (Fig. 135 and Tables 59 and 60).

Available in a wide variety of shot densities and phasings (Fig. 136), the 4-in. HSD gun has 4-, 5-, and 6-spf versions.

Guns can be conveyed using wireline, slickline, tubing, or coiled tubing. Multiple guns are aligned with intercarriers.

Applications

- Natural, stimulated, and sand control completions
- Completion restrictions
- Deep penetration
- Multiple-interval perforating

Table 59. 4-in. HSD Mechanical Specifications

Outside diameter (in.)	4
Shot density (spf), phasing (°)	4, 60; 4, 72; 4, 180
	5, 72; 5, 180
	6, 60
Shot spacing (in.)	4 spf: 3
	5 spf: 2.4
	6 spf: 2
Temperature rating (°F [°C])	400 [204]†
Pressure rating (psi)	12,000
Min. casing size (in.)	5½
Max. diameter including burrs, shot in liquid (in.)	4.44
Max. gun length (ft)	5, 10, 20
Interval missed between guns (in.)	
PowerJet Omega 4005 charge	5 spf: 13.4
PowerJet 3406 or 4006 charge	5 spf: 11.6
Weight of loaded 20-ft gun in air (lbm)	421
Tensile load (lbf)	
Recommended	179,000
Min.	287,000
Max.	364,000

† With high-temperature explosives and seals

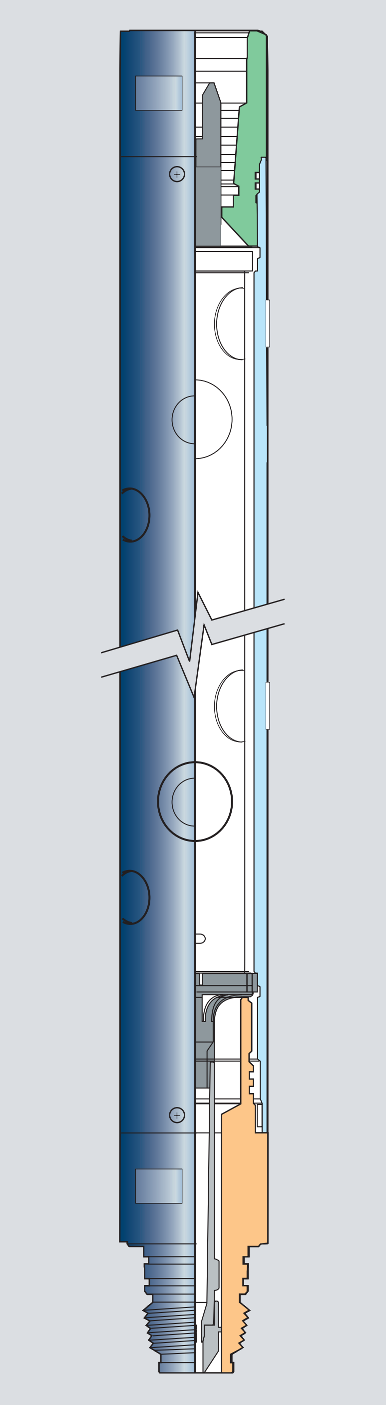

Figure 135. 4-in. HSD gun, 6 spf, 60° phasing.

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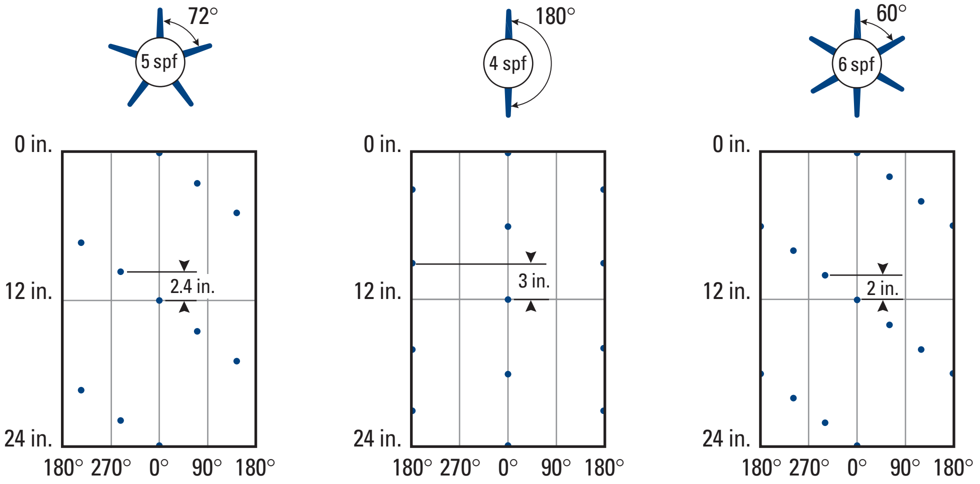
Table 60. 4-in. HSD Performance Summary[†]

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^{2}/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
4-in. HSD	5, 72	PowerJet Omega 4005, HMX	51.7	0.48	–	0.07/0.12	5½, 17.0
4-in. HSD[‡]	5, 0/180	PowerJet 4005, HMX	36.5	0.46	–	0.07/0.10	5½, 17.0

[†] API RP 43 5th edition or API 19B Section 1; blue type identifies API 19B Registered Perforation Systems.
[‡] Unofficial API data



5 spf, 72° Phasing
7-in. casing

4 spf, 180° Phasing
7-in. casing

6 spf, 60° Phasing
5½-in. casing

Figure 136. 4-in. HSD shot patterns for 5½- and 7-in. casing.

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4½-in. HSD Perforating Gun

The 4½-in. HSD guns are for operations in 7-in. casing but have applications in larger completions where downhole restrictions limit gun size (Fig. 137 and Tables 61 and 62).

Available in a wide variety of shot densities and phasings (Fig. 138), the 4½-in. HSD gun has a 12-spf option with 135°/45° phasing. Its use with deep penetrating charges is ideal for sand prevention. A 4-spf gun with 180° phasing is also available.

Guns can be conveyed using wireline, slickline, tubing, or coiled tubing. Multiple guns are aligned with intercarriers.

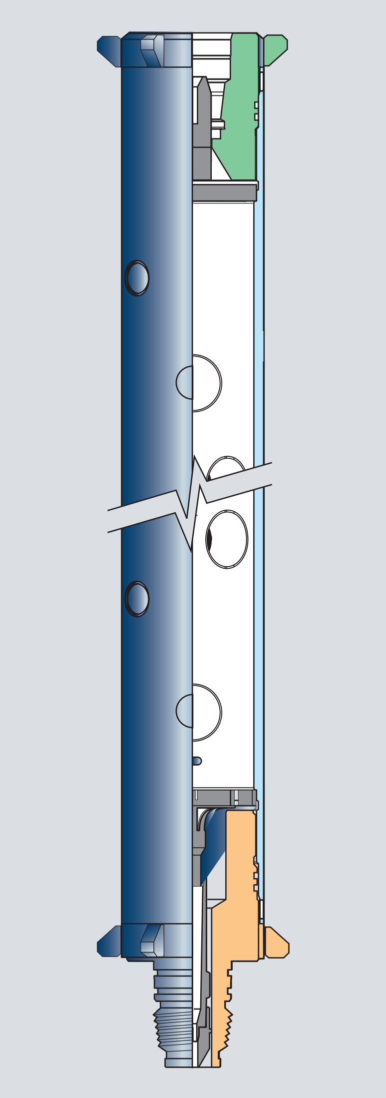

Figure 137. 4½-in. HSD gun, 12 spf, 135°/45° phasing.

Applications

- Natural, stimulated, and sand control completions
- Completion restrictions
- Deep penetration
- Multiple-interval perforating

Table 61. 4½-in. HSD Mechanical Specifications

Outside diameter (in.)	Nominal: 4½
	With fin standoffs: 5.75
Shot density (spf), phasing (°)	4, 0/180
	5, 72
	12, 135/45
Shot spacing (in.)	4 spf: 3
	5 spf: 2.4
	12 spf: 1
Temperature rating (°F [°C])	400 [204]†
Pressure rating (psi)	12,000
Min. casing size (in.)	6⅝
Max. diameter including burrs, shot in liquid‡ (in.)	4.74–4.91
Max. gun length (ft)	5, 10, 20
Interval missed between guns (in.)	12
Weight of loaded 20-ft gun in air‡ (lbm)	248–650
Tensile load (lbf)	
Recommended	135,000
Min.	217,000
Max.	357,000

† With high-temperature explosives and seals

‡ Depends on gun configuration and charge type

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Table 62. 4½-in. HSD Performance Summary[†]

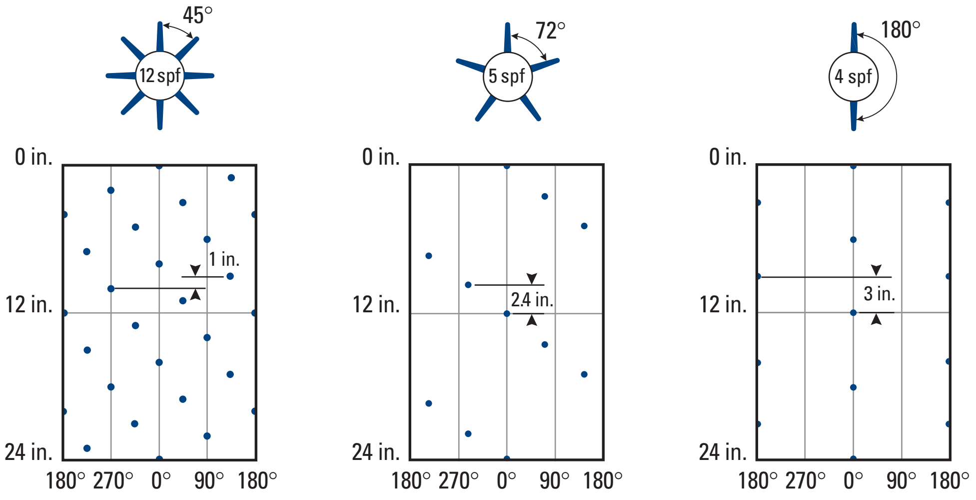
Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF ($in.^2$/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
4½-in. HSD	5, 72	PowerJet Omega 4505, HMX	59.2	0.43	–	0.08/0.11	7, 32.0
4½-in. HSD	5, 72	PowerJet 4505, HMX	46.4	0.47	–	0.08/0.15	7, 32.0
4½-in. HSD[§]	4, 0/180	PowerJet 4505, HMX	50.1	0.36	–	na	7, 32.0
4½-in. HSD	12, 135/45	PowerJet 4512, HMX	30.2	0.34	–	0.07/0.12	7, 32.0
4½-in. HSD	12, 135/45	PowerJet Omega 4512, HMX	34	0.35	–	0.07/0.12	7, 32.0
4½-in. HSD	5, 72	UltraJet 4505, HMX	42.6	0.46	–	0.08/0.13	7, 32.0
4½-in. HSD	5, 72	HyperJet 4505, RDX	37.0	0.57	–	0.11/0.16	7, 32.0
4½-in. HSD	12, 135/45	34B HyperJet II, RDX	17.9	0.39	–	0.07/0.11	7, 32.0
4½-in. HSD	12, 135/45	34JL UltraJet, HMX	28.6	0.34	–	0.07/0.12	7, 32.0

na = not available

[†] API RP 43 5th edition or API 19B Section 1; blue type identifies API 19B Registered Perforation Systems.

[‡] Also available in 4⅝-, 4.72-, and 5-in. perforating systems

[§] Unofficial API data



12 spf, 135°/45° Phasing

5 spf, 72° Phasing

4 spf, 180° Phasing

Figure 138. 4½-in. HSD shot patterns for 7-in. casing.

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4⅝-in. HSD Perforating Gun

The 4⅝-in. HSD guns are for operations in 7-in. casing but have applications in larger completions where downhole restrictions limit gun size (Fig. 139 and Tables 63 and 64). Available in the same range of shot densities and phasings as the 4½-in. HSD gun (Fig. 140), the 4⅝-in. gun has a higher pressure rating.

Guns can be conveyed using wireline, slickline, tubing, or coiled tubing. Multiple guns are aligned with intercarriers.

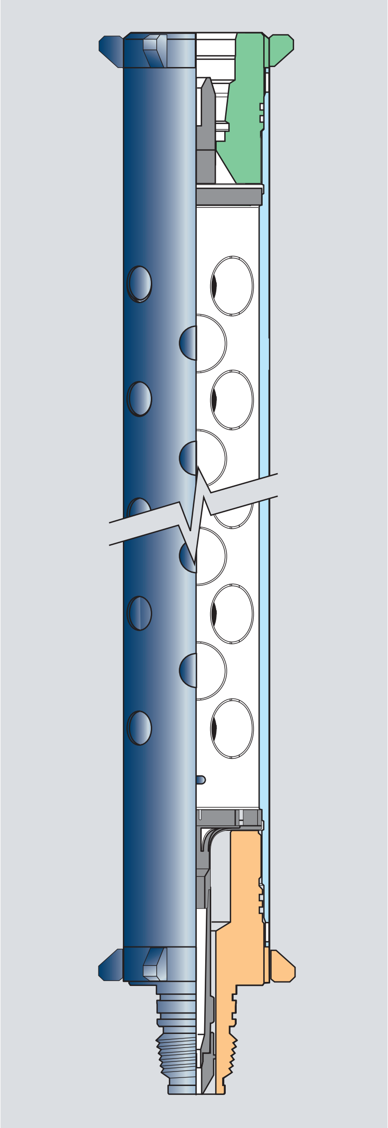

Figure 139. 4⅝-in. Bigshot 21 gun, 12 spf, 120°/60° phasing.

Applications

- Natural, stimulated, and sand control completions
- Deep penetration
- Multiple-interval perforating
- High-pressure operations

Table 63. 4⅝-in. HSD Mechanical Specifications

Outside diameter (in.)	4.62
	With fin standoffs: 5.75
Shot density (spf), phasing (°)	4, 180; 5, 72; 12, 135/45; Bigshot 21 gun: 21, 120/60
Shot spacing (in.)	4 spf: 3
	5 spf: 2.4
	12 spf: 1
	21 spf: 1.7
Temperature rating (°F [°C])	400 [204]†
Pressure rating (psi)	5-spf gun: 17,000
	12-spf gun: 16,000
	Bigshot 21 gun: 15,000
Min. casing size (in.)	7
Max. diameter including burrs, shot in liquid (in.)	4.82
Max. gun length (ft)	5, 10, 20
Interval missed between guns (in.)	12
	Bigshot 21 guns: 13
Weight of loaded 20-ft gun in air (lbm)	604
Tensile load (lbf)	
Recommended	207,000
Min.	331,000
Max.	452,000

† With high-temperature explosives and seals

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Table 64. 4⅝-in. HSD Performance Summary†, ‡

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.²/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
4.58-in. HSD Bigshot 21	21, 120/60	PowerJet 4521, HMX	21.0	0.32	–	0.06/0.11	7, 32.0

† API RP 43 5th edition or API 19B Section 1

‡ See Table 62 for 4½-in. HSD gun systems that are also available as 4⅝- and 4.72-in. systems.

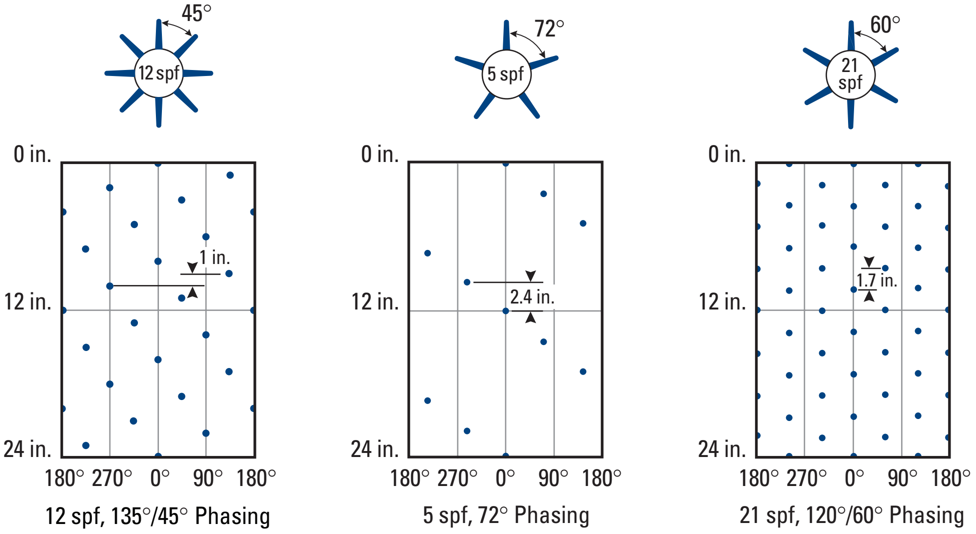

Figure 140. 4⅝-in. HSD shot patterns for 7-in. casing.

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4.72-in. HSD Perforating Gun

The 4.72-in. HSD guns are for operations in 7- and 7⅝-in. casing (Fig. 141 and Tables 65 and 66). Available in the same range of shot densities and phasings as the 4½- and 4.58-in. HSD guns (Fig. 142), the 4.72-in. gun has a higher pressure rating.

Guns can be conveyed using wireline, slickline, tubing, or coiled tubing. Multiple guns are aligned with intercarriers.

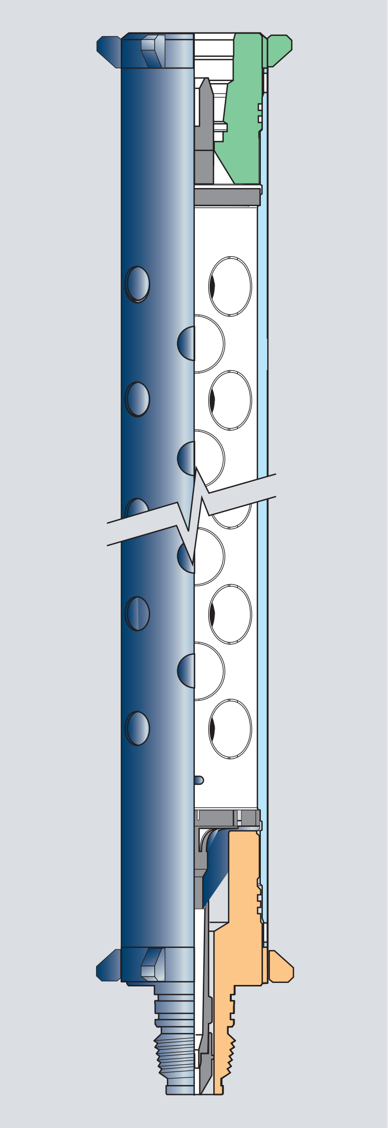

Figure 141. 4.72-in. Bigshot 21 gun, 21 spf, 120°/60° phasing.

Applications

- Natural, stimulated, and sand control completions
- Deep penetration
- Multiple-interval perforating
- High-pressure operations

Table 65. 4.72-in. HSD Mechanical Specifications

Outside diameter (in.)	4.72
	With fin standoffs: 5.75
Shot density (spf), phasing (°)	4, 180
	5, 72
	12, 135/45
	Bigshot 21 gun: 21, 120/60
Shot spacing (in.)	4 spf: 3
	5 spf: 2.4
	12 spf: 1
	Bigshot 21 gun: 1.7
Temperature rating (°F [°C])	500 [260]†
Pressure rating (psi)	20,000
	Bigshot 21 gun: 17,000
Min. casing size (in.)	7
Max. diameter including burrs, shot in liquid (in.)	4.99
Max. gun length (ft)	5, 10, 20
Interval missed between guns (in.)	12
	Bigshot 21 guns: 13
Weight of loaded 20-ft gun in air‡ (lbm)	592–652
Tensile load (lbf)	
Recommended	254,000
Min.	406,000
Max.	528,000

† With high-temperature explosives and seals
‡ Depends on gun configuration and charge type

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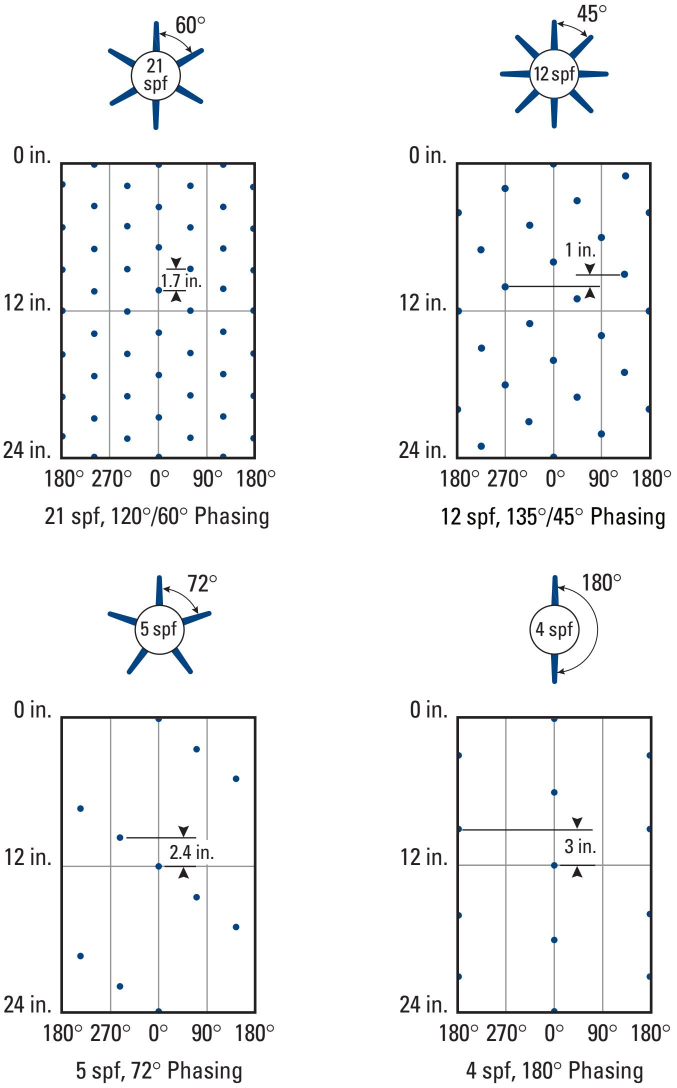
Table 66. 4.72-in. HSD Performance Summary[†, ‡]

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.²/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
4.72-in. HSD	5, 72	PowerJet 4505, HNS	34.4	0.40	–	0.06/0.10	7, 32.0
4.72-in. HSD	12, 135/45	PowerJet 4512, HNS	22.8	0.31	–	0.06/0.11	7, 32.0
4.72-in. HSD	12, 135/45	34B CleanSHOT, RDX	15.4	0.31	–	0.10/0.11	7, 32.0
4.72-in. HSD	5, 72	51J UltraJet, HNS	34.5	0.33	–	0.07/0.12	7, 32.0

[†] API RP 43 5th edition or API 19B Section 1; blue type identifies API 19B Registered Perforation Systems.

[‡] See Table 62 for 4½-in. HSD gun systems that are also available as 4⅝- and 4.72-in. systems.



21 spf, 120°/60° Phasing

12 spf, 135°/45° Phasing

5 spf, 72° Phasing

4 spf, 180° Phasing

Figure 142. 4.72-in. HSD shot patterns for 7-in. casing.

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5-in. HSD Perforating Gun

The 5-in. HSD guns are designed for operations in 7⅝-in. and lightweight 7-in. casing (Fig. 143 and Tables 67 and 68). The same range of shot densities and phasings as the 4½-, 4.58-, and 4.72-in. guns is available (Fig. 144).

Guns can be conveyed using wireline, slickline, tubing, or coiled tubing. Multiple guns are aligned with intercarriers.

Applications

- Natural, stimulated, and sand control completions
- Deep penetration
- Multiple-interval perforating

Table 67. 5-in. HSD Mechanical Specifications

Outside diameter (in.)	5.00
	With fin standoffs: 6.25
Shot density (spf), phasing (°)	5, 72
	8, 135/45; 8, 0/180
	12, 135/45
	Bigshot 21 gun: 21, 60
Shot spacing (in.)	5 spf: 2.4
	8 spf: 1.5
	12 spf: 1
Temperature rating (°F [°C])	400 [204]†
Pressure rating (psi)	11,000
Min. casing size (in.)	7⅝
Max. diameter including burrs, shot in liquid (in.)	5.19
Max. gun length (ft)	5, 10, 20
Interval missed between guns (in.)	13
Weight of loaded 20-ft gun in air (lbm)	593
Tensile load (lbf)	
Recommended	184,000
Min.	294,000
Max.	395,000

† With high-temperature explosives and seals

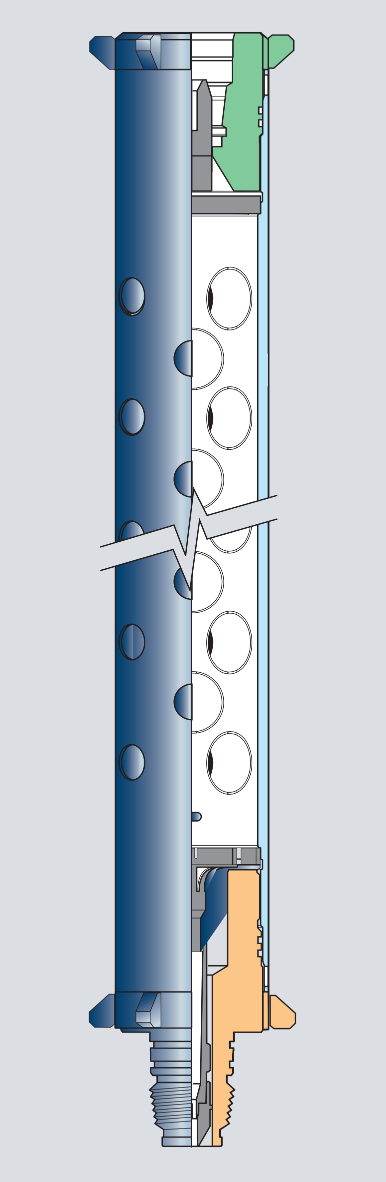


Figure 143. 5-in. Bigshot 21 gun, 21 spf, 120°/60° phasing.

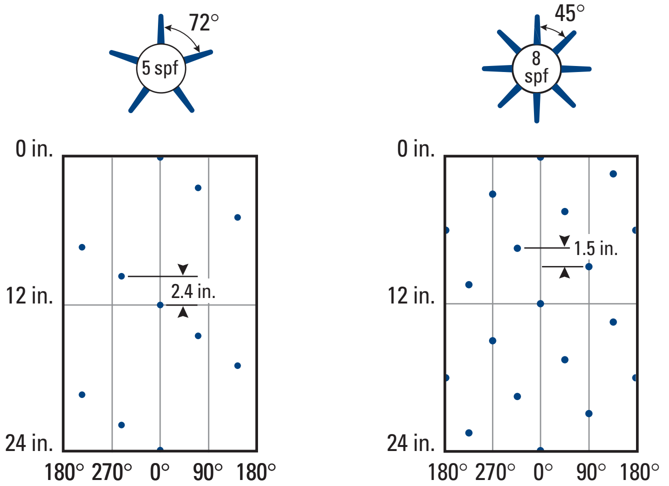
Table 68. 5-in. HSD Performance Summary[†]

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^2/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
5-in. HSD	8, 135/45	UltraJet 5008, RDX	20.2	0.54	–	0.11/0.22	7, 32.0
5-in. HSD[‡]	8, 0/180	UltraJet 5008, RDX	19.1	0.48	–	na	7, 32.0

na = not available

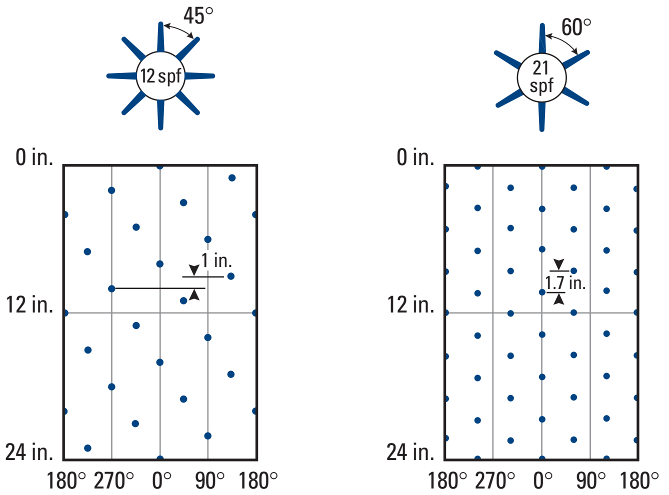
[†] API RP 43 5th edition or API 19B Section 1

[‡] Unofficial API data



5 spf, 72° Phasing

8 spf, 135°/45° Phasing



12 spf, 135°/45° Phasing

Bigshot 21 System
21 spf, 120°/60° Phasing

Figure 144. 5-in. HSD shot patterns for 7-in. casing.

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6⅝-in. HSD Perforating Gun

The 6⅝-in. HSD gun is used to perforate heavyweight 9⅝-in. and larger casing (Figs. 145 and 146 and Tables 69 and 70).

Perforating debris is limited by the patented loading technique, which causes the charge case to break into large pieces when the gun is fired. This debris is too large to exit the gun body.

The 6⅝-in. HSD guns are usually conveyed using tubing or coiled tubing but can also be run on wireline. Multiple guns are aligned with intercarriers.

Applications

- Natural, stimulated, and sand control completions
- Deep penetration
- Multiple-interval perforating

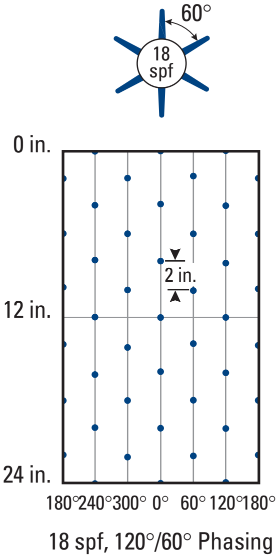

Figure 146. 6⅝-in. HSD shot pattern for 9⅝-in. casing.

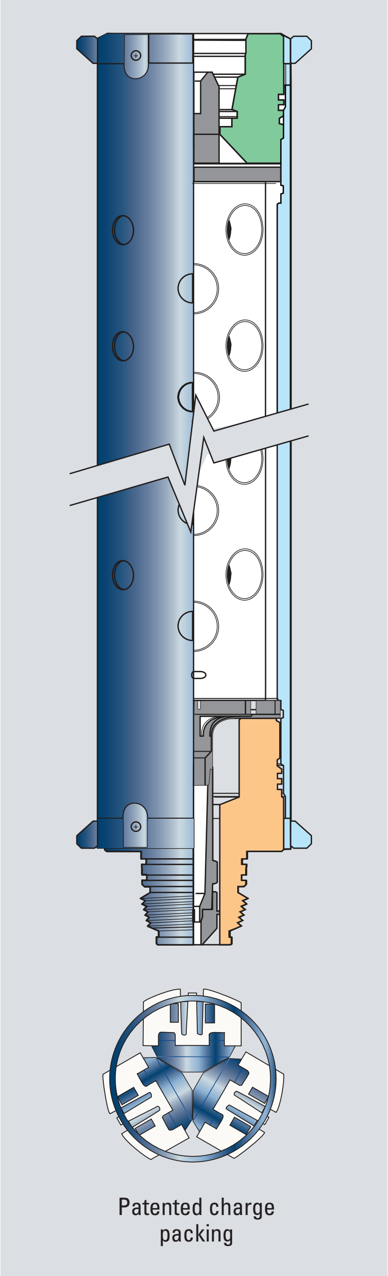

Figure 145. 6⅝-in. HSD gun, 18 spf, 120°/60° phasing.

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Table 69. 6⅝-in. HSD Mechanical Specifications

Outside diameter (in.)	6.625 With fin standoffs: 7.84
Shot density (spf), phasing (°)	18, 120/60
Shot spacing (in.)	2
Temperature rating (°F [°C])	400 [204][†]
Pressure rating (psi)	20,000
Min. casing size (in.)	9⅝
Max. diameter including burrs, shot in liquid[‡] (in.)	6.72–6.73
Max. gun length (ft)	5, 10, 20
Interval missed between guns (in.)	18
Weight of loaded 20-ft gun in air (lbm)	1,310
Tensile load (lbf)	
Recommended	549,000
Min.	878,000
Max.	1,123,000

[†] With high-temperature explosives and seals
[‡] Depends on gun configuration and charge type

Table 70. 6⅝-in. HSD Performance Summary[†]

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^{2}/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
6⅝-in. HSD	18, 120/60	PowerFlow 6618, HMX	6.8	0.91	11.7	0.13/0.24	9⅝, 47.0
6⅝-in. HSD[‡]	18, 120/60	PowerFlow 6618, HMX	8.1	0.85	10.2	na	9⅝, 70.3

na = not available
[†] API RP 43 5th edition or API 19B Section 1; blue type identifies API 19B Registered Perforation Systems.
[‡] Unofficial API data in Q125 casing

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7-in. HSD Perforating Gun

The 7-in. HSD guns are for operations in 9⅝-in. and larger casing (Figs. 147 and 148 and Tables 71 and 72).

Perforating debris is limited by the patented loading technique, which causes the charge case to break into large pieces when the gun is fired. This debris is too large to exit the gun body.

The 7-in. HSD guns are usually conveyed using tubing or coiled tubing but can also be run on wireline. Multiple guns are aligned with intercarriers.

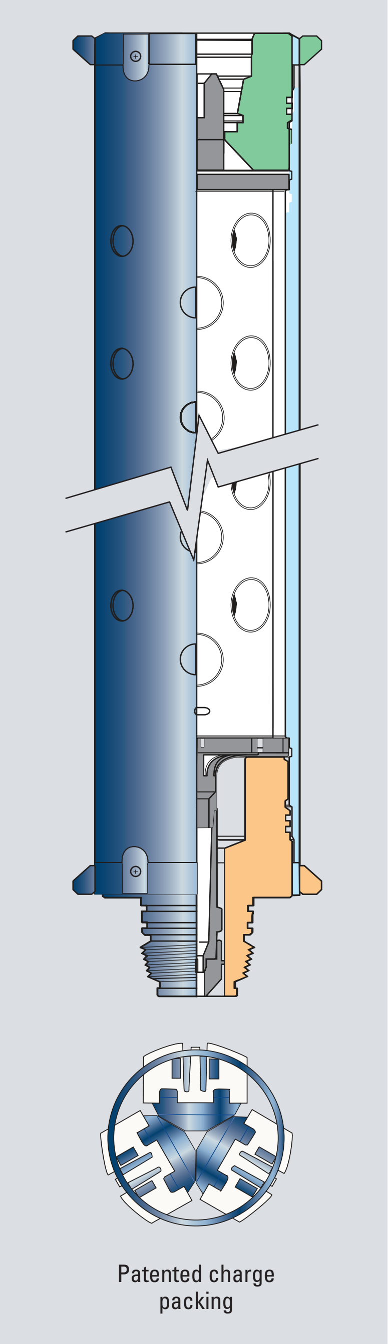

Figure 147. 7-in. HSD gun, 18 spf, 120°/60° phasing.

Applications

- Natural, stimulated, and sand control completions
- Deep penetration
- Multiple-interval perforating
- High-pressure operations

Table 71. 7-in. HSD Mechanical Specifications

Outside diameter (in.)	7 With fin standoffs: 8.25
Shot density (spf), phasing (°)	12, 135/45
	18, 120/60
	27, 120/60
Shot spacing (in.)	12 spf: 1
	18 spf: 2
	27 spf: 1.33
Temperature rating (°F [°C])	400 [204]†
Pressure rating (psi)	10,000
Min. casing size (in.)	9⅝
Max. diameter including burrs, shot in liquid‡ (in.)	7.05–7.50
Max. gun length (ft)	5, 10, 20
Interval missed between guns (in.)	12
Weight of loaded 20-ft gun in air‡ (lbm)	1,210–1,245
Tensile load (lbf)	
Recommended	279,000
Min.	447,000
Max.	791,000

† With high-temperature explosives and seals
‡ Depends on gun configuration and charge type

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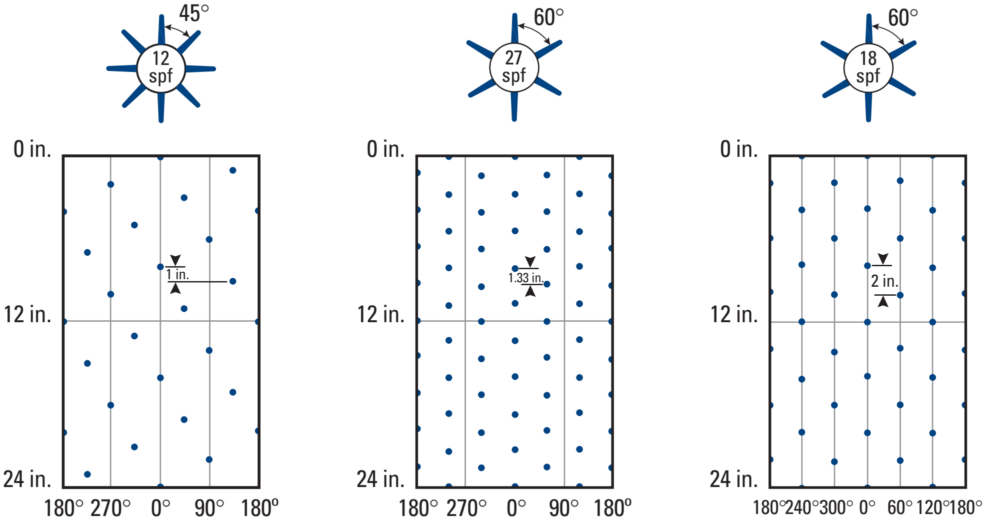
Table 72. 7-in. HSD Performance Summary†

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^{2}/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
7-in. HSD	12, 135/45	PowerJet Omega 4505, HMX	53.2	0.43	–	0.08/0.16	9⅝, 47.0
7-in. HSD	12, 135/45	PowerJet 4505, HMX	43.6	0.44	–	0.08/0.15	9⅝, 47.0
7-in. HSD	12, 135/45	UltraJet 4505, HMX	39.9	0.45	–	0.08/0.16	9⅝, 47.0
7-in. HSD	27, 120/60	PowerJet Omega 7027, HMX	35.5	0.29	–	0.05/0.09	9⅝, 47.0
7-in. HSD	27, 120/60	34JL UltraJet, HMX	26.0	0.27	–	0.05/0.11	9⅝, 47.0
7-in. HSD	12, 135/45	51B HyperJet II, RDX	32.0	0.47	–	0.08/0.14	9⅝, 47.0

† API RP 43 5th edition or API 19B Section 1; blue type identifies API 19B Registered Perforation Systems.



12 spf, 135°/45° Phasing

27 spf, 120°/60° Phasing

18 spf, 120°/60° Phasing

Figure 148. 7-in. HSD shot patterns for 9⅝-in. casing.

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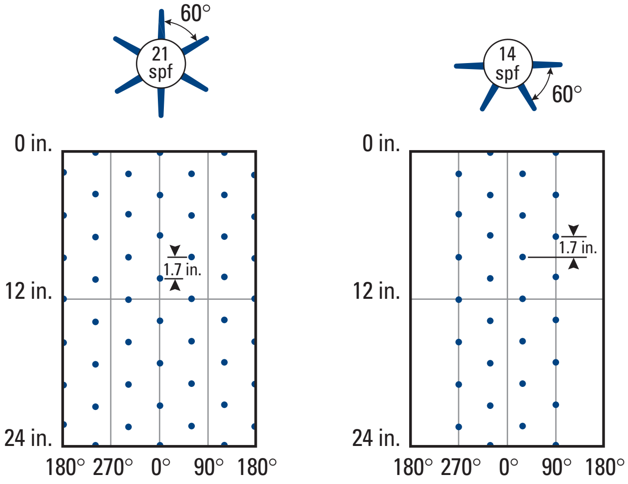
HSD and Bigshot 21 Big Casing Entrance Hole Perforating Guns

HSD and Bigshot 21 perforating guns can be loaded with big hole shaped charges and configured to produce large-diameter perforations. Maximizing the AOF of the perforations is typically used in sand control completions to facilitate the placement of the gravel pack (Figs. 149 and 150 and Table 73).

The mechanical specifications for the various guns are as listed for each HSD gun size previously in this chapter.

Applications

- Sand control
- Gravel-pack completions
  - Frac and pack
  - High-rate water pack



Bigshot 21 System
21 spf, 120°/60° Phasing

Bigshot 21 System
14 spf, 180°/60° Phasing

Figure 150. Bigshot 21 shot pattern in 7-in. casing.

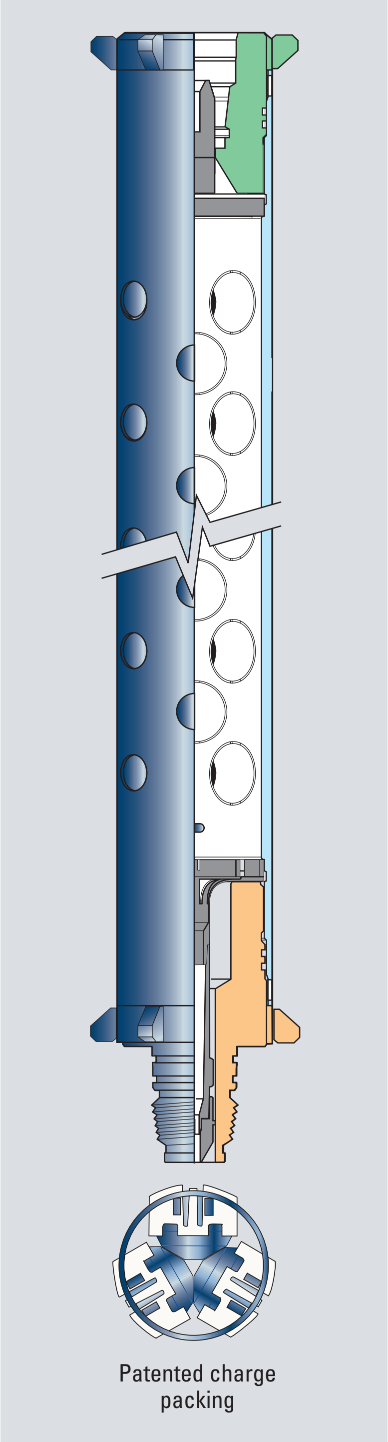


Figure 149. Bigshot 21 gravel-pack gun.

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Table 73. HSD Big Entrance Hole and Bigshot 21 Performance Summary[†]

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^{2}/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
2-in. HSD	6, 60	PowerFlow 2006, HMX	4.5	0.45	0.95	0.06/0.12	3½, 9.2
2-in. HSD	6, 60	UltraPack 2006, HMX	4.5	0.39	0.72	0.04/0.08	2⅞, 6.4
2¼-in. HSD	6, 60	PowerFlow 2306, HMX	4.8	0.52	1.27	0.07/0.11	3½, 9.2
2½-in. HSD	6, 60	PowerFlow 2506, HMX	5.2	0.64	1.93	0.08/0.12	3½, 9.2
2½-in. HSD	6, 60	35B UltraPack, RDX	5.8	0.62	1.81	0.06/0.12	3½, 9.2
2⅞-in. HSD	6, 60	38C CleanPACK*, HMX	6.6	0.70	2.31	0.06/0.08	4½, 11.6
2⅞-in. HSD	6, 60	38C CleanPACK, RDX	8.4	0.62	1.81	0.09/0.13	4½, 11.6
3⅛-in. HSD	10, 135/45	PowerFlow 3412, HMX	4.7	0.67	3.53	0.09/0.13	5, 15.0
3⅛-in. HSD	10, 135/45	38C UltraPack, RDX	5.0	0.63	3.15	0.08/0.11	5, 15.0
3⅜-in. HSD[‡]	12, 135/45	PowerFlow 3412, HMX	4.5	0.64	3.86	0.07/0.10	5½, 17.0
4-in. HSD	5, 120	PowerFlow 5008, RDX	6.3	0.95	3.55	0.09/0.12	5½, 17.0
4½-in. HSD	6, 120	PowerFlow 5008, RDX	6.0	0.93	4.08	0.12/0.18	7, 32.0
4⅝-in. HSD Bigshot 21[§]	21, 120/60	PowerFlow 4621, RDX	5.9	0.83	11.3	0.13/0.24	7, 32.0
4⅝-in. HSD Bigshot 21[§]	21, 120/60	PowerFlow 4621, HMX	6.1	0.83	11.3	0.15/0.28	7, 32.0
5-in. HSD	8, 135/45	PowerFlow 5008, RDX	5.8	0.98	6.05	0.11/0.22	7, 32.0
5-in. HSD Bigshot 21	21, 120/60	43CJ UltraPack II, RDX	7.9	0.74	9.03	0.12/0.20	7⅝, 33.7
5.85-in. HSD[††]	18, 120/60	PowerFlow 5918, HMX	7.2	0.93	12.2	0.24/0.48	8⅝, 56.6[‡‡]
6.625-in. HSD	18, 120/60	PowerFlow 6618, HMX	6.8	0.91	11.7	0.13/0.24	9⅝, 47.0
6.625-in. HSD[††]	18, 120/60	PowerFlow 6618, HMX	8.1	0.85	10.2	na	9⅝, 70.3[‡‡]
7-in HSD	18, 120/60	PowerFlow 7018, RDX	7.4	1.15	18.7	0.16/0.22	9⅝, 47.0
7-in HSD	18, 120/60	PowerFlow 7018, HMX	7.1	1.14	18.53	0.13/0.21	9⅝, 47.0
7-in HSD	14, 140/20	58C UltraPack, RDX	12.2	0.95	9.92	0.12/0.23	9⅝, 47.0
7-in HSD	12, 135/45	64C CleanPACK, RDX	10.1	1.13	11.41	0.10/0.22	9⅝, 47.0

na = not available

[†] API RP 43 5th edition or API 19B Section 1; blue type identifies API 19B Registered Perforation Systems.

[‡] Also available in 3½- and 3.67-in. perforating systems

[§] Also available in 4.72- and 5-in. perforating systems

[††] Unofficial API data

[‡‡] Q125 casing

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PURE Perforating System for Clean Perforations

The PURE perforating system (see the “Perforation Damage and Cleanup” chapter) optimizes the dynamic underbalance through job-specific designs to clean perforations much more effectively than conventional methods of underbalanced perforating (Tables 74 and 75). The result is significantly improved production or injection.

PURE perforating gun

PURE perforating integrates proprietary software and hardware to design specific PURE perforating systems for each perforating job. Any method of conveyance can be used.

Applications

- Wireline or tubing-conveyed perforating
- Perforating long intervals with varying permeability

Table 74. PURE Mechanical Specifications

Outside Diameter (in.)	**2**	**2½**	**2⅞**	**3⅜**	**3½**	**4½**	**4½**	**7**
Shot density (spf), phasing (°)	5.5, 60	5.5, 60	5.5, 60	5.5, 60	5.5, 60	11.5, 135/45	4.5, 72	11.5, 135/45
Shot spacing (in.)	2	2	2	2	2	1	2	1
Temperature rating (°F [°C])	400 [204]	400 [204]	400 [204]	400 [204]	400 [204]	400 [204]	400 [204]	400 [204]
Pressure rating (psi)	20,000	25,000	25,000	20,000	25,000	12,000	12,000	10,000
Min. casing size (in.)	2⅞	3½	4½	4½	5	6⅝	6⅝	9⅝
Max. diameter including burrs, shot in liquid (in.)	2.26	2.59–2.78	3.07	3.75	3.72	4.87	4.83	7.28
Interval missed between guns (in.)	13	12.5	12	12	12	12	12	12
Weight of loaded 20-ft gun in air (lbm)	119	179	237	332	292	501	446	1,245
Max. tensile load (lbf)	63,000	81,000	105,000	150,000	200,000	150,000	150,000	500,000

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Table 75. PURE Performance Summary†

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)
2-in. PURE	5.5, 60	PowerJet	18.6	0.20
2-in. PURE	5.5, 60	PowerJet Omega	21.8	0.22
2½-in. PURE	5.5, 60	PowerJet	18.7	0.34
2½-in. PURE	5.5, 60	PowerJet Omega	30.6	0.32
2⅞-in. PURE	5.5, 60	PowerJet	25.3	0.38
2⅞-in. PURE	5.5, 60	PowerJet Omega	36.0	0.34
3⅜-in. PURE	5.5, 60	PowerJet	36.5	0.37
3½-in. PURE	5.5, 60	PowerJet Omega	44.2	0.44
4½-in. PURE	11.5, 135/45	PowerJet	30.2	0.34
4½-in. PURE	11.5, 135/45	PowerJet Omega	34.0	0.35
4½-in. PURE	4.5, 72	PowerJet	46.4	0.47
4½-in. PURE	4.5, 72	PowerJet Omega	59.2	0.43
7-in. PURE	11.5, 135/45	PowerJet	43.6	0.44
7-in. PURE	11.5, 135/45	PowerJet Omega	53.2	0.43

† Unofficial API RP 43 5th edition or API 19B Section 1; area open to flow available on request, specific per job design

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OrientXact Tubing-Conveyed Oriented Perforating System

Meeting technical challenges in perforating horizontal and deviated wells

Attempts at oriented perforating of horizontal and deviated wells with conventional systems could be as much as 45° out of the desired orientation, with significant decreases in productivity. Caliper logs showed that deviation of the perforation cavities from the optimum orientation was most evident wherever there were changes in the direction of the wellbore, no matter how small.

Decreased productivity has also been attributed to perforating with zinc charges. Zinc-cased charges provide less penetration and produce powdery zinc detonation by-products that combine with chlorides and formation fluids in the wellbore. Severe reductions in permeability can result in addition to mechanical problems that restrict flow through the downhole chokes.

The Schlumberger OrientXact system meets the challenges of perforating horizontal and highly deviated wells by providing effective orienting that performs independently of tortuosity and produces little debris to avoid significantly reducing formation productivity. This innovative system has applications for perforating long horizontal wells, protecting the formation, increasing productivity, and managing sand production.

OrientXact optimized perforating system

The OrientXact perforating system is deployed on tubing, coiled tubing, or drillpipe for underbalanced perforating of long intervals simultaneously.

The OrientXact system is designed with a shot density of 4 to 5 spf and 20° phasing between the charges at ±10° from vertical (Figs. 151 and 152 and Tables 76 and 77). For high-angle and horizontal wells where the angle between the wellbore and the maximum stress direction is greater than 75°, the effective phasing and ±10° orientation accuracy of the charges produce perforation cavities within 10° of the maximum stress direction as needed to prevent sand production.

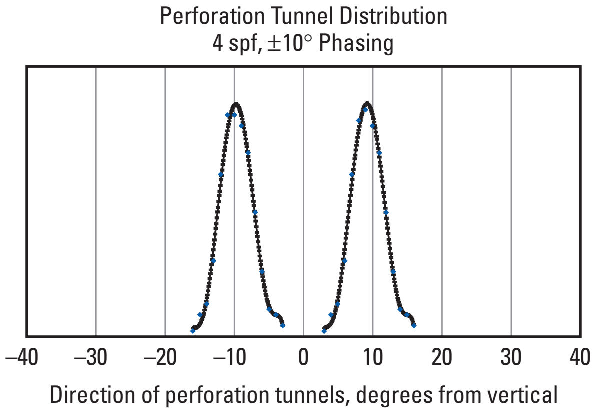

Figure 151. Extensive laboratory and field testing shows that the OrientXact system reliably shoots within 10° of the oriented position.

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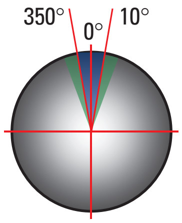

Figure 152. The OrientXact system features a shot density of 4 to 5 spf and 10° phasing from true vertical with a tolerance of ±10°.

Table 76. OrientXact Mechanical Specifications

Outside diameter (in.)	2.88	3.38	3.50	4.50	4.72
Shot density (spf), phasing (°)	4, 0/180 ± 10 5, 10/350 5, 0/180	4, 10/350 5, 10/350 5, 0/180	4, 10, 350 5, 10/350 5, 0/180	4, 10/350 4, 0/180 4, 0/180 ±10	4, 10/350 4, 0/180 4, 0/180 ±10
Shot spacing (in.)	4 spf: 3	4 spf: 3	4 spf: 3	3	3
	5 spf: 2.4	5 spf: 2.4	5 spf: 2.4		
Temperature rating[†] (°F [°C])	330 [165]	330 [165]	330 [165]	330 [165]	330 [165]
Pressure rating[‡] (psi)	20,000	20,000	20,000	10,000	20,000
Min. casing size (in.)	5½	5½	5½	7	7
Max. diameter including burrs, shot in liquid/gas (in.)	3.19/3.20	na/3.78	na/4.04	4.74/4.77	4.99/5.01
Max. gun length (ft)	10, 20, 30	10, 20, 30	10, 20, 30	10, 20, 30	10, 20, 30
Interval missed between guns (in.)	5 spf: 25.4	5 spf: 25.4	5 spf: 25.4	26.1	26.1
Weight of loaded 20-ft gun in air (lbm)	296	438	444	650	795
Max. tensile load (lbf)					
Bend angle	na	170,000	na	240,000	375,000
No bend	124,000	na	165,000	165,000	na

na = not available
[†] For 100 hr
[‡] At 400 degF

Table 77. OrientXact Performance Summary[†]

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^{2}/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
2.88-in. OrientXact[‡]	5, ±10	PowerJet OX 2905, HMX	26.2	0.21	–	na	5½, 17.0
3.38-in. OrientXact	5, ±10	PowerJet OX 3505, HMX	37.7	0.34	1.52	0.06/0.07	5½, 17.0
4.50-in. OrientXact	4, ±10	PowerJet OX 4504, HMX	43.8	0.29	1.58	0.06/0.08	7, 32.0

na = not available
[†] API RP 43 5th edition or API 19B Section 1; blue type identifies API 19B Registered Perforation Systems.
[‡] Unofficial API data

System components

The OrientXact system can be assembled in individual sections of more than 1,000 ft that are connected between high-load-capacity, low-friction swivels and maintain an alignment and orientation tolerance within 10° of nominal. The aligning and orienting hardware (Fig. 153) uses weighted spacers and aligning adapters to lock individual components to each other in the desired configuration.

- Aligning and locking adapters—Adapters lock carriers to each other and eliminate all rotational clearances from manufacturing tolerances in the locking features.
- Carriers, loading tubes, and weighted spacers—Carriers and spacers are manufactured to be independent of the different trajectories of the wellbore for aligned and oriented perforating. The carriers and weighted spacers bend uniformly in dogleg severities of more than 10° per 100 ft of wellbore length. The weighted spacer design eliminates any tendency for these components to try to rotate the string off axis when the string is bent. After the shot, the weighted spacer assemblies continue to provide orientation torque. This keeps the carrier exit holes along the top side of the assembly and minimizes the likelihood of debris inside the carriers falling out during retrieval of the string.

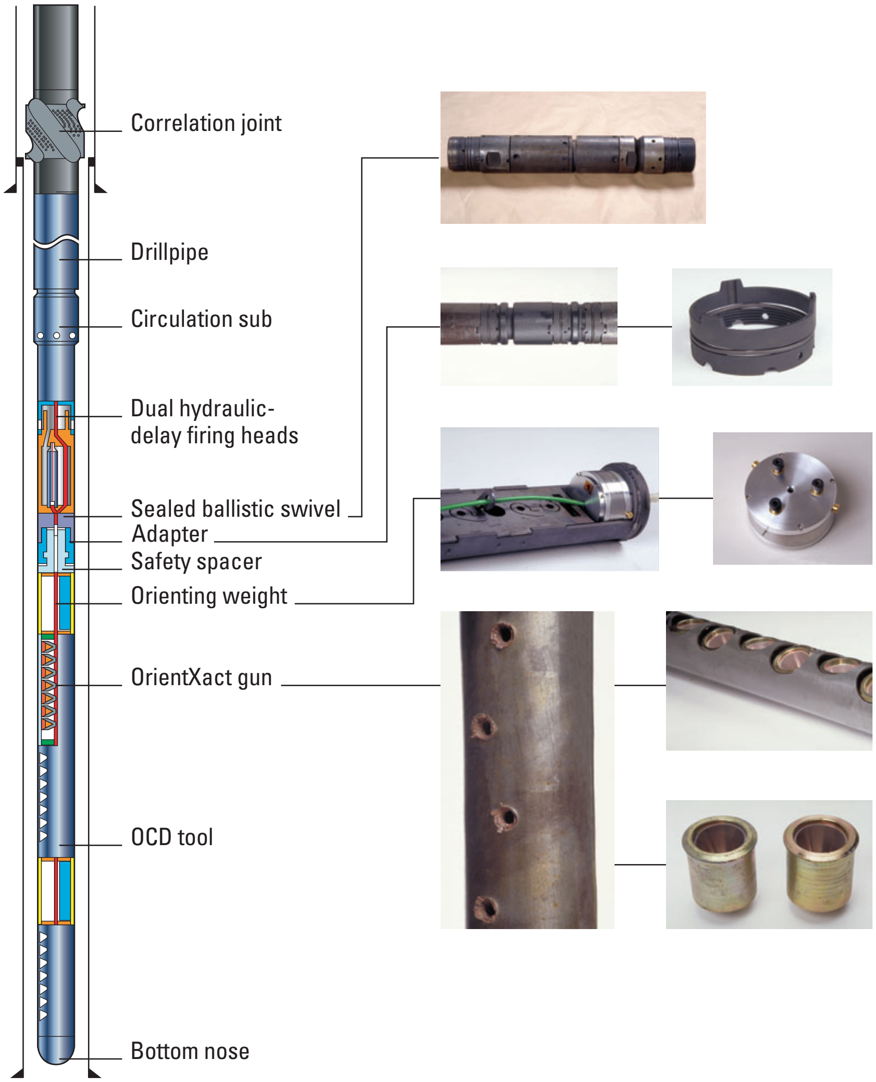

Figure 153. OrientXact perforating system.

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- Swivels—To improve orienting performance, a new swivel was developed to provide very low torsional friction while under simultaneous bending and compressive or tensile loading. Test results demonstrate that the string provides the necessary torque to overcome swivel resistance with tension and compression loads to 55,000 lbf and simultaneous bending to 10° per 100 ft.
- OCD* Orientation Confirmation Device—To verify the accuracy of the perforation operation, the OrientXact system uses the OCD tool, which records the direction the string and perforation tunnels were actually pointing at the exact moment of the detonation. This measurement, which is accurate to 1°, confirms the actual orientation of the perforation tunnels. OCD measurements are available immediately after retrieving the string.

Job planning and reporting

Ensuring an effective perforating operation requires analyzing all well data and completion procedures to develop an appropriate running design for the OrientXact perforating system. The OrientXact string is optimized by experienced TCP specialists using well directional survey data. After each job, charts are produced that identify the actual string orientation versus measured depth and the quantities of perforation tunnels versus deviation from the vertical. Other information useful to job analyses and future job designs is also produced—orientation versus dogleg severities; location of weights, carriers, swivels, and OCD tools; and changes in well direction.

Applications

- Horizontal and highly deviated wells, regardless of tortuosity
- Long, horizontally oriented perforating applications
- Oriented perforating in weak reservoirs

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2-in. Frac Gun Perforating System

The 2-in. Frac Gun perforating system for wells requiring fracture stimulation is engineered for slimhole casing, but has applications in any completions where downhole restrictions limit gun size, including through tubing, dual completion, monobore, and extended reach (Fig. 154 and Tables 78 and 79).

Fracture stimulation requires 60° (or 120°) phased guns that produce a large entrance hole size. The 2-in. Frac Gun system features these phasings and can be loaded with the deep penetrating charges that are used with HSD High Shot Density gun systems (Fig. 155).

The guns are conveyed with wireline or slickline. The gun intercarriers feature a push-in connector, allowing faster operation than comparable systems.

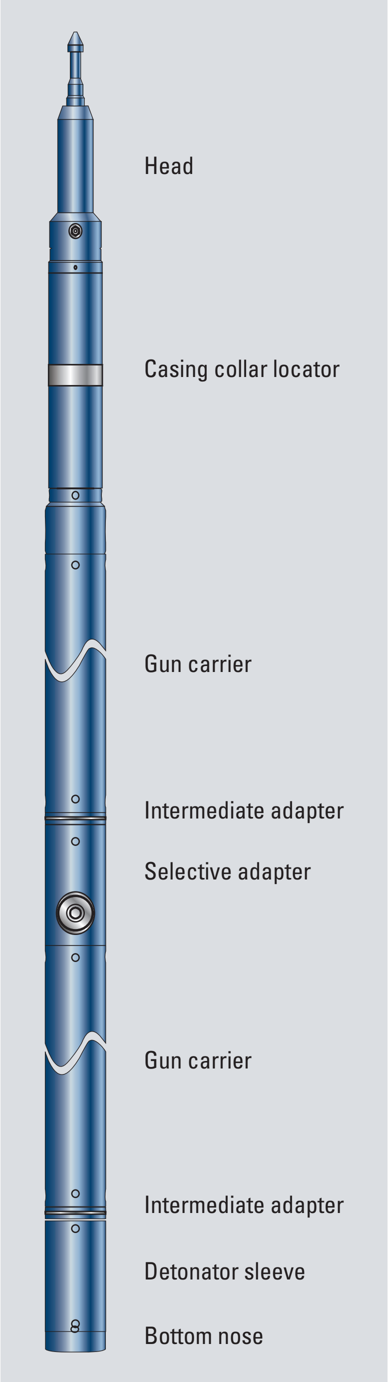

Figure 154. 2-in. Frac Gun perforating system.

Applications

- Wells requiring fracture stimulation
- Slimhole, through-tubing, dual, monobore, and extended-reach completions

Table 78. 2-in. Frac Gun Mechanical Specifications

Outside diameter (in.)	2
Shot density (spf), phasing (°)	4, 120
	6, 60
Shot spacing (in.)	4 spf: 3
	6 spf: 2
Temperature rating (°F [°C])	400 [204]
Pressure rating (psi)	20,000
Min. casing size (in.)	3½
Max. diameter including burrs, shot in liquid[†] (in.)	0.05–0.08
Max. gun length (ft)	1–20 in 20-in. intervals
Weight of loaded 20-ft gun in air (lbm)	124
Max. tensile load (lbf)	26,000

[†] Depends on gun configuration and charge type

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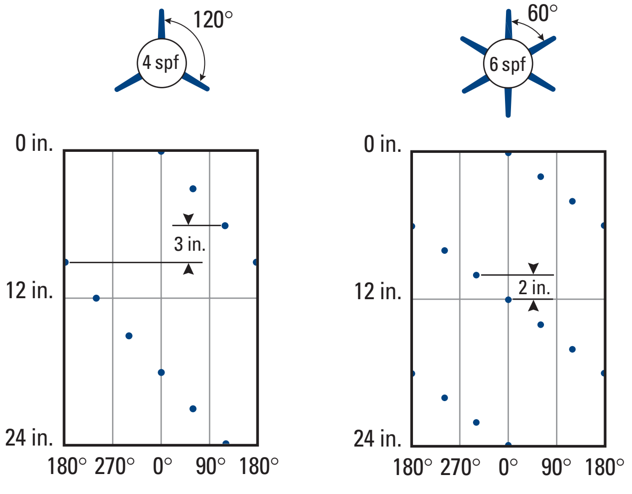
Table 79. 2-in. Frac Gun Performance Summary†

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^{2}/ft)	Burr Height Avg. (in.)	Casing Size (in.), Weight (lbm/ft)
2-in. Frac Gun	6, 60	PowerJet 2006, HMX	18.6	0.20	–	0.05	4½, 11.6
2-in. Frac Gun	6, 60	UltraJet 2006, HMX	14.7	0.28	–	0.07	4½, 11.6
2-in. Frac Gun	6, 60	HyperJet 2006, RDX	9.6	0.33	–	0.08	4½, 11.6

† API RP 43 5th edition or API 19B Section 1, shot in L80 casing



4 spf, 120° Phasing

6 spf, 60° Phasing

Figure 155. 2-in. Frac Gun shot patterns for 4½-in. casing.

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3.12-in. Frac Gun Perforating System

The 3.12-in Frac Gun perforating system is engineered for wells requiring fracture stimulation, sand control operations, and CBM wells (Fig. 156 and Tables 80 and 81).

Fracture stimulation requires 60° (or 120°) phased guns that produce a large entrance hole size. To best execute frac job designs at these phasings, the 3.12-in Frac Gun system uses custom-designed charges to optimize entrance hole size and penetration (Fig. 157).

The guns are conveyed with wireline or slickline. The gun intercarriers feature a push-in connector, allowing faster operation than comparable systems. A plug and shoot adapter makes it possible to set a plug and shoot multiple guns in the same descent, saving operating time.

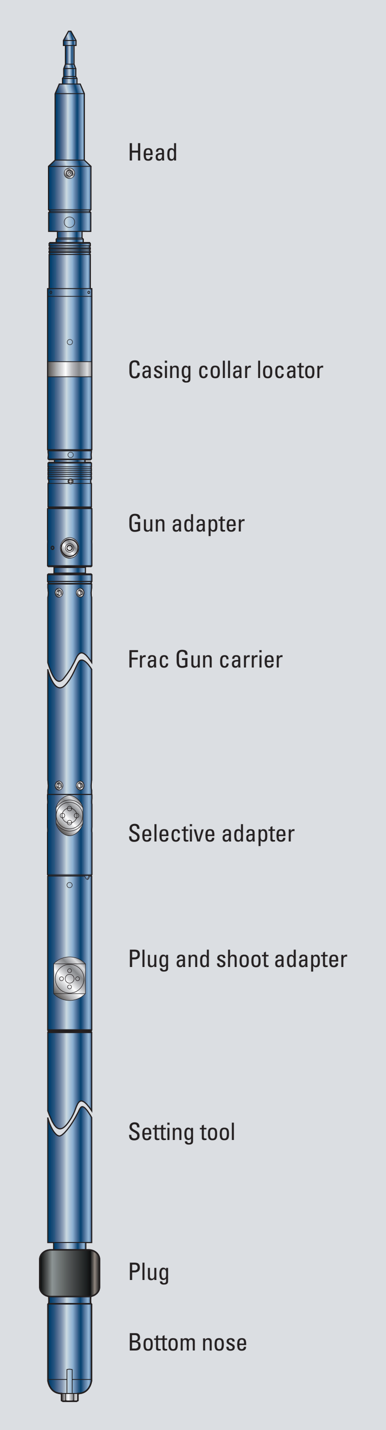

Figure 156. 3.12-in. Frac Gun perforating system.

Applications

- Wells requiring fracture stimulation
- Sand control operations
- CBM wells

Table 80. 3.12-in. Frac Gun Mechanical Specifications

Outside diameter (in.)	3.125
Shot density (spf), phasing (°)	4, 90; 4, 120
	6, 60
Shot spacing (in.)	4 spf: 3
	6 spf: 2
Temperature rating (°F [°C])	300 [149]
Pressure rating (psi)	15,000
Min. casing size (in.)	4½
Max. diameter including burrs, shot in liquid[†] (in.)	0.06–0.07
Max. gun length (ft)	1–20 in 20-in. intervals
Weight of loaded 20-ft gun in air (lbm)	247
Max. tensile load (lbf)	4 spf: 89,000
	6 spf: 25,000

[†] Depends on gun configuration and charge type

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Table 81. 3.12-in. Frac Gun Performance Summary[†]

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^{2}/ft)	Burr Height Avg. (in.)	Casing Size (in.), Weight (lbm/ft)
3.12-in. Frac Gun	6, 60	3106 PFrac*, RDX	24.9	0.44	–	0.06	4½, 11.6
3.12-in. Frac Gun[‡]	4, 120	34B HyperJet, RDX	18.5	0.41	–	0.07	4½, 11.6

[†] API RP 43 5th edition or API 19B Section 1, shot in L80 casing; blue type identifies API 19B Registered Perforation Systems.
[‡] Unofficial API data

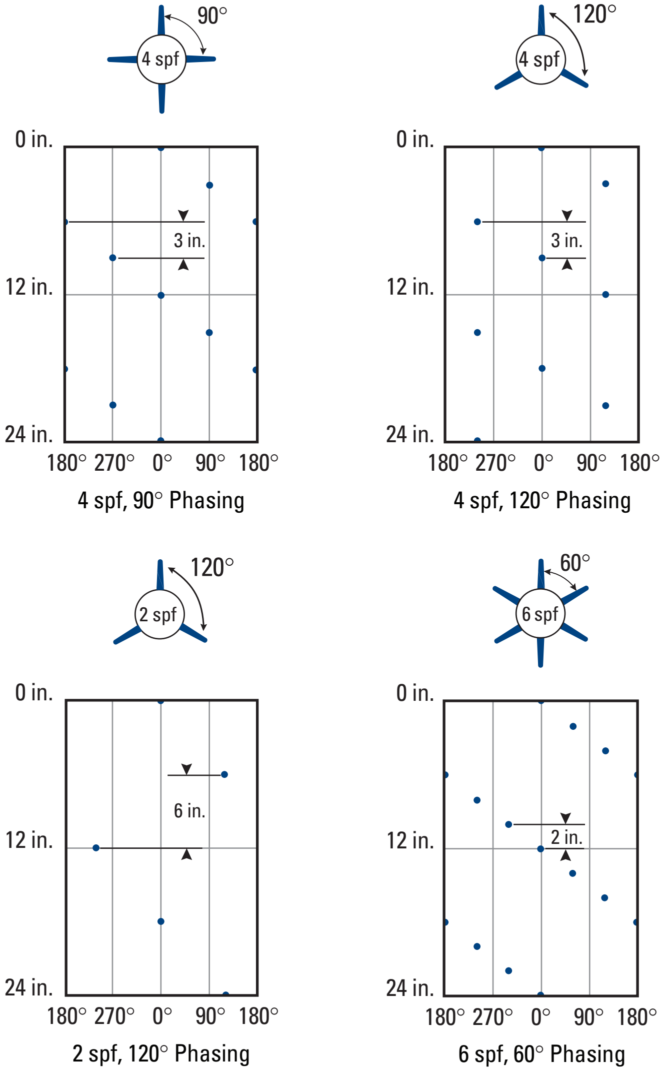

Figure 157. 3.12-in. Frac Gun shot patterns for 4½-in. casing.

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Port Plug and HEGS High-Efficiency Gun Systems

Because Port Plug guns and HEGS High-Efficiency Gun Systems are used to perforate wells before the completion string has been run (or in some cases, after it has been pulled), these hollow carrier guns are also called casing guns. They are usually shot in overbalanced conditions to maintain well control. Port Plug guns are designed specifically for use on electric wireline cable and are retrievable.

Port Plug guns feature multiple-gun selectivity to shoot several zones per run in the well. Instead of percussion switches, Port Plug guns use the ASFS Addressable-Switch Firing System, which attaches a uniquely addressed electronic switch to each detonator. In addition to providing flexibility for remote operations, Port Plug guns require only minimal amounts of hardware for perforating large intervals. Compared with the faster-loading HEGS guns, the Port Plug guns have higher pressure ratings.

HEGS High-Efficiency Gun Systems are hollow carrier casing guns similar to Port Plug guns but designed specifically for fast loading with minimal carrier preparation. Conveyed on electric wireline cable, the HEGS guns are expendable. They can be combined for selective perforating and run in lengths up to 40 ft.

Deep penetrating charges for natural and stimulated completions and big hole charges for gravel-pack completions are available for Port Plug and HEGS guns. To ensure that performance meets design specifications, charges are QC-tested during production in actual gun carriers. Because the loaded guns contain only secondary high explosives (detonating cord, boosters, and charges), they are safe to transport and handle following standard Schlumberger safety procedures.

Figure 158 illustrates the configuration of the Port Plug and HEGS guns.

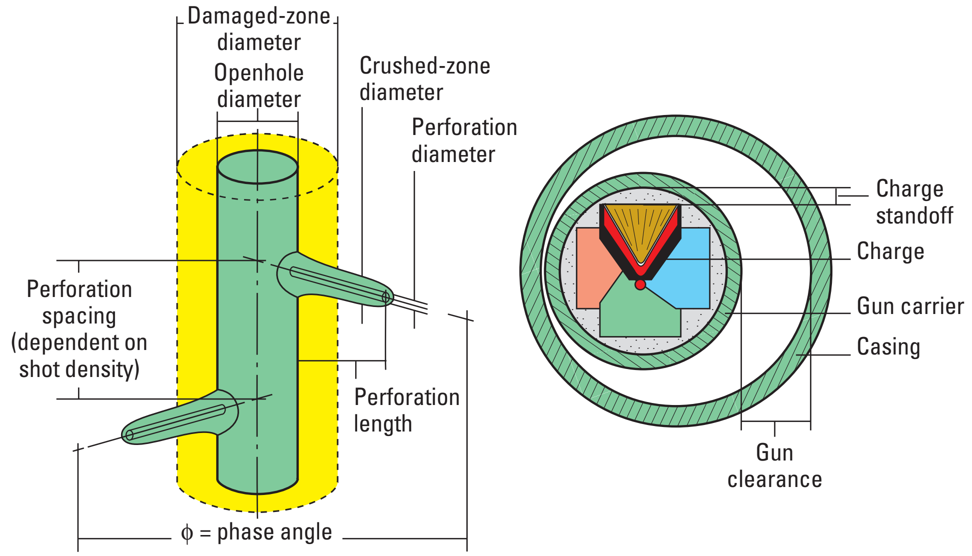

Figure 158. Port Plug and HEGS gun systems.

Specifications for the Port Plug and HEGS guns are listed in the following data sheets.

3⅛-in. Port Plug Gun

The 3⅛-in. Port Plug gun system is designed to provide maximum perforating performance at low pressures and temperatures (Fig. 159 and Tables 82 and 83). By shooting the charges through replaceable plugs in a reusable gun carrier, the 3⅛-in. Port Plug gun provides highly flexible multiple-gun selectivity for remote operations (Fig. 160).

The guns are conveyed on wireline.

Applications

- Selective perforating
- Remote operations
- Deep penetration
- Multiple-interval perforating
- Shot-by-shot perforating

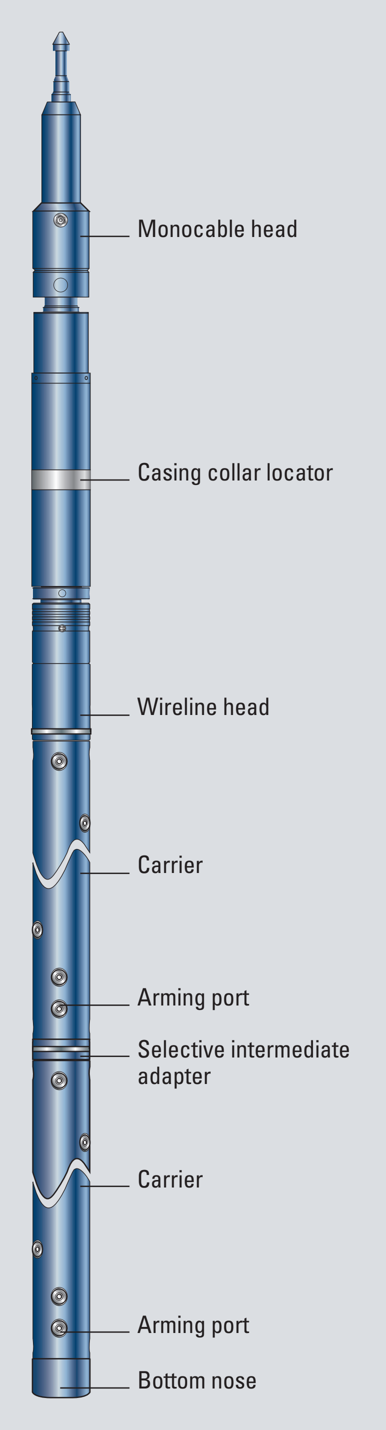

Figure 159. 3⅛-in. Port Plug gun.

Table 82. 3⅛-in. Port Plug Gun Mechanical Specifications

Outside diameter (in.)	3.125
Shot density (spf), phasing (°)	1, 0
	4, 120; 4, 180
Shot spacing (in.)	3
Temperature rating (°F [°C])	250 [121] With high-pressure feed-through: 340 [171]
Pressure rating (psi)	5,000 With high-pressure feed-through: 10,000
Min. casing size (in.)	4½
Max. gun length (ft)	1, 2, 3, 4, 5, 6, 7, 10, 15
Weight of loaded 15-ft gun in air (lbm)	234
Max. tensile load (lbf)	239,000

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Table 83. 3⅛-in. Port Plug Gun Performance Summary†

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.²/ft)	Casing Size (in.), Weight (lbm/ft)
3⅛-in. Port Plug	4, 120	Port Plug 3104, RDX	15.0	0.38	–	4½, 11.6

† API RP 43 5th edition or API 19B Section 1, shot in L80 casing

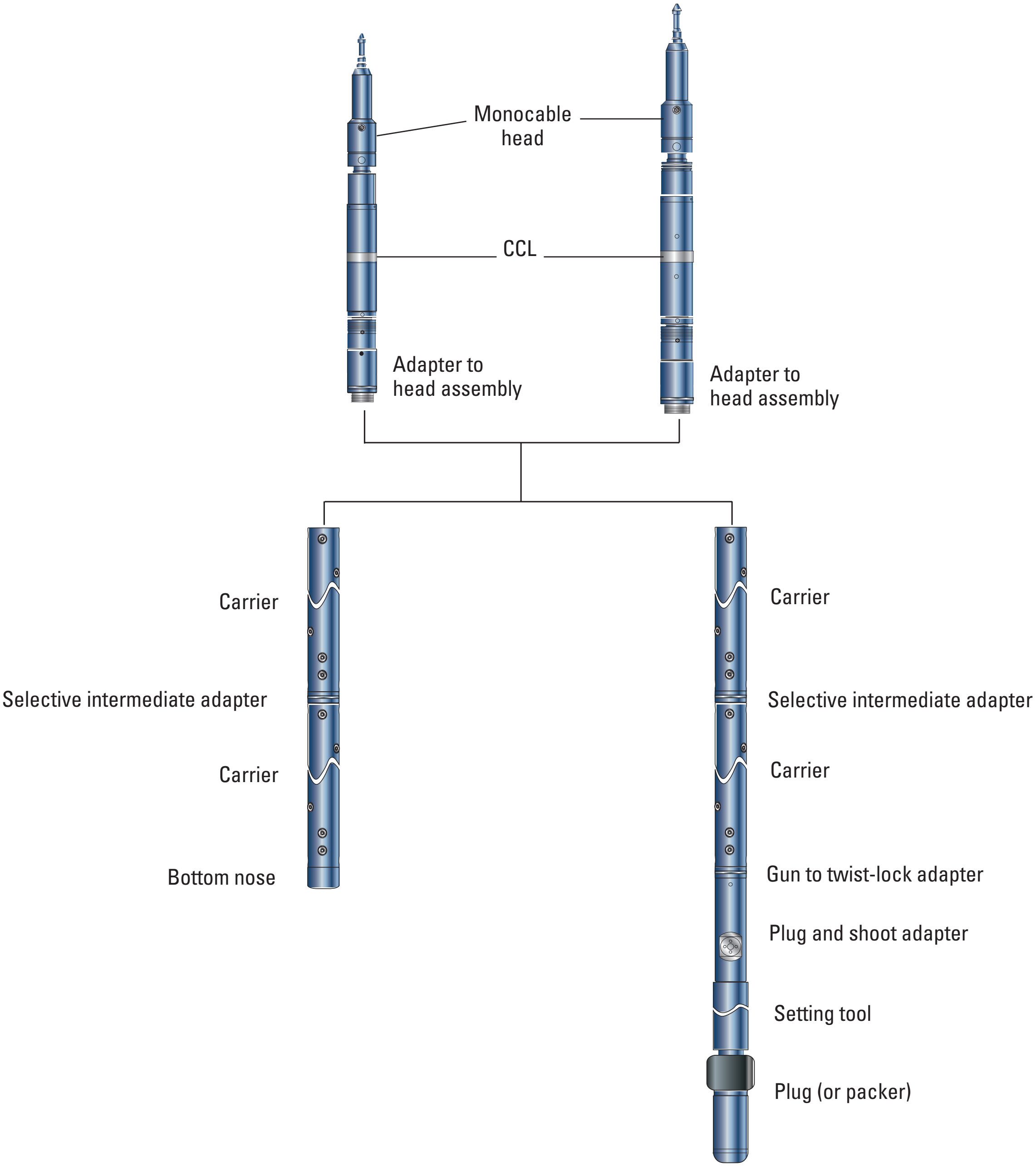

Figure 160. 3⅛-in. Port Plug gun configurations.

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3⅜-in. Port Plug Gun

The 3⅜-in. Port Plug gun is a 4-spf, 90°-phased gun system designed to provide maximum perforating performance at higher pressures and temperatures (Fig. 161 and Tables 84 and 85). By shooting the charges through replaceable plugs in a reusable gun carrier, the 3⅜-in. Port Plug gun provides highly flexible multiple-gun selectivity for remote operations.

The guns are conveyed on wireline.

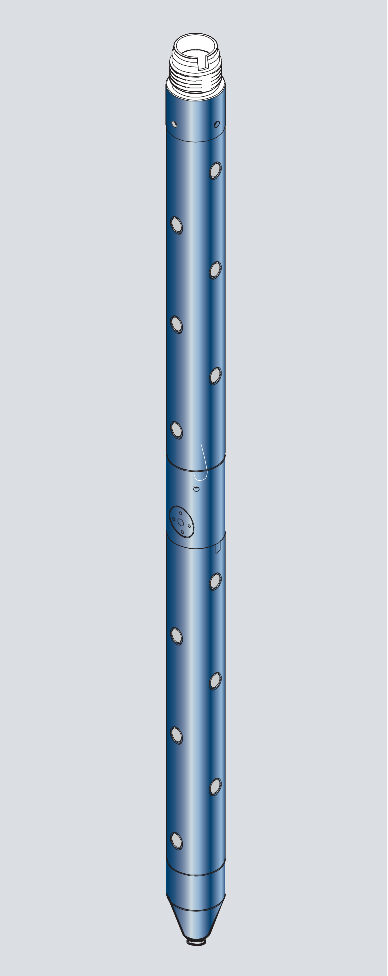

Figure 161. 3⅜-in. Port Plug gun.

Applications

- Selective perforating
- Remote operations
- Deep penetration
- Multiple-interval perforating

Table 84. 3⅜-in. Port Plug Gun Mechanical Specifications

Outside diameter (in.)	3⅜
Shot density (spf), phasing (°)	4, 90
Shot spacing (in.)	3
Temperature rating (°F [°C])	330 [166]
	400 [204]†
Pressure rating (psi)	25,000
Min. casing size (in.)	4½
Max. gun length (ft)	1, 1.5, 2, 4, 7, 10, 15, 20
Weight of loaded 15-ft gun in air (lbm)	300
Max. tensile load (lbf)	330,000

† With high-temperature explosives and seals

Table 85. 3⅜-in Port Plug Gun Performance Summary†

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^{2}/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
3⅜-in. Port Plug gun	4, 90	38B HyperJet II, RDX	21.5	0.35	–	0.05/0.08	4½, 11.6

† API RP 43 5th edition or API 19B Section 1

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4-in. Port Plug Gun

The 4-in. Port Plug gun is a 4-spf, 90°-phased gun system designed to provide maximum perforating performance at low pressures and temperatures (Fig. 162 and Tables 86 and 87). By shooting the charges through replaceable plugs in a reusable gun carrier, the 4-in. Port Plug gun provides highly flexible multiple-gun selectivity for remote operations.

The guns are conveyed on wireline.

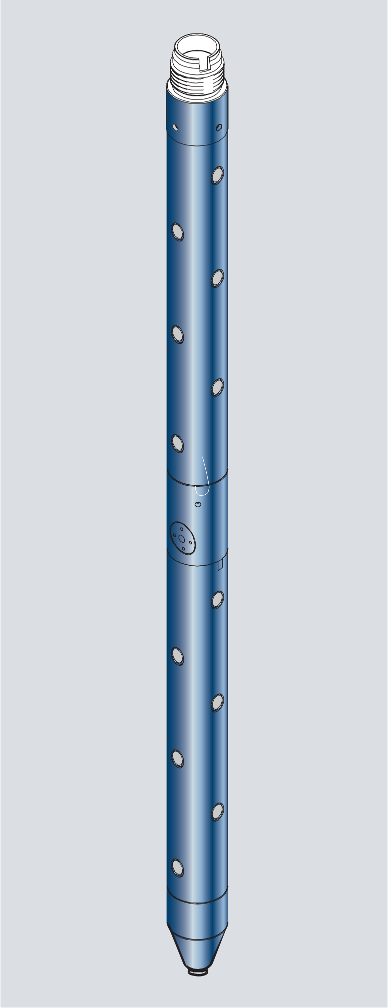

Figure 162. 4-in. Port Plug gun.

Applications

- Selective perforating
- Remote operations
- Deep penetration
- Multiple-interval perforating

Table 86. 4-in. Port Plug Gun Mechanical Specifications

Outside diameter (in.)	4
Shot density (spf), phasing (°)	4, 90
Shot spacing (in.)	3
Temperature rating (°F [°C])	330 [166]
	400 [204]†
Pressure rating (psi)	25,000
Min. casing size (in.)	4½
Max. gun length (ft)	1, 1.5, 2, 4, 7, 10, 15, 20
Weight of loaded 20-ft gun in air (lbm)	597
Max. tensile load (lbf)	380,000

† With high-temperature explosives and seals380

Table 87. 4-in. Port Plug Gun Performance Summary†

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^{2}/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
4-in. Port Plug gun	4, 90	41B HyperJet II, RDX	23.6	0.38	–	0.07/0.09	5½, 17.0
4-in. Port Plug gun	4, 90	41B HyperJet II, HMX	27.6	0.37	–	0.07/0.09	5½, 17.0
4-in. Port Plug gun	4, 90	41B UltraPack, RDX	14.3	0.56	0.99	0.13/0.19	5½, 17.0

† API RP 43 5th edition or API 19B Section 1

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3⅛-in. HEGS Perforating Gun

The 3⅛-in. HEGS gun is an economical wireline-conveyed perforating gun (Fig. 163 and Tables 88 and 89). Designed for low-pressure, low-temperature operations in 4½-in. casing, the 3⅛-in. HEGS gun also has applications in completions where downhole restrictions limit gun size.

For special applications, other phasings and shot densities can be made from the standard configurations (Fig. 164). The guns are usually conveyed by wireline, one at a time, but can be combined and selectively fired using a special intercarrier and standard switch.

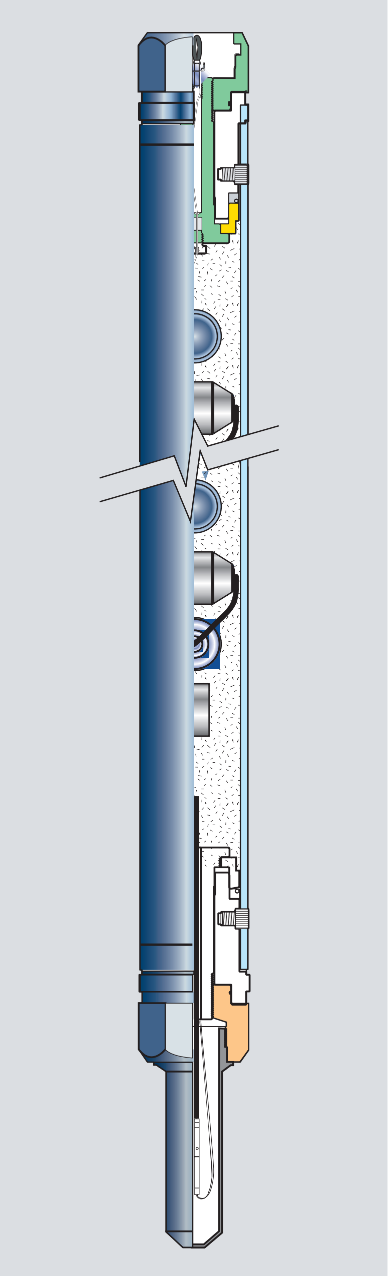

Figure 163. 3⅛-in. HEGS gun.

Applications

- Selective perforating
- Deep penetration or big hole
- Multiple-interval perforating

Table 88. 3⅛-in. HEGS Mechanical Specifications

Outside diameter (in.)	3.125
Shot density (spf), phasing (°)	2, 120
	4, 90; 4, 120
	6, 60
Shot spacing (in.)	2 spf: 6
	4 spf: 3
	6 spf: 2
Temperature rating (°F [°C])	With foam loading tube: 210 [99] 340 [171]
Pressure rating (psi)	6,200
Min. casing size (in.)	4½
Max. diameter including burrs, shot in liquid/gas (in.)	3.38/3.65
Max. gun length (ft)	Foam loading tube: 1 to 40
	Steel loading tube: 10, 20
Weight of loaded 40-ft gun in air (lbm)	340

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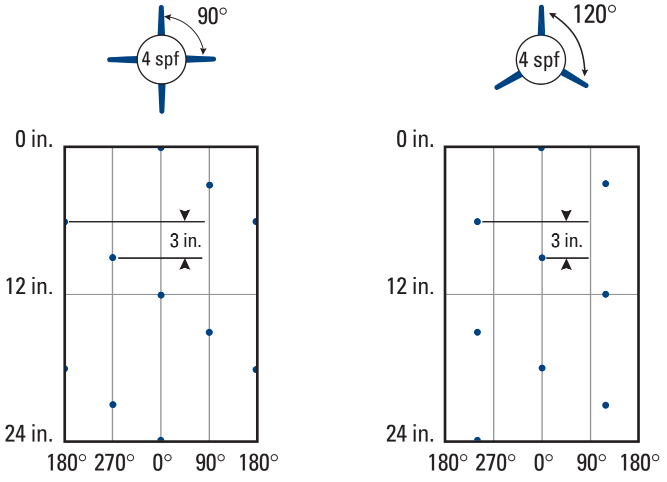
Table 89. 3⅛-in. HEGS Performance Summary†

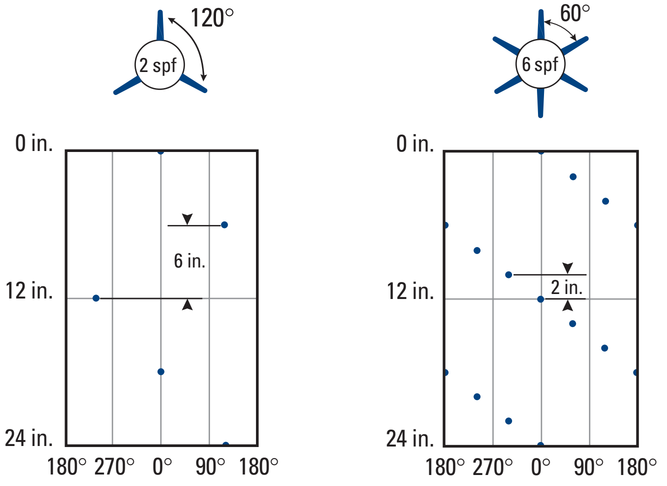
Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^{2}/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
3⅛-in. HEGS	4, 90	34B HyperJet, RDX	18.5	0.41	0.53	0.07/0.10	4½, 11.6

† API RP 43 5th edition or API 19B Section 1



4 spf, 90° Phasing

4 spf, 120° Phasing



2 spf, 120° Phasing

6 spf, 60° Phasing

Figure 164. 3⅛-in. HEGS shot patterns for 4½-in. casing.

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4-in. HEGS Perforating Gun

The 4-in. HEGS gun is an economical wireline-conveyed perforating gun (Fig. 165 and Tables 90 and 91). Designed for low-pressure, low-temperature operations in 5½- to 7-in. casing, the 4-in. HEGS gun has applications in larger completions where downhole restrictions limit gun size.

For special applications, other phasings and shot densities can be made from the standard configurations (Fig. 166). The guns are usually conveyed by wireline, one at a time, but can be combined and selectively fired using a special intercarrier and standard switch.

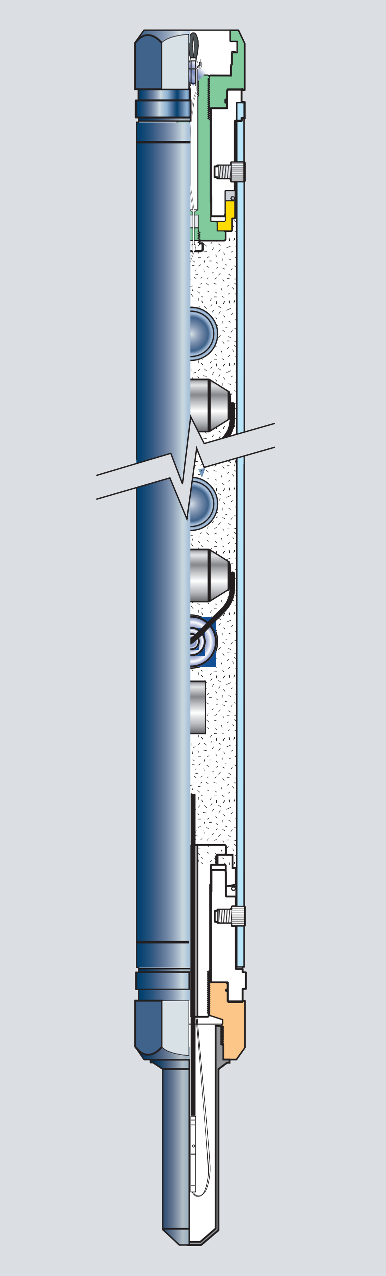


Figure 165. 4-in. HEGS gun.

Applications

- Selective perforating
- Deep penetration or big hole
- Multiple-interval perforating

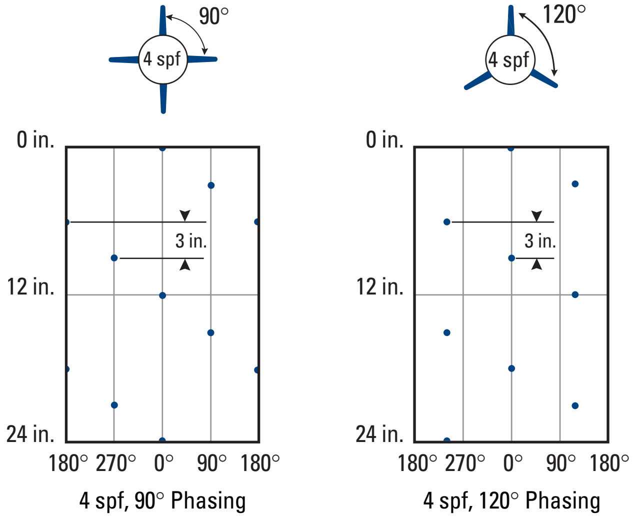
Table 90. 4-in. HEGS Mechanical Specifications

Outside diameter (in.)	4
Shot density (spf), phasing (°)	4, 90; 4, 120
Shot spacing (in.)	3
Temperature rating (°F [°C])	With white-foam loading tube: 210 [99]
	With black-foam loading tube: 230 [110]
Pressure rating (psi)	4,000
Min. casing size (in.)	5½
Max. diameter including burrs, shot in liquid/gas (in.)	4.28/4.50
Max. gun length (ft)	Foam loading tube: 1 to 40
	Steel loading tube: 20
Weight of loaded 40-ft gun in air (lbm)	520

Table 91. 4-in. HEGS Performance Summary[†]

Gun	Shot Density (spf), Phasing (°)	Charge	Penetration (in.)	Entrance Hole (in.)	AOF (in.^{2}/ft)	Burr Height Avg./Max. (in.)	Casing Size (in.), Weight (lbm/ft)
4-in. HEGS	4, 90	41B HyperJet, SX1	21.7	0.42	0.53	0.06/0.10	5½, 17.0
4-in. HEGS	4, 90	43C HyperPack, RDX	9.4	0.60	1.13	0.09/0.12	7, 23.0

[†] API RP 43 5th edition or API 19B Section 1



4 spf, 90° Phasing

4 spf, 120° Phasing

Figure 166. 4-in. HEGS shot patterns for 5½-in. casing.

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Hollow Carrier Gun Performance and Mechanical Data Summary

Tables 92, 93, and 94 summarize the mechanical and performance data for the individual hollow carrier guns.

Table 92. Mechanical and Performance Data Summary for Deep Penetrator Hollow Carrier Guns

Perforating System Designation	Shot Density, spf	Phasing, °	Charge	API RP 43 Fifth Edition Section 1 or API 19B Section 1						Maximum Explosive Load, g	Maximum Pressure Rating, psi	Weight of Loaded 20-ft Gun in Air, lbm	Maximum Diameter Including Burrs, Shot in Liquid, in	Maximum Diameter Including Burrs, Shot in Gas, in
				Penetration, in	Entrance Hole, in	Area Open to Flow, in²/ft	Burr Height Avg/Max., in	Casing Size, in	Casing Weight, lbm/ft					
1.56-in HSD*	6	60	PowerJet* 1606, HMX	11.3	0.17	–	0.04/0.08	2⅞	6.4	3.5	20,000	74	1.72	1.75
2-in HSD	6	60	PowerJet Omega* 2006, HMX	21.8	0.22	–	0.05/0.08	3½	9.2	7.3	20,000	119	2.29	2.31
2-in HSD[1]	6	60	PowerJet 2006, HNS	15.3	0.22	–	0.03/0.05	2⅞	6.4	8.0	20,000	119	2.16	2.21
2-in HSD	6	60	PowerJet 2006, HMX	18.6	0.2	–	na	2⅞	6.4	6.5	20,000	119	2.16	2.31
2-in HSD[2]	6	0/180	PowerJet 2006, HMX	17.9	0.20	–	na	2⅞	6.4	6.5	20,000	119	na	na
2-in HSD	6	60	HyperJet* 2006, RDX	9.6	0.33	–	0.05/0.08	3½	9.2	6.5	20,000	119	2.16	2.21
2-in HSD	6	60	UltraJet* 2006, HMX	16.6	0.23	–	0.04/0.05	3½	9.2	6.5	20,000	119	2.17	2.23
2¼-in HSD	6	60	PowerJet 2306, HMX	17.7	0.30	–	0.08/0.10	3½	9.2	8.5	20,000	136	2.46	2.48
2¼-in HSD	6	60	PowerJet 2306, HNS	15.7	0.27	–	0.06/0.09	3½	9.2	9.5	20,000	136	2.46	2.48
2½-in HSD	6	60	PowerJet Omega 2506, HMX	30.6	0.32	–	0.04/0.07	3½	9.2	12.0	25,000	179	2.78	–
2½-in HSD	6	60	PowerJet 2506, HNS	16.7	0.30	–	0.07/0.09	3½	9.2	13.5	25,000	179	2.66	2.75
2½-in HSD	6	60	PowerJet 2506, HMX	18.7	0.34	–	0.07/0.11	3½	9.2	10.5	25,000	179	2.59	2.75
2½-in HSD	6	60	UltraJet 2506, HMX	16.6	0.32	–	0.07/0.11	3½	9.2	10.5	25,000	179	2.66	2.75
2½-in HSD	6	60	HyperJet 2506, RDX	13.1	0.43	–	0.07/0.11	3½	9.2	10.5	25,000	179	2.66	2.75
2½-in HSD	6	60	31J CleanSHOT*, HMX	19.2	0.30	–	0.06/0.07	3½	9.3	10.2	25,000	177	2.69	–
2⅞-in HSD	6	60	PowerJet Omega 2906, HMX	36.0	0.34	–	0.05/0.08	4½	11.6	16.0	25,000	237	3.16	3.32
2⅞-in HSD	6	60	PowerJet 2906, HMX	25.3	0.38	–	0.06/0.08	4½	11.6	15.0	25,000	237	2.98	3.08
2⅞-in HSD	6	60	PowerJet 2906, HNS	21.0	0.31	–	0.06/0.09	4½	11.6	19.5	25,000	232	2.96	3.08
2⅞-in HSD	6	60	UltraJet 2906, HMX	22.1	0.36	–	0.07/0.09	4½	11.6	15.0	25,000	237	2.98	3.08
2⅞-in HSD	6	60	HyperJet 2906, RDX	15.0	0.39	–	0.06/0.09	4½	11.6	15.0	25,000	237	2.98	3.08
2⅞-in HSD	4	0/180	PowerJet 2906, HMX	27.7	0.36	–	na	4½	11.6	15.0	25,000	232	2.98	3.08
2⅞-in OrientXact*, 2	5	±10	PowerJet OX 2905, HMX	26.2	0.21	–	na	5½	17.0	15.1	20,000	296	3.19	3.20
2⅞-in HSD	6	60	34J CleanSHOT, RDX	17.7	0.27	–	na	4½	11.6	15.0	25,000	232	2.98	3.08
3⅛-in HSD	6	60	PowerJet Omega 3106, HMX	36.9	0.34	–	0.06/0.10	4½	11.6	20.0	20,000	292	3.57	–
3.12-in Frac Gun*	6	60	PFrac* 3106, RDX	24.9	0.44	–	0.06/0.10	4½	11.6	22.5	10,000	292	3.50	–
3⅛-in HSD	6	60	34JL UltraJet, HMX	24.0	0.41	–	0.07/0.11	4½	11.6	22.7	20,000	280	3.57	–
3⅛-in HSD	5	0/180	34JL UltraJet, HMX	23.8	0.42	–	0.07/0.11	4½	11.6	22.7	20,000	272	3.45	–
3⅜-in HSD[3]	6	60	PowerJet 3406, HMX	36.5	0.37	–	0.06/0.09	4½	11.6	22.7	20,000	332	3.66	–
3⅜-in HSD[3]	6	60	PowerJet 3406, HNS	28.8	0.31	–	0.05/0.10	4½	11.6	25.0	20,000	332	3.66	–
3⅜-in OrientXact	5	±10	PowerJet OX 3505, HMX	37.7	0.34	1.52	0.06/0.07	5½	17.0	22.5	20,000	438	na	3.76
3⅜-in HSD[3]	6	60	UltraJet 3406, HMX	31.4	0.44	–	0.06/0.13	4½	11.6	22.7	20,000	332	3.66	3.70
3⅜-in HSD[3]	6	60	HyperJet 3406, RDX	23.5	0.49	–	0.05/0.12	4½	11.6	22.5	20,000	332	3.66	–
3⅜-in HSD[2, 3]	21	120/60	PowerJet 2006, HMX	16.2	0.18	–	na	5½	17.0	6.5	10,000	na	3.60	–
3⅜-in HSD[3]	6	60	34B CleanSHOT, RDX	18.5	0.31	–	0.04/0.08	4½	11.6	21.7	20,000	327	3.56	3.77
3⅜-in HSD[3]	6	60	34B Hyperjet II, RDX	21.9	0.40	–	0.05/0.09	4½	11.6	20.5	20,000	332	3.61	–
3⅜-in HSD[2, 3]	6	99	34B HyperJet II, RDX	20.2	0.38	–	na	5½	17.0	20.5	20,000	332	3.61	–
3⅜-in HSD[3]	6	60	34JL UltraJet, HMX	28.9	0.37	–	0.06/0.09	4½	11.6	22.7	20,000	332	3.61	–
3.5-in HSD	6	72	PowerJet Omega 3506, HMX	44.2	0.44	–	0.06/0.14	5	15.0	27.0	25,000	378	3.72	–
3.67-in HSD	5	60	37J CleanSHOT, RDX	31.2	0.36	–	0.05/0.08	5	15.0	34.0	25,000	443	3.96	4.01
3.67-in HSD[2]	5	60	37J CleanSHOT, HMX	32.7	0.38	–	na	5	15.0	34.0	25,000	443	3.96	–
4-in HSD	5	72	PowerJet Omega 4005	51.7	0.48	–	0.07/0.12	5½	17.0	38.8	20,000	421	4.44	–
4-in HSD[2]	5	0/180	PowerJet 4005, HMX	36.5	0.46	–	0.07/0.10	5½	17.0	24.5	20,000	421	na	–

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Table 92. Mechanical and Performance Data Summary for Deep Penetrator Hollow Carrier Guns (continued)

Perforating System Designation	Shot Density, spf	Phasing, °	Charge	API RP 43 Fifth Edition Section 1 or API 19B Section 1						Maximum Explosive Load, g	Maximum Pressure Rating, psi	Weight of Loaded 20-ft Gun in Air, lbm	Maximum Diameter Including Burrs, Shot in Liquid, in	Maximum Diameter Including Burrs, Shot in Gas, in
				Penetration, in	Entrance Hole, in	Area Open to Flow, in^2/ft	Burr Height Avg/Max., in	Casing Size, in	Casing Weight, lbm/ft					
4½-in HSD[4]	5	72	PowerJet Omega 4505, HMX	59.2	0.43	–	0.08/0.11	7	32.0	38.8	12,000	446	4.74	–
4½-in HSD[4]	5	72	PowerJet 4505, HMX	46.4	0.47	–	0.08/0.15	7	32.0	38.6	12,000	446	4.74	–
4½-in HSD[2, 4]	4	0/180	PowerJet 4505, HMX	50.1	0.36	–	na	7	32.0	38.6	12,000	428	na	–
4½-in HSD[4]	12	135/45	PowerJet 4512, HMX	30.2	0.34	–	0.07/0.12	7	32.0	22.0	12,000	501	4.91	–
4½-in HSD[4]	12	135/45	PowerJet Omega 4512, HMX	34	0.35	–	0.07/0.12	7	32.0	22.0	12,000	501	4.91	–
4½-in OrientXact	4	±10	PowerJet OX 4504, HMX	43.8	0.29	1.58	0.06/0.08	7	32.0	38.8	12,000	650	4.77	–
4½-in HSD[4]	5	72	UltraJet 4505, HMX	42.6	0.46	–	0.08/0.13	7	32.0	38.3	12,000	446	4.74	–
4½-in HSD[4]	5	72	HyperJet 4505, RDX	37.0	0.57	–	0.11/0.16	7	32.0	38.8	12,000	446	4.74	–
4½-in HSD[4]	12	135/45	34B HyperJet II, RDX	17.9	0.39	–	0.07/0.11	7	32.0	20.5	12,000	501	4.77	–
4½-in HSD[4]	12	135/45	34JL UltraJet, HMX	28.6	0.34	–	0.06/0.11	7	32.0	22.7	12,000	501	4.77	–
4⅝-in HSD Bigshot 21*[, 5]	21	120/60	PowerJet 4521, HMX	21.0	0.32	–	0.06/0.11	7	32.0	15.0	15,000	604	na	4.82
4.72-in HSD	5	72	PowerJet 4505, HNS	34.4	0.40	–	0.06/0.10	7	32.0	38.0	20,000	615	na	–
4.72-in HSD	12	135/45	PowerJet 4512, HNS	22.8	0.31	–	0.06/0.11	7	32.0	22.5	20,000	652	na	–
4.72-in HSD	12	135/45	34B CleanSHOT, RDX	15.4	0.31	–	0.10/0.11	7	32.0	21.7	20,000	636	4.99	–
4.72-in HSD	5	72	51J UltraJet, HNS	34.5	0.33	–	0.07/0.12	7	32.0	38.5	20,000	592	na	–
5-in HSD	8	135/45	UltraJet 5008, RDX	20.2	0.54	–	0.11/0.22	7	32.0	24.0	12,000	593	5.19	5.22
5-in HSD[2]	8	0/180	UltraJet 5008, RDX	19.1	0.48	–	na	7	32.0	23.0	12,000	593	na	–
7-in HSD	12	135/45	PowerJet Omega 4505, HMX	53.2	0.43	–	0.08/0.16	9⅝	47.0	38.8	10,000	1,245	7.28	–
7-in HSD	12	135/45	PowerJet 4505, HMX	43.6	0.44	–	0.08/0.15	9⅝	47.0	38.6	10,000	1,245	7.05	–
7-in HSD	12	135/45	UltraJet 4505, HMX	39.9	0.45	–	0.08/0.16	9⅝	47.0	38.3	10,000	1,245	7.05	–
7-in HSD	27	120/60	PowerJet Omega 7027, HMX	35.5	0.29	–	0.05/0.09	9⅝	47.0	20.0	10,000	1,210	7.05	–
7-in HSD	27	120/60	34JL UltraJet, HMX	26.0	0.27	–	0.05/0.11	9⅝	47.0	22.7	10,000	1,210	7.50	–
7-in HSD	12	135/45	51B HyperJet II, RDX	32.0	0.47	–	0.08/0.14	9⅝	47.0	37.0	10,000	1,245	7.05	–

Notes: Every attempt has been made to verify the accuracy of the data tabulated; contact your Schlumberger representative for further information.

Other shot densities and phasings are available; Schlumberger also custom designs perforation systems to meet specific needs.

na = not available

Blue type identifies API 19B Registered Perforation Systems.

[1] Nonswell version available

[2] Unofficial API data

[3] Available in 3⅜-, 3.5-, and 3.67-in perforating systems

[4] Available in 4½-, 4⅝-, 4.72-, and 5-in perforating systems

[5] Available in 4⅝-, 4.72-, and 5-in perforating systems

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Table 93. Mechanical and Performance Data Summary for Big Casing Entrance Hole Hollow Carrier Guns

Perforating System Designation	Shot Density, spf	Phasing, °	Charge	API RP 43 Fifth Edition Section 1 or API 19B Section 1						Maximum Explosive Load, g	Maximum Pressure Rating, psi	Weight of Loaded 20-ft Gun in Air, lbm	Maximum Diameter Including Burrs, Shot in Liquid, in	Maximum Diameter Including Burrs, Shot in Gas, in
				Penetration, in	Entrance Hole, in	Area Open to Flow, in^2/ft	Burr Height Avg/Max., in	Casing Size, in	Casing Weight, lbm/ft					
2-in HSD	6	60	PowerFlow* 2006, HMX	4.5	0.45	0.95	0.06/0.12	3½	9.2	6.4	20,000	119	2.16	2.21
2-in HSD	6	60	UltraPack* 2006, HMX	4.5	0.39	0.72	0.04/0.08	2⅞	6.4	6.5	20,000	119	2.16	2.21
2¼-in HSD	6	60	PowerFlow 2306, HMX	4.8	0.52	1.27	0.07/0.11	3½	9.2	–	20,000	136	2.46	2.48
2½-in HSD	6	60	PowerFlow 2506, HMX	5.2	0.64	1.93	0.08/0.12	3½	9.2	11.2	25,000	185	2.66	2.75
2½-in HSD	6	60	35B UltraPack, RDX	5.8	0.62	1.81	0.06/0.12	3½	9.2	10.5	25,000	185	2.80	2.80
2⅞-in HSD	6	60	38C CleanPACK*, HMX	6.6	0.70	2.31	0.06/0.08	4½	11.6	15.0	25,000	232	3.09	3.20
2⅞-in HSD	6	60	38C CleanPACK, RDX	8.4	0.62	1.81	0.09/0.13	4½	11.6	15.0	25,000	232	3.09	3.20
3⅛-in HSD	10	135/45	PowerFlow 3412, HMX	4.7	0.67	3.53	0.09/0.13	5	15.0	15.0	20,000	286	3.34	–
3⅛-in HSD	10	135/45	38C UltraPack, RDX	5.0	0.63	3.15	0.08/0.11	5	15.0	15.0	20,000	286	3.34	–
3⅜-in HSD[1]	12	135/45	PowerFlow 3412, HMX	4.5	0.64	3.86	0.07/0.10	5½	17.0	14.2	20,000	325	3.52	3.58
4-in HSD	5	120	PowerFlow 5008, RDX	6.3	0.95	3.55	0.09/0.12	5½	17.0	30.0	20,000	421	4.19	–
4½-in HSD	6	120	PowerFlow 5008, RDX	6.0	0.93	4.08	0.12/0.18	7	32.0	30.0	12,000	501	4.74	–
4⅝-in HSD Bigshot 21[2]	21	120/60	PowerFlow 4621, RDX	5.9	0.83	11.3	0.13/0.24	7	32.0	19.0	15,000	604	4.82	–
4⅝-in HSD Bigshot 21[2]	21	120/60	PowerFlow 4621, HMX	6.1	0.83	11.3	0.15/0.28	7	32.0	19.4	15,000	604	4.82	–
5-in HSD	8	135/45	PowerFlow 5008, RDX	5.8	0.98	6.05	0.11/0.22	7	32.0	30.0	11,000	565	5.19	–
5-in HSD Bigshot 21	21	120/60	43CJ UltraPack II, RDX	7.9	0.74	9.03	0.12/0.20	7⅝	33.7	19.0	11,000	595	5.14	–
5.85-in HSD[3, 4]	18	120/60	PowerFlow 5918, HMX	7.2	0.93	12.2	0.24/0.48	8⅝	56.6	34.0	20,000	1,112	5.96	–
6.625-in HSD	18	120/60	PowerFlow 6618, HMX	6.8	0.91	11.7	0.13/0.24	9⅝	47.0	34.0	20,000	1,310	6.73	–
6.625-in HSD[3, 4]	18	120/60	PowerFlow 6618, HMX	8.1	0.85	10.2	na	9⅝	70.3	34.5	20,000	1,310	6.72	–
7-in HSD	18	120/60	PowerFlow 7018, RDX	7.4	1.15	18.7	0.16/0.22	9⅝	47.0	45.0	10,000	1,330	7.13	–
7-in HSD	18	120/60	PowerFlow 7018, HMX	7.1	1.14	18.53	0.13/0.21	9⅝	47.0	49.5	10,000	1,330	7.13	–
7-in HSD	14	140/20	58C UltraPack, RDX	12.2	0.95	9.92	0.12/0.23	9⅝	47.0	61.0	10,000	1,289	7.27	–
7-in HSD	12	135/45	64C CleanPACK, RDX	10.1	1.13	11.41	0.10/0.22	9⅝	47.0	59.0	10,000	1,231	7.75	–

Notes: Every attempt has been made to verify the accuracy of the data tabulated; contact your Schlumberger representative for further information.

Other shot densities and phasings are available; Schlumberger also custom designs perforation systems to meet specific needs.

na = not available

Blue type identifies API 19B Registered Perforation Systems.

[1] Available in 3⅜-, 3.5-, and 3.67-in perforating systems

[2] Available in 4⅝-, 4.72-, and 5-in perforating systems

[3] Unofficial API data

[4] Q-125 casing

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Table 94. Mechanical and Performance Data Summary for Port Plug Guns and HEGS Hollow Carrier Guns

Perforating System Designation	Shot Density, spf	Phasing, °	Charge	API RP 43 Fifth Edition Section 1 or API 19B Section 1						Temperature Rating for 1 h, degF	Maximum Explosive Load, g	Maximum Pressure Rating, psi	Weight of Loaded Gun in Air, lbm	Maximum Diameter Including Burrs, Shot in Liquid, in	Maximum Diameter Including Burrs, Shot in Gas, in
				Penetration, in	Entrance Hole, in	Area Open to Flow, in^2/ft	Burr Height Avg/Max., in	Casing Size, in	Casing Weight, lbm/ft						
3⅜-in Port Plug Gun	4	90	38B HyperJet II, RDX	21.5	0.35	–	0.05/0.08	4½	11.6	340	15.0	25,000	300 (15 ft)	–	–
4-in Port Plug Gun	4	90	41B HyperJet II, RDX	23.6	0.38	–	0.07/0.09	5½	17.0	340	22.5	25,000	597 (20 ft)	–	–
4-in Port Plug Gun	4	90	41B HyperJet II, HMX	27.6	0.37	–	0.07/0.09	5½	17.0	340	22.5	25,000	597 (20 ft)	–	–
4-in Port Plug Gun	4	90	41B UltraPack, RDX	14.3	0.56	0.99	0.13/0.19	5½	17.0	340	22.5	25,000	597 (20 ft)	–	–
3⅛-in HEGS*, [1]	4	90	34B HyperJet, RDX	18.5	0.41	0.53	0.07/0.10	4½	11.6	340	16.1	6,200	340 (40 ft)	3.38	3.65
4-in HEGS	4	90	41B HyperJet, SX1	21.7	0.42	0.53	0.06/0.10	5½	17.0	210	22.0	4,000	520 (40 ft)	4.28	4.50
4-in HEGS	4	90	43C HyperPack*, RDX	9.4	0.60	1.13	0.09/0.12	7	23.0	210	24.0	4,000	520 (40 ft)	4.28	4.50

Notes: Every attempt has been made to verify the accuracy of the data tabulated; contact your Schlumberger representative for further information.

Other shot densities and phasings are available; Schlumberger also custom designs perforation systems to meet specific needs.

[1] Temperature rating of 210 degF if plastic foam loading tube used

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Special Application Perforating Systems

Introduction to special application perforating gun systems

The Schlumberger special application guns are tubing punchers, through-tubing drop-off guns, and shot-by-shot guns. Each of these gun systems is designed and optimized for a specific application.

Tubing punchers are used in situations that require a hole in an interior tubing or casing string with minimal damage to the surrounding string. The hole may be necessary to achieve circulation, relieve differential pressure across a packer, or, in some cases, allow production.

Through-tubing drop-off guns are designed on request to provide maximum performance in a nonretrievable gun application. A special thin-walled carrier has the minimum OD required to maintain the pressure rating. When the gun detonates, it fires a drop-off charge that separates the carrier from the positioning device, leaving the carrier in the well. This allows safe entry and exit through small-ID nipples with larger size gun performance. The dropped carrier is in one piece and can be fished during a workover. Contact your Schlumberger representative for more information on this customized perforating system.

Shot-by-shot guns are used for limited-entry applications in which single perforations are needed spaced over a large interval. The ASFS addressable-switch firing system is a smart gun system that uses a microcontroller device attached to each detonator, with status monitoring and skip-over capability. The ASFS system is fully described in the following chapter, “Wireline Perforating Techniques.”

Special application perforating gun datasheets

Tubing punchers

The 1⅜ and 1¹¹⁄₁₆-in. tubing punchers are used to pass through small restrictions in BHAs and punch holes in tubing or casing to achieve circulation or relieve pressure differentials (Table 95). These retrievable tools are wireline conveyed only.

Charge selection for tubing punchers is based on the wall thickness, desired exit hole size, and allowable penetration into a surrounding pipe string (Table 96).

Applications

- Pressure equalization between tubing and annulus
- Establish circulation between tubing and annulus when a sliding sleeve is not available or functional

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Table 95. 1⅜- and 1¹¹⁄₁₆-in. Tubing Puncher Mechanical Specifications

	16DS	16CL	20ES	20DM	20DL
Outside diameter (in.)	1 3/8	1 3/8	1 11/16	1 11/16	1 11/16
Shot density (spf)	4	4	4	4	4
Phasing (°)	0	0	0	0	0
Shot spacing (in.)	3	3	3	3	3
Temperature rating, 1 hr (°F [°C]	HNS: 500 [260]	HNS: 500 [260]	HNS: 500 [260]	HNS: 500 [260]	HNS: 500 [260]
Pressure rating (psi)	25,000	25,000	25,000	25,000	25,000
Min. casing size (in.)	2 1/16	2 1/16	2 3/8	2 3/8	2 3/8
Min. restriction (in.)	1.5	1.5	1.78	1.78	1.78
Max. gun length (ft)	1 to 20	1 to 20	1 to 20	1 to 20	1 to 20
Debris fill per charge (in.^{2}/ft)	None	None	None	None	None

Table 96. 1⅜- and 1¹¹⁄₁₆-in. Tubing Puncher Performance Summary[†]

Puncher, Charge	Tubing or Casing Wall Thickness (in.)	Average Size of Exit Hole in Inner Pipe (in.)	Max. Penetration in Outer String (in.)
16DS, HNS			
Min. recommended wall thickness	0.19	0.30	0.10
Max. recommended wall thickness	0.375	0.23	0.05
16CL, HNS			
Min. recommended wall thickness	0.375	0.22	0.10
Max. recommended wall thickness	0.50	0.13	0.05
20ES, HNS			
Min. recommended wall thickness	0.19	0.32	0.10
Max. recommended wall thickness	0.375	0.24	0.05
20DM, HNS			
Min. recommended wall thickness	0.375	0.30	0.10
Max. recommended wall thickness	0.50	0.23	0.05
20DL, HNS			
Min. recommended wall thickness	0.50	0.25	0.10
Max. recommended wall thickness	0.58	0.016	0.05

[†] Data apply to tubing and casing grade L80, 0 to 15,000 psi, 75 to 500 degF in fluid, with 0.25-in. clearance between inner and outer pipe.

Customized perforating systems

Schlumberger can provide customized perforating products or systems on request. These are generally RapidResponse projects, as described in "RapidResponse client-driven product development" in the "Perforating Gun Systems" chapter.

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Wireline Perforating Techniques

Basic wireline perforating strings

The basic wireline perforating string is made up of a cable head, correlation device, positioning device for through-tubing applications, and one or more guns. Most Schlumberger gun systems can be used with S.A.F.E. Slapper-Actuated Firing Equipment or a Secure detonator system. These systems provide added levels of safety in the presence of RF fields and other sources of stray electrical current.

The cable head serves three functions:

- connects the gun string to the electric wireline
- provides a controlled weakpoint for freeing the cable if the guns become stuck
- provides a fishing profile.

The weakpoint rating is selected to avoid exceeding the cable strength when attempting to free the cable at the weakpoint or pull-off. The type of cable, gun system, well depth, and well deviation all dictate the choice of a weakpoint.

Before starting perforating operations, personnel should record the perforation intervals on the perforation worksheet. Selected intervals are documented on the reference log, which can be an openhole or cased hole log or a perforating depth control log. A correlation nuclear log or CCL should be run across the interval being perforated, and it should be on depth with the reference log (Fig. 167). Correlation log depths must be corrected to the reference log depths if there is a depth difference between the two logs. The depth difference should be noted on the perforation worksheet.

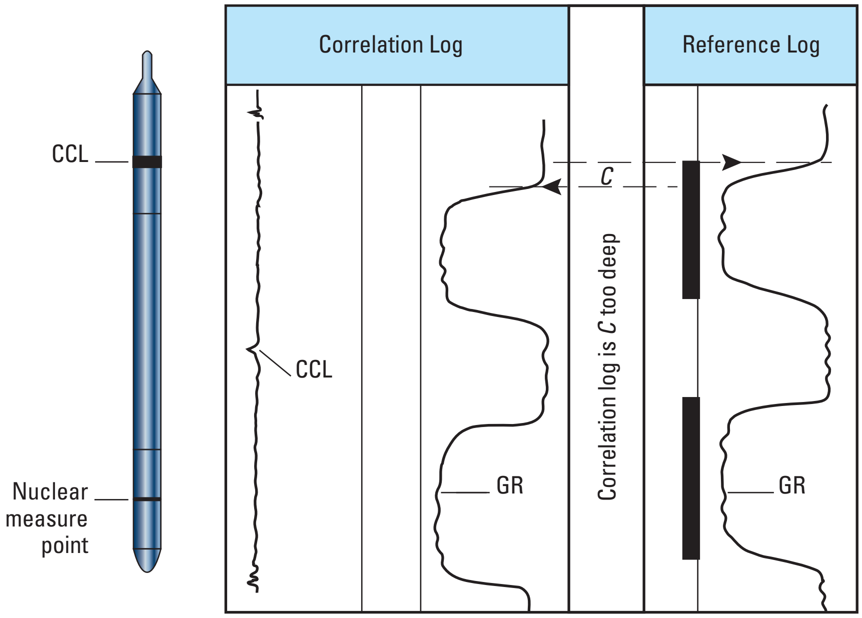

Figure 167. Depth and perforation interval correlation between reference and correlation logs.

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The correlation device is normally a CCL (Fig. 168 and Table 97) or a gun gamma ray (GR) with a CCL. If a log has already been run that correlated the casing collars to the formation depths, a CCL alone can be used in a gun string to identify the collar distance variations and their placement with respect to the formation and the interval to be perforated. If a casing string is made up of uniform lengths of pipe, running a shorter "pup" joint somewhere near and above the perforation interval is recommended so the pup can be easily distinguished by the CCL.

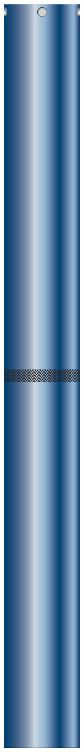

Figure 168. Casing collar locator.

Table 97. CCL Specifications

Assembly	Temperature (°F [°C])	Pressure (psi)	OD (in.)	Weight (lbm)	Length (in.)
CCL-N	350 [177]	20,000	1⅜	6	17.8
CCL-L	350 [177]	20,000	1¹¹⁄₁₆	12	18.0
CCL-AG	500 [260]	20,000	1¹¹⁄₁₆	12	18.0
CCL-AT	500 [260]	25,000	1¹¹⁄₁₆	12	18.0
CAL-B	350 [177][†]	20,000	3⅜	60	18.0
CCL-AF[‡]	350 [177]	20,000	3⅜	90	58.1

[†] Modification available for 480°F [249°C]

[‡] Not shock proof; recommended for setting-tool operations in large casing

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When no previous correlation logs have been run, the gun GR-CCL combination is used to convey and place the gun string at the perforation interval in the same run in the well. The gun GR, such as the UPCT* Universal Perforating and Correlation Tool, is used to correlate the formation depths and the perforating interval with the reference openhole evaluation logs.

A positioning device on through-tubing gun systems orients the shots toward the casing and minimizes the gun-to-casing clearance. Two types of positioning devices are available—spring and magnetic (Fig. 169 and Table 98). The spring device is generally used in applications involving nonmagnetic casing. The magnetic positioning device is more commonly used because of its simplicity and relatively short makeup length.

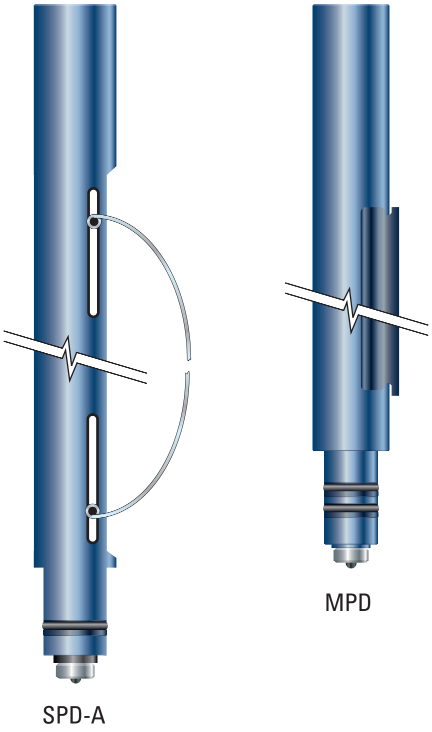

Figure 169. Magnetic and spring positioning devices.

Table 98. Positioning Device Specifications

Tool	Temperature (°F [°C])	Pressure (psi)	Hole Size (in.)		OD (in.)	Weight (lbm)	Length (in.)
			Min.	Max.			
Magnetic devices							
MPD-NB[†]	500 [260]	25,000	1.5	No limit	$1\frac{3}{8}$	11	19.4
MPD-LB[†]	500 [260]	25,000	1.82	No limit	$1\frac{11}{16}$	14	19.4
MPD-MB[†]	500 [260]	25,000	2.125	No limit	2	17	19.4
Spring device							
SPD-A	500 [260]	25,000	1.82	7	$1\frac{11}{16}$	10	28.3

[†] The MPD-NB, MPD-LB, and MPD-MB have pull-off forces of 30, 35, and 50 lbf, respectively.

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The gun is the lowermost component of a wireline string. A gun has a head that connects electrically and mechanically to the CCL or positioning device and a lower head or bottom nose. In hollow carrier guns, the lower head provides pressure confinement and access to the detonating cord and electrical connections. Schlumberger gun systems also have a pressure-relief feature built into the lower head to vent pressure trapped in the gun. A selective switch adapter is used when the guns are shot selectively. The adapter houses the switch and provides a pressure seal between the guns.

The wireline X-Tools automatic release (WXAR) can be used to drop the bottom section of an HSD High Shot Density gun string. The small WXAR device allows a long gun string to be shot in an underbalanced condition and the top section to be retrieved without killing the well.

Figure 170 shows examples of gun systems.

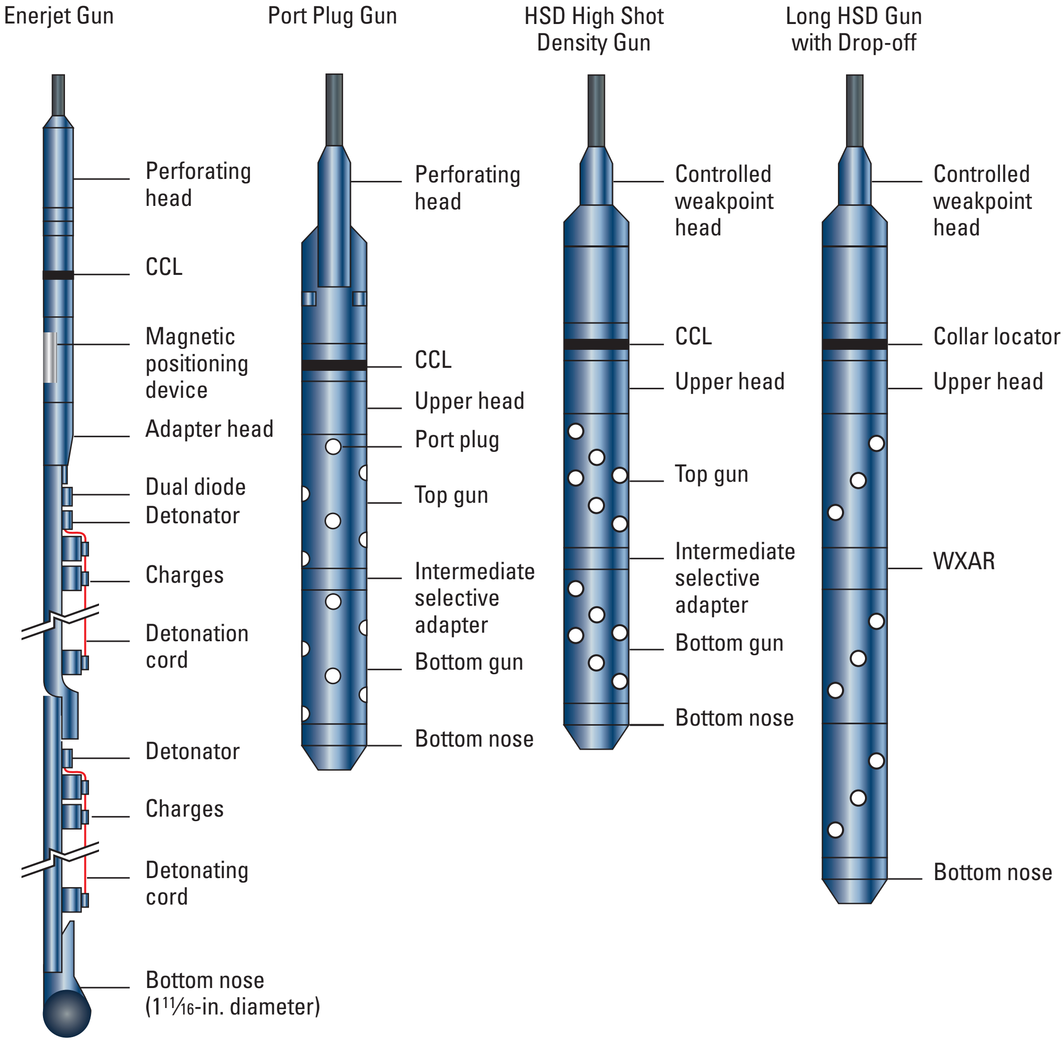

Figure 170. Examples of Schlumberger gun systems.

Selective perforating

Selective perforating is necessary when more than one gun is shot during a single trip into the well. Two types of selective switches are used to control gun firing: electronic addressable switches and mechanical pressure-actuated switches.

ASFS addressable-switch firing system

The ASFS addressable-switch firing system (Fig. 171) is a smart gun system that uses a microprocessor-controlled electronic switch attached to each detonator. Each electronic switch has a unique address for identifying each gun before shooting. Because two-way communication is required to shoot any gun, inadvertent detonation is prevented. Bulkheads between guns are simple one-wire feed-throughs. A safety surface gun tester exercises all circuits before use and supports fast setup and troubleshooting.

The system accommodates up to 40 guns per descent. No maintenance is necessary because the electronic switches are fully expendable, which makes them a reliable, cost-efficient replacement for pressure-actuated switches. Complete skip-over capability means that a dead gun or pressure switch no longer kills the whole gun string. The real-time positive shot indication is beneficial in situations where single-shot detonations are otherwise difficult to detect.

The ASFS addressable-switch system is available for all hollow carrier perforating gun systems (Table 99); it is compatible with conventional and Secure detonators.

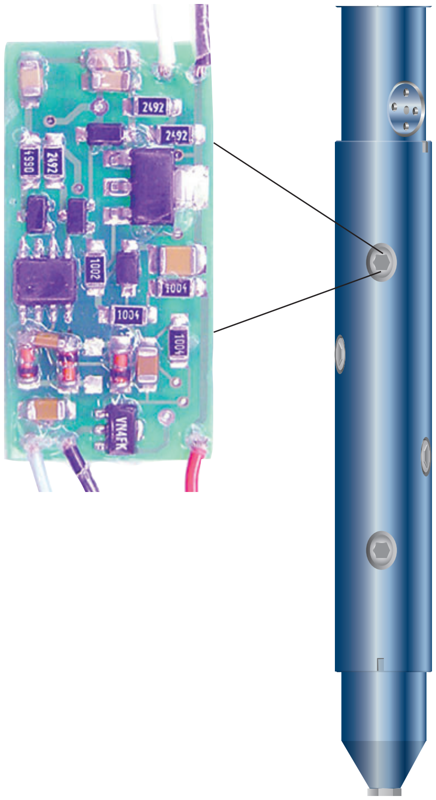

Figure 171. Switch and gun of the ASFS addressable-switch firing system.

Table 99. ASFS Specifications

Temperature rating for 1 hr	340°F [170°C]

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Mechanical switches

Mechanical switches are used for selective perforating operations by placing one between each multiple-shot gun. The switch is a pressure-operated electric contact that allows current to pass through to the bottom gun in a string while using open circuit protection to prevent current flow to the upper guns. Positive- and negative-polarity-sensitive electrical diodes prevent detonation of an upper gun after firing the lower gun and activating the switch. The four-gun string shown in Fig. 172 has both types of polarity switches. The bottom gun is usually fired on positive polarity with the Type I positive-polarity-blocking switch. The next gun is fired on negative polarity with the Type II negative-polarity-blocking switch. The remaining guns are fired by alternating the polarity of the shooting current. As each gun is fired, the force of the detonation actuates a piston that closes the switch and connects the firing circuit to the next higher gun in the string.

A simple method using the Schlumberger dual-diode system (Fig. 173) is available for shooting only two guns per run.

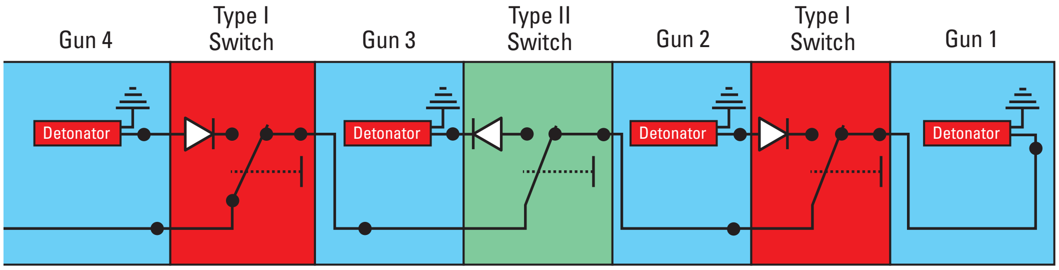

Figure 172. Four-gun selective switch string.

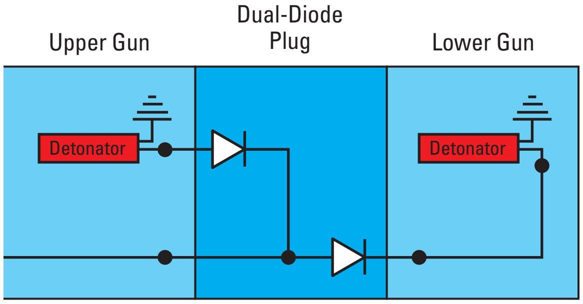

Figure 173. Dual-diode selective system.

Operations

Job preparation

The success of a perforating job typically depends on effective prejob planning. Job preparation begins with a thorough understanding of important reservoir parameters and the completion objective. On the basis of this information, the most appropriate system can be chosen to achieve the desired results. Prejob planning ensures selection of the optimum perforating system and the highest return from the perforated completion. Figure 174 illustrates the many variables to consider in prejob planning.

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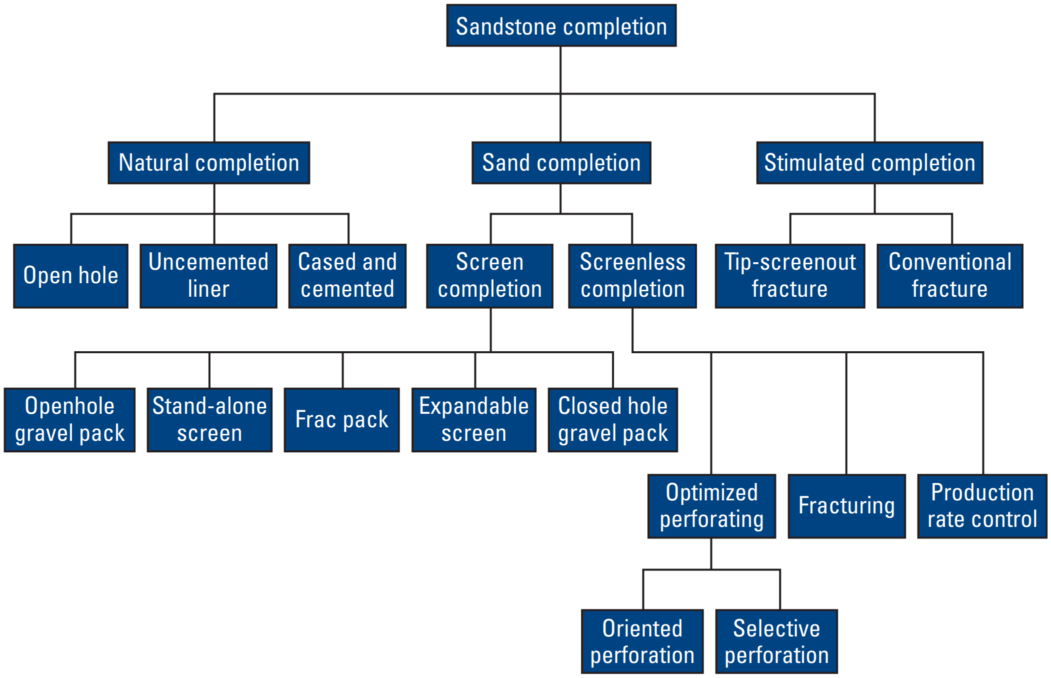

Figure 174. Planning a wireline perforating job in a sandstone reservoir.

Operational procedures

A perforating operation involves many steps, which are common to all gun systems. The typical operation includes the following:

- prejob design
- review of safety procedures
- rig-up
- gun arming
- running in hole
- depth control
- gun firing
- gun retrieval
- rig-down.

These steps are discussed in the following sections.

Prejob design

Table 100 lists the prejob information needed to develop a perforation program.

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Table 100. Information Required for Prejob Design

Information	Purpose
Casing ID, tubing size and weight, ID restrictions	Gun size limitations
Depth of well, casing liner, tubing and ID restrictions	Operational requirements
Pressure and temperature at perforation depth	Gun rating
Underbalanced formation pressure–hydrostatic pressure	Control of wellhead pressure
Fluid in well at shooting depth, before and after perforation	Gun limitations
Wellhead pressure, before and after perforation	Control of wellhead pressure
Radio power, frequency and distance of antenna to well	Detonator selection
Rig or mast height and wellhead access	Perforation program requirements
Wellhead connection	Operational requirements
Perforation intervals, type of gun, shot density and phasing	Perforation program requirements
Depth reference, kelly bushing, ground level, mud level	Depth correlation
Nuclear and collar logs	Depth correlation

A perforation program is developed from this prejob information by using a job questionnaire (Fig. 175). The perforation program should minimize the number of gun runs within the limitations of the rig-up, type of gun, and well conditions. Rig or mast height limitations are usually obvious and difficult to change. In general, the rig or mast should be 2.5 times the length of the longest gun to accommodate lifting the lubricator between runs. A suitable alternative for shorter rig or mast heights is to lower the gun out of the lubricator and into the mouse hole to disconnect the head, and then move the gun with an air line or pick up the guns inside the lubricator. If a lubricator is not used, gun length limitations are based on gun weight, type of cable used to convey the gun, selectivity, and rathole below the gun. The cable weakpoint should be at least 3 times the weight of the gun string in air. The rathole below the guns should be equal to the gun length or greater. Longer strings can be run if a shock absorber is used or automatic gun release is planned.

Safety

Before starting perforating operations, all involved personnel should discuss safety rules, procedures to follow, and potential hazards. Everyone involved in the operation must strictly observe the safety rules in Fig. 2, in the “Perforating Fundamentals” chapter. Additional safety precautions are required when the perforating guns are loaded on the rig:

- The drilling supervisor, toolpusher, safety officer, crane operators, and deck foreman should be aware of explosives storage and handling locations. These areas should be clearly marked with “Danger Explosive” signs.
- Welding, smoking, and overhead crane operation are prohibited in explosives storage and handling areas. Access to the area should be limited to authorized personnel.
- All spare and scrap explosives must be stored in approved containers. All explosives must be removed from the operating area after loading the guns.

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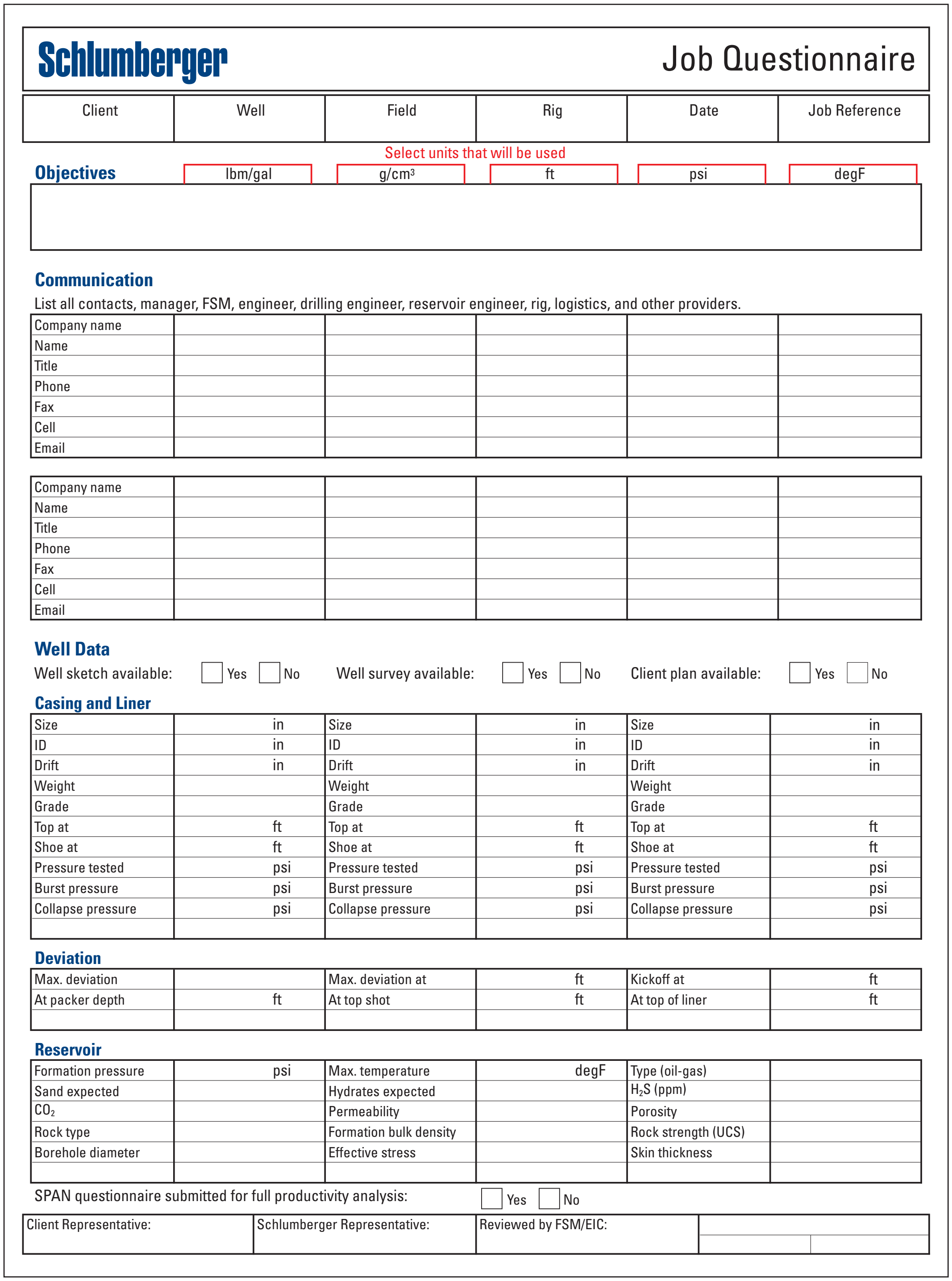

Schlumberger Job Questionnaire

Client	Well	Field	Rig	Date	Job Reference

Select units that will be used

Objectives

lbm/gal	g/cm^3	ft	psi	degF

Communication

List all contacts, manager, FSM, engineer, drilling engineer, reservoir engineer, rig, logistics, and other providers.

Company name					
Name					
Title					
Phone					
Fax					
Cell					
Email					

Company name					
Name					
Title					
Phone					
Fax					
Cell					
Email					

Well Data

Well sketch available: ☐ Yes ☐ No Well survey available: ☐ Yes ☐ No Client plan available: ☐ Yes ☐ No

Casing and Liner

Size	in	Size	in	Size	in
ID	in	ID	in	ID	in
Drift	in	Drift	in	Drift	in
Weight		Weight		Weight	
Grade		Grade		Grade	
Top at	ft	Top at	ft	Top at	ft
Shoe at	ft	Shoe at	ft	Shoe at	ft
Pressure tested	psi	Pressure tested	psi	Pressure tested	psi
Burst pressure	psi	Burst pressure	psi	Burst pressure	psi
Collapse pressure	psi	Collapse pressure	psi	Collapse pressure	psi

Deviation

Max. deviation		Max. deviation at	ft	Kickoff at	ft
At packer depth	ft	At top shot	ft	At top of liner	ft

Reservoir

Formation pressure	psi	Max. temperature	degF	Type (oil-gas)	
Sand expected		Hydrates expected		H_2S (ppm)	
CO_2		Permeability		Porosity	
Rock type		Formation bulk density		Rock strength (UCS)	
Borehole diameter		Effective stress		Skin thickness	

SPAN questionnaire submitted for full productivity analysis: ☐ Yes ☐ No

Client Representative:	Schlumberger Representative:	Reviewed by FSM/EIC:	

Figure 175. One page from a job questionnaire.

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Gun arming

Wireline carrier guns are generally armed for bottom-up firing as described here. After all safety precautions have been taken, the detonator is placed in a safety loading tube designed to contain the blast if an accidental detonation occurs when making the electrical connections (Fig. 176). Schlumberger also uses a safety interlock system (safety switch and key) to ground and electrically isolate the wireline cable from accidentally applied voltages and to shut down the AC power to the firing circuits. The ballistic connection is made to the detonating cord only after the detonator is electrically connected.

Figure 177 is a schematic of a bottom-armed gun system. The distance from the measure point of the CCL or gun GR to the bottom of the total gun string is measured before the gun is picked up for running in the well. This distance is recorded on the perforation worksheet and later entered into the surface acquisition system. The distance from the CCL or gun GR measure point to the top shot of each gun in the string (Fig. 178) is also entered. A final check then verifies that the guns are connected in the correct sequence and the proper interval is loaded for each gun.

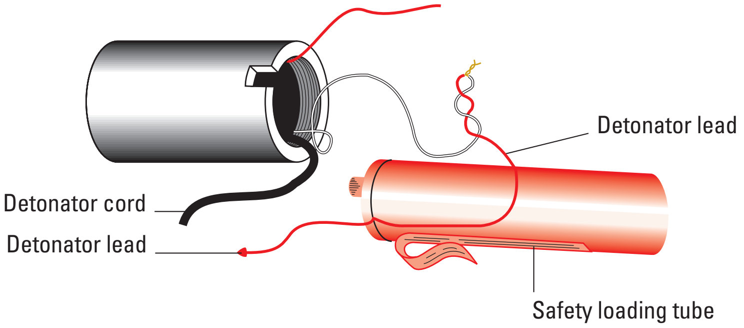

Figure 176. Safety loading tube used to contain the detonator during gun arming.

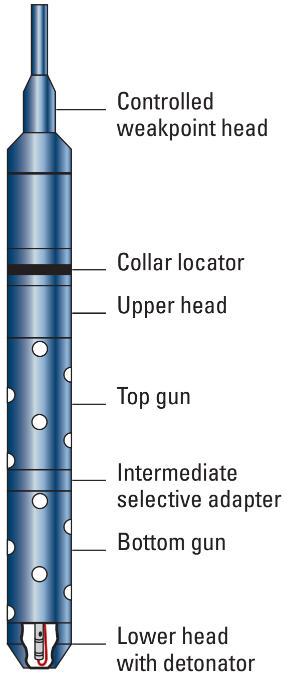

Figure 177. Bottom-armed gun system.

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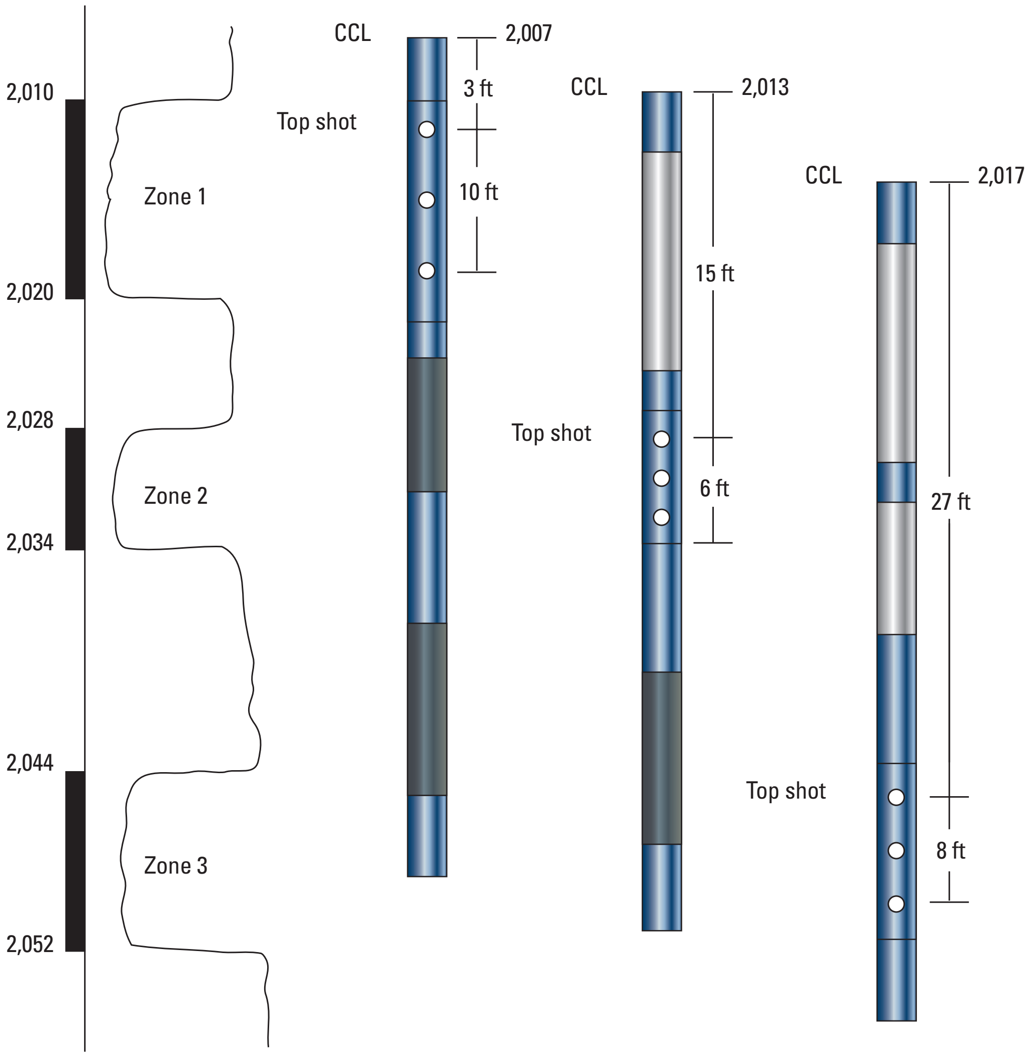


Figure 178. Perforating gun measurements versus perforation intervals and depth position.

Running in hole

After the gun is depth-zeroed at the permanent depth reference point, the gun is run into the hole to the perforation depth. These precautions are recommended during run-in:

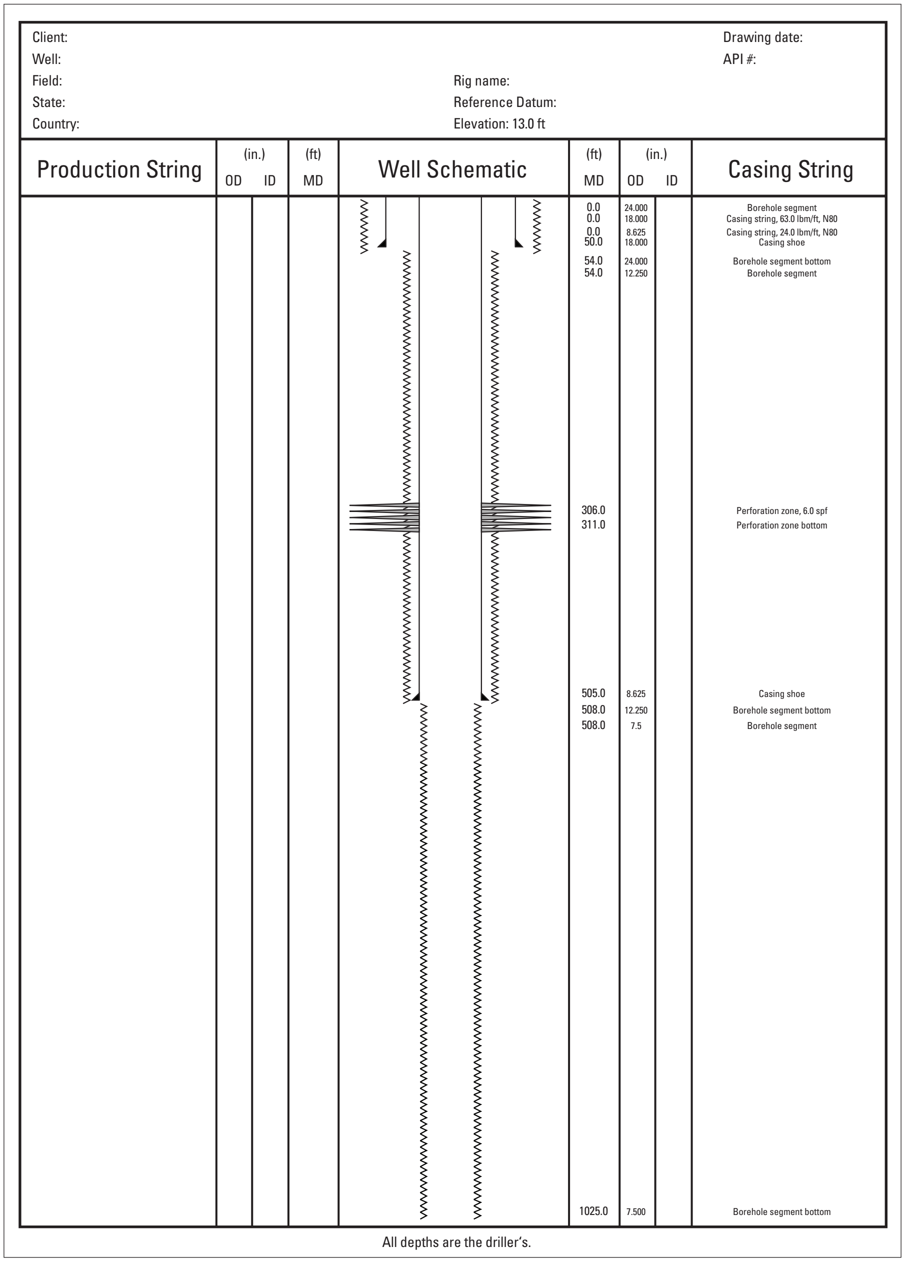
- Lower the gun as quickly as practical without compromising safety, losing the grease seal on the injector, or overrunning the gun and tying a knot in the cable.
- Record all restrictions or ID changes and reduce speed as the gun passes them. If the well is not full, note the fluid level from the weight indicator and enter it on the perforation worksheet for each run in the hole.

Depth control

Upon reaching the perforation depth, the gun must be accurately positioned opposite the zone being perforated. A CCL or gun GR tool is typically used for gun positioning.

With a CCL or gun GR, an "up-pass" tie-in log is recorded and compared with the correlation log. Any depth discrepancy is then eliminated, and a confirmation pass is recorded. As the gun is logged into position for firing, the surface acquisition system generates a log with previously entered correlation casing collars. The previous collars can be compared with those being recorded on the tie-in pass. After correct positioning, the gun is detonated and retrieved from the well, or moved to the next zone if a selective gun string is being used.

The perforation record provides the depth locations of the top and bottom shots and the CCL (Fig. 179), a gun sketch at the perforation depth, and a perforation summary (Fig. 180).



Client:
Well:
Field:
State:
Country:
Rig name:
Reference Datum:
Elevation: 13.0 ft
Drawing date:
API #:

(ft) MD	(in.) OD	(in.) ID	Casing String
0.0	24.000		Borehole segment
0.0	18.000		Casing string, 63.0 lbm/ft, N80
0.0	8.625		Casing string, 24.0 lbm/ft, N80
50.0	18.000		Casing shoe
54.0	24.000		Borehole segment bottom
54.0	12.250		Borehole segment
306.0			Perforation zone, 6.0 spf
311.0			Perforation zone bottom
505.0	8.625		Casing shoe
508.0	12.250		Borehole segment bottom
508.0	7.5		Borehole segment
1025.0	7.500		Borehole segment bottom

All depths are the driller's.

Figure 179. Perforation record example.

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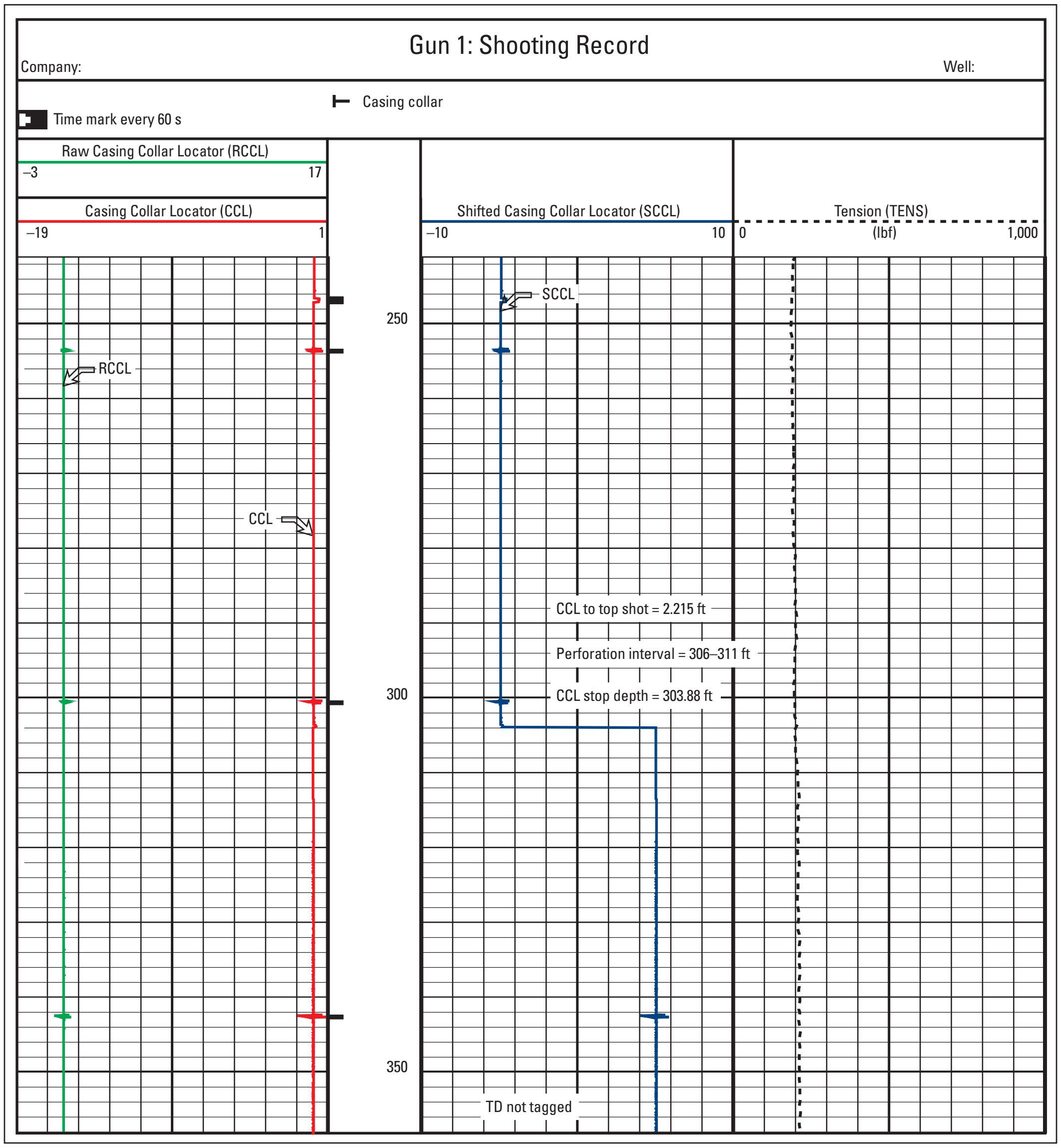

Figure 180. Perforation summary example.

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Gun firing

Computer simulations of gun behavior at detonation suggest large-scale interactions between the gun and the wellbore. These interactions can be described as pressure events within the wellbore resulting from jet penetration of the well fluid, gun swell, reservoir response, and fluid column response.

The earliest event is an increase in pressure. This increase results from the jet penetration of the well fluid, the gun swell from charge-case impact, and the production of high-pressure detonation gases. A pressure reduction occurs next, caused by the cooling of the detonation products, followed by the reservoir and fluid column's attempt to fill the empty gun string.

This gun-filling effect results in a fluid hammer that interacts with well fluid pressures to produce gun movement. The direction of movement of wireline guns depends on the following factors, with well and gun geometry having the greatest impact on the magnitude and severity of the fluid hammer effect:

- firing technique (top down, bottom up, selective)
- gun lengths (especially when fired selectively)
- gun diameter versus wellbore diameter
- hydrostatic pressure
- amount of rathole beneath the gun.

Although there are no analytical models to accurately predict the exact behavior of a firing gun, the forces involved may be largely responsible for the occasional and unintentional parting of the weakpoint in the cable head.

Well flow rates also have a pronounced effect on the wireline and have moved the gun string uphole, causing entanglement of the wireline and preventing retrieval from the well.

Gun retrieval

All safety rules for running the gun into the well must be observed when retrieving the fired gun from the well. Well restrictions, clearance of the gun to casing or tubing, and the completion fluid determine how quickly the gun should be pulled from the well.

At the surface, the gun is treated as unfired until perforations in the gun are visually verified. The gun system must also be carefully checked for trapped pressure. This pressure should be relieved before rigging down the gun. In case of a misfire, the engineer disarms the gun as soon as it returns to the surface.

Wireline perforating datasheets

In addition to basic wireline perforating strings, Schlumberger provides advanced wireline perforating strings, gamma ray wireline perforating tools, auxiliary wireline services, shallow well perforating trucks, and mechanical wireline perforating services. The remainder of the chapter comprises datasheets, concisely listing specifications for these tools and services. For special applications, contract your Schlumberger representative.

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WPP Wireline Perforating Platform

The WPP* Wireline Perforating Platform is a downhole orienting and imaging platform that meets the various requirements for sensor packages run with perforating guns (Fig. 181 and Table 101). This rugged, modular arsenal of sensors and actuators provides extreme flexibility for positioning perforating guns and monitoring results in real time. The WPP platform also provides intelligent control of the downhole power supply to improve the safety and reliability of perforating. The first three applications that have been developed for the WPP platform are for orienting the guns in any direction in downhole conditions, rotating the tool and gun to avoid bottomhole completion (e.g., long string in a dual-string well, control lines), and measuring pressure and temperature before, during, and after firing of the guns.

Designed for use with Secure detonators, the WPP platform is also compatible with the ASFS addressable-switch firing system for selective firing of multiple guns in a single run. The WPP modules are employed as necessary:

- Telemetry module provides the interface between the logging cable and the downhole tools (WPP modules and guns).
- Motor module rotates the toolstring and guns below the motor sonde for directional perforating.
- Pressure and temperature module records pressure and temperature measurements while perforating.
- Completion mapper module is used to detect other completion strings in the wellbore for shooting into or away from them.
- Gyroscope carrier is a pressure housing for a gyroscope.
- Shooting module is an intelligent component that allows measurements while perforating and selective perforating, including downhole shot indication.
- Gamma ray module is used for depth control in addition to the built-in CCL.

Applications

- Oriented perforating
- Completion mapping
- Pressure and temperature measurement while perforating

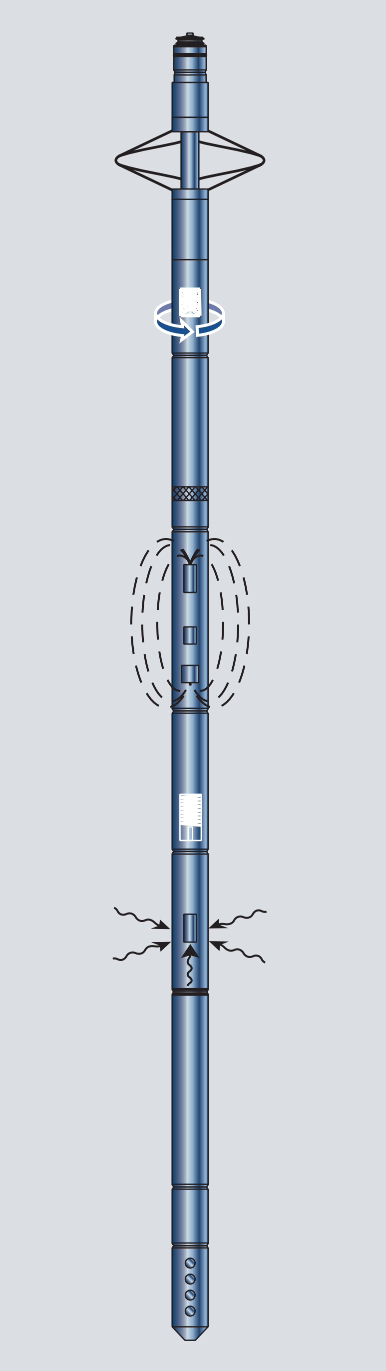

Figure 181. WPP platform with multiple application options.

Table 101. WPP Specifications

Outside diameter (in.)	1.6975 Gyroscope carrier: 1.75
Temperature rating (°F [°C])	300 [149]
Pressure rating (psi)	20,000
Length† (ft)	9.47 to 25.98

† Not including gyroscope module

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Wireline Oriented Perforating Tool

The wireline oriented perforating tool (WOPT) assembly is used to orient perforating guns conveyed on wireline in 5° increments (Fig. 182 and Table 102). Two runs are required to complete the operation. The first run uses a gyroscope to find the natural lie of the string in the well. The second perforating run is made without a gyroscope, which would be damaged by the perforation shock. During the gyroscope run, deviation and relative bearing are recorded using the wireline perforating inclinometer tool (WPIT). The gyroscope finds the azimuth, enabling personnel at the surface to index the guns to point in the desired perforating direction. The WPIT inclinometer stays on the string during the second run and is used to confirm position repeatability before shooting.

Applications

- Minimize fracture pressure and prevent multiple competing fractures by aligning 180°-phased guns within ±10° of the preferred fracture plane
- Minimize sand production by aligning perforations on either side of maximum stress direction
- Orient perforations away from known mechanical obstacles

Table 102. WOPT Specifications

Outside diameter (in.)	3.375	4.5
Temperature rating (°F [°C])	350 [177]	350 [177]
Pressure rating (psi)	20,000	20,000

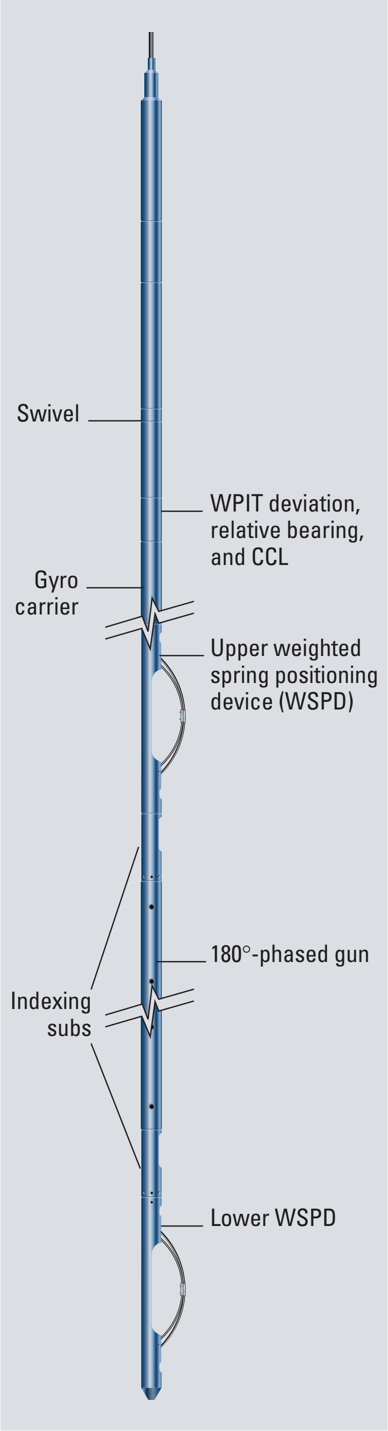

Figure 182. WOPT.

S.A.F.E. Slapper-Actuated Firing Equipment and Secure Detonators

S.A.F.E. technology

The S.A.F.E. detonating system was developed to provide immunity from electric potential differences created by RF transmissions, impressed current for cathodic protection, electric welding, high-tension power lines, and inductive coupling from large induction motors such as topdrives on drilling rigs. S.A.F.E technology eliminates the need to shut down radio communication and other vital equipment during perforating jobs.

The S.A.F.E. detonating mechanism (Fig. 183) is the exploding foil initiator (EFI), which has proved resistant to stray voltages because of the high currents required for detonation. It contains no primary high explosives.

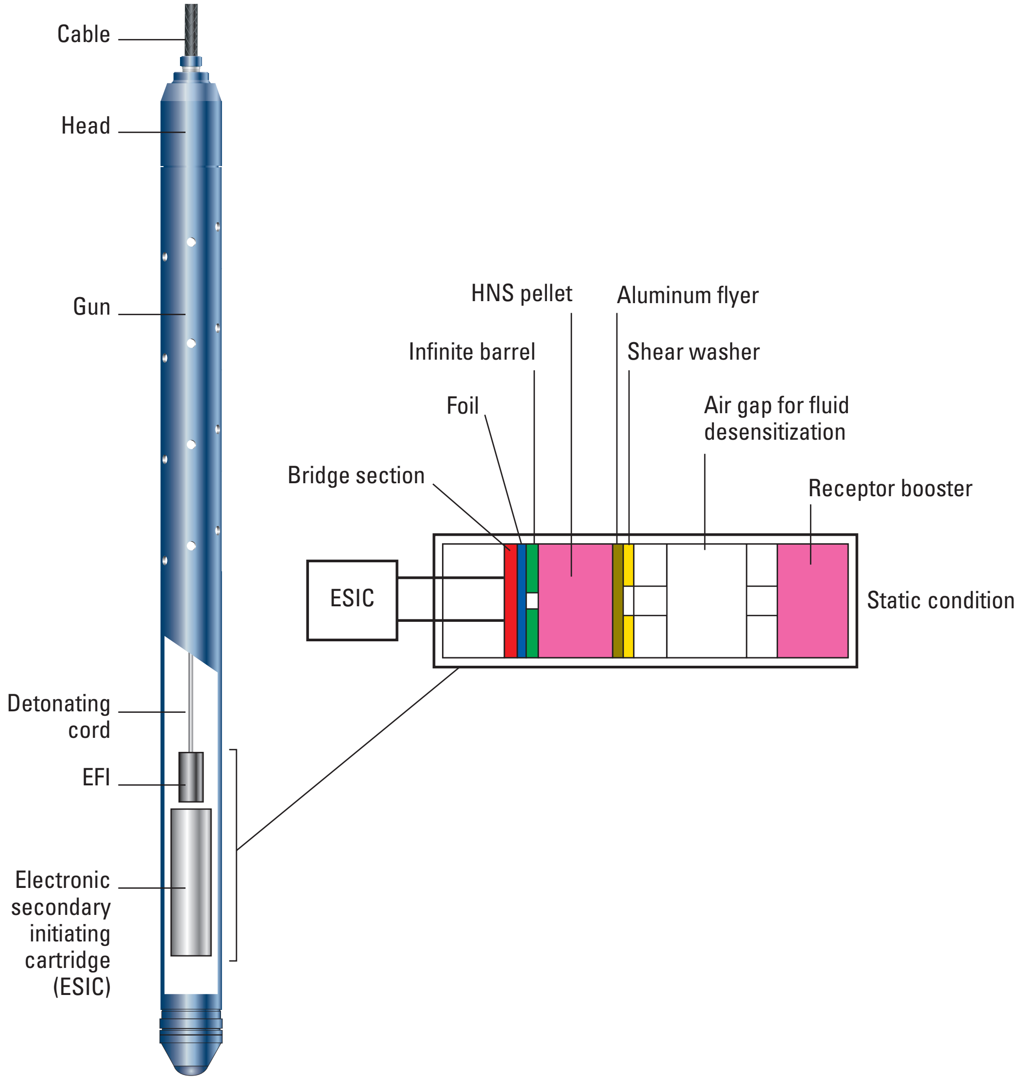

Figure 183. EFI operation of the S.A.F.E. perforating system.

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When shooting power is applied, a section of metal foil is instantly vaporized, which causes a neighboring (secondary) high-explosive pellet to detonate and shear a small aluminum flyer. The flyer travels across a fluid desensitization gap in the EFI housing and strikes a booster that initiates the detonation of the gun.

Secure detonator

The Secure detonator (Fig. 184) is the third generation of S.A.F.E. initiators. It performs like a conventional detonator but without the added safety concerns, cost, and inconvenience of shutting down RF transmitters, turning off cathodic protection, and postponing welding operations.

The use of EFI technology makes the Secure detonator one of the safest detonators in the industry. Its inherent safety results from the specific high voltage and current pulse required for detonation. The power threshold for the EFI technology in the Secure detonator is 3 MW, compared with 1 W for a typical standard resistor detonator and 2 W for a semiconductor bridge detonator. No primary high explosives are used in the detonator. The Secure detonator does not use any pyrotechnics, which may burn to detonation if exposed to fire.

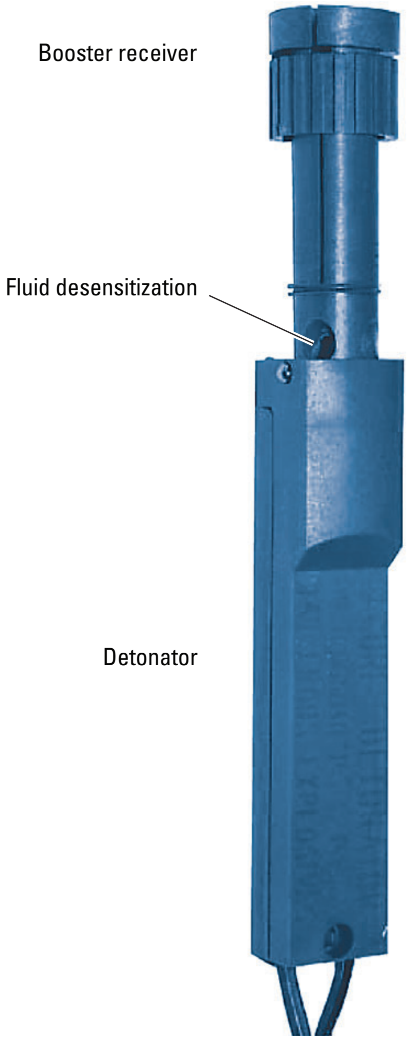

Figure 184. Secure detonator (actual size).

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The Secure detonator does not require a downhole cartridge to provide the electric pulse to initiate the firing sequence. All electronics are fully expendable and contained in the detonator package. As a result, operations are simple, reliable, and flexible.

Three versions of the Secure detonator are available: for hollow carrier gun applications, for exposed gun applications, and for setting tool and chemical cutter applications.

S.A.F.E. system

The S.A.F.E. detonator system is preferred for applications in which the temperature exceeds 340°F [170°C]. The S.A.F.E. detonation system can be located at the bottom (Fig. 185), at the top, or between two guns. Three versions of the detonator are available:

- carrier detonator: for hollow carrier perforating gun systems and explosive cutters
- exposed detonator: for exposed perforating gun systems
- pyrotechnic detonator: for setting tools and chemical cutters.

A high-temperature version of the initiating cartridge can be used to up 400°F [204°C], and a Dewar flask assembly for standard system components extends use up to 500°F [260°C].

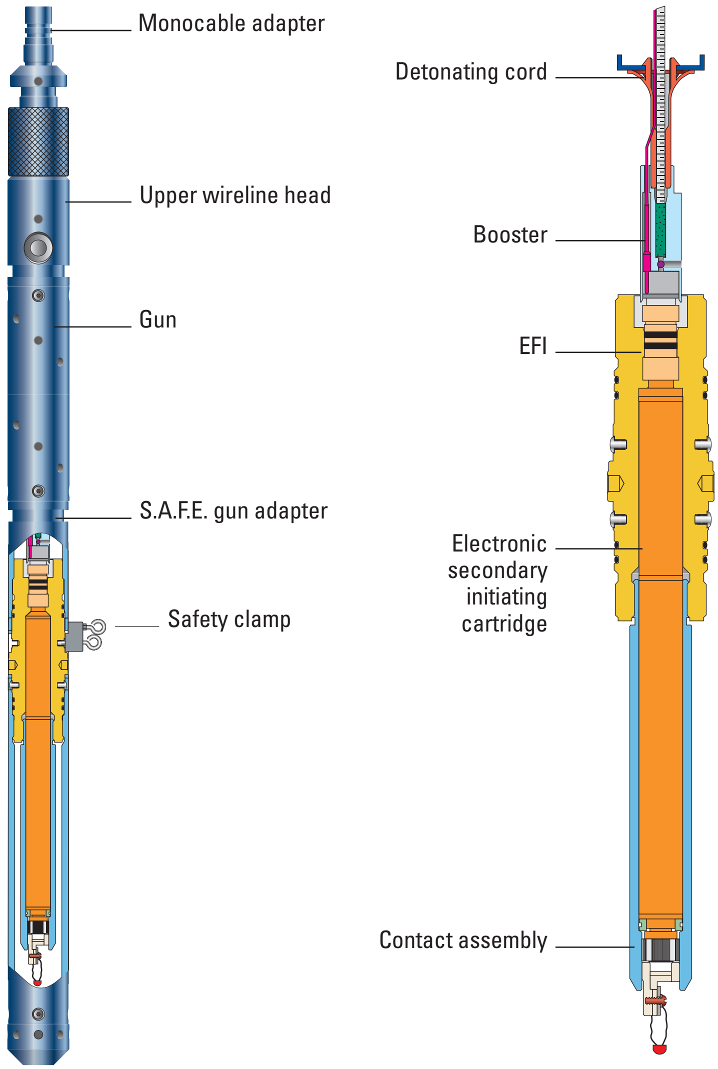

Figure 185. S.A.F.E. detonating system in a bottom-up fired perforating gun.

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UPCT Universal Perforating and Correlation Tool

The UPCT Universal Perforating and Correlation Tool is a 1$^{11}/_{16}$-in. gamma ray–casing collar locator (GR-CCL) for perforating operations (Fig. 186 and Table 103). The scintillation GR detector measures the natural radioactivity of the formation, and the sensitive CCL clearly identifies the location of tubing and casing collars. The resulting depth correlation provided by the UPCT tool to previous logs enables precise positioning of perforating guns and other through-tubing explosive devices.

The tool's rugged design and reliability improve upon existing through-tubing GR-CCL tools. The UPCT tool can be used for correlation and perforating in a single run. A shock absorber sub is not required.

The detector and electronics are similarly ruggedized through improved shock mounting in a corrosion-proof pressure housing rated to 20,000 psi. The UPCT tool is compatible with all detonator types, including the ASFS addressable-switch firing system and the S.A.F.E. and Secure systems, on both polarities. This capability is maintained even at the extreme conditions of a 30,000-ft cable at 350°F [177°C].

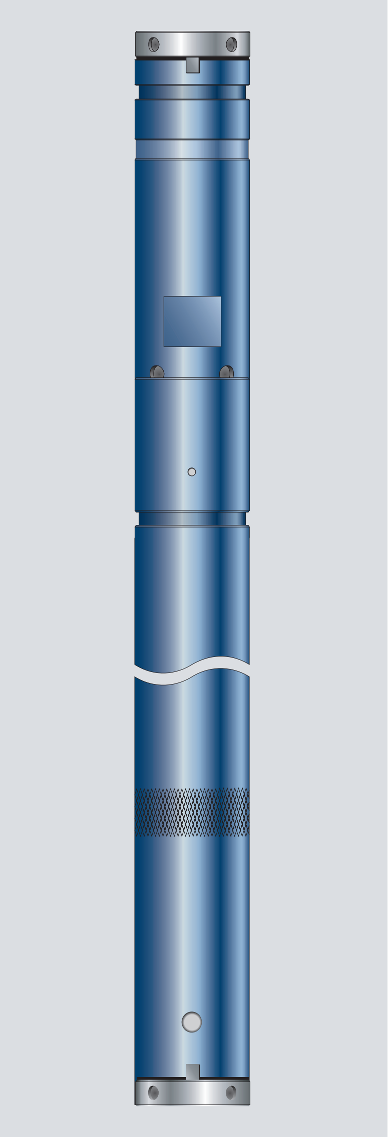

Figure 186. UPCT tool.

Applications

- GR-CCL correlations
  - During perforating run
  - Through tubing
  - In tubing and casing
  - Extreme depth and temperature conditions
  - Ruggedized high-sensitivity CCL, for measurement of tubing and casing collars

Table 103. UPCT Specifications

Outside diameter (in.)	1.718
Temperature rating (°F [°C])	350 [177] 1-hr excursion: 400 [204]
Pressure rating (psi)	20,000
Length† (ft)	4.5
Weight (lbm)	25

† Without gun

PGGT Powered Gun Gamma Tool

The PGGT* Powered Gun Gamma Tool (Fig. 187 and Table 104) records naturally occurring gamma rays in the formation near the wellbore. This nuclear measurement, effectively made in any environment, indicates the radioactive content of the formations.

The PGGT tool is used with perforating guns to correlate depths with those of previous logs. The measurements used for correlation are the gamma ray and casing collars. The 1¹¹⁄₁₆-in. PGGT-C tool uses a 1-in. × 8-in. sodium iodide crystal for the gamma ray detector and is typically deployed with through-tubing guns. The PGGT-B tool is the same as the PGGT-C tool except that the cartridge is in a vacuum flask inside a larger 2⅛-in. housing. The flask enables operation at temperatures above 350°F [177°C] with a holding time of 6 hr at 500°F [260°C]. The 3.625-in. PGGT-D tool is used with casing guns, plugs and packers, and core guns.

Because the PGGT and perforating gun combination operates on monocable, the circuitry is designed to block tool power from the gun during logging and to disconnect the cartridge electronics from the cable when higher voltages or negative voltages are applied to shoot the perforating gun.

A shock absorber at the lower end of the cartridge-flask assembly protects it from the shocks that occur in perforating. A flexible adapter, called a tool-saver adapter, is inserted between the PGGT tool and perforating guns to decrease the transmission of shock from a gun to the tool.

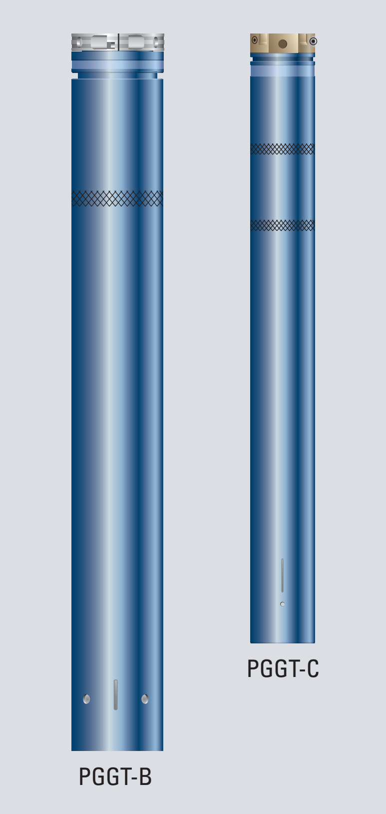

Figure 187. PGGT tool.

Applications

- Accurate positioning of TCP guns
- Correlation of perforating guns, plugs and packers, and core guns

Table 104. PGGT Specifications

	PGGT-C	PGGT-B	PGGT-D
Outside diameter (in.)	1.69	2.125	3.625
Min. casing size (in.)	2⅜	2⅞	4½
Temperature rating (°F [°C])	350 [177]	500 [260]	350 [177]
Pressure rating (psi)	20,000	20,000	20,000
Length (in.)	77	98	70
Weight (lbm)	37	58	97

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Wireline Perforating Anchor Tool

The WPAT is designed for perforating monobore wells under very high underbalance pressure (Fig. 188). This method of anchoring wireline-conveyed guns is a practical, reliable, and economical technique for completing monobore wells. The WPAT makes perforating with very high underbalance possible by eliminating gun movement during perforating. Higher underbalance improves the perforation cleanup, resulting in greater well productivity.

The WPAT positively anchors guns from below by using three circumferentially distributed slips. Upon an electrical command from the surface, the slips are anchored in the casing before the gun is fired. The profile of the slips is carefully crafted to prevent movement when set without causing damage to the tubing. After a preprogrammed time interval, which can be extended to 30 min, the slips are automatically released and retracted.

The tool is designed to work in 2⅞-, 3½-, and 4½-in. casing (Table 105). The anchoring mechanism withstands force to 17,000 lbf in an upward or downward direction. As a result of high-rate flow during perforation cleanup, the holding capacity increases as the force acting on the gun string increases. The WPAT prevents guns from jumping, thus helping to prevent inadvertent breaking of the wireline cable head weakpoint.

Applications

- Underbalanced perforating in small casing sizes
- Determination of crossflow or depletion by running memory gauges below the perforating guns
- Enhanced cleanup from the ability to flow the well immediately after perforating

Table 105. WPAT Specifications

	WPAT-AA	WPAT-AC	WPAT-BA
Outside diameter (in.)	2.125	2.125	3.375
Tubing size (in.)	2⅞	3½	4½
Temperature rating (°F [°C])	400 [204]	400 [204]	400 [204]
Pressure rating (psi)	10,000	10,000	10,000
Length (ft)	9.3	9.3	11.1
Weight (lbm)	100	110	250

Figure 188. WPAT.

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Wireline Perforating Shock Absorber

The shock associated with the detonation of large perforating guns can damage sensitive instruments run with the string, possibly leading to a premature parting of the wireline weakpoint. The wireline perforating shock absorber (WPSA) is designed to protect downhole equipment during the wireline-conveyed perforating of wells (Table 106).

The shock absorber, placed directly above the top perforating gun, is compatible with all wireline gun heads 3⅛ in. and larger. The WPSA (Fig. 189) has a crushable element that deforms to absorb and dissipate the transient forces generated during perforating. It provides proven protection for the electronic instrumentation associated with such tools as the PGGT Powered Gun Gamma Tool. The shock absorber reduces weakpoint failures attributable to perforating gun shock.

The crushable element is actively deformed during both compressive and tensile loading of the gun string. The WPSA can be easily disassembled in the field to replace the disposable element. Typical element replacement frequency is one to four descents, depending on well conditions.

When used with other best practices for hollow carrier gun perforating, the WPSA has enabled wireline crews to successfully convey large gun strings that were once considered impractical.

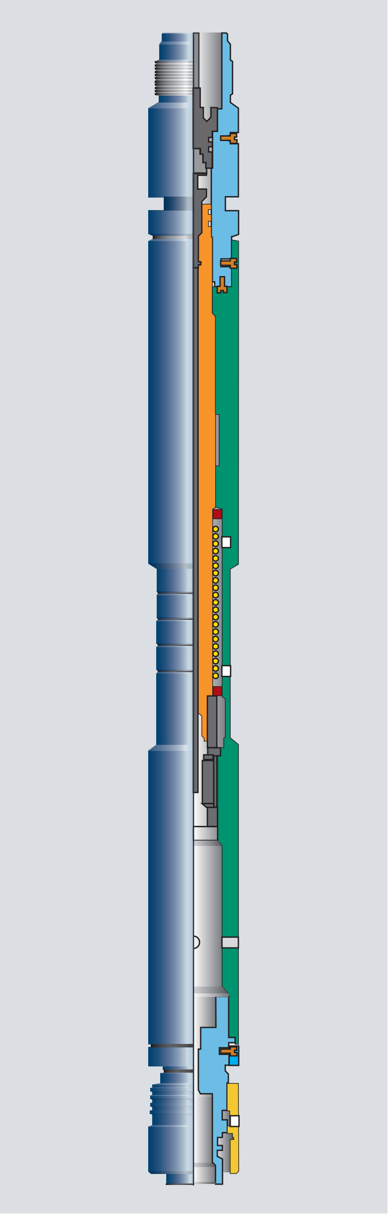

Figure 189. WPSA.

Applications

- Protection from shock associated with gun detonation
- Reduction of weakpoint failures

Table 106. WPSA Specifications

	WPSA-BA	WPSA-AA
Outside diameter (in.)	1.6875	3.375
Temperature rating (°F [°C])	400 [204]	400 [204]
Pressure rating (psi)	20,000	20,000
Length (ft)	2.1†	3.5
Weight (lbm)	16	83
Max. load below tool (lbf)	500	3,000

† Not including 2.3-ft wet connect and 0.66-ft optional flex adapter

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Wireline X-Tools Automatic Release

The WXAR disconnect (Fig. 190 and Table 107) is a member of the X-Tools family of perforating gun–activated completion tools. This explosive-type gun release enables shooting long HSD gun strings underbalanced and retrieving the running string without killing the well.

In the North Sea, gun strings longer than 300 ft (2⅞-in. HSD guns) have been run using the WXAR disconnect to automatically drop off the bottom portion of the gun string at the instant the guns fire. The instant gun release prevents the guns from being sanded in. The bottom portion of the gun string falls to the bottom. The remaining guns still attached to the wireline provide enough weight to allow removing the guns from the well under pressure, without killing the well. The wireline assembly can then be rigged down with a lubricator.

Because the WXAR is run in line with the gun system, it can be used with any firing system, as well as coiled tubing or other conveyance methods. Adapters for the 3.06-in. tool are available for HSD gun sizes from 2⅞ to 7 in. (Fig. 191). The lower adapter incorporates an internal fishing profile to aid in gun retrieval after dropping.

Pressure control equipment is used to ensure that the perforating equipment can be inserted and retrieved with pressure at the surface. The guns are run into the well, and setting depth is generally determined by correlation, depth measurements, or tagging bottom. Long or heavy gun strings require careful handing at the surface and while running in to prevent the weakpoints from breaking.

The guns are fired at perforating depth electrically if wireline or electric coiled tubing is used for conveyance; pressure is used if conveyance is by coiled tubing only. Underbalance is created by circulating a lighter fluid through the tubing or through the coiled tubing.

The WXAR disconnect releases automatically when the guns fire, dropping the guns to the bottom. The high-order detonation that occurs after the firing head is activated causes the break plug to disintegrate, which in turn allows the release piston to shift up and disengage the release fingers. Until this point, the release fingers are held against a matching profile in the lower gun adapter. The release and dropping of the guns take place the instant detonation occurs. The WXAR disconnect and everything above it are brought back to the surface with the firing head as the wireline or coiled tubing is retrieved through its corresponding pressure control equipment.

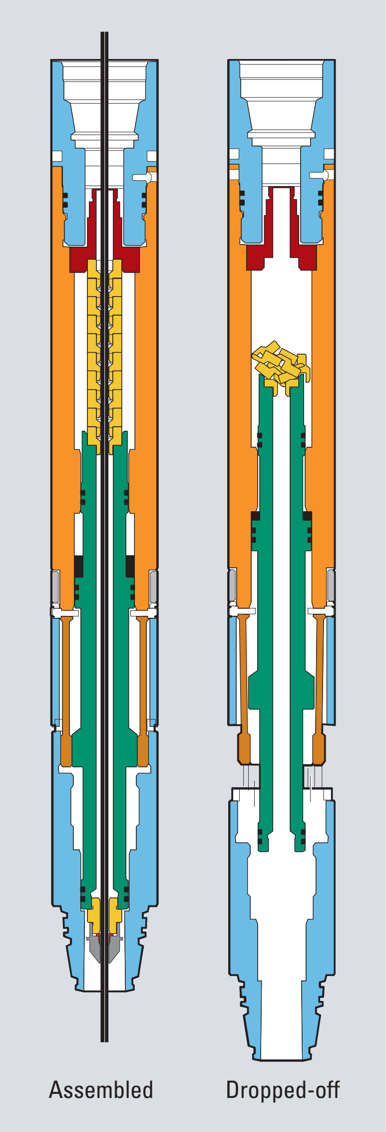

Figure 190. WXAR disconnect.

Applications

- Permanent completions
- Long perforating intervals with limited wellhead lubricator length
- Reperforating or extending existing perforation intervals
- Wireline and through-tubing perforating

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Table 107. WXAR Specifications

Outside diameter (in.)	3.06
Temperature rating (°F [°C])	400 [204]
Pressure rating (psi)	20,000
Min. pressure to actuate (psi)	300
Weight (lbm)	50
Tensile strength[†] (lbf)	71,250

[†] 75% min. yield

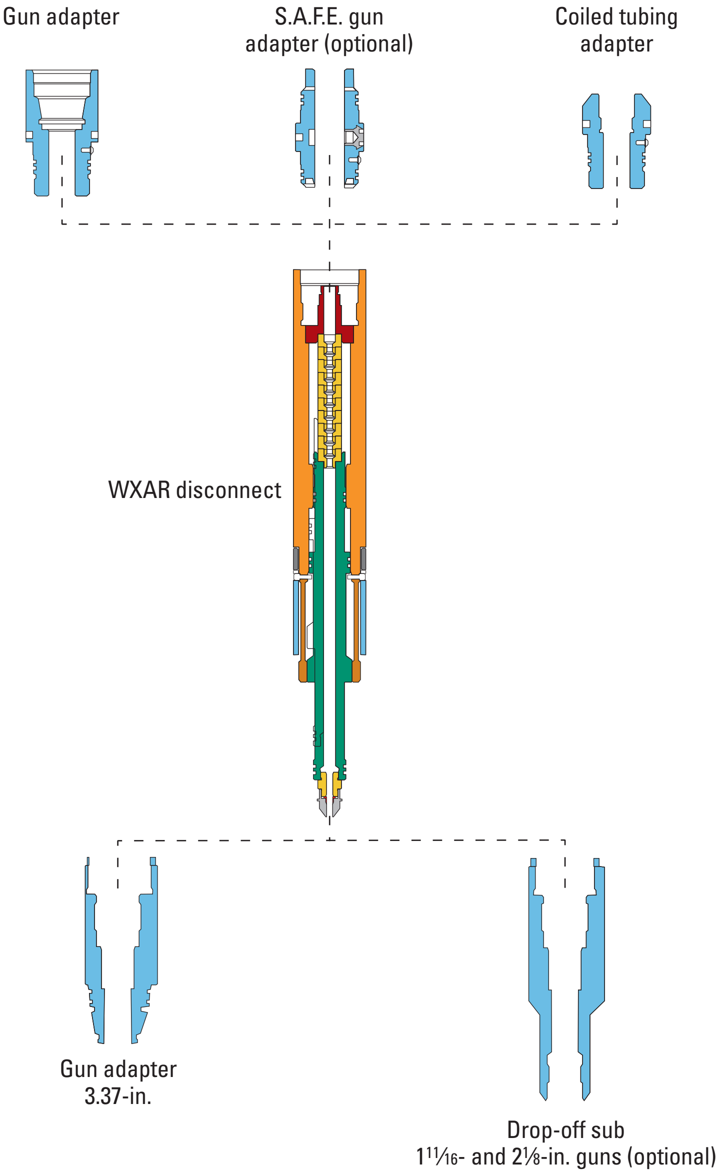

Figure 191. WXAR configuration options.

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Shallow-Well Perforating Truck

The shallow-well perforating truck (SWPT) was designed specifically for completion and perforating operations on wells shallower than 18,000 ft. The SWPT models are available on two- or four-wheel drive chassis, with or without a mast (Fig. 192 and Tables 108 and 109). The crew cab is equipped with a Modular Configuration MAXIS (MCM) completion acquisition system and a winch control panel, configured to enable one person to operate both the acquisition and winch systems during logging operations.

The optional tripod mast can be deployed to a maximum of 48 ft for rigless operations. The quick, simple rig-up requires only two people. The tripod boom of the mast is pivoted up and down by a pair of hydraulic cylinders. The center leg is a hydraulically telescoping boom; the two outrigger legs are manually telescoped for height adjustment.

The mast operates 11° aft of vertical and pivots 101° forward for transport. The mast can be used in the retracted (33 ft) or extended (48 ft) position or at two intermediate positions (38 and 43 ft).

Applications

- Lightweight alternative to a standard logging truck
- Multiple shallow-well completions and perforating operations

Figure 192. SWPT-GAB on a 4 × 2 chassis with integral mast.

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Table 108. SWPT Vehicle Specifications

	SWPT-GAA	SWPT-GAB	SWPT-GBA	SWPT-GBB
Chassis	4 × 2	4 × 2	4 × 4	4 × 4
Wheel base (in.)	207	207	207	207
Overall length (in.)	308	378	322	358
Overall width† (in.)	100	100	97	97
Max. gross weight (lbm)	34,000	34,000	34,000	34,000

† Not including mirrors

Table 109. SWPT Operation Specifications

Mast vertical height (ft)	Fully retracted: 33
	Intermediate: 38 or 43
	Fully extended: 48
WDR-61 drum dimensions (in.)	Flange diameter: 29
	Core diameter: 13
	Core width: 27
WDR-61 drum capacity (max. cable length, ft)	0.23-in.-diameter cable: 24,500
	0.25-in.-diameter cable: 19,900
	0.32-in.-diameter cable: 12,700
	0.39-in.-diameter cable: 8,400
	0.39-in.-diameter cable: 8,400

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PosiSet Through-Tubing Plugs

PosiSet* plugs perform reliably in through-tubing plugback operations in casing through a minimum tubing restriction (Fig. 193 and Table 110). The drillable plug consists of a compressed elastomer seal, metal antiextrusion backups, and rugged anchors.

The PosiSet plug is set with the PosiSet mechanical plugback setting unit (MPSU), which has a downhole electric motor that contracts the elastomer sealing assembly to form a firm seal against the casing wall. An anchoring system keeps the tool in place while cement is placed on top of the plug to a height of 10 ft or more to provide additional differential pressure. Release is accomplished with a 15,000-lbf tension stud. A standard CCL is used for depth control.

Applications

- Plug off nonproductive zones
- Deviated holes, including horizontal
- Open holes, across perforations, and at screens

Table 110. PosiSet Plug Specifications

Casing size (in.)	4½	5	5½	7	7⅝	9⅝
Outside diameter (in.)	1.69	1.69	1.69	1.69 2.125	2.125	2⅝
Min. restriction (in.)	1.77	1.77	1.77	1.69 in.: 1.77 2.125 in.: 2.18	2.18	2.75
Temperature rating (°F [°C])	340 [177]	340 [177]	300 [149]	1.69 in.: 300 [149] 2.125 in.: 340 [171]	275 [135]	275 [135]
Pressure rating[†] (psi)	1,000	1,000	500	1.69 in.: 500 2.125 in.: 1,500	1,000	500
Length						
Delivery (in.)	90	90	130	1.69 in.: 134 2.125 in.: 110–123	126	145
Seal (in.)	2.7	2.5	9	1.69 in.: 2.25 2.125 in.: 4.3–4.5	4.1	5.5
Weight (lbm)	28	28	37	1.69 in.: 40 2.125 in.: 45	56	67

[†] Without cement plug

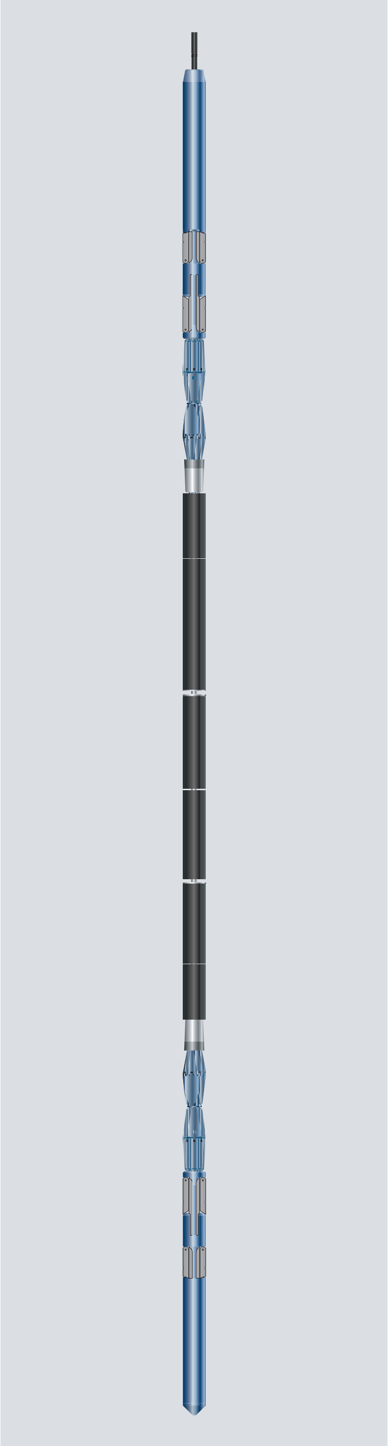

Figure 193. PosiSet mechanical plugback unit for setting PosiSet plugs.

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Casing Packer Setting Tool

The casing packer setting tool (CPST) provides a reliable method of setting bridge plugs, cement retainers, and packers on wireline (Fig. 194 and Table 111). The CPST has the following features:

- hydraulic operation through the use of a separate gas generator
- pressure-balanced design to allow setting without having to overcome well pressure
- no secondary igniter needed
- spiral pins to prevent the tool from presetting while running in the hole
- no special alignment or orientation of components required during assembly or disassembly
- efficient redressing.

Applications

- Completions using wireline-set packers

Table 111. CPST Specifications

	CPST-AA	CPST-BC	CPST-CC
Outside diameter (in.)	3.625	2.125	2.75
Casing size (in.)			
Min.	5	3½	4½
Max.	13⅜	5	5½
Temperature rating (ºF [°C])	400 [204]	400 [204]	400 [204]
Pressure rating (psi)	15,000	15,000	15,000
Length (ft)	7.5	11.25	7.35
Weight (lbm)	180	81.8	79.5

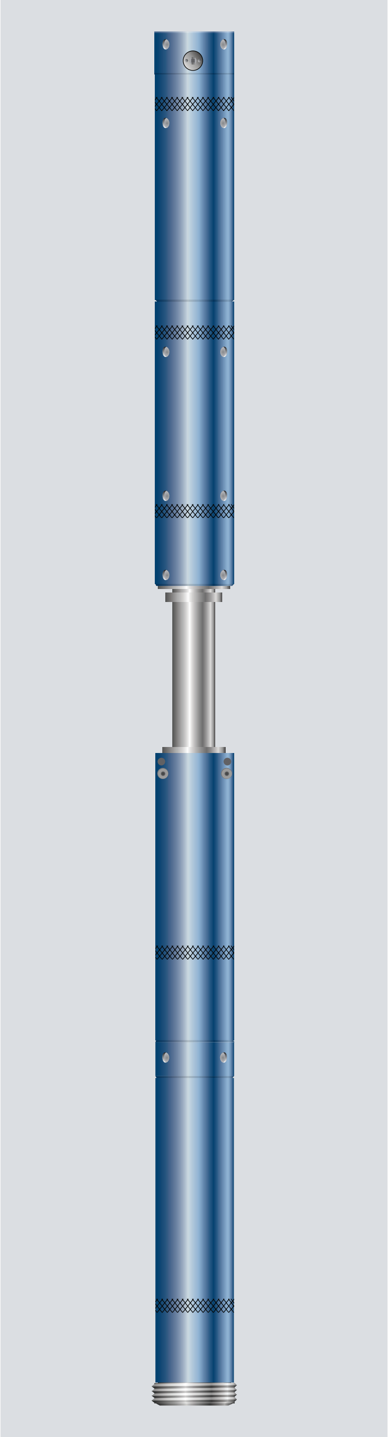

Figure 194. CPST.

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Tubing-Conveyed Perforating Completion Techniques

Overview

Historically, TCP referred to perforating jobs using tubing or drillpipe to run hollow carrier gun systems into the well. TCP completion techniques enable running large, long gun strings and shooting them underbalanced to optimize well productivity. With recent technology developments, other methods are used to convey TCP equipment, including coiled tubing and slickline. Many of the products described in this chapter can be conveyed using a variety of methods, such as pipe, wireline, and the aforementioned coiled tubing and slickline.

The most striking new development is the evolution of TCP into the area of completion perforating, especially perforating without killing the well. Including the perforating string in the completion procedure is far more common today than in the past and results in numerous benefits:

- Efficiency—A single trip in the well installs both completion and perforating equipment. HSD guns of any type and length can be conveyed without killing the well.
- Flexibility—Fired guns can be retrieved or left in place without killing the well. Firing heads and unfired guns can be retrieved, reconfigured, and rerun without killing the well.
- Conveyance—Each method (tubing, drillpipe, coiled tubing, snubbing, electric wireline, stranded cable, and slickline) has a specific application, even when using large-diameter guns.
- Well productivity and injectivity—Not exposing the formation to completion fluids eliminates fluid-related formation damage during perforating, and the PURE perforating system can be used to optimize the dynamic underbalance for obtaining clean perforations.
- Hostile environment—Enhanced seal types and designs, explosives, and techniques are available for use in hostile environments involving high temperatures, high pressures, long durations, and corrosive fluids.
- Safety—New options for conveying and retrieving firing heads after the guns are in the wellbore and innovative systems such as the eFire* electronic firing head system and ProFire programmable firing head help ensure safer surface handling of perforating equipment, especially when conditions involve wellhead pressure.
- Customized hardware—Materials, connections, and sizes are designed for specific requirements; one size no longer has to fit all. New orienting systems, such as the OrientXact tubing-conveyed oriented perforating system, ensure precise placement and orientation of guns with tight tolerances.
- Qualification testing—Qualification testing that replicates the well environment and operational sequences can be performed for any completion type when necessary.

With the wide variety of perforating options available (Fig. 195), proper planning of perforating completion projects is more important than ever. The selection of perforating tools requires the same care and attention given to the other completion hardware. The information in this and subsequent chapters provides a guide to available options. A qualified Schlumberger representative should assist with conceptual and detailed selection and planning. Unless otherwise noted, all guns and firing heads described in this catalog and used in TCP operations are designed and manufactured by Schlumberger.

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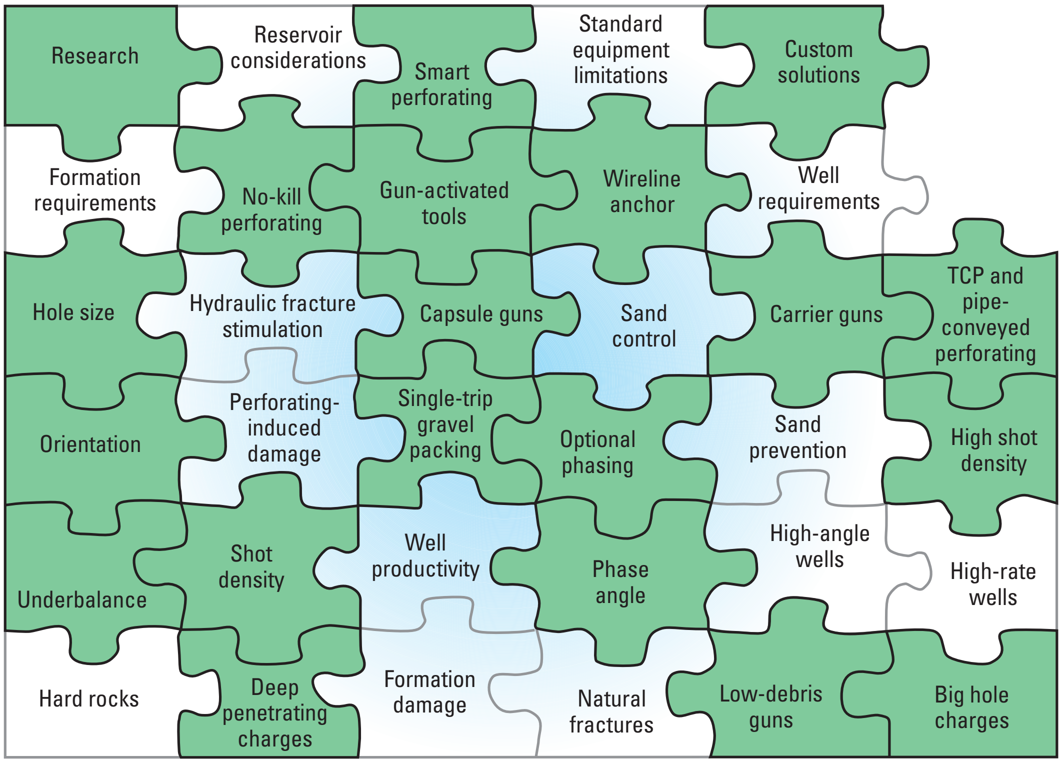

Figure 195. Fitting perforating completion options to the job.

Customized hardware solutions

Requirements for specific reservoirs and completion jobs often demand customized solutions. The Schlumberger RapidResponse group assists with such needs by developing projects off the normal engineering cycle, working in conjunction with the field units to reduce project completion time. The projects are usually developed from existing operational hardware systems, which helps optimize engineering and development and speed implementation of the customized solution.

Qualification testing

Completion perforating equipment is customized to fit unique applications or function under severe downhole conditions. Confirmation is needed in some situations to ensure that the equipment will perform as designed. Qualification testing at the SRC Technology Center subjects perforating equipment to anticipated downhole conditions through simulation testing. The tests expose equipment components to the anticipated pressure, temperature, and fluids for a specified time to ensure that they work at the expected downhole conditions. Qualification testing includes firing heads, automatic gun releases, sealed ballistic transfers, anchors, and special connectors such as CIRP Completion Insertion and Removal under Pressure equipment and the GunStack stackable perforating gun system, as well as other critical components such as detonators and seals. Some tests also verify delay properties of hydraulically operated firing heads and other equipment.

Test facilities include pressure vessels (Fig. 196) that can accommodate complete systems (Fig. 197). A test example is shown in Fig. 198. Schlumberger usually arranges for the TCP specialist from the field location to participate in the qualification testing to become fully familiar with the equipment and techniques. Testing also gives the engineering group, field personnel, and often the client an opportunity to collaborate on the project.

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Figure 196. Pressure vessel PV-40.

Figure 197. Qualification setup for the MAXR automatic release anchor.

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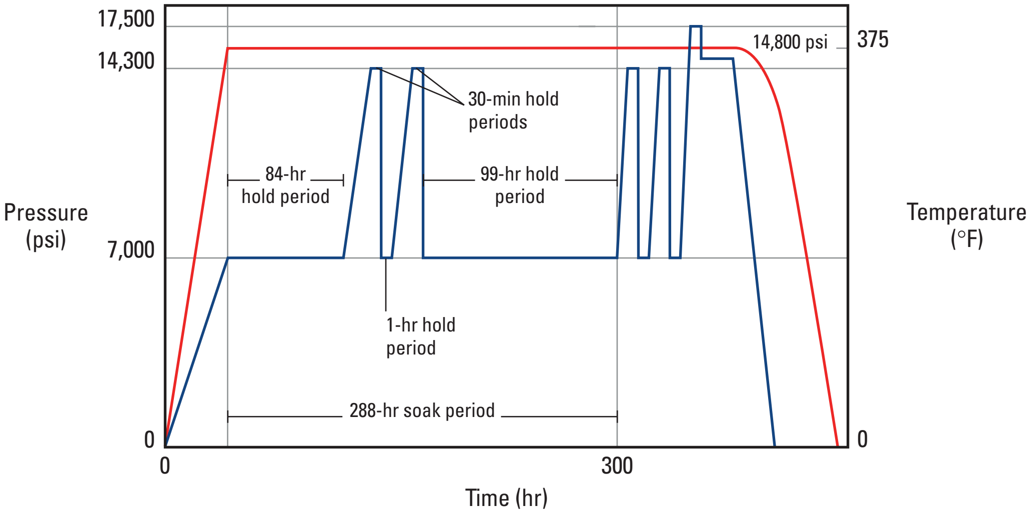

Figure 198. Typical test pressure and temperature cycling profile, from the start of gun deployment through the shooting sequence.

Planning: Specifications and requirements

Most systems described in this catalog contain explosives and elastomer seals (moving and static) that are exposed to a wide range of wellbore conditions, including high temperatures, high pressures, corrosive wellbore fluids, and long exposure times. Conditions are considered severe when temperatures, pressures, and exposure times approach 330°F [166°C], 15,000 psi, and 100 hr, respectively. Exposure to one or more of these severe conditions can degrade the integrity of the explosives and seals.

Carefully selecting the most suitable materials is important for any operation, especially for those in extreme conditions. Qualification testing should be considered if previous job data for similar conditions is unavailable. Specifications for most systems are for applications of short duration unless otherwise stated.

Planning a perforated completion, whether simple or complex, follows a four-step process:

1. Conceptual design—Consider the initial perforating system as early as possible when evaluating completion strategies. Early attention to the perforating system is helpful in optimizing perforating capabilities and allows time for engineering unique solutions and nonstandard components.
2. Detail design—When the completion string is approved, the perforating equipment must be fully detailed, including components, specifications (e.g., sizes, materials, quantities), contingencies, delivery, and qualification testing requirements. All well data and planned completion procedures should be available.
3. Deliverables—The equipment procurement process must be clear and unambiguous; equipment must conform to established specifications. Deviations, such as changes in well configuration, delivery times, or quantities, must be addressed promptly.
4. Qualification testing—Field locations can often qualify components for simple operations by testing as part of the project requirements. As complexity and risk increase, engineering generally needs to perform qualification testing using specialized equipment and personnel. When necessary, training on new equipment or techniques can be provided during qualification testing.

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Project management

The following project management tools are necessary to ensure that the preceding planning steps take place smoothly and efficiently:

- organization chart with responsibilities, including all individuals directly involved in project management or execution
- interface matrix of individuals who supply critical data
- master schedule that outlines the entire project, from conceptual design to closeout
- project file containing all project documents organized and subdivided in logical sequence.

Simple jobs require only a simple project file whereas unique, complex, or multiple completions and projects in hostile environments require thorough planning using proven project management procedures.

The criticality of a perforated completion can be assessed using the TCP service delivery procedure (SDP). As criticality increases, so does the need for early planning, contingency options, and allocation of resources.

Service delivery procedure

The success of a TCP operation depends on how well it designed and planned. As with all operations, the preparation phase prior to shipping to the wellsite is also critical. Execution is therefore a series of actions planned ahead of time. The TCP SDP has been developed to ensure that all required steps are taken for every job within the four main phases identified:

- design and planning
- preparation
- execution
- closeout.

In each phase the user is reminded of all required steps and minimum standards (Figs. 199 and 200). Document templates are available where required. The SDP is a live resource, continually being updated through the Schlumberger InTouchSupport.com knowledge base with best practices, lessons learned, and other relevant technical information.

This current information is captured in the design and planning flowcharts specific to each tool in the string. Where required, operational contingency flowcharts are also available (Fig. 201). Examples of design and planning flowcharts for specific tools are included in subsequent chapters.

Throughout the complete procedure, documents generated are filed in the job quality file, which is prepared for every operation.

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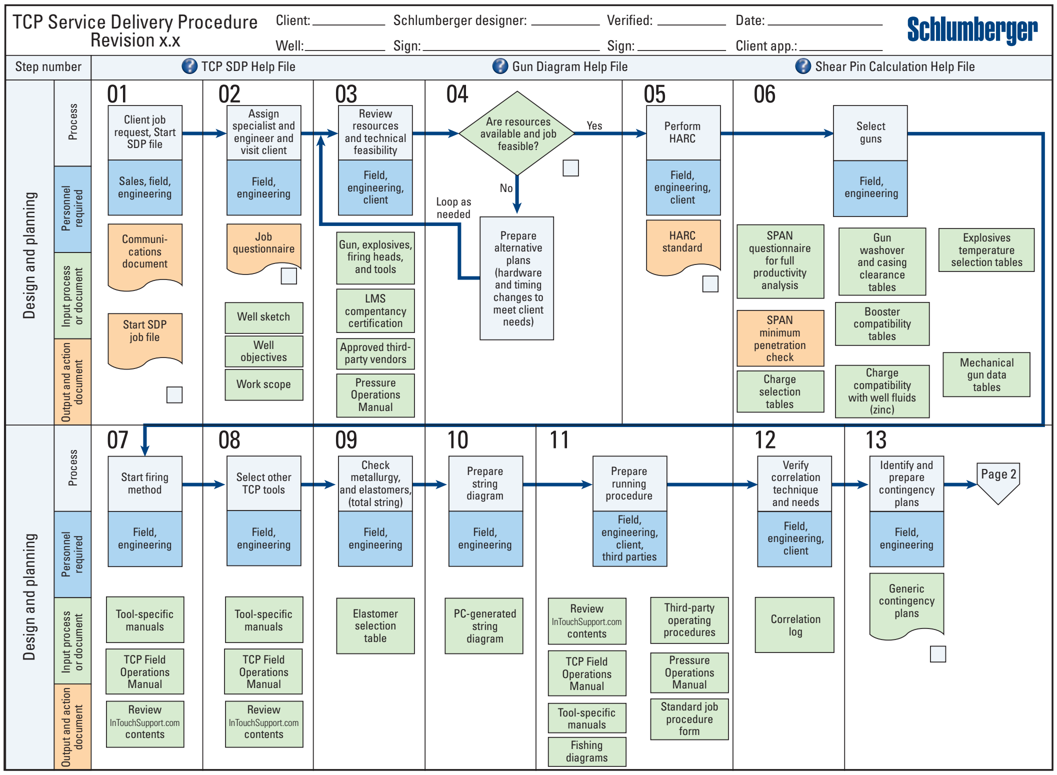

Figure 199. Example TCP SDP for the initial design and planning phase.

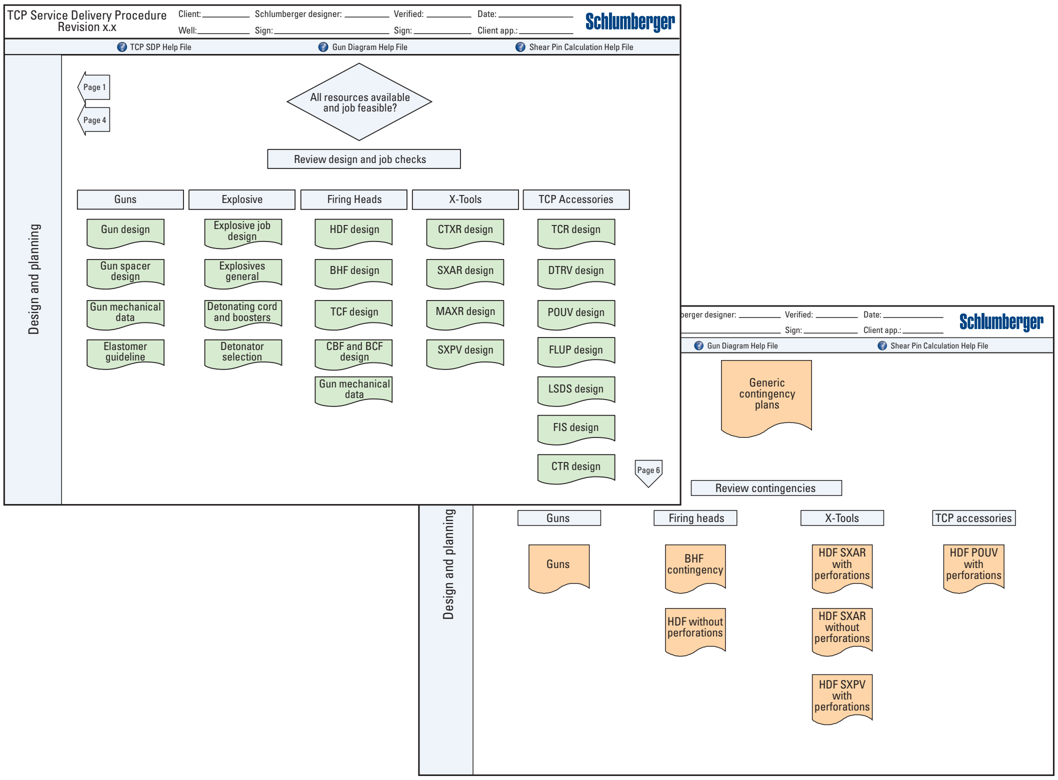

Figure 200. Examples of step details for the design and planning phase.

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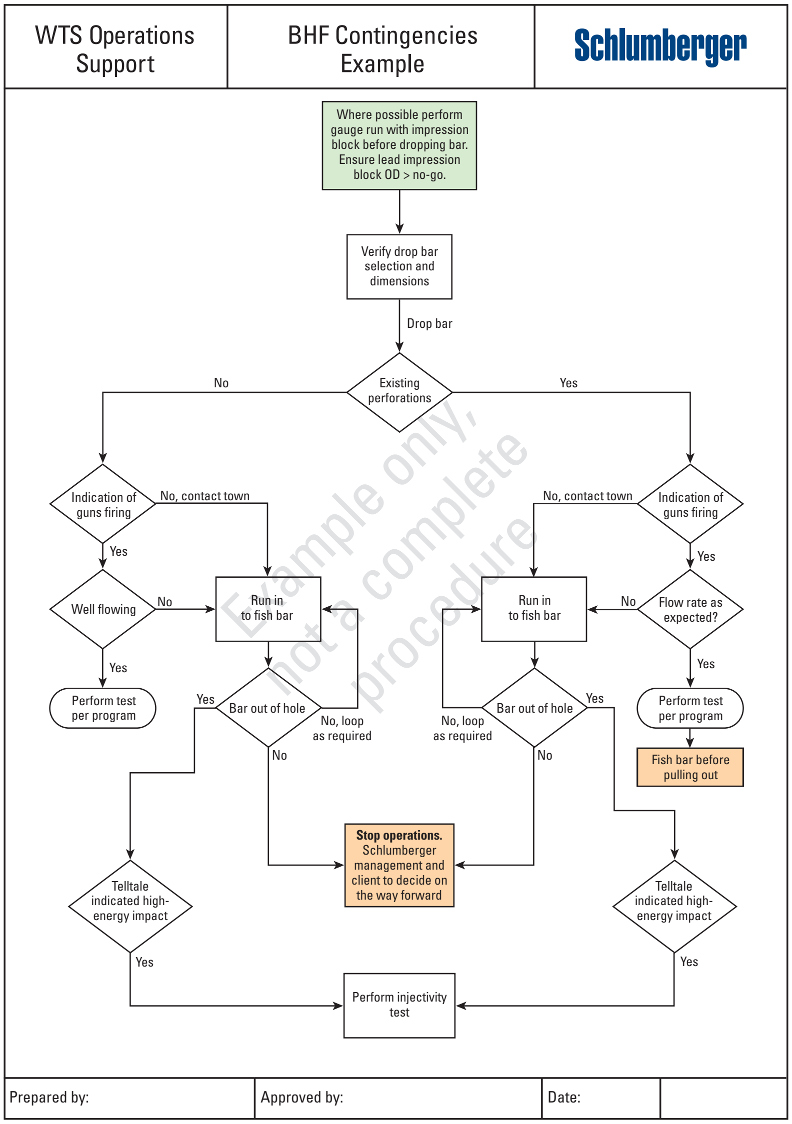

Figure 201. Example contingency flowchart.

Detailed job planning

Determining the safest, most efficient TCP method requires accurate assessment of the operating environment, completion objectives, and testing requirements. Nonstandard or unusual conditions, such as high bottomhole temperatures and pressures, long exposure times, high well deviations, small restrictions, or an H_2S environment, can require special equipment and techniques.

The reservoir and completion type form a unique set of conditions that determines the selection of various options:

- Casing size and formation characteristics usually dictate the gun size and charge type (see "Capsule gun selection" in the "Capsule Gun Perforating Systems" chapter and "Hollow carrier gun selection" in the "Hollow Carrier Gun Perforating Systems" chapter).
- Sand prevention, the well profile, or stimulation requirements may necessitate a specific gun orientation at the time of firing.

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- Computer-generated simulations such as SPAN Schlumberger perforating analysis help in selecting the best gun and charge options (see the “Reservoir Completion Types” chapter).
- When guns are conveyed on coiled tubing in highly deviated wells, the forces acting on the guns and tubing require careful analysis to avoid helical buckling while running in and excessive tensile loads when pulling out. Schlumberger coiled tubing design and evaluation software assists in making these determinations.
- Perforating services performed with hydraulic firing heads in wells where the firing head is exposed to surface pressure require specific job preparation, coordination, and approval.
- Selection of a suitable explosive package is based on the anticipated maximum exposure time of the gun string at or near bottomhole temperature (see “Operating Environment and Engineering of Perforating Operations” chapter).
- The requirements for well testing operations can affect the selection of TCP firing heads and accessories and the size of perforating guns.
- Formation characteristics, along with safety and economic considerations, determine the amount of underbalance and how it is established (see the “Perforation Damage and Cleanup” chapter).
- The amount of underbalance, completion type, and installation influence the selection of a firing system and accessories.
- Accurate knowledge of the ID of all string restrictions is essential in choosing the firing system and planning for possible fishing tool, positioning tool, or cutter runs.

A detailed completion sketch including the OD, ID, and depth or length of all components and the exact location of restrictions, along with an intended job prognosis, provides the basis for review and discussion by clients and Schlumberger.

Additional required planning steps are completion of a job questionnaire (Fig. 175 in the preceding “Wireline Perforating Techniques” chapter) to organize information and preparation of a hazard analysis and risk control (HARC) record form, which delivers a standardized assessment of risk likelihood and severity and the effect of prevention and mitigation measures.

TCP systems and operational techniques

This section reviews the basic TCP systems and their primary components. Details are provided in the following chapters. Examples of string designs using the various conveyance systems and components are also in the “TCP Applications” chapter.

Conveyance systems

Although TCP conveyance initially was limited to running hollow carrier guns on tubing or drillpipe, with recent developments in technology, numerous methods can be used to convey TCP-type equipment:

- drillpipe
- tubing
- coiled tubing
- wireline
- slickline.

All these conveyance methods enable running large, long gun strings and shooting underbalanced to optimize well productivity. Selection of the best TCP conveyance method for a well depends on many different parameters, such as

- well geometry
- depth
- deviation
- gun length
- gun weight
- gun OD
- perforating without killing the well.

The growing number of highly deviated and horizontal wells has increased the requirement for TCP as the only means for gaining access to the perforating interval. Because the success of a TCP operation can be defined by the extent to which it meets planned objectives, which in turn are closely linked with those of the completion itself, completion objectives must be considered carefully when planning the perforating operation.

Downhole open string TCP system

The downhole open string TCP system (Fig. 202) is one of the simplest and most commonly used string designs for temporary and permanent completions. It is suitable for moderately deviated wells.

The underbalance is achieved in several ways:

- The tubing can be displaced with a lighter fluid, such as brine or diesel, or with nitrogen before setting the packer. If an underbalancing valve is available above the packer, tubing displacement can be completed after setting the packer.
- The tubing can be swabbed out after setting the packer.
- The tubing fluid can be lifted with nitrogen or gas through coiled tubing or gas lift valves.

Displacing the tubing fluid with a lighter fluid is the most frequently used technique.

A debris-circulating sub is recommended for most firing systems. The sub is positioned 30 ft (one joint) above the firing head, and the volume between the debris-circulating sub and the firing head is filled with a clean fluid.

Firing can be done with an eFire electronic firing, drop bar, or trigger charge firing (TCF) system. Alternatively, an absolute pressure firing system can be used, with a hydraulic delay firing (HDF) head as a primary or redundant firing system. The HDF head uses tubing pressure to fire the guns, operates at any deviation with restricted BHAs, and is virtually immune to debris. The use of an HDF head requires that tubing is filled with liquid to the surface unless nitrogen is used to apply the required activation pressure.

A gun release sub can be run with the string, either as a safety joint or to drop off the guns after perforating. The gun release sub is usually positioned one joint above the flow sub to keep the gun release sub clean or to activate it hydraulically. After the guns are dropped, at least 60 ft of open casing is required above the top shot on permanent completions to allow production logging.

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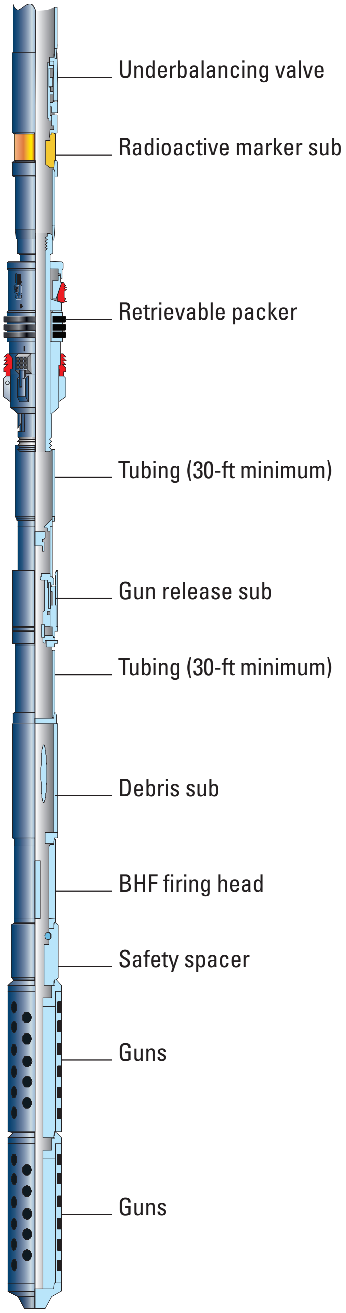

Figure 202. Downhole open string TCP system.

Downhole closed string system

The downhole closed string TCP system (Fig. 203) is used on temporary, permanent, and workover completions in moderately deviated oil, gas, and injector wells. The closed string system is especially well-adapted for situations that require a large underbalance, where perforations exist below the packer, or for "closed-chamber" applications of the PURE system for clean perforations.

The underbalance is achieved by filling the tubing to the required cushion height while running it in the hole. The production valve below the packer stays closed until the packer is set. The valve is opened by passing a drop bar or a TCF head.

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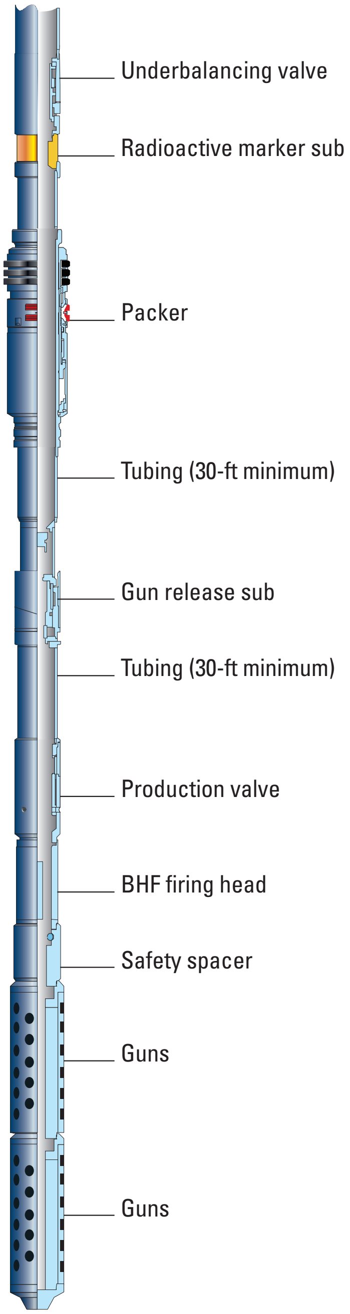

Figure 203. Downhole closed string TCP system.

A closed system achieves a large underbalance because the tubing can be run dry. A minimum hydrostatic cushion pressure of 500 psi with clean fluid is required for most firing heads. Also, the downhole temperature at the top of the cushion should be lower than the boiling point of the cushion fluid to prevent the cushion from boiling dry.

High underbalance can also be achieved by using a surge-disc sub. The surge disc shatters as the drop bar passes through it. Precautions are necessary to avoid the accumulation of excessive debris on top of the surge-disc sub. Too much debris makes it impossible to break the disc.

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A drop bar is commonly used in reperforating applications. The production valve, which is a fast-acting, one-shot sliding sleeve, is opened by rathole pressure as the bar passes through it. This action creates an instantaneous underbalanced condition below the packer just before the guns fire, allowing simultaneous backsurging of both new and previous perforations.

A gun release sub may be run with the string, either as a safety joint or to drop off the guns after perforating. The gun release sub is typically positioned one joint above the production valve to keep the gun release sub clean or allow hydraulic actuation. After the guns are dropped, at least 60 ft of open casing should be left above the top shot on permanent completions to allow production logging.

TCP with DST and packer (shoot and pull)

The DST TCP system (Fig. 204) allows the well to be perforated and tested without having to kill the well until after the tests have been completed. Various firing systems can be used, in either single or redundant configurations.

A Schlumberger PosiTrieve* downhole retrievable packer with hold-down section or FlexPac* high-performance packer is used to isolate the annulus and tubing downhole and provide an integral flow path to the debris sub.

The downhole test valve opens as annulus pump pressure is increased at the surface. A pressure difference is created across the packer, with the cushion pressure below it and the annulus plus pump pressure above it. The firing head is set to fire at a specific pressure differential, which can also enable confirmation of the packer seal before the guns are fired. Opening the test valve while simultaneously firing the guns is an option for applications in which there are open perforations in the well.

Firing redundancy can be achieved using the HDF head with full fluid columns or nitrogen application from the surface. A redundant firing head, such as an eFire electronic firing, bar hydrostatic firing (BHF), HDF, or TCF head, can also be used with a differential pressure firing (DPF) head.

To avoid the risk of prematurely aborting the test when a DPF system is used, reversing valves that are operated by the annulus pressure are set to operate at pressures well above those required to fire the guns.

Underbalance can be established as a closed system by using the downhole test valve. Alternatively, underbalance can be established as an open system by circulating light fluid through the packer bypass or by displacing the tubing fluid with nitrogen.

A controlled tension gun release can be combined with the fullbore packer conversion kit to easily release the guns.

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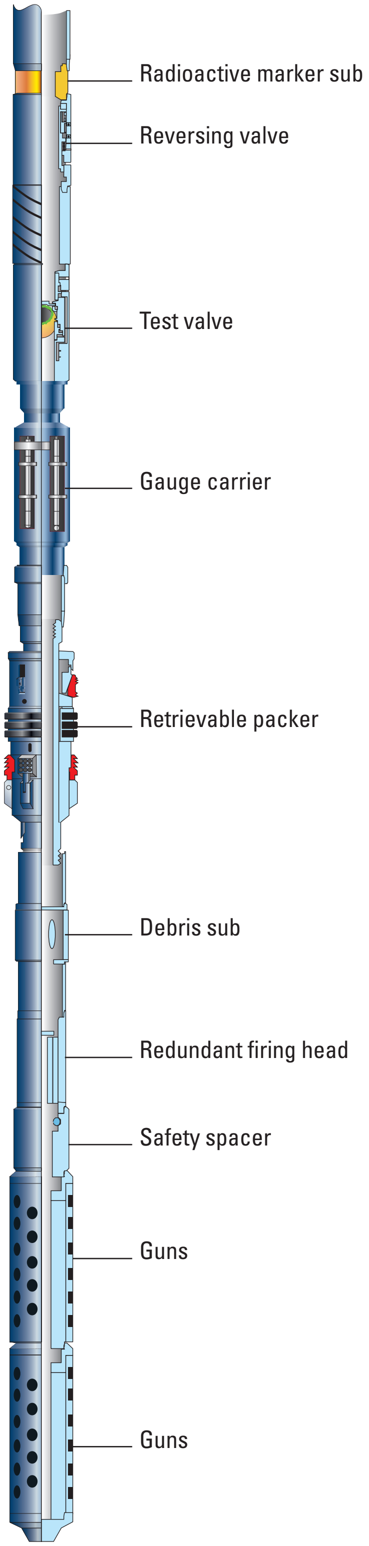

Figure 204. TCP system for testing.

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Perforating without killing the well

Several TCP completion techniques are available for situations where guns cannot be run with the completion, the well is already perforated, or retrieving the fired guns is desirable. All these techniques allow perforating without killing the well.

Monobore automatic release anchor

The monobore automatic release anchor (MAXR) is used to run guns and anchor them in the casing or liner of a monobore well before the completion string has been run or install them in a conventional tubing completion.

The MAXR tool (Fig. 205) and guns are conveyed on wireline, tubing, drillpipe, or coiled tubing. The anchor is set with a conventional packer setting tool. After the completion is installed and the correct underbalance created, the firing head is conveyed on slickline and the well is perforated. The firing head can be a TCF head—such as a jar-down or HDF head—ProFire programmable firing head, or eFire electronic firing head system. On firing, the anchoring slips are automatically retracted by the X-Tools release system, and the MAXR tool drops to the bottom along with the guns.

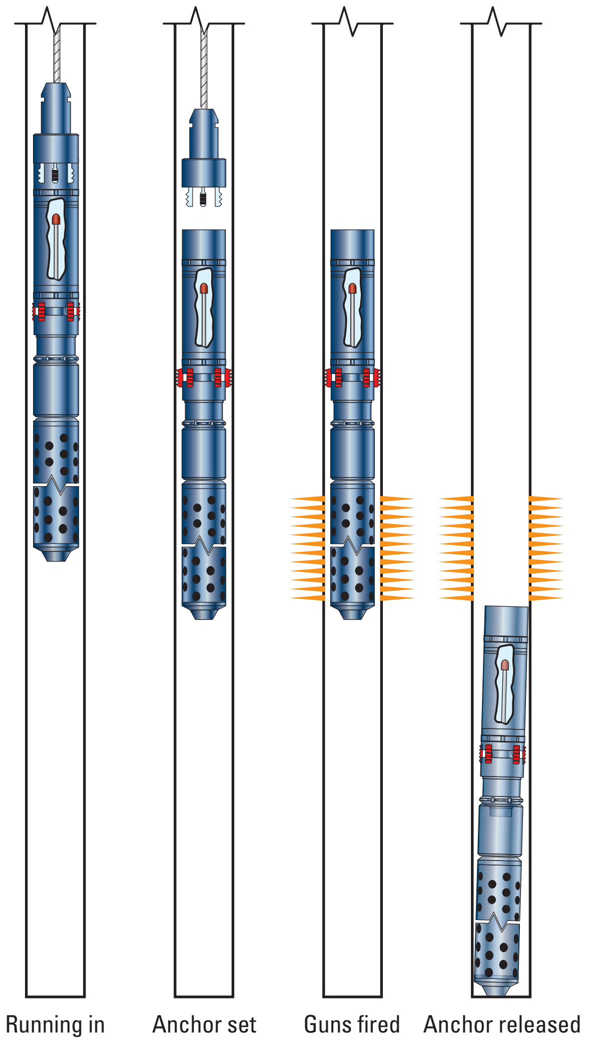

Figure 205. MAXR operation.

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GunStack stackable perforating gun system

The GunStack stackable perforating gun system (Fig. 206) is used to convey guns on slickline, retrieve spent guns, or reperforate without killing the well. The system allows an anchor to be run and set on wireline below the zone being perforated. Individual sections of guns are then run and latched downhole, one on top of the other. The surface lubricator length determines the length of each individual section. All explosive components are protected by the sealed ballistic transfer system.

Once all guns are in the well, the firing head is conveyed and connected to the guns, and the well is perforated. Compatible firing heads are any TCF component (such as a drop bar, jar-down, or HDF head), ProFire firing head, or eFire electronic firing system. On firing, the guns either drop to the bottom (if a MAXR anchor is used) or remain in place (if a mechanical releasable anchor [MRA] is used). With either anchor, the automatic release at each gun section is activated after firing and the guns disconnect approximately 30 s later. To retrieve the guns, slickline is rigged up the with the retrieving tool and each gun section is fished separately, finishing with the anchor latch adapter and finally the MRA.

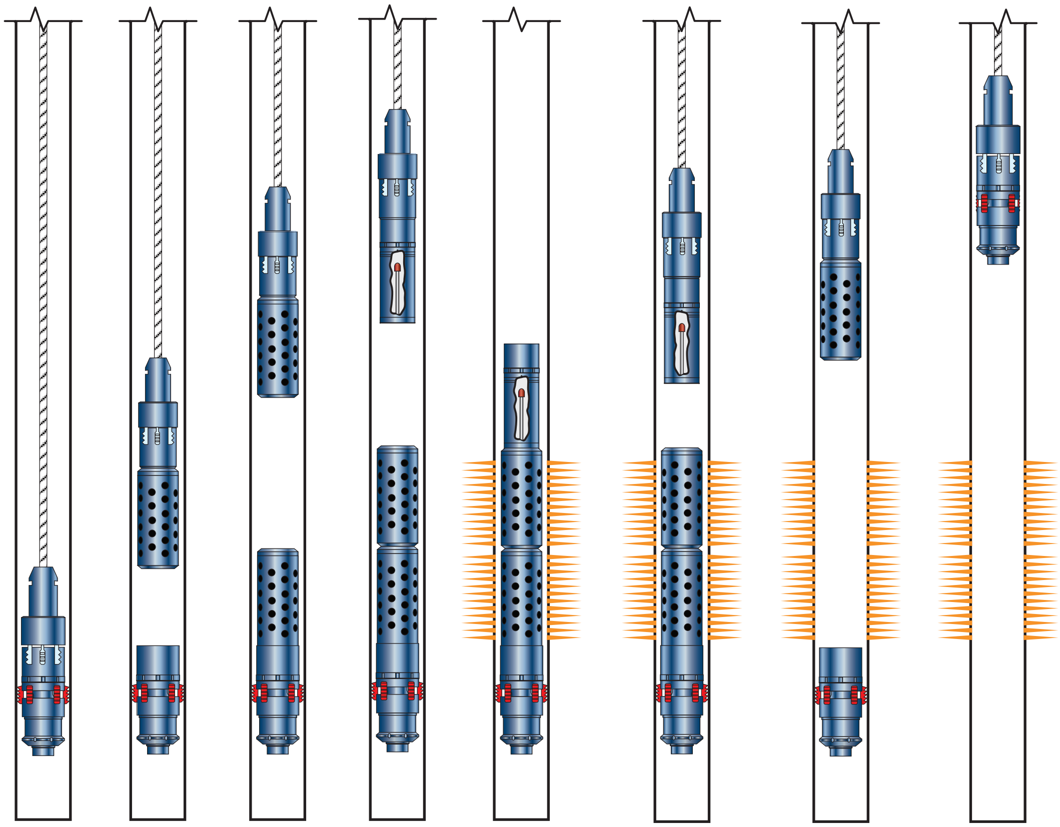

Figure 206. GunStack stackable perforating gun system.

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CIRP Completion Insertion and Removal under Pressure

Schlumberger has developed special connectors (Fig. 207) for CIRP Completion Insertion and Removal under Pressure equipment that enable makeup and breakdown of guns at the surface using a special connect/disconnect stack that sits on the top of the blowout preventers (BOPs), lubricators, and gate valves. CIRP equipment allows connecting an additional gun onto the gun already in the wellhead. The wellhead pressure is contained by the pressure control equipment. Retrieval is simply the reverse of the running-in procedure. As an option, the guns can dropped using the WXAR wireline X-Tools automatic release (see the “Completion Perforating Without Killing the Well” chapter). CIRP equipment for HPHT is available to extend the operating envelope.

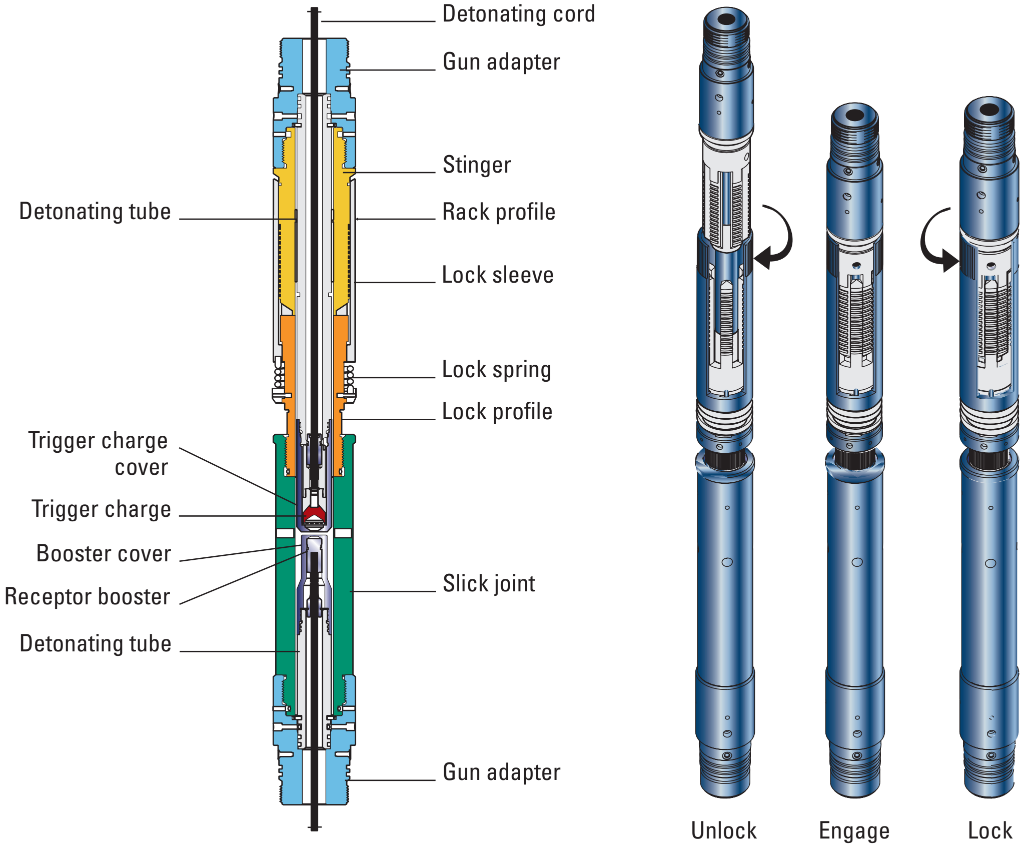

Figure 207. CIRP connectors.

FIV Formation Isolation Valve

The FIV* Formation Isolation Valve technology (Fig. 208) isolates formations—without requiring the application of kill fluids—to protect them with a two-way barrier against damage caused by fluid loss during completion operations. The FIV tool is also used as a downhole lubricator valve to run and retrieve long strings of service equipment while the formation is completely isolated.

This full-opening ball valve is mechanically opened and closed as many times as necessary with a shifting tool. The valve can also be opened with cycles of tubing pressure by using the Trip Saver* one-trip operation feature. In perforating operations, the bottom of the gun string is fitted with the FIV shifting tool, which causes the ball valve to close as the gun string

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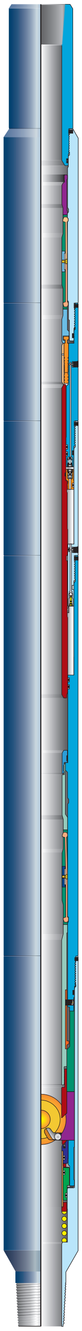

Figure 208. FIV tool.

passes back up through it. Once closed, the ball valve holds pressure from both directions. The tubing pressure can then be bled and the guns retrieved without surface pressure.

Reliable, proven FIV technology is available for numerous applications:

- HPHT FIV system is qualified to 15,000-psi differential pressure across the ball in high-temperature (425°F [218°C]) environments.
- SFIV* surface-controlled FIV system is a specialized surface-controlled version of the downhole lubricator valve.

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- AFIV* annular-controlled FIV system uses a sleeve, not a ball, to isolate the tubing from the annulus.
- MFIV* mechanical FIV system does not include the Trip Saver section to operate only mechanically, unaffected by changes in well pressure or differential pressure.

Firing heads

TCP firing heads are available for a variety of completion needs, with the unique features of each firing head benefiting specific applications. Firing heads are differentiated mainly by their method of activation. For safer operations, all hydraulic firing heads require a minimum of 150-psi hydrostatic pressure to activate the firing pin. This pressure is not present at surface ambient conditions and when a firing head is being handled.

Firing heads are presented in detail in the following chapter, “Firing Systems”.

eFire electronic firing head system

eFire electronic firing heads employ a revolutionary method of using precise coded signals to activate the firing mechanism. The coded signal that activates an eFire firing head cannot be replicated randomly by environmental conditions at the surface or in the well or by unintended actions such as applied pressure or shock.

Three types of eFire firing heads have been developed:

- eFire-TCP* electronic firing head system for TCP deployment
- eFire-CT* electronic firing head system for coiled tubing deployment
- eFire-Slickline electronic firing head system for slickline deployment.

Hydraulic delay firing head

The HDF head is an absolute pressure–activated time-delay firing head. Tubing pressure shears the calibrated pins when a preset pressure level is reached to activate the head. A delay period follows for the establishment of underbalance pressure before the guns are fired. When the delay expires, pressure at the firing head drives the firing pin into the detonator.

Extreme overbalance firing head

The extreme overbalance firing (EOF) head is a simplified version of the HDF head. This pressure-operated firing head has no hydraulic delay, so it fires as soon as the tubing pressure reaches a predetermined threshold. The EOF head is designed for operations where TCP guns or other devices can be initiated while applying firing pressure, such as in extreme overbalance perforating.

Trigger charge firing system

The TCF system consists of a firing head run on electric wireline or slickline and a detonating cord extension, receptor booster assembly, and fill sub assembly run with the gun string. The firing head is run into the well after the guns are positioned and latched onto the booster assembly. This technique improves overall safety because the guns are not armed with a detonator after they have been positioned in the well until the firing head is attached just before firing.

The different versions of the TCF system use the same mechanisms in the eFire, ProFire, HDF, and BHF heads. A jar-down version is also available.

Bar hydrostatic firing head

The BHF head is a drop bar–activated device. Once the head has been activated, hydrostatic pressure drives the firing pin into the detonator. Pressure equalization across the firing head, which occurs in the rare event of a leak resulting in flooded guns, prevents firing the flooded gun string.

ProFire programmable firing head system

The ProFire programmable firing head system is a hydraulically activated firing system with a programmable actuator and a delay module firing head for underbalanced perforating. The actuator controls the operating pressure level and the number of pressure cycles applied before firing. The firing head incorporates the delay mechanism and firing sections.

The ProFire head is ideally suited for permanent completions requiring several pressure operations (such as packer setting and pressure testing) and long periods on bottom before perforating. It prevents inadvertent or premature actuation of the hydraulic firing head during such operations.

Differential pressure firing head

The DPF head is activated by differential pressure between the annulus above the packer and the rathole pressure below. The DPF head is ideally suited for combination with DST tools. Pressure equalization across the firing head is used to prevent firing flooded guns. The packer must be sealed before the guns can be fired.

Circulation ball drop-activated firing heads

The 2⅛-in.-OD circulation ball drop-activated (CBF) firing head and 1¹¹⁄₁₆-in.-OD ball-activated (BCF) firing head are pressure-operated firing heads designed for coiled tubing operations. The BCF head is used with 2-in. or smaller guns.

Firing is controlled from the surface by circulating a ball down to the head and applying pump pressure when the ball seals in the ball seat. Because coiled tubing jobs typically include operations with surface pressure, special safety procedures and techniques are required.

Both the CBF and BCF heads enable circulation before and after firing. The firing head is activated by differential pressure built up across the seated ball, not by absolute pressure.

Redundant firing systems

Redundant firing systems enable combining different types of firing heads on one gun string. The number and type of firing heads depends on the well design and job characteristics. Two firing heads can be combined at the top of a gun string to provide backup firing capability. Configurations of three firing heads are possible when additional redundancy is important, such as in permanent completions. For greater safety, redundant firing heads are positioned above the perforating guns and spaced apart from the guns with a safety spacer.

Safety spacer

Running a safety spacer to provide a blank section between the firing head and guns in a TCP string ensures that the shaped charges are below the rotary table while the gun string is being armed or disarmed.

Perforating guns

As described in the “Hollow Carrier Gun Perforating Systems” chapter, guns used in TCP operations have specific design features:

- No primary explosives are used in Schlumberger guns or intercarrier adapters.
- Various gun connections are available for specific applications such as orienting or conveying and retrieving guns under pressure. Intercarriers can also have built-in locks for gun alignment.
- Intercarrier connections are designed to increase the speed and safety of gun makeup.
- The intercarrier connection blank footage is the minimum possible for the connection design.

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- When the firing head is installed or removed at the surface, the safety spacer at the top of the upper gun positions the shaped charges below the rotary table.
- Trapped pressure preventers are available for longer spacer intervals; all firing head adapters are equipped with a pressure vent.
- Sealed ballistic bulkheads and swivels are available for long gun strings to prevent flooding of the entire gun string before firing.

Job execution example

Gun handling at surface

Safety

Safety is the primary concern when handling guns at the wellsite. Schlumberger TCP guns contain only secondary explosives to prevent detonation during handling and transportation. Because the firing head contains the primary explosive (detonator), it is connected to the gun above the safety spacer on the rig floor, which ensures that the charges are below the rotary table.

In addition, Schlumberger crews follow these safety procedures:

- Only a trained Schlumberger TCP specialist is allowed to arm and disarm the guns.
- No undue force or hammering may be used on perforating equipment.
- Operations involving wellhead or surface pressure must be handled with utmost caution to prevent surface detonations.
- The rig crew is educated that careless handling of explosives can result in a serious accident. All nonessential personnel are asked to stay away from the gun assembly area, catwalk, and drilling floor until the guns are 200 ft below ground or sea level.
- The heavy TCP guns are moved by crane, forklift, or air hoist with proper handling caps or pickup subs.
- The rig crew assembles the guns under Schlumberger staff supervision. Careful use of slips and safety clamps is required to keep the guns from accidentally dropping into the well.

Gun loading

Perforating guns can be loaded at the rig immediately before use or at the operating base before dispatch to the rig. The following safety rules apply to gun loading on the rig:

- The drilling supervisor, toolpusher, safety officer, crane operators, and deck foreman are informed of the locations for storage and handling of explosives.
- No welding, cutting, grinding, or smoking is allowed in the explosives area. Overhead lifts are also banned from this area.
- All spare and scrap explosives are stored in approved magazines. No explosives are left in the area after gun loading is complete.

Gun rig-up without wellhead pressure

Schlumberger TCP guns are handled carefully even though they contain only secondary high explosives. The following sequence is recommended for making up guns:

1. Position guns on the catwalk or pipe rack in proper order.
2. Pick up guns one at a time in the proper sequence and place them in the mouse hole or latch them directly into the elevators.

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3. Raise the upper gun in the elevators, preparing it for connection to the lower gun.
4. Remove the handling cap only when the upper gun is in position.
5. Remove the handling plug from the lower gun.
6. Check the booster position in both guns.
7. Stab the upper gun into the lower gun.
8. Tighten the connection to about 1,000 lbf with chain wrenches. Rig power tongs are unnecessary.
9. Pick up the entire gun with the blocks.
10. Remove the safety dog collar.
11. Remove the slips by picking up farther on the blocks.
12. Lower the guns into the hole, set the slips carefully around the top gun, and install a safety clamp.
13. Place the next gun into the elevators and repeat the preceding steps.

Gun rig-up with wellhead pressure

Pressure control equipment is used to perform operations safely when pressure at the wellhead is present or may develop during the job. The techniques used when running guns with wellhead pressure are lubrication, CIRP equipment, and the GunStack system:

- A fully lubricated gun fits in the available riser or in the space created by a suitable downhole lubricator valve such as the SFIV tool. These guns are run with coiled tubing or a snubbing unit.
- CIRP equipment employs special connectors that allow guns to be connected and disconnected inside a special wellhead pressure control system. The CIRP system consists of a modified coiled tubing BOP connected to a set of lubricators and gate valves. Using CIRP equipment, the operation can be performed in the presence of surface pressure. The guns are conveyed with coiled tubing or wireline.
- The GunStack system uses special connectors that allow guns to be connected downhole and automatically disconnected after firing. The guns can be conveyed and retrieved under pressure with wireline using conventional wellhead pressure control equipment.

See the “Completion Perforating Without Killing the Well” chapter for a full description of these systems.

Gun string arming

Procedures for gun arming differ by firing head type. Only a Schlumberger TCP specialist may connect and arm the firing head. No extraneous work is allowed in the derrick, on the rig floor, or under the rotary table while the TCP string is being armed.

Safety spacer

The topmost section of the TCP string is a safety spacer containing no shaped charges (Fig. 209). The purpose of this spacer is to place all shots below the rig floor or working height at the time of firing head installation.

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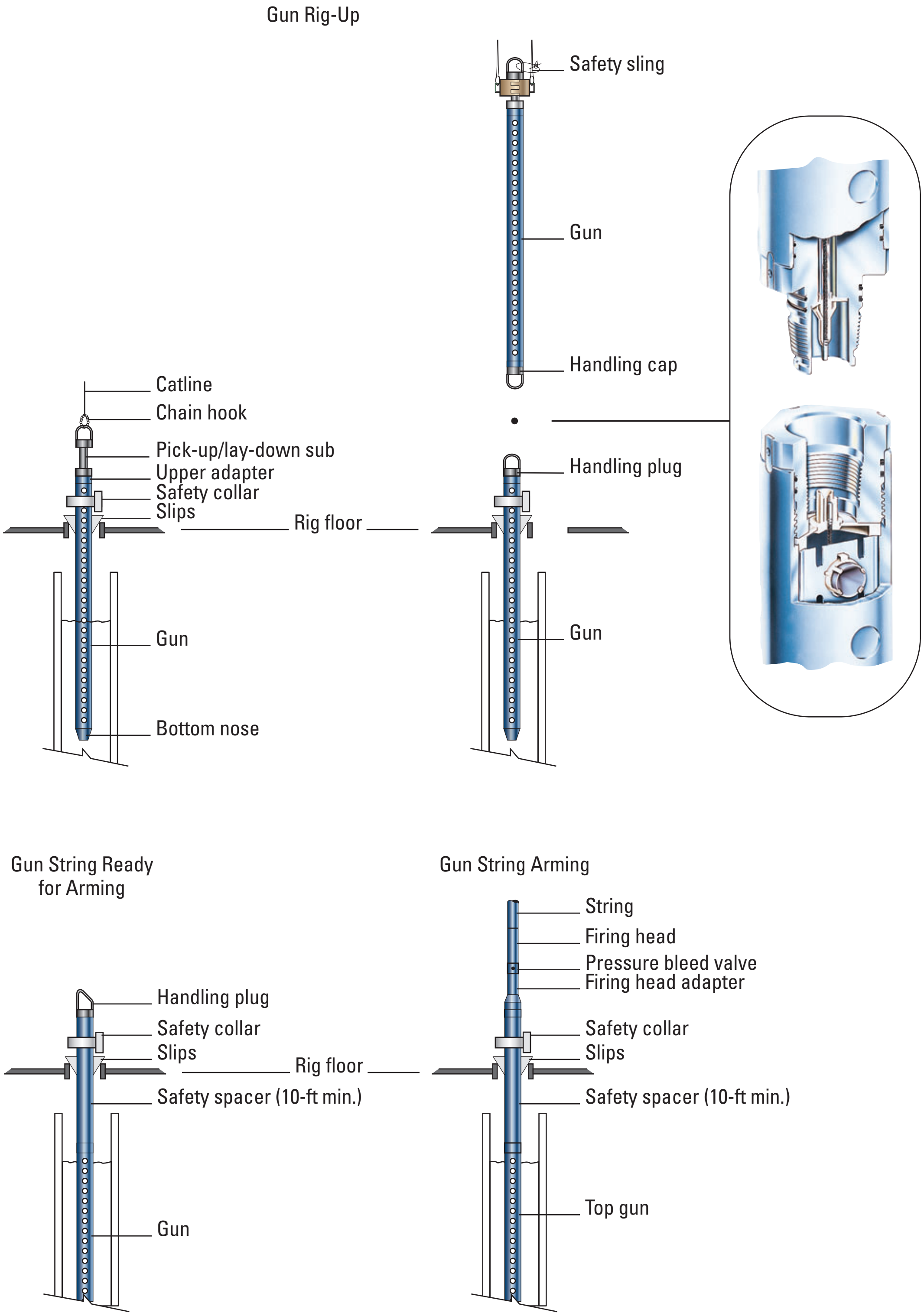

Figure 209. TCP gun string arming procedures.

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Running in

The TCP gun assembly resists damage during running in the hole because the guns use a one-piece steel loading tube to secure the charges and boosters. Although the speed depends on other equipment in use, such as the packer, a smooth running speed is required. Sudden jarring from abrupt starts and stops should be avoided whenever possible. Setting the slips before the string has completely stopped moving is unacceptable.

Special care is necessary when the bottom of the string is passing through a restriction, such as a liner hanger, or where packers or plugs are.

Firing systems require additional precautions when running in the hole. These precautions are designed to protect drop bar and TCF systems from damage caused by environmental well conditions:

- Keep tubulars clean. Each joint should be drifted with a rabbit larger than the largest OD (e.g., drop bar, running tools) to be run in the tubing. A blanked end pipe trip (flex trip) to eliminate rust scale, mill scale, or dried mudcake is also recommended.
- Keep the string clean. Avoid using excessive pipe dope and dope only the pin connector.
- Use only profiled restrictions.
- Use a debris-circulating sub or a fluid- and debris-isolation sub with clean fluid between the sub and the firing head.

Differential pressure and hydraulic delay pressure firing systems require accurate knowledge and control of the hydrostatic, annulus, and tubing pressures. This requirement includes controlling transient pressures such as surge-in and swab pressures when running in and out, rathole compression pressure when stinging through or stabbing into a permanent packer, and circulation break pressure. Shear pins should be selected to prevent unintentional gun detonation and provide reasonable safety margins within the constraints imposed by other equipment or the well tubulars.

Depth control

Four standard techniques are used to verify that the guns are at the correct perforating depth:

- Run a through-tubing GR-CCL log to locate a reference point in the string and correlate to previously run logs.
- Set the packer with electric wireline at a known depth using GR-CCL data for correlation and then sting the guns and completion string through the packer.
- Set the packer and guns with wireline at a known depth and stab the completion string into the packer.
- Tag a fixed, accurate reference point, such as a bridge plug or sump packer.

The first technique, using a through-tubing GR-CCL tool, is the most accurate. A radioactive marker sub is placed in the string at a precisely known distance from the top shot. The string is run in the hole to approximately the correct depth, and a short section of GR-CCL log is recorded over the zone where the sub is located. The log locates the position of the sub (a sharp radioactive peak anomaly) relative to the formation gamma rays (Fig. 210). Because the distance from the sub to the top shot is known, the position of the guns can be calculated and adjusted if necessary by spacing out the string at the surface. After the packer is set, the GR-CCL tool can be rerun to ensure that the guns are at the correct depth.

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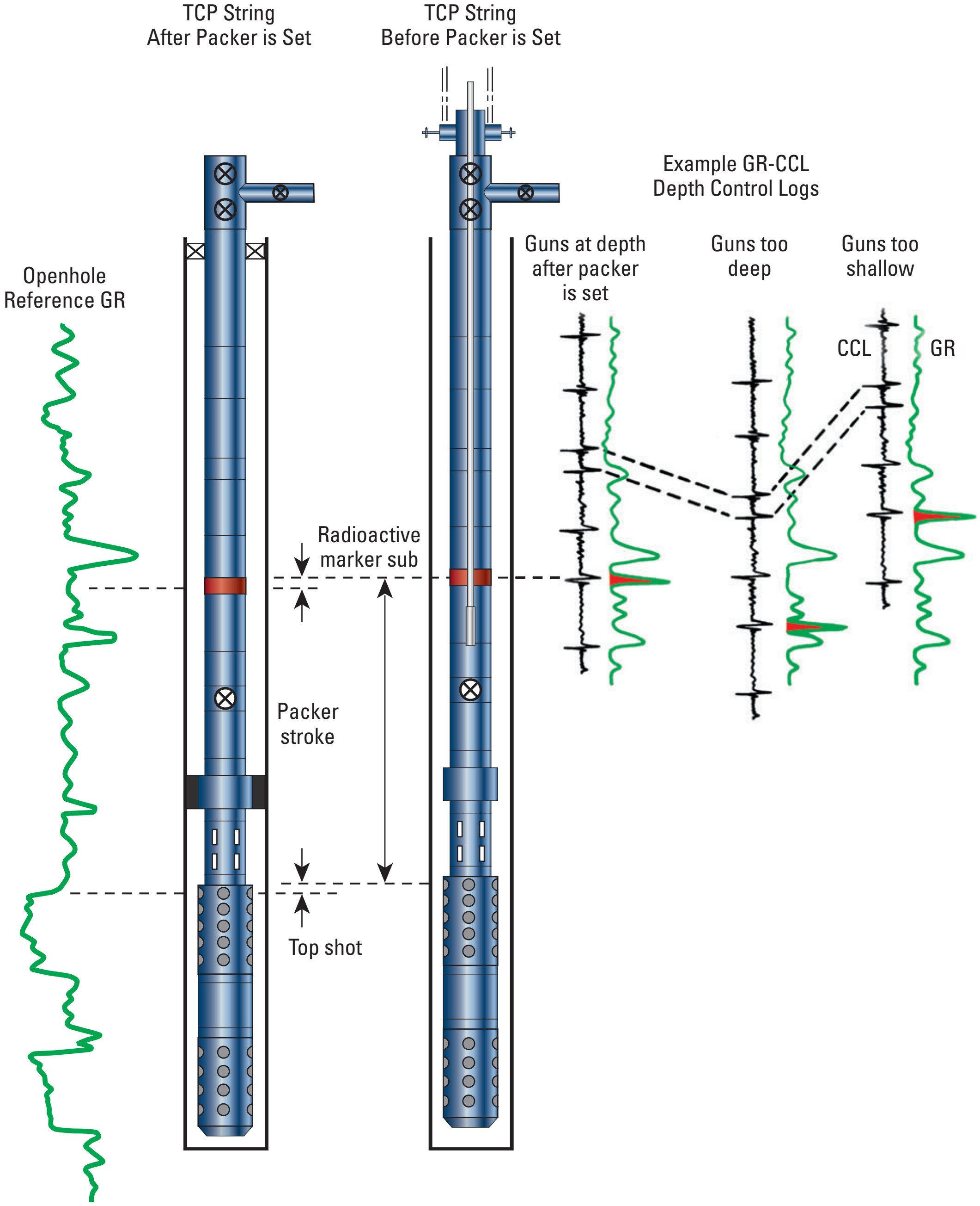

Figure 210. Through-tubing correlation log.

Because the GR log, which is recorded in tubing inside the casing, is usually attenuated, a slow logging speed achieves better correlation results between the depth control and openhole GR logs. Radioactive pip tags should be placed in one or more casing joints before running casing as a marker if the formation GR curve shows little activity. Alternatively, if the neutron log shows good activity, a neutron log or the RST* Reservoir Saturation Tool sigma log may produce a more satisfactory correlation log than a GR device.

The second technique relies on setting a permanent packer at a known, accurate depth by using wireline and then stinging the guns and completion string with the seal assembly through the packer (Fig. 211). A radioactive marker tag is placed on the tubing at the desired distance from the top shot.

Using the third technique, the guns are run on wireline below a permanent packer, which is set at a known depth with wireline. The completion string and seal assembly are then stabbed into the permanent packer (Fig. 212). This method is used only with relatively short strings because of the strength limitations of wireline.

The fourth technique involves setting a bridge plug or sump packer at a known depth and lightly tagging it with the bottom of the gun string (Fig. 213). This method may be inaccurate if there is fill on top of the plug. Using a snap-latch collet and sump packer gives a better indicator for locating the string position.

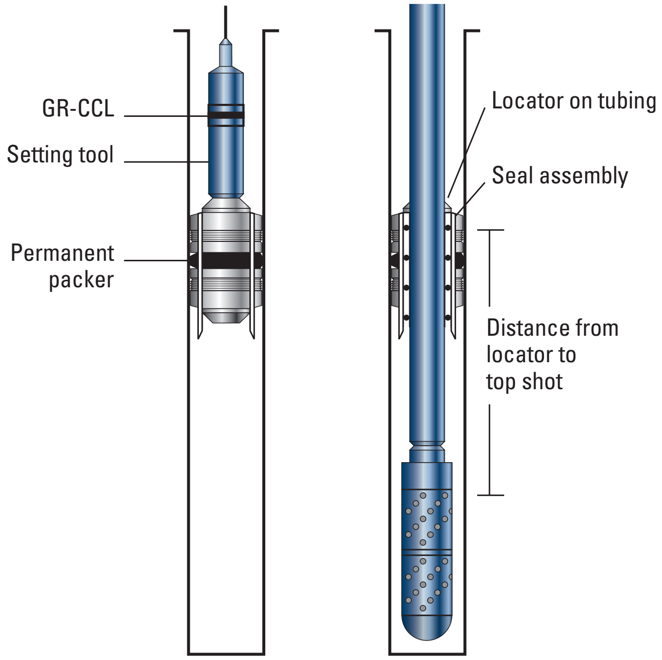

Figure 211. Stinging through a permanent packer.

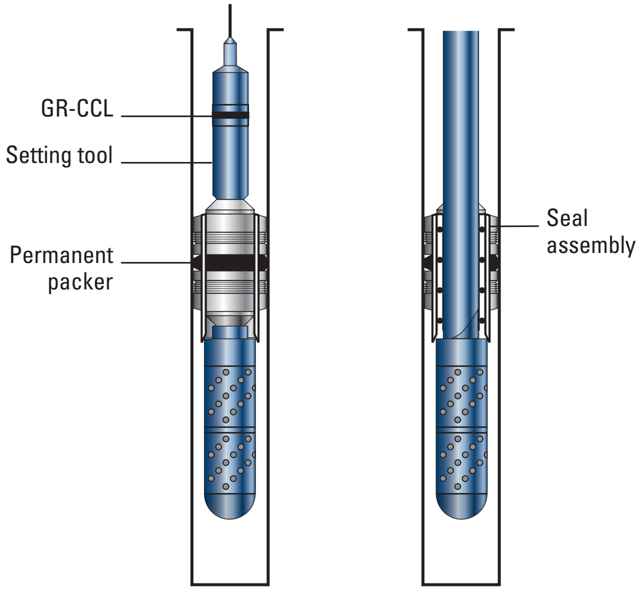

Figure 212. Stabbing into a permanent packer and gun assembly.

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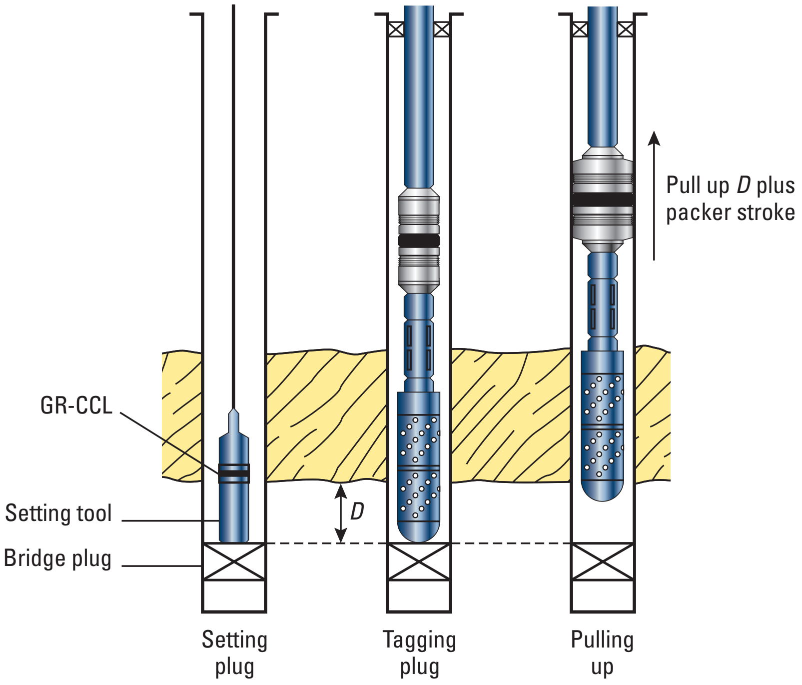

Figure 213. Tagging a bridge plug.

Depth control on floating rigs

A special depth control technique used on floating rigs with mechanically set packers is derived from GR-CCL correlations (Fig. 214). A reference point in the string (radioactive marker sub) is tied to the openhole logs, taking into account the closure of various pieces of equipment in the string after the packer is set and string weight is applied.

The following terms apply to the technique, as shown in Fig. 214:

T = total slip joint closure available
D = desired slip joint closure (typically $\frac{1}{3}$ to $\frac{2}{3}T$)
J = jar + reference tool closure
P = packer stroke while setting.

1. Run in hole with TCP-DST string and subsea hanger, land in subsea BOP stack, and run a GR-CCL correlation log.
2. Position the radioactive marker at a depth corresponding to the desired top shot, minus the length of assembly from top shot to radioactive marker measured in tension (including $D + J$).
3. Pull out of hole to subsea hanger and add or remove tubing, drillpipe, or both below hanger as required in Step 2. Run back in hole with the subsea hanger and add the subsea tree assembly.
4. When the subsea tree is landed, the top shot is at $D + J$ below desired top shot location.
5. Pull up $D + J + P$, rotate to the right, and start to apply weight. At this point the top shot is P above its desired final location.
6. As the weight is applied further, the setting stroke P of the packer brings the top shot to the desired location. Confirmation with GR-CCL log is possible after setting the packer.

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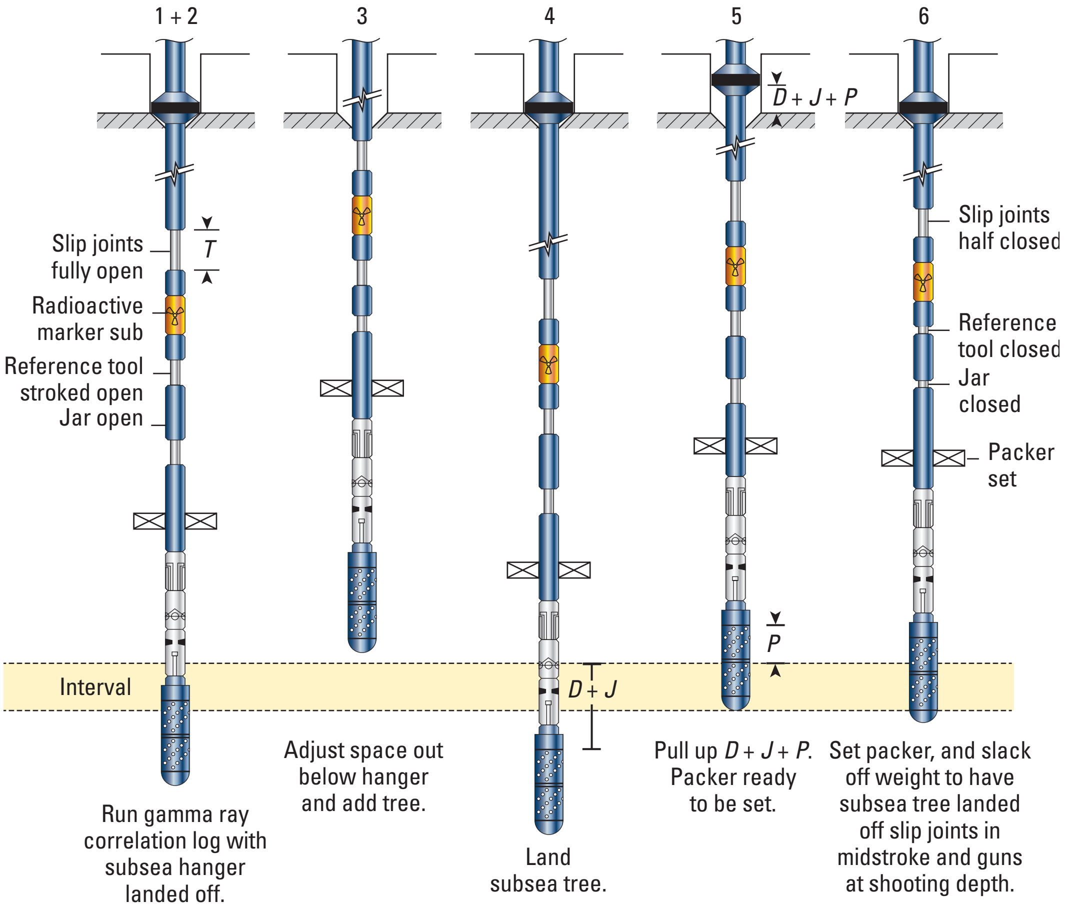

Figure 214. TCP depth technique on floating rigs.

Gun string firing

The firing procedure used is specific to the firing system. All firing systems require verification of the following factors:

- Guns are at the required depth, the packer is set, the surface equipment is installed, and the entire string and surface equipment have been pressure tested.
- The surface valves are in the correct open or closed positions.
- The shot detection equipment is turned on and operating.
- All affected personnel are aware of the imminent firing.

Gun string retrieval

Gun string retrieval is conducted by Schlumberger personnel, and only trained Schlumberger TCP specialists are allowed to disarm guns. Whether the TCP operation is completed in a few hours or the gun has been left in place for years, safety procedures are strictly followed, particularly in fishing for a drop bar. Because of strict adherence to safety procedures and the incorporation of safety features in the firing systems, retrieving the gun string does not present a special hazard. The following retrieval procedures apply to all systems:

1. Pull out of hole until the gun assembly reaches 200 ft below ground level or seafloor. Clear all nonessential personnel from the rig floor and all personnel from below and above the rig floor.
2. Pull the firing head adapter and firing head to the drill floor.

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3. Carefully open the pressure vent in the firing head adapter to relieve any trapped pressure. (All firing systems are equipped with a pressure release valve.) Remove the firing head to disarm the guns.
4. If the guns have fired, break down the guns in the usual way (rig tongs may be necessary). Hard-to-break connections may indicate trapped pressure inside the gun string as a result of debris, particularly in the spacers.
5. If the guns have not fired, it must be assumed that there is trapped pressure inside the gun string, possibly caused by low-order detonation.
6. Break down the guns in the usual way. Break each intercarrier connection, install the metal handling cap and plug, and lay down the guns individually. Observe correct use of the safety clamp before releasing the elevator.

Gun string release

The following conditions are recommended before releasing the gun string:

- Sufficient rathole is available.
- Gun release is either automatic or dressed for the chosen actuation method (up or down mechanical shifting or hydraulic shifting).
- Gun release is positioned 60 ft above the top shot and above the production valve or ports for hydraulic release.
- Positioning (shifting) the tool does not interfere with other completion components higher in the tubing.
- String restrictions allow passage of the shifting tool or activating ball.
- Weight of the gun string is compatible with the deviation and minimum release weight.
- Depth of the top of the fish is known for eventual fishing.

Releasing the guns automatically at firing is preferred.

Automatic activation

The use of automatic gun releases is recommended whenever possible. Automatic gun release tools, such as the CTXR, SXAR, MAXR, and WXAR, offer unique advantages in drop efficiency and ease of operation. These tools incorporate X-Tools technology developed by Schlumberger to ensure the fastest possible separation of the gun string after firing because the same ballistic train is used to activate the drop. Release does not depend on a mechanical or hydraulic system.

The rapid drop has two advantages:

- The drop works better in high deviations (up to 80°) because it benefits from the violent but transient shocks created by gun detonation. The shocks break the frictional forces holding the guns in place against the casing wall. Once the guns start to move, they tend to keep moving.
- Because the drop occurs at high speed immediately after firing, the guns move down and away from the perforations before they can become sanded in.

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Slickline activation

The shift-up mechanical tubing-conveyed gun release (TCR) requires standard or nonselective keys in the shifting tool.

1. Rig up the slickline lubricator and pressure test against the lubricator valve.
2. Run in hole with the shifting tool, sinker bars, and jars.
3. Check the holdup depth on the depth meter before releasing the guns. Shift the sleeve and drop the guns. Check the holdup depth to verify drop-off.

Although jar-down shifting is an option, it is generally not recommended except as a backup for the pressure release.

Tubing pressure activation

Some gun release subs can be activated hydraulically using a type-N testing tool, either dropped from the surface or run on wireline with a running tool or a ball. The drop time depends on depth, string ID, fluid contents, and deviation.

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Firing Systems

General requirements of firing systems

TCP firing systems must be designed for safety, reliability, and simplicity of operation in line with API RP 67, *Recommended Practices for Oilfield Explosives Safety*. Safety considerations are the primary design concern for the personnel, the well, and the equipment. Strict safety procedures are required when using firing systems. Personnel safety is the overriding consideration, particularly for the handling of guns and firing heads. Once the string is beneath the rig floor, the safety of the well becomes paramount.

General safety procedures and safety features of firing systems address the following main safety concerns:

- Handling of explosives—Local government regulations and Schlumberger policies control the transportation, handling, and storage of explosives and remnants. Only trained and qualified personnel may handle the explosives.
- Restricted use of primary explosives—The firing head detonator is the only primary explosive used in the string. Accidental detonation while assembling and disassembling the guns is virtually impossible because no primary explosives are used in gun-to-gun connections.
- Safety spacer—Inclusion of a safety spacer is required (except for systems using the eFire electronic firing head) on top of the gun string to ensure that the guns are below the rig floor when the firing head is connected or disconnected.
- Top-down firing—The firing head is connected last, to the top of the guns, so that personnel are never exposed to an armed gun string while running in and pulling out of the well. Firing systems are considered safe at the surface because they require a minimum hydrostatic pressure to fire. The dry-hole drop bar system is the only firing system that does not depend on a minimum hydrostatic operating pressure to fire.

Individual firing systems also have specific built-in safety features, described in subsequent sections of this chapter. In particular, the TCF system allows the gun string to be run unarmed, without a detonator.

Except for electrical firing systems, all Schlumberger firing heads incorporate the basic safety feature of requiring two separate actions to fire the head. Both actions involve the firing pin, which is first unlocked by applying pressure or mechanically and is then driven into the percussion detonator by the well pressure. For example, when the drop bar of a drop bar head is released and hits the firing head, it shifts the locking sleeve to allow release of the locking balls holding the firing pin. The well pressure at the firing head then propels the freed firing pin into the detonator, firing the guns. If the well pressure is less than the minimum operating pressure, the head does not activate. Specifications for each firing head include the minimum operating pressure for the firing pin to activate. The minimum operating pressure is adjustable. The only situation that could result in accidental firing at the surface is if the head is lowered into a well with surface pressure present, such as well pressure or pressure from testing a lubricator. Specific operating standards apply to such situations.

In addition to safety considerations, firing systems must be reliable and, to the extent practical, uncomplicated to operate. Reliability is enhanced by incorporating redundant firing heads and heads that can be retrieved and rerun without pulling the completion.

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New technologies are continually integrated to advance Schlumberger firing systems. Examples of recent innovations include the eFire systems, which incorporate intelligence capabilities, and the ProFire systems, which enable configuring the absolute pressure firing head for multiple pressure cycles before activation. These new technologies are used in many TCP applications, and their features are ideally suited for permanent completions because they increase operating flexibility.

Next in this chapter are detailed descriptions of the firing systems developed and provided by Schlumberger.

eFire electronic firing head system

The eFire electronic, computer-controlled firing head system (Fig. 215) is a revolutionary method of using precisely coded signals to activate the firing mechanism. Most importantly, the coded signal cannot be replicated randomly, either by environmental conditions at the surface or in the well or by unintended acts such as applied pressure or shock. The three eFire configurations of the eFire-TCP, eFire-CT, and eFire-Slickline electronic firing heads enable applying this flexible, reliable technology in a wide variety of operations (Fig. 216).

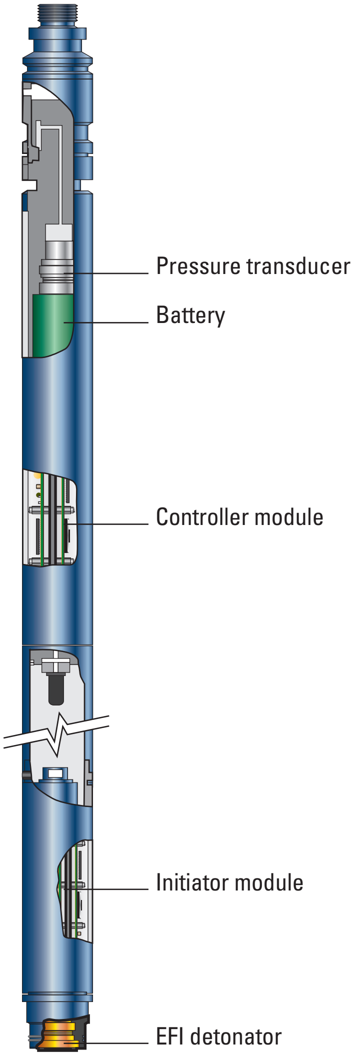

Figure 215. eFire electronic firing head system.

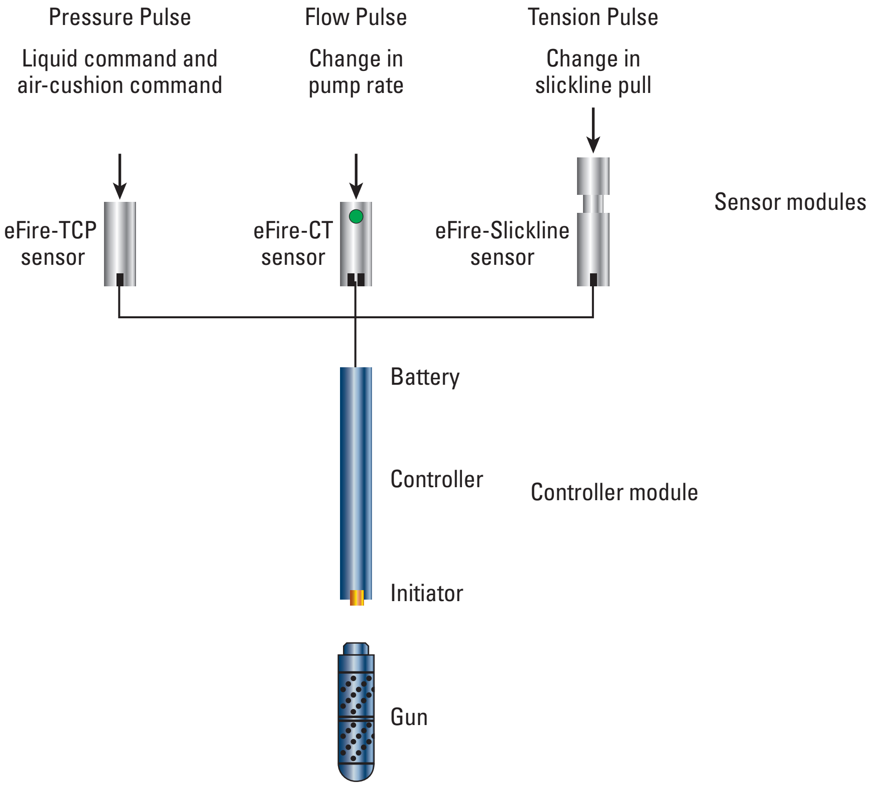

Figure 216. eFire system configurations.

The eFire system combines two proven Schlumberger technologies: the IRIS* Intelligent Remote Implementation System and detonators that are unaffected by RF transmissions. The IRIS system in the dual-valve DST tool incorporates an electronic, programmable mechanism that controls operation (opening and closing the test and circulating valves) by applying coded pressure pulses at the surface through the annulus or tubing. The RF-safe detonator contains no primary high explosives but instead uses an exploding foil initiator (EFI) that requires a precise electrical signal for initiation (see the "Detonators" section of the "Perforating Fundamentals" chapter).

The primary eFire module common to all firing heads consists of the following components:

- pressure transducer
- battery
- controller circuits
- initiator circuits
- RF-safe electronic detonator.

eFire version 3 also records fast-gauge effects, with the capability of capturing transient data at 1,000 samples/s.

The eFire module is adapted to firing heads for TCP, coiled tubing (CT), and slickline applications through the use of sensors (Fig. 216). The sensors convert specific pulses into signals recognized by the processor in the firing head. The TCP sensor converts tubing pressure pulses with a full or partial liquid cushion into signals, the CT sensor converts coiled tubing flow pulses (i.e., changes in pump rates) across the differential pressure transducer in the sensor into signals, and the slickline sensor converts tension pulses (i.e., changes in slickline pull) into signals. The controller communicates with the sensor and connects battery power to the initiator when the command is approved. The controller instructs the initiator to fire.

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The eFire system can be disabled after the firing sequence has been initiated. The head can be reinitiated as required by using the set pulse commands.

Features and benefits

- Increased reliability—The eFire design has no moving parts.
- Insensitivity to well and pressure operations—The combination of low-pressure initiation and the unique command system shields the eFire system from the affects of pressure testing, packer setting, shock, etc.
- Operational efficiency—The eFire system is readily converted for many applications. A separate slickline run is not necessary, as it is for conventional firing heads.
- Safer, more economical operations—The combination of two field-proven technologies incorporates multiple safety barriers and the ability to abort anytime during the operation. Set-up and maintenance are also simplified, along with reduced equipment requirements.
- Control of underbalance—Precise time delay allows pressure control and reduces rig time.
- Reduced risk—EFI technology does not use primary high explosives and is RF immune.
- Postjob validation—The tool stores a job log, including the formation pressure response.

Safety considerations

Safety was a primary design parameter for the eFire system, resulting in total operational control through its unique command requirements from surface that cannot be accidentally reproduced. Additional safety-promoting features are precise delay times and low-pressure initiation. No primary explosives are used, and the eFire system does not impose radio silence or shutting down RF sources. eFire operations can be aborted at any time. The system cannot be fired unintentionally at the surface or while pulling out of the well.

Applications

The eFire electronic firing system replaces traditional drop bar– and pressure-activated firing heads in numerous applications.

- Wells with a small margin for applied pressure—The unique coded sequence of the eFire system uses low-pressure pulses.
- Deviated wells—The eFire system can be controlled with an air cushion command that is sent by using standard high-pressure nitrogen bottles or run on coiled tubing.
- Wells with a partial cushion or dry wells—Dry tubing can be perforated without the need for a nitrogen-pumping unit by using the eFire-TCP air cushion command for partially filled tubing.
- Jobs requiring pressure cycles before guns are fired—The eFire firing heads are insensitive to well pressure conditions.

eFire operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, eFire system operations begin with thorough design and planning using the applicable flowchart, an abbreviated example of which is shown in Fig. 217.

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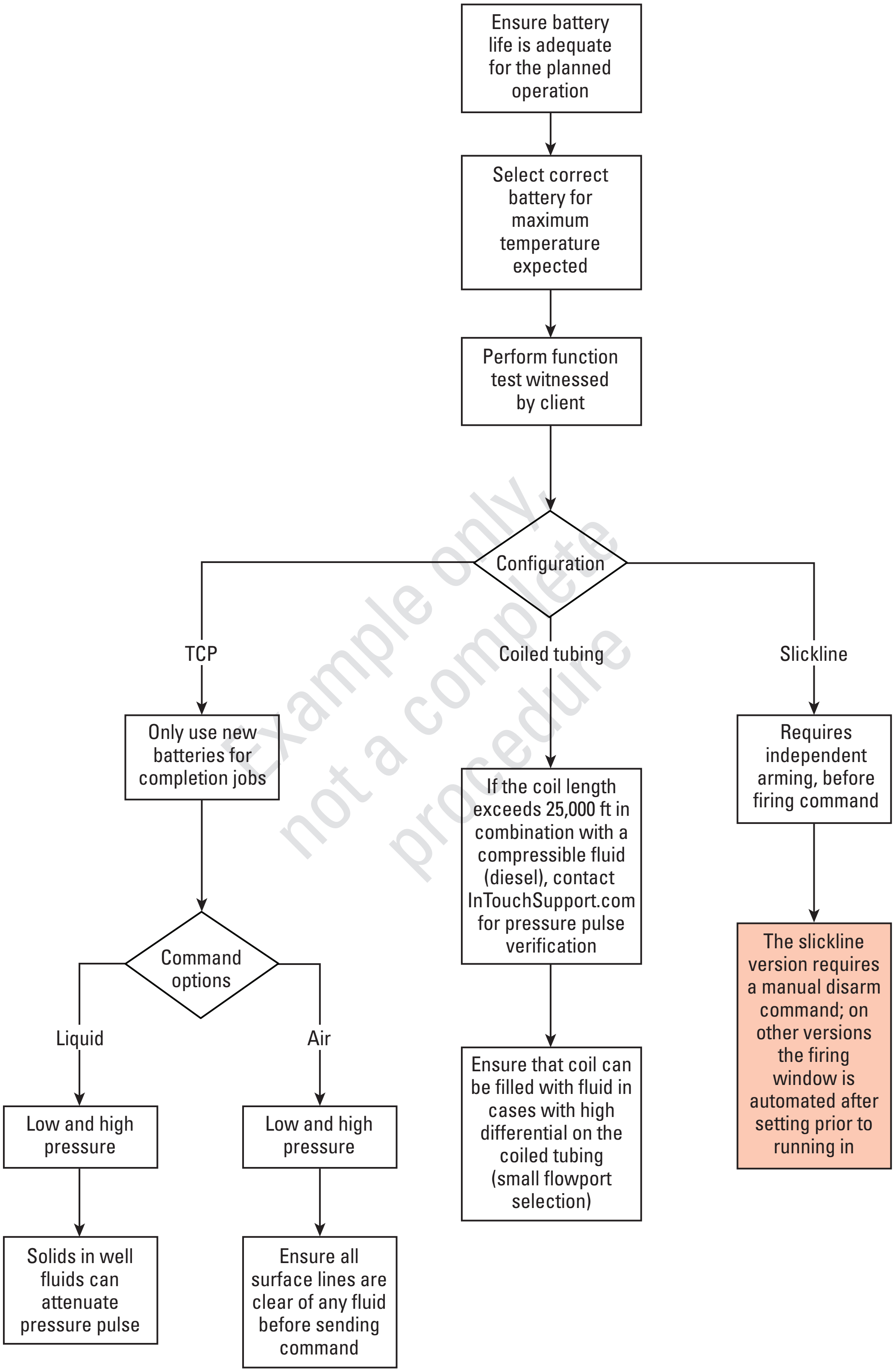

Figure 217. Excerpt of an example SDP design and planning flowchart for eFire operations.

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The setup and function testing procedure for the eFire system (Fig. 218) consists of the following steps. Operational procedures specific to the eFire-TCP, eFire-CT, and eFire-Slickline firing heads are in the following sections for those eFire systems.

Preparation

All job preparation for the eFire system, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes following the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

The eFire system is assembled in the shop.

Execution

The eFire firing system arrives at the wellsite assembled. The EFI detonator is placed in the assembly on the deck, away from the loaded guns. The system is considered armed only after the head is attached to the live gun string, with the following procedure:

1. Set up the tool and run the function test (Fig. 218).

   a. Remove the electronic detonator.
   b. Connect PC to the firing head.
   c. Set specific job parameters.
   d. Function test the firing head.

   The tool is not enabled unless the function test is performed first.

2. Ensure that all guns are properly made up in the correct order and set the safety spacer in the slips with a safety clamp installed.
3. Pick up the firing head assembly with detonator installed and hang it in the blocks above the safety spacer.
4. Stab the firing system assembly into the safety spacer.
5. Tighten all connections to the proper torque.
6. Continue running in hole.

Firing procedures specific to the eFire-TCP, eFire-CT, and eFire-Slickline firing heads are in the following sections for those eFire systems.

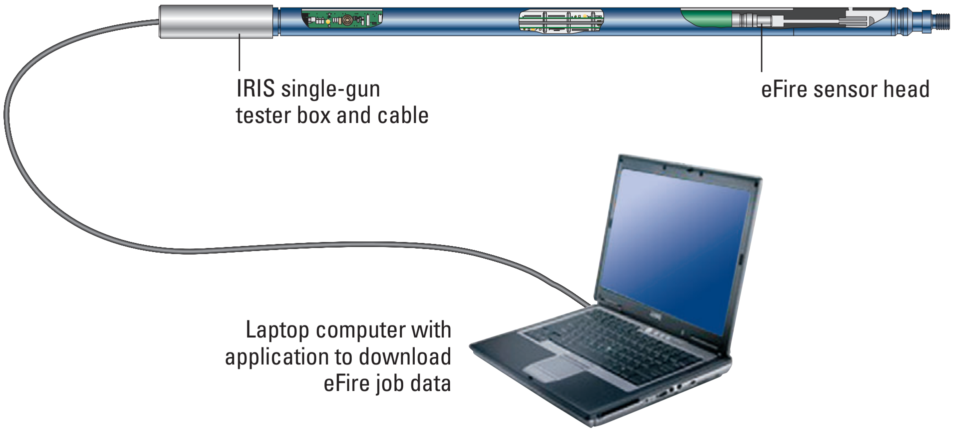

Figure 218. Tool setup and function testing.

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eFire-TCP electronic firing head system for tubing-conveyed perforating deployment

The eFire-TCP electronic firing system (Fig. 219 and Table 112) is an innovative electronic firing head for use in temporary and permanent TCP operations. Low-level coded pressure pulses in the liquid- or partly air-filled tubing are used to communicate with the firing head. This unique command system eliminates problems associated with high levels of applied pressure during operations such as setting packers or pressure testing. The eFire-TCP system can be run with the perforating string to avoid having to convey the firing head later with slickline, unlike conventional high-pressure, hydrostatically activated firing heads.

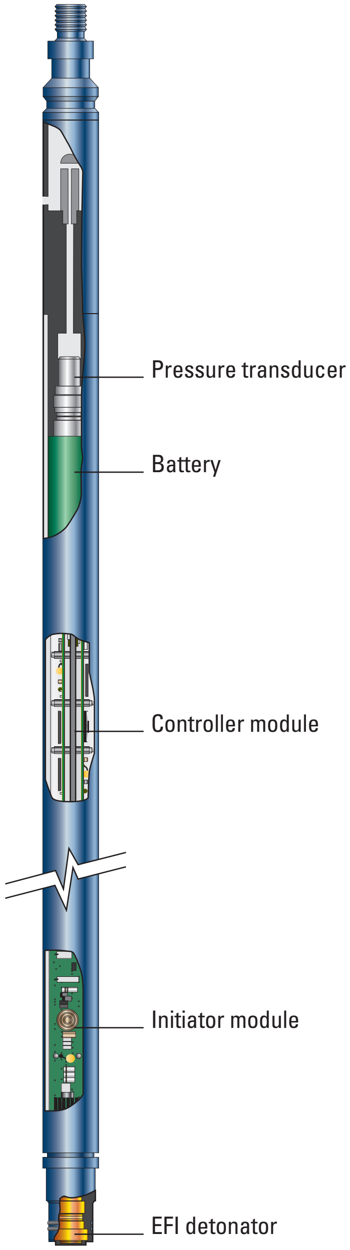

Figure 219. eFire-TCP firing head.

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Table 112. eFire-TCP Specifications

	eFire-TCP Head	eFire-TCP Head V3
Outside diameter (in.)	1.707	1.707 High-pressure version: 1.75
Temperature rating[†] (°F [°C])	400 hr: 320 [160] 1,000 hr: 302 [150]	100 hr: 350 [177] 1,000 hr: 302 [150]
Pressure rating (psi)	15,000	15,000 High-pressure version: 22,500
Length (in.)	79.51	69.14 to 143.70 High-pressure version: 78.62 to 149.5
Tensile strength (lbf)	30,000	43,000
Shock rating (g)	20 shocks at 0.5 ms: 500	20 shocks at 0.5 ms: 500
Transient pressure recording rate (samples/s)	5	1,000
Firing time delay[‡] (min)	5 to 480 Accuracy: ±12 s	5 to 480 Accuracy: ±12 s

[†] Ballistic components limit tool operation to HMX time and temperature ratings. See Table 17 and Fig. 84 in the "Operating Environment and Engineering of Perforating Operations" chapter and consult with your Schlumberger representative if the temperature or time exposure exceeds the HMX curve.

[‡] Delay time can be extended on request through modification.

A pressure transducer in the tool detects the pulses applied from surface. Two separate processors in the controller module are required to independently verify the specific command. The initiator module then converts battery power to the high voltage level required to initiate the electronic detonator.

The eFire detonator does not include primary explosives. The unique signature of the pressure pulse (Fig. 220) is a highly effective safety feature. In addition, the eFire-TCP tool is not armed until it has been at 75% of full hydrostatic pressure for at least 1 hr (Fig. 221).

A tool setup and function test is always performed through a PC interface before connecting the detonator. The interface is also used to download the job log and install new firmware as necessary.

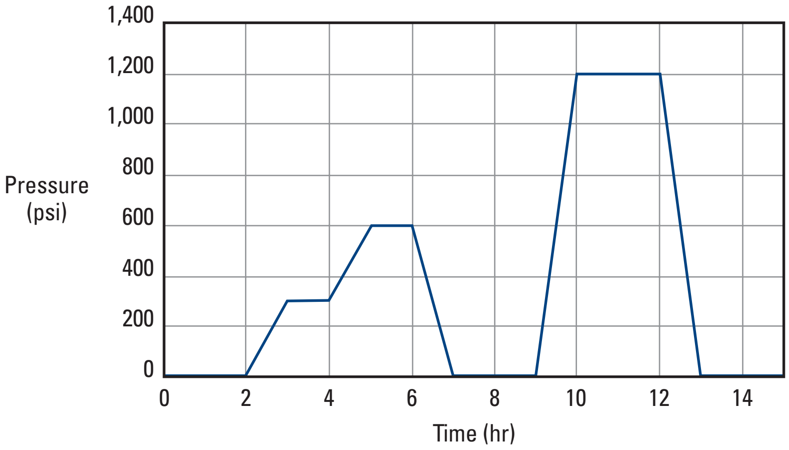

Figure 220. Unique eFire-TCP pressure pulse signature.

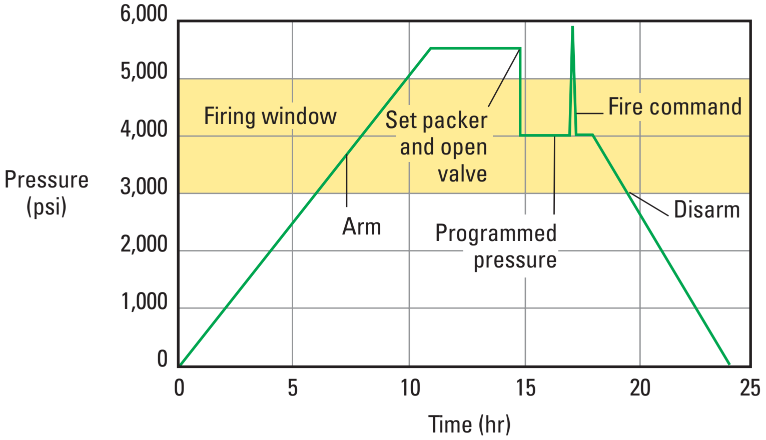

Figure 221. Downhole arming of the eFire-TCP tool.

eFire-TCP features and benefits

In addition to the features and benefits previously listed for the eFire system, the eFire-TCP system has the following features and benefits:

- Facilitated redundant configurations—The eFire-TCP head is compatible with all Schlumberger firing heads (Fig. 222) to easily add redundancy for hydraulically operated firing heads.
- Safer, simpler operation in partially filled tubing—The air cushion command used for activation in partially filled tubing is a safer alternative to the drop bar firing head in empty tubing and highly deviated wells and a simpler alternative to firing heads activated with annulus pressure.
- Cost effective—The ability to use air cushion commands does not require nitrogen to operate.

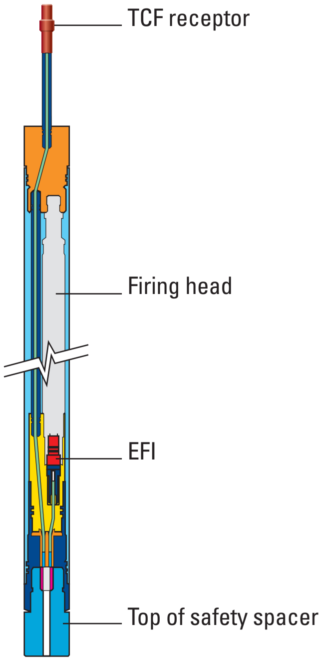

Figure 222. Redundant configuration of the eFire tool in a fill sub with a TCF receptor.

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eFire-TCP operational procedures

Figure 223 shows the fire command profile for a typical TCP job with a full liquid cushion. In applications where the tubing contains liquid to the surface, the tool is activated using pressure pulses sent by rig pumps. The well fluid must be clean because solids content can attenuate the pressure pulses. The unique pulse sequences can be sent at low pressure, which prevents accidental activation of the firing head. After the command is received and implemented, the precise, programmable firing delay—which can extend from 5 min to 8 hr—allows time for final preparations before perforating. The fire command can be aborted during the delay if necessary by simply applying pressure. The fire command can be re-sent later.

Figure 224 shows the fire command profile of a typical TCP job with a partial liquid cushion. Nitrogen bottles provide the necessary tubing pressure pulses to activate the fire command. The number of bottles is determined by the volume of the empty tubing. The pressure increase is determined by the firmware and the number of pulses. Because the pressure increase is small, it can usually be accomplished with a reasonably low quantity of nitrogen. All surface lines must be free of any fluid before commands are sent. Figure 225 shows a job example in the Gulf of Mexico where two pulses of about 70 psi each were used to successfully initiate the fire command.

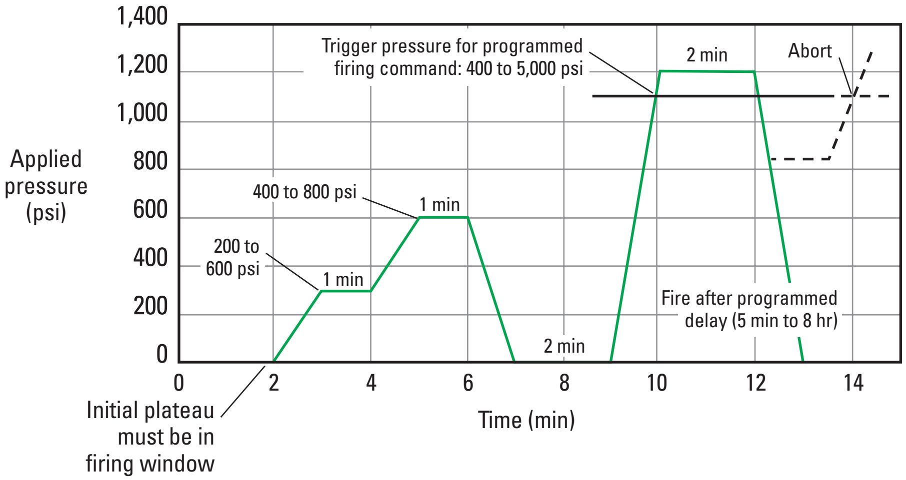

Figure 223. Applied pressure versus time profile of a fire command for a typical TCP job with a full liquid cushion.

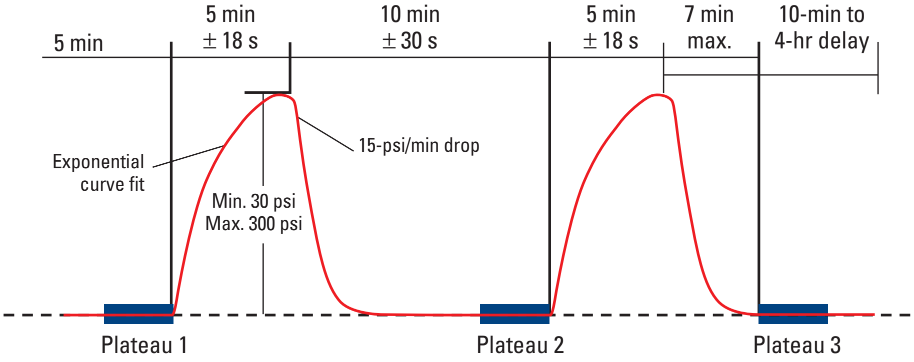

Figure 224. Applied pressure versus time profile of a fire command for a typical TCP job with a partial liquid cushion. In each 3-min plateau, the pressure must be within ±5 psi. Plateau 1 is the reference pressure. Plateaus 2 and 3 are within a ±15-psi window of the reference pressure.

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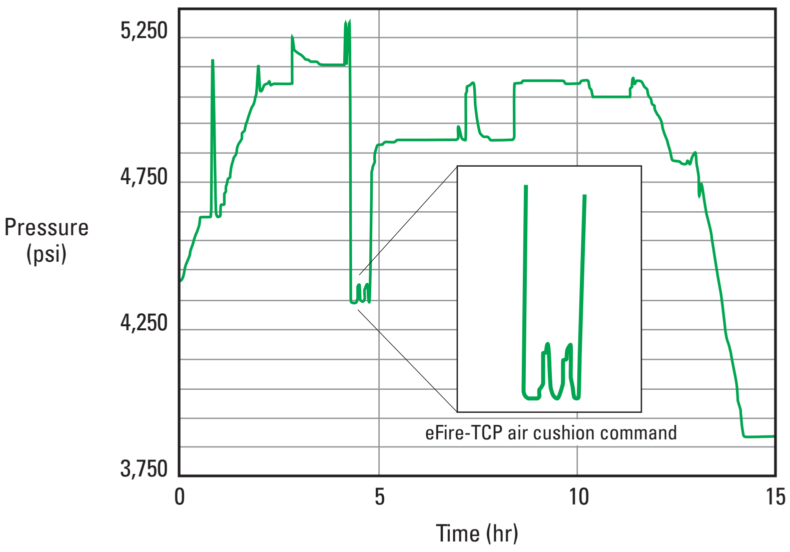

Figure 225. Air cushion command for TCP job in the Gulf of Mexico.

eFire-CT electronic firing head system for coiled tubing deployment

The eFire-CT firing system (Fig. 226 and Table 113) is an electronic firing head for coiled tubing explosive services. In addition to perforating operations, it can be used to trigger cutters and set packers and plugs. The eFire-CT head is operated by a coded sequence of pump rate changes through the coiled tubing. The change in pump rate is measured at an orifice in the eFire-CT head sensor. The unique combination of the pulses creates the special signature required to communicate with the firing head. The eFire-CT system allows pumping at any rate, limited only by the coiled tubing. It does not require pumping down a ball to operate like the ball-activated systems.

Table 113. eFire-CT Specifications

	eFire-CT Head	eFire-CT Head V3
Outside diameter (in.)	2.875	1.6875 2.875
Temperature rating† (°F [°C])	400 hr: 320 [160] 1,000 hr: 302 [150]	100 hr: 350 [177] 1,000 hr: 302 [150]
Pressure rating (psi)	15,000	15,000
Length (in.)	105.66	1.6875: 71.08 2.875: 95.23
Shock rating (g)	20 shocks at 0.5 ms: 500	20 shocks at 0.5 ms: 500
Nominal port size (bbl/min)	0.25, 0.5, 0.75, 1, 2, 3, 4	0.25, 0.5, 0.75, 1, 2, 3, 4
Firing time delay (s)	90	75

† Ballistic components limit tool operation to HMX time and temperature ratings. See Table 17 and Fig. 84 in the "Operating Environment and Engineering of Perforating Operations" chapter and consult with your Schlumberger representative if the temperature or time exposure exceeds the HMX curve.

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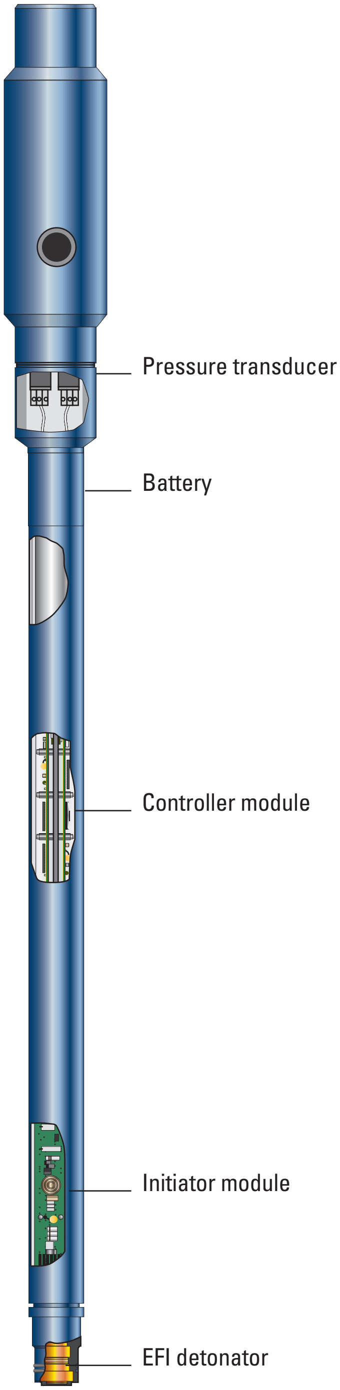

Figure 226. eFire-CT firing head.

A differential pressure transducer in the tool detects the command from surface. Two separate processors in the controller module are required to independently verify the unique command before the initiator module converts battery power to the high voltage level required to initiate the electronic detonator. The eFire-CT head does not include primary explosives. In addition to the safety offered by the unique signature of the command pulse, a selectable arming delay allows pressure testing at surface without affecting the tool. The eFire-CT head is RF safe and has been approved by Thale Missile Electronics Ltd (TME, formerly Thomson-Thorn Missile Electronics Ltd) for operation during radio communication, welding, and cathodic protection.

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A tool setup and function test is always performed through a PC interface before connecting the detonator. This interface is also used to download the job log and install new firmware as necessary.

eFire-CT features and benefits

In addition to the features and benefits previously listed for the eFire system, the eFire-CT system has the following features and benefits:

- Reduced sensitivity to debris—Control does not require pumping a ball down.
- More accurate underbalance control—Not having to pump a ball down lessens the amount of pumping necessary.
- Compatibility—The eFire-CT head is compatible with ball-operated coiled tubing tools and does not require electric line in the coiled tubing.
- Circulation flexibility—The range of orifice sizes provides flexibility in circulating rates, including high rates, and the tool allows circulation at all times.

eFire-CT operational procedures

Figure 227 shows the applied pump rate profile of the fire command for a typical coiled tubing perforating job. The pump rate is changed at the surface in a specified sequence, causing differential pressure changes measured across the flow port in the eFire-CT sensor. The flow command requires a change in flow rate approximately equal to the nominal rating of the flow port.

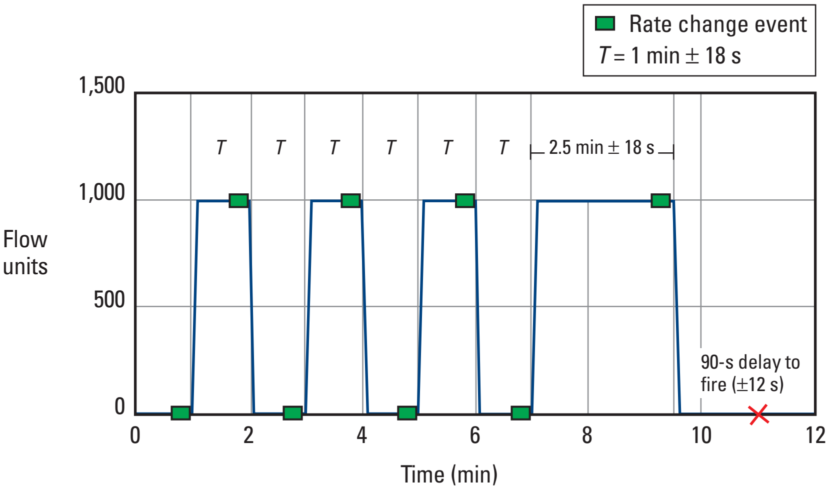

Figure 227. Applied pump rate versus time profile of the fire command for a typical coiled tubing perforating job.

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eFire-Slickline electronic firing head system for slickline deployment

The eFire-Slickline system provides an electronic firing head for slickline explosive services (Fig. 228 and Table 114). In addition to firing perforating guns, it can be used to trigger cutters and set packers and plugs. The eFire-Slickline head is operated by a coded sequence of tension pulses on the slickline wire, which the hydraulic strain sensor in the tool converts to pressure pulses superimposed on the bottomhole pressure (Fig. 229). The unique combination of the pulses creates the signature required to communicate with the firing head. In addition to the unique command signature, the tool must be enabled by a preset hydrostatic pressure followed by the arming command sent from the surface before it accepts the fire command. Fully controlled from the surface, the eFire-Slickline system does not require inputting prerecorded downhole parameters for operation.

The pressure transducer in the tool detects the command from the surface. Two separate processors in the controller module are required to independently verify the command before the initiator module converts battery power to the high voltage level required to initiate the electronic detonator. The eFire-Slickline head does not include primary explosives. The eFire-Slickline firing head has been approved by TME for operation during radio communication, welding, and cathodic protection.

A tool setup and function test is always performed through a PC interface before connecting the detonator. This interface is also used to download the job log and install new firmware as necessary.

Table 114. eFire-Slickline Specifications

	eFire-Slickline Head	eFire-Slickline Head V3
Outside diameter (in.)	1.707	1.707
Temperature rating[†] (°F [°C])	400 hr: 320 [160] 1,000 hr: 302 [150]	100 hr: 350 [177] 1,000 hr: 302 [150]
Pressure rating (psi)	15,000	15,000
Length (in.)	81.2	71.71
Tensile rating (lbf)	30,000	30,000
Shock rating (g)	20 shocks at 0.5 ms: 500	20 shocks at 0.5 ms: 500

[†] Ballistic components limit tool operation to HMX time and temperature ratings. See Table 17 and Fig. 84 in the "Operating Environment and Engineering of Perforating Operations" chapter and consult with your Schlumberger representative if the temperature or time exposure exceeds the HMX curve.

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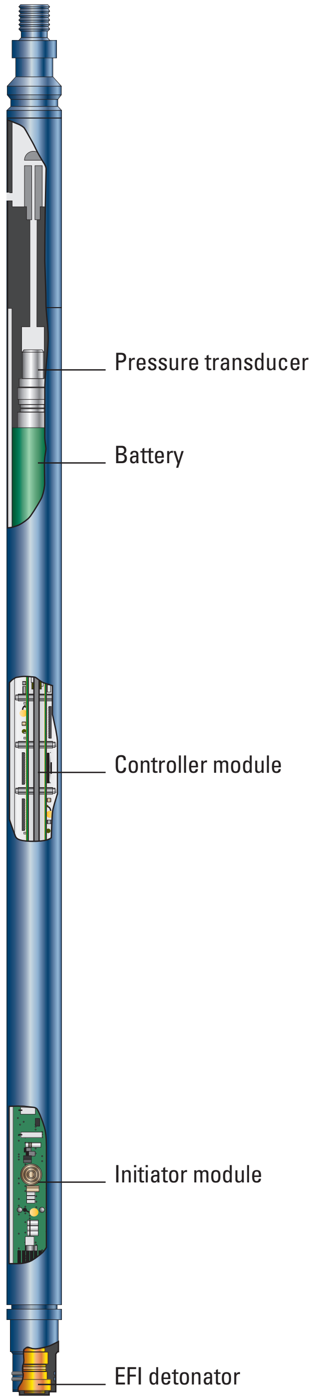

Figure 228. eFire-Slickline firing system.

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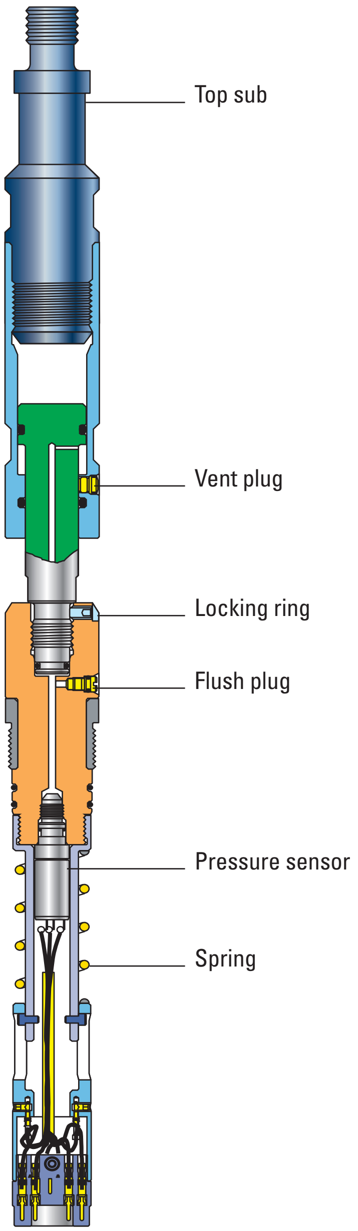

Figure 229. eFire-Slickline tension converter translates the vertical movements of the slickline wire into downhole pressure pulses to eliminate the need for pressure pulses through the wellbore for controller recognition.

eFire-Slickline features and benefits

In addition to the features and benefits previously listed for the eFire system, the eFire-Slickline system has the following features and benefits:

- Independent tool operation for dual tasks—Using a different command signal for each firing head enables running more than one firing head and operating them sequentially to conduct more than one operation in a single run.
- Alternative to electric line—The eFire-Slickline system provides an alternative approach for operations involving perforating guns, plugs and packers, cutters, or dump bailers.

- Time savings—No parameter run is required to survey the borehole before perforating because the eFire-Slickline system is controlled from the surface and not limited to a preset pressure range.

eFire-Slickline operational procedures

Figure 230 shows a command signal profile for a typical slickline operation. In this example, a 2- to 3-ft pull at 7,500 ft generates a pressure pulse that is transmitted to the pressure transducer.

Figure 231 shows a typical command sequence. The eFire-Slickline head is run into the well and remains dormant until reaching the preset hydrostatic pressure (which can be set at any value, starting at zero). The head can be armed once the hydrostatic pressure is met. Arming is accomplished by a predetermined series of pulls, followed by a programmed delay. Firing is accomplished by another series of pulls, followed by a delay to reach the correct depth and a final delay at depth.

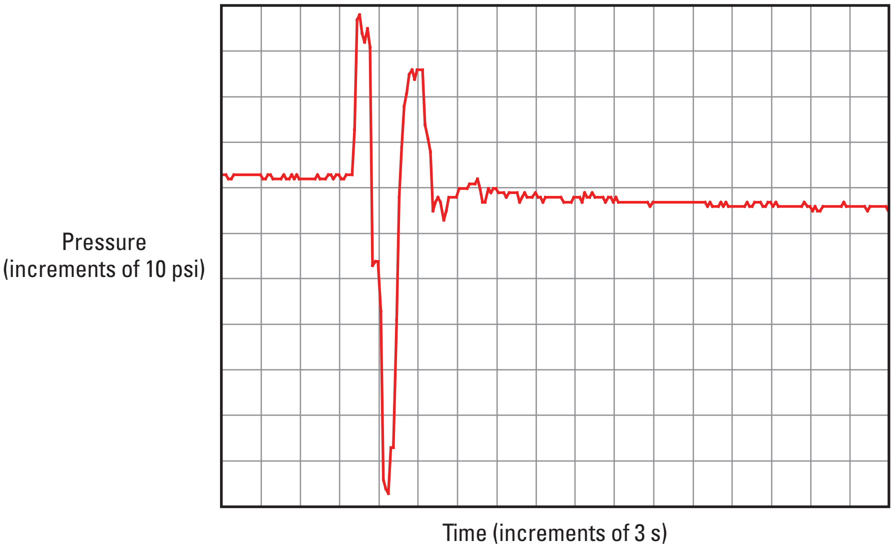

Figure 230. Command signal on a pressure versus time profile of a typical slickline operation.

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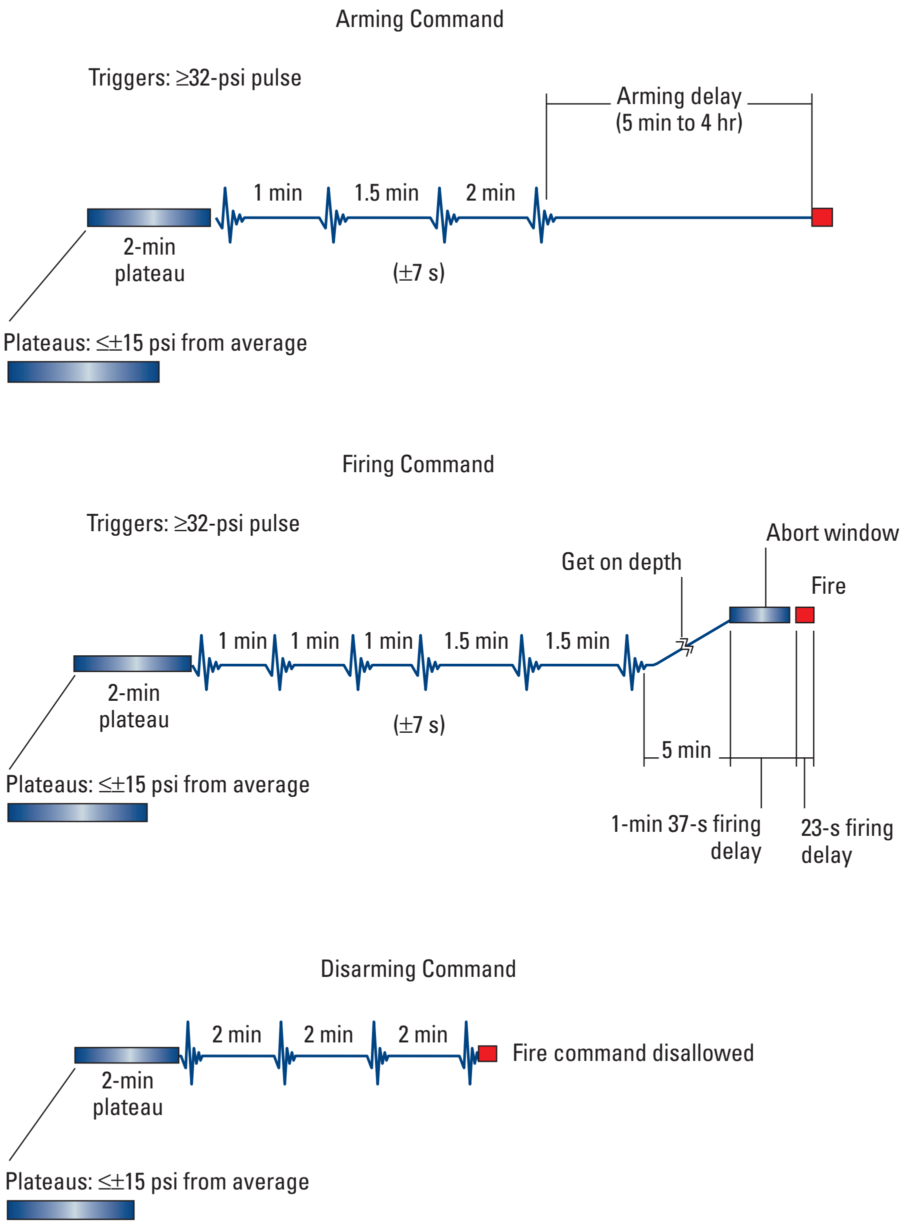

Figure 231. Typical eFire-Slickline command sequence. The arming command consists of four tension pulls on the tension converter. Six additional tension pulls are required to initiate firing. For safety, a disarming command is delivered to the eFire-Slickline tool before it reaches the surface.

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Hydraulic delay firing head

The HDF system (Fig. 232 and Table 115) consists of a firing head and adapters for stand-alone or redundant firing applications. Once triggered by a predetermined absolute pressure, the HDF system fires the guns after a preselected delay. During the delay, the pressure in the well is bled off to the desired underbalance. The HDF head incorporates a specially designed chamber that cannot be infiltrated by debris, which makes it immune to wellbore fluids with a high solids content. The placement of the ball retainer ensures proper functioning of the retainer, regardless of the condition of the wellbore fluid. The design also isolates the shear pins from the wellbore fluid. The HDF head for standard operations is the HDF-D. For HPHT applications, the HDF-H head is used. The pressure-activated extreme overbalance firing head (EOF), a modified version of the HDF head, has no time delay. Used for extreme overbalance perforating operations, the EOF head is described in detail later in this chapter.

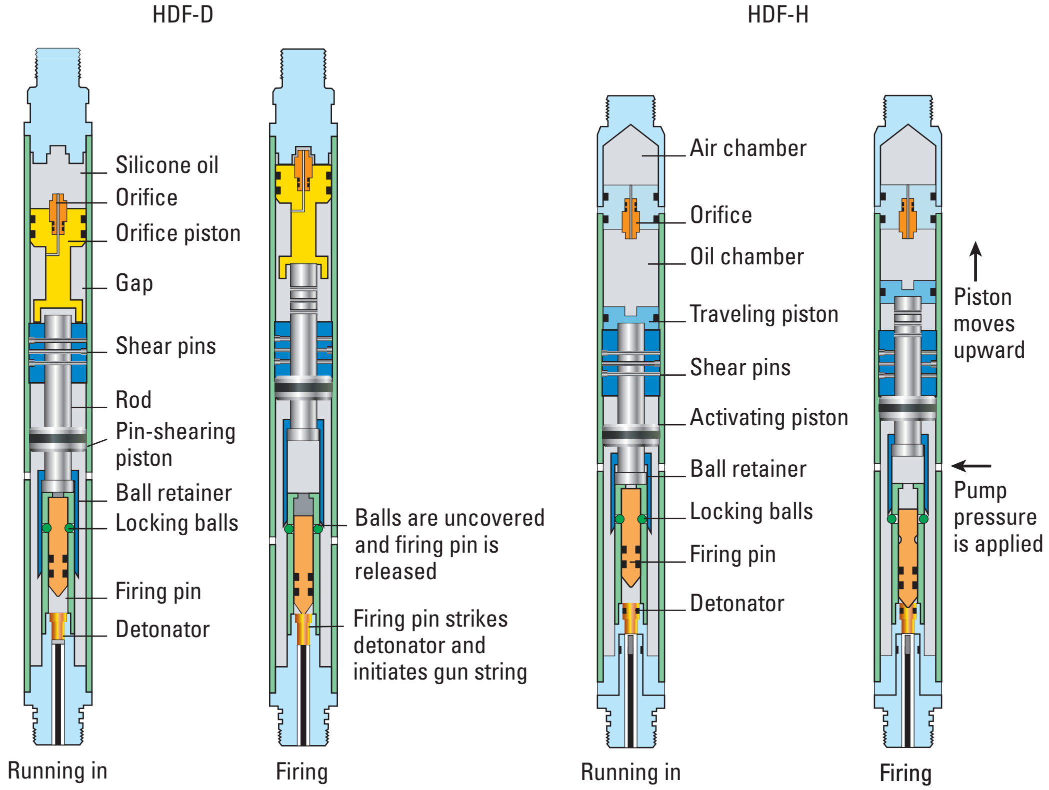

Figure 232. HDF heads for standard (left) and HPHT (right) applications.

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Table 115. HDF Specifications

	HDF-D Head	**HDF-H Head**
Outside diameter (in.)	1.375	1.5
Temperature rating (°F [°C])	400 [204]†	400 [204]†
Pressure rating (psi)	25,000	27,000
Min. operating pressure (psi)	500	1,000
Makeup length (in.)	54	61.6
Weight (lbm)	16.6	19
Tensile strength (lbf)	42,000	46,000
H_2S service	No	No
	End-to-End Fill Sub	
	3.06 in.	**3.68 in.**
Max. OD (in.)	3.075	3.710
Min. no-go ID (in.)	1.185	1.185
Top connection, 8 RD box, EUE	2⅜	2⅞
Bottom connection, 6 Stub Acme box	2⅜	3
Temperature rating (°F [°C])	330 [165]	330 [165]
Pressure rating (psi)	20,000	20,000
Burst pressure (psi)	18,961	12,976
Collapse pressure (psi)	16,129	11,165
Length (in.)	71.4	84.5
Weight (lbm)	76	87
Tensile strength (lbf)	234,919	144,962
H_2S service	No	No

† Maximum temperature rating depends on seal package used. Time at maximum temperature is 100 hr for the HDF-D and 200 hr for the HDF-H. See Table 17 and Fig. 84 in the "Operating Environment and Engineering of Perforating Operations" chapter and consult with your Schlumberger representative if the temperature or time exposure exceeds the HMX curve.

Features and benefits

- Absolute pressure triggering—The firing head is triggered by absolute pressure, which is the sum of the hydrostatic pressure and the applied pressure. When the absolute pressure exceeds a predetermined level, the activating piston is forced upward, breaking the shear pins. The operating pressure range is 500 to 25,000 psi.
- Adjustable hydraulic delay—The delay provides sufficient time to reduce pressure, even when nitrogen gas is used, and to establish underbalance before detonating the guns. The HDF system can be used for multizone TCP operations to delay firing of the guns until all firing heads in the string are activated.

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- Predictable firing delay—After the shear pins are broken, the pressure-driven pistons travel upward at a controlled speed by forcing oil through a small orifice into an atmospheric pressure chamber. The firing pin is locked by steel balls held in place by a ball retainer linked to the traveling piston. When the traveling piston pulls the ball retainer past the balls, they are forced outward, releasing the firing pin. The firing pin is propelled into the percussion blasting cap by the rathole pressure. Orifice size and downhole pressure and temperature determine the delay needed after shearing the pins until the firing pin is released. The delay is adjustable from a minute to several hours.
- Independent and sequentially operated shear pin and hydraulic sections—Hydraulic delay cannot affect the shear-out process.
- Adjustable activation pressure—Shear pins are used to adjust the firing head activation pressure at predetermined values from 500 to 25,000 psi in nominal 500-psi increments, with a ±5% tolerance. The actual shear pressure depends on the number of pins used and the temperature to which they are exposed.
- Jar-down isolator—Including a jar-down isolator is recommended when a small number of shear pins are used in the HDF head run in TCF mode. The isolator prevents damage to the shear pins when jarring down to release the HDF head from the slickline.
- Redundant firing capability with all other firing systems—Any firing system can be combined with an HDF head to make redundant firing systems as well as nonfullbore DST equipment. The firing heads can be assembled in several sizes and numerous combinations. For details, see “Redundant firing systems” in this chapter.

Safety considerations

For safety at the surface, the firing pin requires a minimum of 150-psi hydrostatic pressure to fire the percussion detonator. The firing mechanism is not exposed and thus cannot be accidentally struck by falling debris in the string. If the guns flood, the pressure is balanced across the firing pin to prevent firing. The gun string remains sealed if a ballistic misfire occurs in the firing head.

Inclusion of a safety spacer is required (except for systems using the eFire electronic firing head) on top of the gun string to ensure that the guns are below the rig floor when the firing head is connected or disconnected (Fig. 233). In case of trapped pressure in the safety spacer, a pressure vent in the firing head adapter is used to bleed off the pressure. Hardware to prevent trapped pressure is available and its use is recommended.

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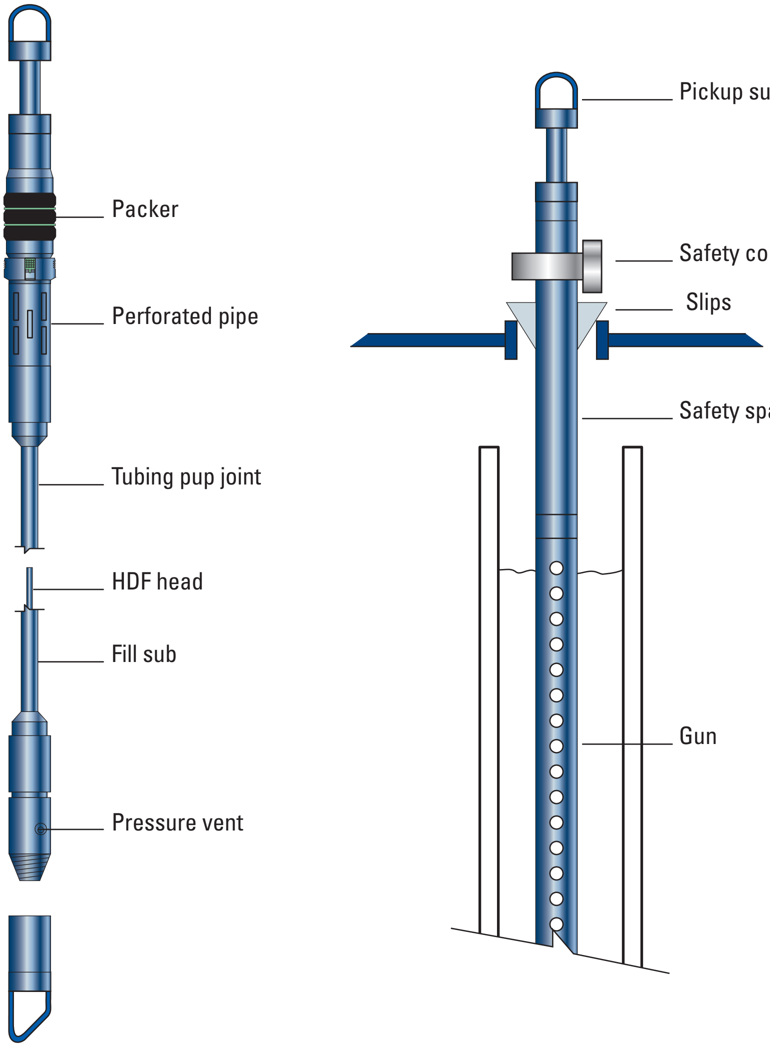

Figure 233. The guns are well below the rig floor when the HDF head is connected.

Applications

- Multizone TCP—The adjustable, reliable hydraulic delay of the HDF head is used to delay firing of the guns until all firing heads in the string are activated.
- Underbalanced perforating—The HDF hydraulic delay can be adjusted to provide sufficient time to reduce pressure, even when nitrogen gas is used, to establish underbalance before detonating the guns.
- Perforating in HPHT wells—The HDF-H head operates reliably and efficiently in extreme conditions.
- Highly deviated wells—Well deviation does not limit use of the HDF head, which is also unaffected by heavy mud or tubing restrictions.

HDF operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, HDF head operations begin with thorough design and planning, using the applicable flowchart, an abbreviated example of which is shown in Fig. 234.

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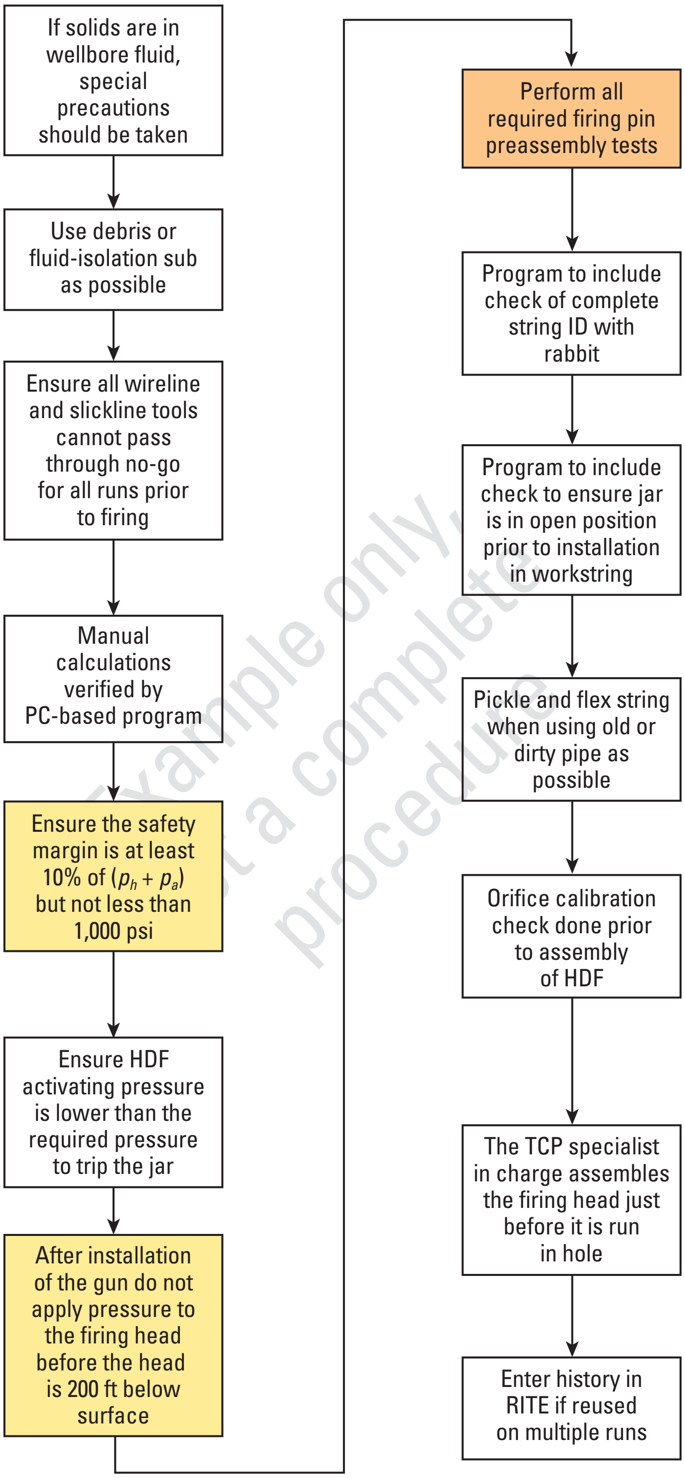

Figure 234. Exerpt of an example SDP design and planning flowchart for HDF operations.

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Design and planning

HDF head operation (Fig. 235) requires knowledge and control of downhole pressures, particularly of the factors that can affect the absolute pressure to which the firing head is sensitive. The HDF head responds to the absolute pressure at the depth of the firing head. The pressure acts against the shear pins, causing them to break. A time delay begins when the shear pins break, and the guns are fired at the end of the delay.

Actual pressure at the head may vary from several hundred to several thousand psi above the anticipated hydrostatic annulus pressure derived from true vertical depth and fluid density measurements. The difference between the actual pressure and the calculated pressure can result from one or more sources, including

- pressures used to test the string, casing, or packer
- surge pressures during running in hole
- compression pressure at the time of stinging through or stabbing in
- overpressure required to break circulation
- circulating valve operating pressure
- packer-setting operating pressure.

Because some pressures can only be estimated, a safety margin must be added to the estimates, within the limits imposed by casing, tubing, or other equipment ratings. A minimum safety margin is 1,000 psi between the maximum absolute bottomhole pressure and the shear pin lower limit rating. A larger margin is recommended when conditions allow.

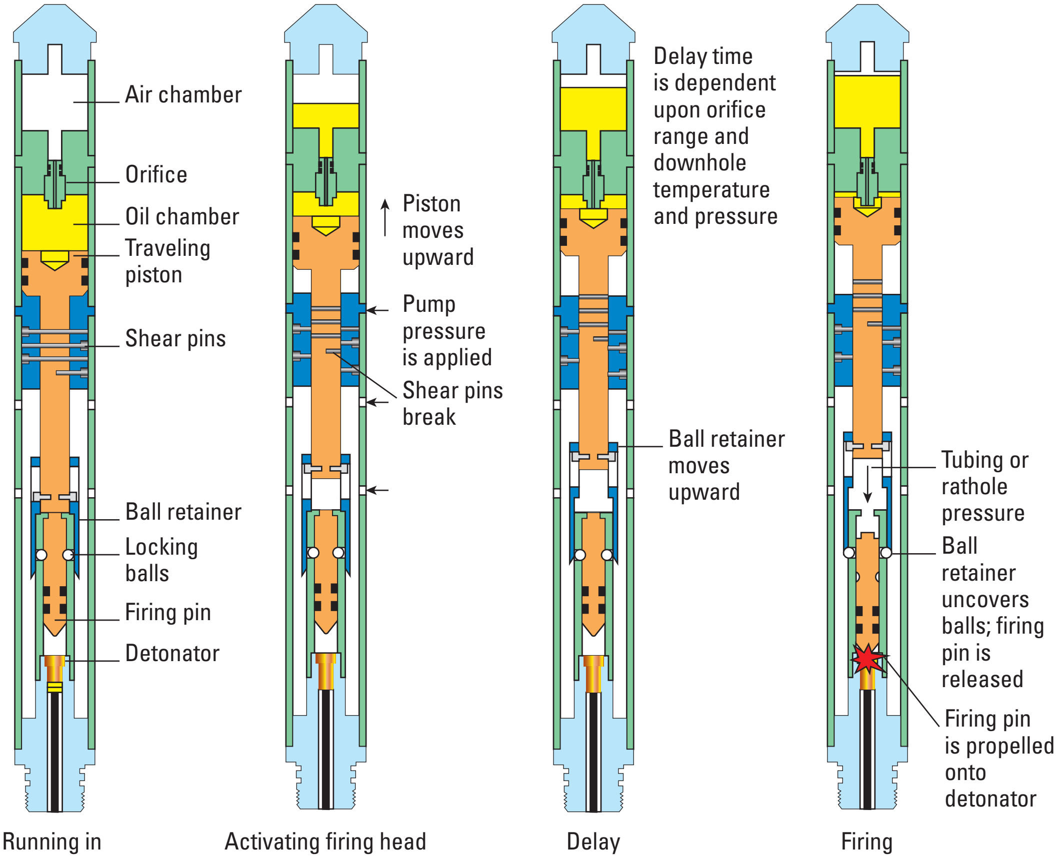

Figure 235. HDF principle of operation.

Calculation of HDF head parameters

Prejob planning includes selecting the shear pins on the basis of the calculations described in this section. The shear pin calculations determine the minimum number of shear pins to ensure that the head is not triggered during normal operation prior to the application of the firing pressure. The theoretical activating pressure of the HDF head is expressed as

$$p_t = p_h + p_a + p_s, \tag{16}$$

where

p_t = theoretical firing activating pressure

p_h = hydrostatic pressure at the firing head from the column of mud, completion fluid, or both

p_a = maximum additional pressure that could possibly be applied to the firing head from any source

p_s = pressure safety margin.

A safety margin is added because some additional pressures can only be estimated. The safety margin should be 1,000 psi or 10% of the sum ($p_h + p_a$), whichever is greater.

The theoretical activating pressure p_t determined from the Eq. 16 is then used to select the appropriate shear pins:

$$\text{number of long shear pins} = \frac{p_t}{\text{TVL} \times G \times 0.95}, \tag{17}$$

where G is the shear pin temperature correction factor, derived from Fig. 236. TVL is the true value (psi) of a long pin, which is on the shear pin package (typically between 920 and 990 psi). If a short shear pin is used, the true value (TVS) indicated on the package is typically between 460 and 495 psi. If the fractional portion of the calculated number of long shear pins is equal to or greater than 0.5, round up to add one long shear pin. If the fraction is less than 0.5, add one short shear pin.

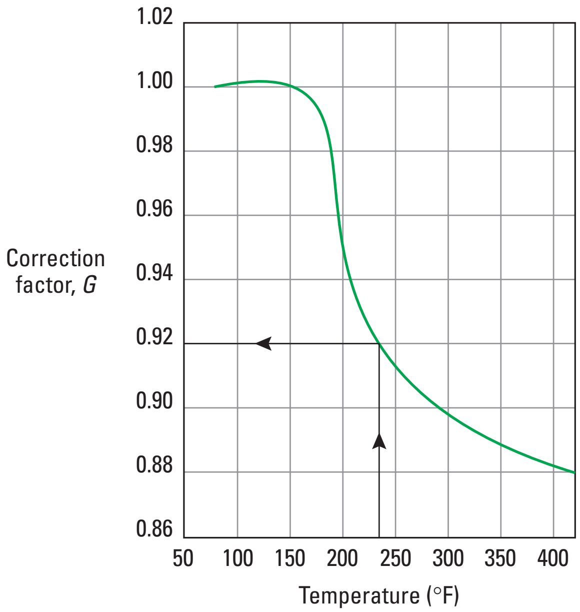

Figure 236. HDF shear pin temperature chart.

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The next step is to calculate the nominal shear pin value E (Fig. 237), which verifies the accuracy of the considerations and calculations:

- Multiply the number of long shear pins (A) by TVL = C.
- Multiply the number of short shear pins (B) by TVS = D.
- Multiply the sum ($C + D$) by the temperature correction factor G to obtain E.

The actual pressure at the firing head that activates the head is the nominal shear pin value $E \pm 5\%$. The low shear value is $(0.95 \times E)$, which means the pressure at the head must be less than $(0.95 \times E)$ to prevent premature firing. The high shear value is $(1.05 \times E)$. To ensure firing, the pressure at firing must be at least $(1.05 \times E)$ plus 500 psi. The additional 500 psi is added to allow for tolerances in pump pressures, pressure gauge readings, and fluid friction. The value $(1.05 \times E) + 500$ psi is termed the total pressure downhole at the firing head to ensure firing at p_{firing}.

The last calculation step is to determine the surface pump pressure required to develop a pressure level at the firing head equal to p_{firing}:

$$p_{pumpf} = p_{firing} - p_{cushion} \tag{18}$$

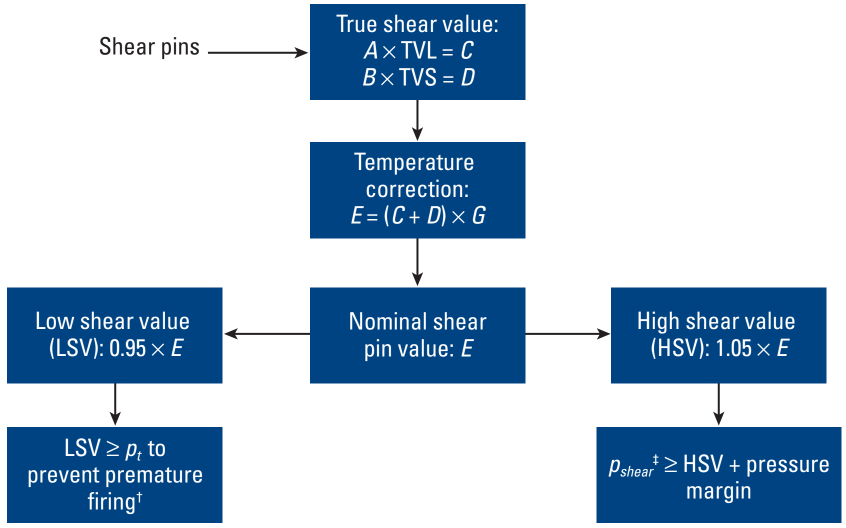
where

p_{pumpf} = pump pressure necessary to ensure firing
$p_{cushion}$ = hydrostatic pressure from the fluid column above the firing head.

The value $p_{cushion}$ should be measured or calculated from fluid density and depth and not taken from the difference between formation pressure and underbalance pressure. The pump pressure p_{pumpf} is limited by the following factors:

- tubing burst pressure
- casing burst pressure
- packer unseating
- pump limitations
- wellhead equipment rating.

Values for an example calculation are given in Table 116.



†Exceeding 0.95E means the firing cycle may start at any time.
‡p_{shear} is the total downhole pressure necessary to ensure firing.

Figure 237. HDF shear pin determination and verification. p_{shear} = total downhole pressure necessary to shear the pins.

Table 116. Example Shear Pin Calculation Values

Hydrostatic pressure, p_h	7,115 psi
Maximum additional pressure, p_a	2,500 psi
Safety pressure margin, p_s	1,000 psi
Theoretical firing pressure, p_t	10,615 psi
Bottomhole temperature, T_{bh}	235°F [113°C]
Temperature correction factor, G	0.92
Number of long shear pins	12.27
True value of a long pin, TVL	990 psi
True value of a short pin, TVS	495 psi

Because the fractional portion of the number of long shear pins is less than 0.5, 12 long shear pins and 1 short shear pin are called for (i.e., $A = 12$ and $B = 1$). The following computation determines the nominal shear pin value, which is the pressure to shear the pins:

$$A \times \text{TVL} = C = 12 \times 990 = 11{,}880 \text{ psi}$$

$$B \times \text{TVS} = D = 1 \times 495 = 495 \text{ psi}$$

$$E = (C + D) \times G = (11{,}880 + 495) \times 0.92 = 11{,}385 \text{ psi.}$$

The theoretical firing pressure p_t must be less than $(0.95 \times E)$, or 10,816 psi, to prevent premature firing. Firing pressure at the head is

$$p_{firing} = 1.05\text{E} + 500 = 1.05(11{,}385) + 500 = 12{,}454 \text{ psi.}$$

For a cushion pressure $p_{cushion} = 4{,}188$ psi,

$$p_{pumpf} = 12{,}454 - 4{,}188 = 8{,}266 \text{ psi.}$$

In practice, the surface pump pressure is quickly increased to 8,300 psi, held for 1 min, and then reduced to the cushion pressure.

Time delay estimation

The traveling piston of the HDF head forces oil through an orifice from the oil chamber into an air chamber. The speed of the piston movement and the resulting time delay depend on the orifice selected, as well as the pressure and bottomhole temperature.

Each orifice has a calibration factor. Charts can be used to determine the theoretical calibration factor to provide the desired time delay for expected downhole conditions. The selected time delay can range from 1 min to several hours. The orifice is selected to provide the desired delay within a certain tolerance. The main factor affecting time delay prediction is the inconstant pressure at the firing head. This pressure changes as the traveling piston moves from the pressure required to shear the pins to the cushion pressure.

Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

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Execution

The firing system typically is assembled at the wellsite. The detonator is placed in the assembly on the deck, away from the loaded guns. The system is considered armed only after the head is attached to the live gun string, with the following procedure:

1. Ensure that all guns are properly made up in the correct order and set the safety spacer in the slips with a safety clamp installed.
2. Pick up the pressure-transfer assembly, packer, and firing head assembly and hang it in the blocks above the safety spacer.
3. Stab the assembly into the safety spacer.
4. Tighten all connections to the proper torque.
5. Continue running in hole.

The procedure for firing HDF heads is as follows:

1. Open the test valve with annulus pressure (if applicable). Ensure that the packer is set and the string is not leaking.
2. Apply tubing pressure to activate the firing head. Pressure the tubing to the predetermined level to shear the pins (upper limit). Hold for 1 min, and then bleed to the tubing pressure required to achieve the correct underbalance. The hydraulic delay begins when the pins are sheared, and the guns fire when the delay is complete.
3. If no firing indication is detected, wait for a period that is 1.5 times the estimated delay. Slowly increase tubing pressure until pressure below the packer is just above formation pressure and monitor for fluid leakoff. If there is no leakoff into the formation, increase tubing pressure to the tubing test pressure. Hold briefly and bleed rapidly to achieve the required underbalance pressure. Continue to monitor for firing. If no firing indication is detected after 1.5 times the estimated delay, resort to a redundant firing system (if present).

HDF operational procedure examples

The first example is a typical DST-TCP job. Figure 238 shows the various pressures the HDF firing head senses before firing the guns. Labels in the figure and their values are listed in Table 117. A tubing-pressure-operated circulating valve (MCCV) is used to circulate the cushion into the test string. Surge pressures are present while running in but are not shown in the example. The example assumes that these pressures are kept well below the safety margin by using controlled running procedures.

The difference between hydrostatic pressure at the test valve and the firing head is not considered in the following sequence on the pressure versus time plots in Fig. 238.

1. The HDF head firing pressures are calculated. The theoretical activating pressure is $p_h + p_{PCT} + p_s$ = 7,400 psi. Based on the previously outlined method for calculating shear pin setting, eight long shear pins and one short shear pin are selected. The lower shear pin value is 7,700 psi, and the upper shear pin value is 8,500 psi. Therefore, the firing pressure p_{firing} is 9,000 psi.
2. The test string and guns are run into the hole, and the string fills with mud. The value of p_{HDF} increases with the hydrostatic pressure p_h as the string is run into the well:

$$p_{tubing} = p_h,$$

$$p_{HDF} = p_{ann} = p_h.$$

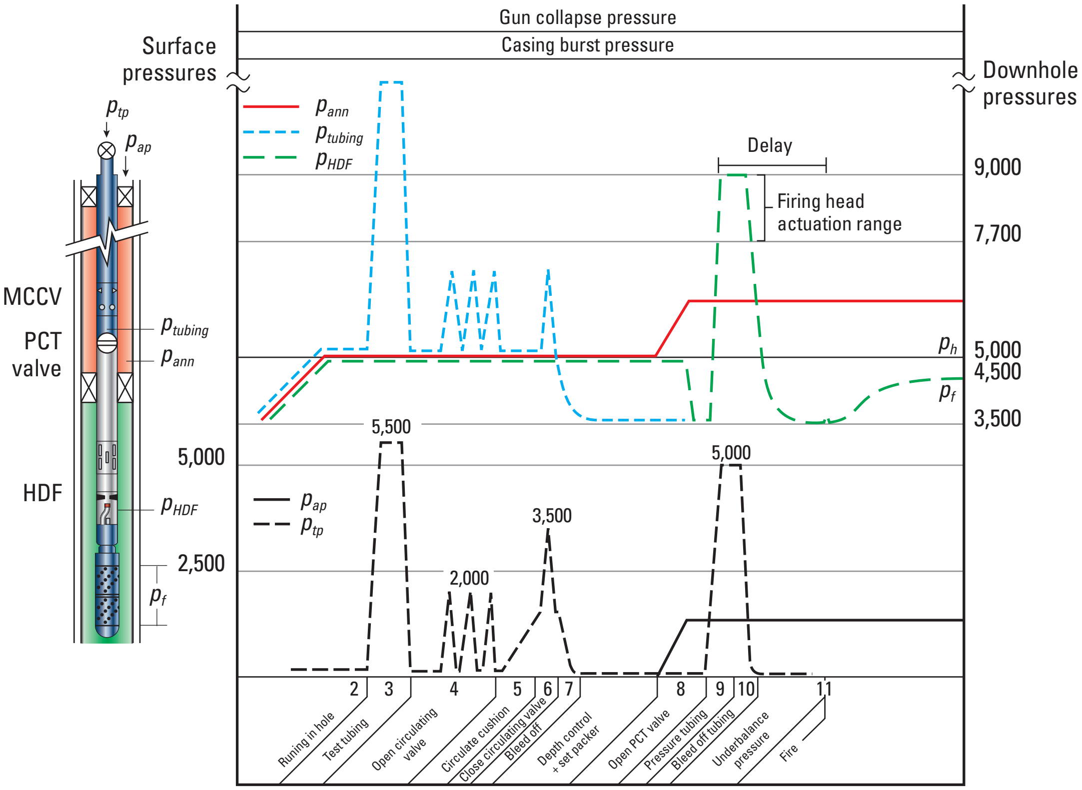

Figure 238. Sequence of events during a typical DST with HDF head.

Table 117. Symbols and Their Definition and Value in Fig. 238

Symbol	Definition and Value
T_{bh}	Bottomhole temperature—190°F [88°C]
p_h	Hydrostatic pressure at firing head from the column of mud, completion fluid, or both—5,000 psi
p_f	Formation pressure—4,500 psi
p_u	Desired underbalance pressure—1,000 psi
$p_{cushion}$	Cushion pressure—$(p_f - p_u) = 3{,}500$ psi
p_{PCT}	PCT* Pressure Controlled Tester valve operating pressure—1,400 psi
p_s	Safety margin pressure—1,000 psi
p_{HDF}	Pressure sensed at the firing head at any given time
p_{ap}	Pressure applied at surface to the annulus
p_{ann}	Annulus pressure downhole at any given time
p_{tp}	Tubing pressure applied at surface
p_{tubing}	Tubing pressure downhole above test valve at any given time
p_{firing}	Upper shear pin value plus 500 psi

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3. With the PCT Pressure Controlled Tester valve closed, the string is pressure tested well above the pressures that will be applied later. For example, p_{tp} = 5,500 psi, which is considered safe if the packer is not set and the BOP rams are open:

$$p_{tubing} = p_h + 5{,}500 \text{ psi},$$

$$pHDF = p_{ann} = p_h.$$

   Pressure testing the tubing to a pressure higher than the HDF activation pressure depends on client policy. An alternative is to run the HDF in TCF mode after the pressure tests.
4. The MCCV circulating valve is cycled to the open position by applying tubing pressure cycles (typically, p_{tp} = 2,000 psi):

$$0 < p_{tp} > 2{,}000 \text{ psi},$$

$$p_h < p_{tubing} > p_h + 2{,}000 \text{ psi},$$

$$p_{HDF} = p_{ann} = p_h.$$

5. Cushion fluid is circulated into the string to establish the desired underbalance. The value of p_{tp} increases to the final desired differential between p_h and $p_{cushion}$ of 1,500 psi while p_{tubing} remains equal to p_h. At the end of circulation:

$$p_{tp} = 1{,}500 \text{ psi};\ p_{tubing} = p_h,$$

$$p_{HDF} = p_{ann} = p_h.$$

6. The amount of p_{tp} is reduced after closing the circulating valve. The MCCV is cycled closed by applying tubing pressure at a level (2,000 psi) above the tubing surface pressure (1,500 psi). Thus, p_{tp} increases from 1,500 to 3,500 psi, while p_{tubing} increases from p_h to p_h + 2,000 psi:

$$p_{HDF} = p_{ann} = p_h.$$

   After the circulating valve closes,

$$p_{tp} = 1{,}500 \text{ psi};\ p_{tubing} = p_h,$$

$$p_{HDF} = p_{ann} = p_h.$$

7. Tubing pressure is reduced, a depth correlation log is run, and the packer is set:

$$p_{tp} = 0;\ p_{tubing} = p_h - 1{,}500 \text{ psi} = p_{cushion},$$

$$p_{HDF} = p_{ann} = p_h.$$

8. The annulus is pressurized to open the PCT test valve (p_{PCT} = 1,400 psi):

$$p_{PCT} = 1{,}400 \text{ psi};\ p_{ann} = p_h + 1{,}400 \text{ psi},$$

$$p_{HDF} = p_{tubing} = p_h - 1{,}500 \text{ psi} = p_{cushion}.$$

   Annulus pressure is monitored to verify that the packer is set.
9. The HDF head is activated by pressurizing the tubing to 5,500 psi:

$$p_{tp} = p_{firing} - p_{cushion} = (9{,}000 - 3{,}500) \text{ psi} = 5{,}500 \text{ psi},$$

$$p_{tubing} = p_{tp} + p_{cushion} = p_{firing} = 9{,}000 \text{ psi}.$$

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10. Tubing pressure is reduced to the desired underbalance of 1,000 psi.

$$p_{tp} = 0;\ p_{tubing} = p_{cushion} = 3{,}500 \text{ psi} = p_f - p_u,$$

$$p_u = 1,000 \text{ psi},$$

$$p_{HDF} = p_{cushion}.$$

11. After the preset delay time, the guns fire.

The second example uses a string with an Intelligent Remote Dual Valve (IRDV) tester valve (Fig. 239). Figure 240 shows the various pressures the HDF firing head senses before firing the guns. Labels in the figure and their values are the same as in Table 117, except the shear pressure value for the tubing fill tester valve (TFTV) is p_{TFTV} = 1,200 psi and the maximum valve pressure at the time the guns are fired is p_{IRDV} = 1,400 psi.

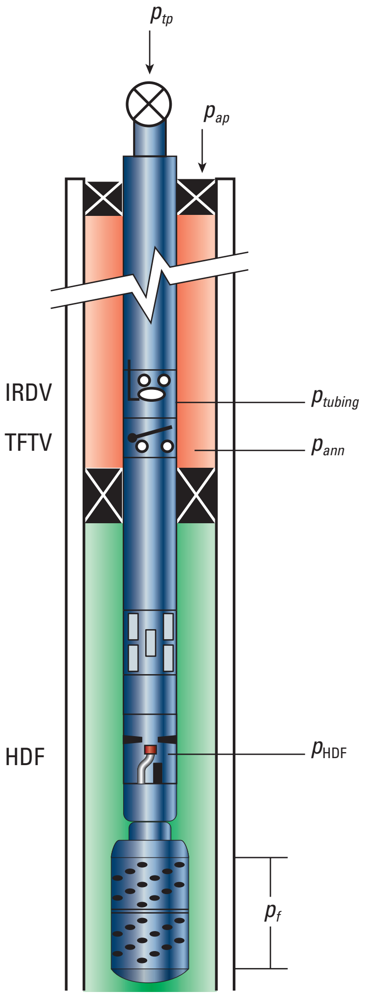

Figure 239. Test string for second example, incorporating IRDV and TFTV valves and an HDF head.

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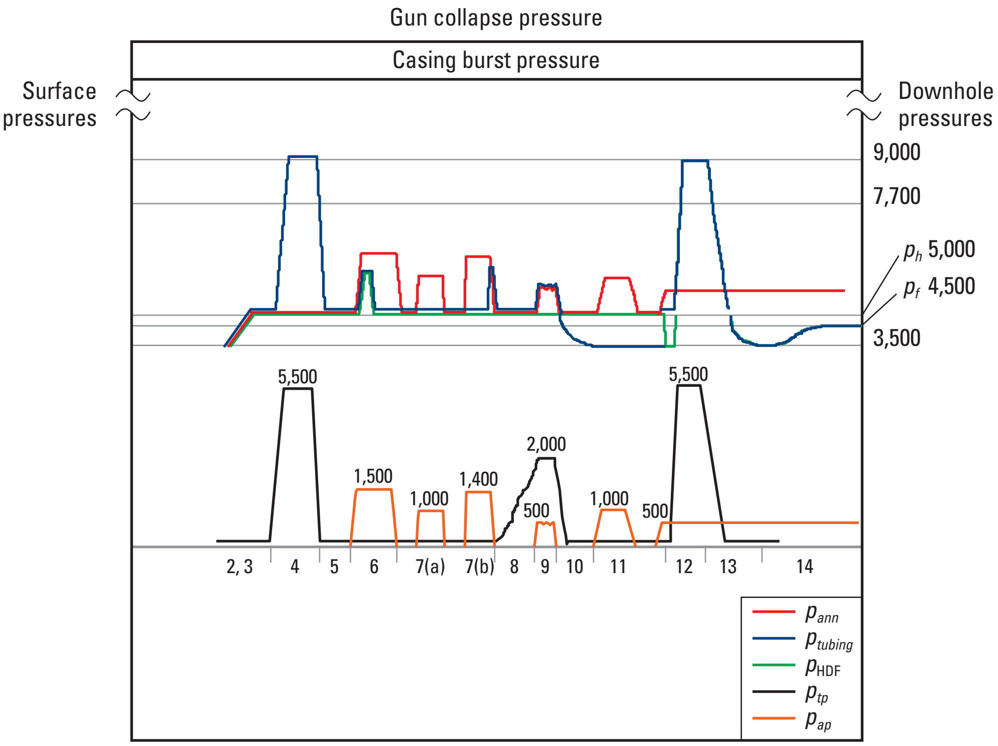

Figure 240. Sequence of events during a typical DST with IRDV valve and HDF head.

1. The HDF head firing pressures are calculated. The theoretical activating pressure is $p_h + p_{IRDV} + p_s = 7{,}400$ psi. Based on the previously outlined method for calculating shear pin setting, eight long shear pins and one short shear pin are selected. The lower shear pin value is 7,700 psi, and the upper shear pin value is 8,500 psi. Therefore, the firing pressure p_{firing} is 9,000 psi.
2. The test string and guns are run into the hole, and the string fills with mud. The value of p_{HDF} increases with the hydrostatic pressure p_h as the string is run into the well:

$$p_{tubing} = p_h,$$

$$p_{HDF} = p_{ann} = p_h.$$

3. The tubing is spaced out to position the guns at depth, and the final joint of tubing is made up.
4. With the TFTV closed, the string is pressure tested at a pressure much higher than the pressures that will be applied later. For example, $p_{tp} = 5{,}500$ psi, which is considered safe if the packer is not set and the BOP rams are open:

$$p_{tubing} = p_h + 5{,}500 \text{ psi},$$

$$p_{HDF} = p_{ann} = p_h.$$

   Pressure testing the tubing to a pressure higher than the HDF activation pressure depends on client policy. An alternative is to run the HDF head in TCF mode after the pressure tests.
5. The packer is set mechanically:

$$p_{tp} = 0;\ p_{tubing} = p_h = p_{cushion},$$

$$p_{HDF} = p_{ann} = p_h.$$

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6. Annulus pressure of 1,500 psi is applied to shear out the TFTV valve flapper to open position, allowing pressure to isolate the annulus from the tubing:

$$p_{ann} = p_h + 1{,}500 \text{ psi},$$

$$1{,}200 \text{ psi} = p_{HDF} = p_{tubing} = p_{TFTV}.$$

The amount of p_{tp} is bled off and the annulus pressure is observed for confirmation that the TFTV was sheared:

$$p_{tp} = 0,\ p_{HDF} = p_{tubing} = p_h,$$

$$p_{ann} = p_h + 1{,}500 \text{ psi}.$$

The annulus pressure is held for 10 min to test the packer, and then the annulus pressure is bled off:

$$p_{ann} = p_h = p_{HDF} = p_{tubing}.$$

7. Pressure pulses are applied to the annulus to close the IRDV tester valve (TV) and open the IRDV circulating valve (CV).
   a. During the initial pulses, the TV is open and the CV is closed:

$$0 < p_{ap} > 1{,}400 \text{ psi},$$

$$p_h < p_{ann} < p_h + 1{,}400 \text{ psi},$$

$$p_{HDF} = p_{tubing} = p_h.$$

   b. When the second pressure pulse increases more than 1,000 psi (<1,400 psi), the TV closes and 30 s after that the CV opens:

$$p_h < p_{an} = p_{tubing} < p_h + 1{,}400 \text{ psi},$$

$$p_{HDF} = p_h.$$

8. A nitrogen cushion is circulated into the string to establish the desired underbalance. The returns are taken to the pits via the annulus. The value of p_{tp} increases to the final desired differential between p_h and $p_{cushion}$ of 1,500 psi while p_{tubing} remains equal to p_h. At the end of circulation:

$$p_{tp} = 1{,}500 \text{ psi};\ p_{tubing} = p_h.$$

9. Pressure at 500 psi is applied to both the annulus and tubing for 5 min, and then the pressure is bled off via the annulus:

$$p_{tp} = (1{,}500 + 500) \text{ psi};\ p_{tubing} = 500 \text{ psi},$$

$$p_{ap} = p_{ann} = 500 \text{ psi},$$

$$p_{HDF} = p_h.$$

10. The circulating valve closes 100 s after bleeding off the annulus pressure.

$$p_{ap} = p_{tp} = 0 \text{ psi},$$

$$p_{ann} = p_{HDF} = p_h,$$

$$p_{tubing} = p_h - 1{,}500 \text{ psi} = p_{cushion}.$$

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11. Pressure pulses are applied to the annulus.
    a. The first step applies a pressure pulse to set the IRDV to sequential mode:

$$p_{ann} = p_h + 1{,}400 \text{ psi},\ p_{HDF} = p_h,\ p_{tubing} = p_h - 1{,}500 \text{ psi}.$$

    b. The second step applies a pressure pulse to open the TV:

$$p_{ann} = p_h + 500 \text{ psi},\ p_{HDF} = p_{tubing} = p_h - 1{,}500 \text{ psi} = p_{cushion}.$$

    Annulus pressure is monitored to verify that the packer is set.
12. The HDF head is activated by pressurizing the tubing to 5,500 psi:

$$p_{tp} = p_{firing} - p_{cushion} = (9{,}000 - 3{,}500) \text{ psi} = 5{,}500 \text{ psi},$$

$$p_{tubing} = p_{tp} + p_{cushion} = p_{firing} = 9{,}000 \text{ psi}.$$

13. Tubing pressure is bled off to the desired underbalance of 1,000 psi:

$$p_{tp} = 0;\ p_{tubing} = p_{cushion} = 3{,}500 \text{ psi} = p_f - p_u,$$

$$p_u = 1{,}000 \text{ psi},$$

$$p_{HDF} = p_{cushion}.$$

14. After the preset delay time, the guns fire.

Extreme overbalance firing head

The EOF head (Fig. 241 and Table 118) is a simplified version of the HDF head. This pressure-operated firing head with no hydraulic delay fires as soon as the tubing pressure reaches a predetermined threshold. It is designed for operations in which TCP guns or other devices can be initiated while the firing pressure is still applied, such as extreme overbalance perforating.

Table 118. EOF Specifications

	EOF-BA
Outside diameter (in.)	1.375
Temperature rating (°F [°C])	400 [204]†
Pressure rating (psi)	25,000
Min. operating pressure (psi)	500
Makeup length (in.)	21.8
Weight (lbm)	7.43
Tensile strength (lbf)	28,000
H_2S service	No

† Maximum temperature rating depends on seal package used. See Table 17 and Fig. 84 in the "Operating Environment and Engineering of Perforating Operations" chapter and consult with your Schlumberger representative if the temperature or time exposure exceeds the HMX curve.

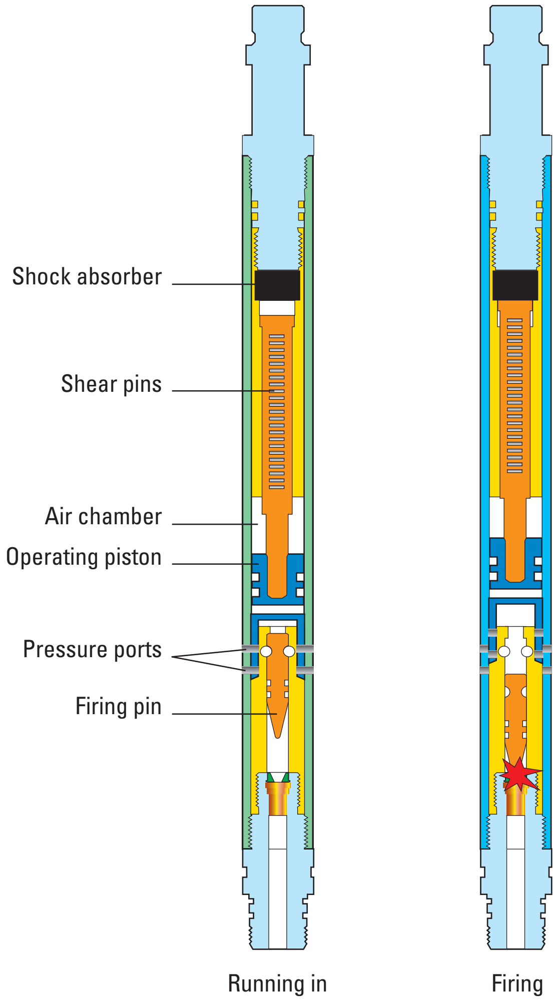

Figure 241. EOF head.

Features and benefits

- Absolute pressure triggering—The EOF head is triggered by absolute pressure, which is the sum of the hydrostatic pressure and the pressure increase in the workstring. When the absolute pressure exceeds a predetermined level, the traveling piston is forced upward, breaking the shear pins. The operating pressure range is 500 to 25,000 psi.
- Instant firing without delay—The moment the firing head is triggered by absolute pressure, the firing pin is released and propelled by the absolute pressure into the percussion blasting cap.
- Simplified, flexible operation—Because the EOF head is an HDF head without the hydraulic delay, it is a simpler option for most applications that do not require underbalance. Well deviation does not limit use of the EOF head, and it is unaffected by heavy muds or tubing restrictions.
- Redundant firing capability—Multiple EOF firing heads can be combined to provide redundancy.

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Safety considerations

The EOF head incorporates all the safety features of the HDF firing head. For safety at the surface, the firing pin requires a minimum of 150-psi hydrostatic pressure to fire the percussion detonator. The firing mechanism is not exposed so it cannot be accidentally struck by falling debris in the string. If the guns flood, the pressure is balanced across the firing pin to prevent firing. The gun string remains sealed if a ballistic misfire occurs in the firing head.

Because the operating piston has to move upward to release the firing pin, the EOF is not affected by water hammer effects and is insensitive to vertical drops.

Inclusion of a safety spacer is required (except for systems using the eFire electronic firing head) on top of the gun string to ensure that the guns are below the rig floor when the firing head is connected or disconnected. In case of trapped pressure in the safety spacer, a pressure vent in the firing head adapter is used to bleed off the pressure. Hardware to prevent trapped pressure is available and its use is recommended.

Applications

- Extreme overbalance perforating—The EOF head is ideal for extreme overbalance perforating operations because it does not require shutting down the pumping of fluid or gas to wait for the TCP gun to fire.
- Packerless completions in live wells or coiled tubing operations—The EOF head can be run at the end of a closed tubing string for perforating in a packerless completion by applying the firing pressure only to the tubing, not the annulus.
- Dropping guns—The EOF head can be used in combination with an automatic gun release sub when the guns are dropped and left downhole. When the hydrostatic pressure at the EOF head reaches the activating pressure, the guns are fired and the sub disengages the gun string from the tubing or workstring.
- Setting packers and plugs and initiating tubing cutters—Applications for the EOF head are not limited to perforating guns. The EOF head can also be used to ignite propellants for setting plugs and packers with conventional wireline setting tools or to initiate tubing cutters.
- Highly deviated wells—Well deviation does not limit use of the EOF head, which is also unaffected by heavy mud or tubing restrictions.

EOF operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, EOF system operations begin with thorough design and planning using the applicable flowchart.

Design and planning

Operating the EOF firing head requires knowledge and control of downhole pressures because the head responds to the absolute pressure at the depth of the firing head and fires as soon as the shear pins are sheared. Shear pins selection is calculated by accurately determining the maximum pressure the head will be exposed to prior to firing and adding a safety factor to prevent premature firing. See “Calculation of HDF head parameters” in this chapter for the calculation sequence.

Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

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Execution

The firing system typically is assembled at the wellsite. The detonator is placed in the assembly on the deck, away from the loaded guns. The system is considered armed only after the head is attached to the live gun string, with the following procedure:

1. Ensure that all guns are properly made up in the correct order and set the safety spacer in the slips with a safety clamp installed.
2. Pick up the firing head assembly with detonator installed and hang it in the blocks above the safety spacer.
3. Stab the firing system assembly into the safety spacer.
4. Tighten all connections to the proper torque.
5. Continue running in hole.

The procedure for firing EOF heads is as follows:

- Firing the guns for a closed string
  - a. Before firing, the string must be filled with liquid, unless nitrogen is used to pressure up the head.
  - b. Pressure up to the firing pressure and watch for signs of the guns firing.
  - c. After the guns have shot, bleed off pressure and proceed with operations.
- Firing the guns for an open string
  - a. If no packer is run, the head can be activated by pressuring up either the annulus or the tubing (tubing only if a packer is run) to the calculated pump pressure. In both cases firing pressure is applied to the formation and the guns when the guns are shot.
  - b. For TCP run with a packer, the valves in the test tools on the string must be open before the EOF head is activated.
  - c. If the rathole is large, a significant amount of fluid must be pumped on top of what was recorded during pressure testing against the valves to reach firing pressure.

Trigger charge firing system

The TCF system is a retrievable firing system. It consists of a firing head conveyed on electric wireline or slickline and a detonating cord extension, receptor booster assembly, and fill sub assembly run with the gun string (Tables 119 and 120). The firing head is run into the well after the guns are positioned and latched onto the booster assembly (Fig. 242). This technique improves overall safety because the guns are not armed with a detonator after they have been positioned in the well until the firing head is attached just before firing.

The TCF head contains a firing mechanism, high-explosive detonator, and trigger charge to transfer the detonation to the receptor booster through pressure barriers. TCF heads are available in four versions: jar down–activated head, drop bar–activated head, absolute pressure–activated head, and timed pressure-activated head. All versions of the TCF head have a simple latching mechanism that holds the head in place during firing.

The jar-down version is run on slickline and activated by jarring action, with the slickline connected to the tool during firing. The drop bar version is run on slickline or wireline, which is retrieved before the bar is dropped or run in on slickline. The absolute-pressure and timed-pressure versions are HDF heads run on either slickline or wireline, which can be removed before firing if required.

When any version of the TCF head is activated, the firing pin is released and propelled by well pressure into a percussion detonator. The detonator initiates a small shaped charge—the trigger charge. The jet from the charge penetrates the two pressure barriers of the firing head and the downhole assembly, setting off the secondary explosive receptor booster to initiate the firing of the gun string.

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Table 119. TCF Side-by-Side Fill Sub Assembly Specifications

Side-by-Side Fill Sub	3.06 in.	3.68 in.	3.68 in.	5 in.
Outside diameter (in.)	3.06	3.68	6.68	5.0
No-go ID (in.)	1.55	1.55	1.55	1.55
Min. ID (in.)	2.485	2.441	2.441	2.441
Top connection (8 RD box, EUE)	2⅜	2⅞	2⅞	2⅞
Burst pressure[†] (psi)	15,000	10,500	10,500	10,500
Collapse pressure[†] (psi)	15,000	11,000	11,000	11,000
Makeup length (in.)	115.5	117	114	117
Weight (lbm)	125	185	180	190
Yield strength[†] (lbf)	183,000	145,000	145,000	145,000
Detonating Cord Extension Housing and Booster Cover				
Temperature rating (°F [°C])	400 [204][‡]			
Pressure rating (psi)	25,000			
H_2S service	No			

[†] At 75% minimum burst for burst pressure, 75% minimum collapse for collapse pressure, and 75% yield for yield strength

[‡] For temperatures above 400°F or extended operations, special seals and explosives are required. See Table 17 and Fig. 84 in the “Operating Environment and Engineering of Perforating Operations” chapter and consult with your Schlumberger representative if the temperature or time exposure exceeds the HMX curve.

Table 120. TCF End-to-End Fill Sub Assembly Specifications

	Stand Alone		Redundant	
	3.06 in.	3.68 in.	3.06 in.	3.68 in.
Max. OD (in.)	3.075	3.710	3.075	5.0
Min. no-go ID (in.)	1.535	1.535	1.535	1.55
Top connection (8 RD box, EUE)	2⅜	2⅞	2⅜	2⅞
Pressure rating (psi)	20,000	20,000	20,000	20,000
Min. hydrostatic firing pressure (psi)	500	500	500	500
Burst pressure (psi)	18,961	16,028	18,961	10,500
Collapse pressure (psi)	16,129	13,353	16,129	11,000
Makeup length (in.)	71.4	69.7	119.1	117
Weight (lbm)	65	85	127	190
Tensile strength (lbf)	234,919	229,027	234,919	145,000
H_2S service	No	No	No	No

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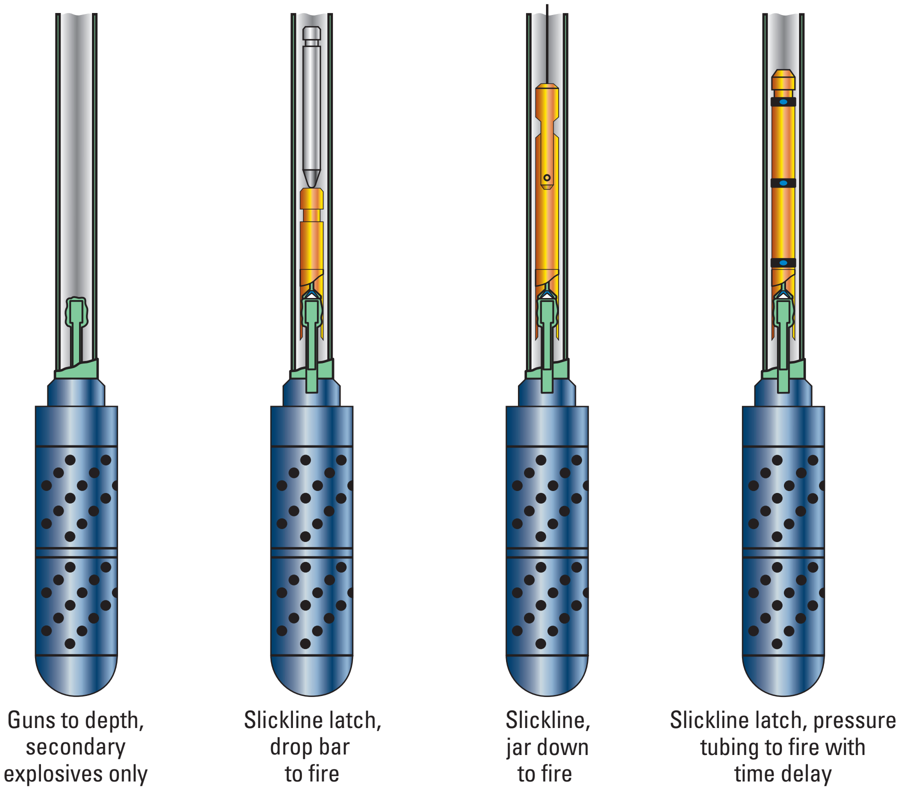

Figure 242. TCF principle of operation.

Fill subs are available for both stand-alone and redundant TCF head systems. Different sizes and thread types are available on request. The downhole fill sub assembly on all the TCF heads is made up to the top of the gun string. The assembly is composed of a debris fill sub with a no-go guide and a detonating cord extension housing with a receptor booster mounted on top. The booster is contained inside a pressure-proof cover. The cover is part of the latching system.

Features and benefits

- Improved overall safety—The TCF system allows running the gun string unarmed, without any primary explosives. The gun string is armed only at shooting depth. If a problem occurs, the TCF system allows the gun string to be disarmed by unlatching the firing head. Because a minimum hydrostatic pressure of 150 psi is required to fire the percussion detonator, the firing head cannot be activated at surface.
- Operational verification—If a misfire is suspected, the firing head can be unlatched and brought to the surface for examination. The engineer can then decide whether to rerun with another firing head or to run a lead-tipped impression block. An inspection of the impression block reveals whether the trigger charge jet penetrated the receptor booster cover.
- Reliability through firing system redundancy—Any TCF system is combinable with an HDF head to form a redundant firing system, housed in a single fill sub. The redundancy is an economical and safer solution when using the TCF system as a secondary firing system. The backup TCF firing head is lowered only if the primary firing system fails.
- Debris protection—The booster cover is mounted on top of the detonating cord extension tube inside the fill sub, allowing debris to settle past the cover and preventing obstruction of the latching process.

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Safety considerations

No safety spacer is required when running the TCF system because there is no primary high explosive in the system until the firing head has been installed downhole.

Additional specific safety considerations for the different TCF head versions are listed in the following sections.

Applications

Contact your Schlumberger representative to see if the versatile TCF system is applicable to your job design and operational environment.

TCF operational procedures

As described in "Service delivery procedure" in the "Tubing-Conveyed Perforating Completion Techniques" chapter, TCF system operations begin with thorough design and planning using the applicable flowchart, an abbreviated example of which is shown in Fig. 243.

Operational procedures specific to the various TCF firing heads are in the following sections for those TCF systems.

Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

Execution

The firing system typically is assembled at the wellsite. The detonator is placed in the assembly on the deck, away from the loaded guns. The system is considered armed only after the head is attached to the live gun string.

No special precautions are necessary in conducting the TCF head arming procedure. The downhole part of the firing system in the fill sub assembly contains no primary explosive. The running assembly containing the primary explosive, in the detonator, is run later, before perforating.

The firing procedure is as follows:

1. Rig up slickline lubricator and pressure test against the lubricator or swab valve.
2. Open test valve with annulus pressure (if applicable).
3. Run in hole with firing head sinker bars and spang jars.
4. Go slowly through test valve, verifying that it is fully open (if applicable).
5. Go through mechanical production valve or debris-circulating sub, if present.
6. Continue down and stop near the TCF receptor booster.
7. Pull up and record pulling line weight.
8. Continue slowly and locate TCF receptor booster. Latch gently.
9. Confirm latching by overpulling 300 lbf.
10. Follow the specific operating sequence for the head to fire the guns:

- Jar down–activated head
    a. Open spang jars.
    b. Jar down sharply to fire guns.
    c. Retrieve firing head by jarring off receptor booster after receiving indication of firing. This step may be taken after the initial flow period to clean up perforations or during initial shut-in at surface (if applicable).

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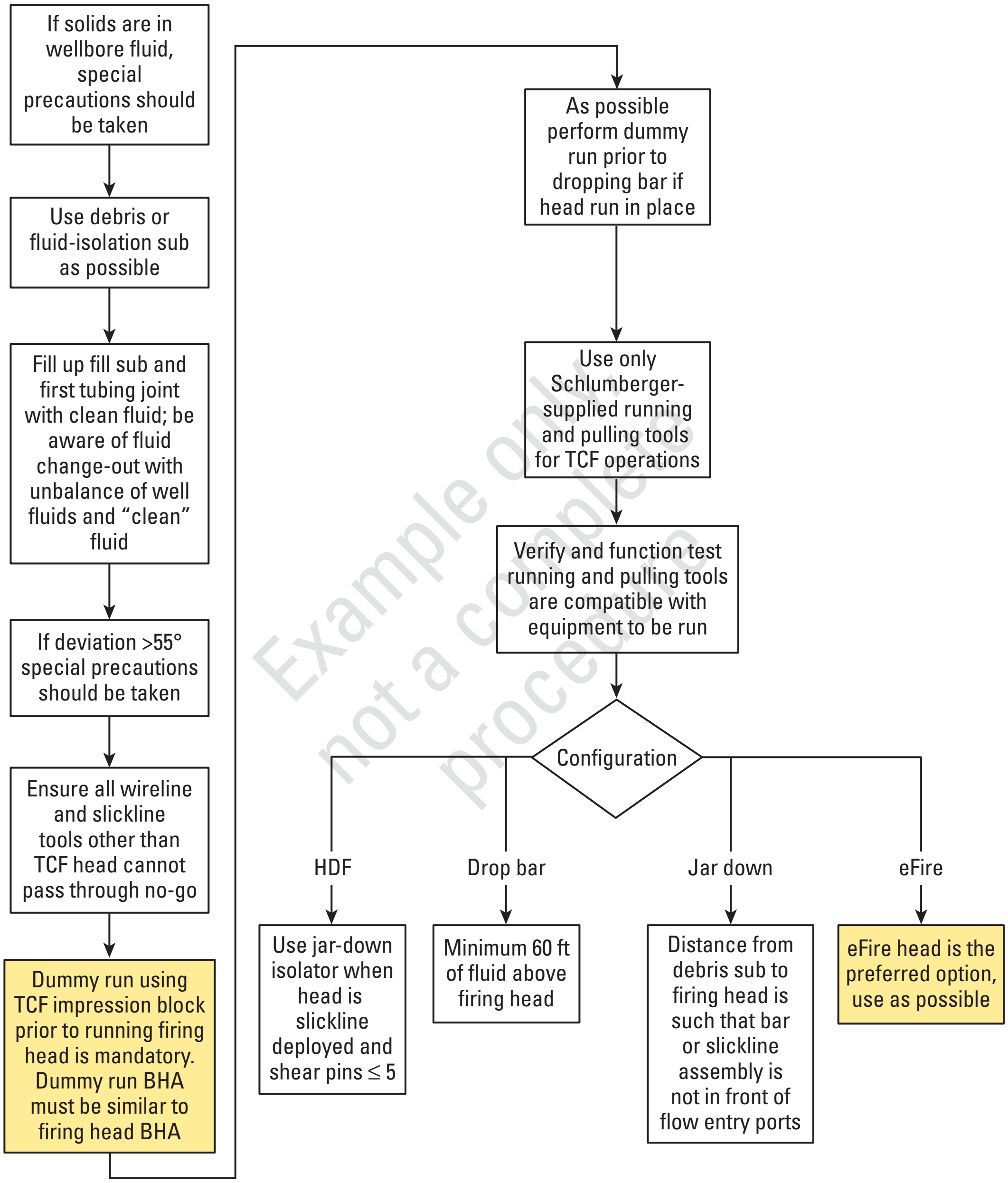

Figure 243. Excerpt of an example SDP design and planning flowchart for TCF operations. Additional specific SDP procedures are also followed for the individual firing heads.

- Drop bar–activated head
    a. Jar down and release firing head.
    b. Recover toolstring from well.
    c. Continue with drop bar firing system procedure as described for the BHF head in this chapter.

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- Pressure-activated heads
  a. Jar down and release firing head.
  b. Recover tool string from well.
  c. Continue with HDF system procedure as previously described for the HDF head in this chapter.

11. If there is no indication that the TCF system fired, retrieve the firing head and inspect it. A lead-tipped impression block can be run on slickline to reveal whether the trigger charge jet penetrated the receptor booster cover. Depending on the findings, one of the following actions is taken:
    - Rerun a new firing head and repeat the sequence.
    - Bail debris from the receptor booster.
    - Resort to a secondary firing system.

Jar down–activated TCF head

The jar down–activated TCF head (Fig. 244 and Table 121) is run separately from the gun string. The downhole fill sub assembly is run with the gun string. The slickline operator has complete control over the firing head, allowing precise control from the surface of the time of gun firing.

Table 121. Jar Down–Activated TCF Specifications

Outside diameter (in.)	1.375
Max. OD after firing (in.)	1.40
Temperature rating (°F [°C])	400 [204][†]
Pressure rating (psi)	20,000
Min. operating pressure (psi)	500
Overall length (in.)	19.5
Weight (lbm)	5.5
Max. unlatch pull (slow) (lbf)	15,000
H_2S service	No

[†] For temperatures above 400°F or extended operations, special seals and explosives are required. See Table 17 and Fig. 84 in the “Operating Environment and Engineering of Perforating Operations” chapter and consult with your Schlumberger representative if the temperature or time exposure exceeds the HMX curve.

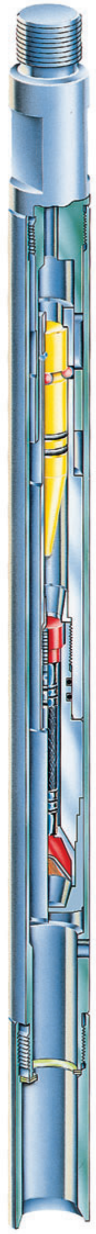

Figure 244. Jar down–activated TCF head.

Safety considerations

The jar down–activated TCF system improves overall safety by allowing the gun string to be run unarmed and without primary explosives. The guns are armed only at shooting depth. If a problem occurs, the gun string can be disarmed by unlatching the firing head before it is pulled to the surface.

The firing head cannot be activated at the surface because a minimum hydrostatic pressure of 150 psi is required to fire the percussion detonator.

Tubulars are protected while the firing head is running in: In the unlikely event that the jar-down mechanism is accidentally activated while spudding against debris, the shaped charge jet develops vertically along the axis of the tubing, which helps prevent damage. In addition, the well fluid dampens the jet before it reaches the bottom of the firing head housing.

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Jar down–activated TCF operational procedures

The first step is to latch the firing head. Once the gun string has been positioned at shooting depth, the jar down–activated TCF head is connected to the end of a slickline string with weights and a jar. The assembly is lowered in the tubing and gently latched onto the booster cover inside the fill sub. A light overpull is used to confirm latching.

Jarring down against the booster cover shears the pins holding the jar-down adapter to the firing pin housing (Fig. 245). The jar-down adapter acts as a release sleeve for the firing pin, and its downward movement uncovers the balls holding the firing pin. The balls are forced out into the openings of the jar-down adapter. Hydrostatic pressure then propels the released firing pin onto the detonator, initiating the firing sequence: detonator, trigger charge, receptor booster, and guns.

After firing, jarring up unlatches the firing head from the booster. The firing head and slickline tools can then be pulled out.

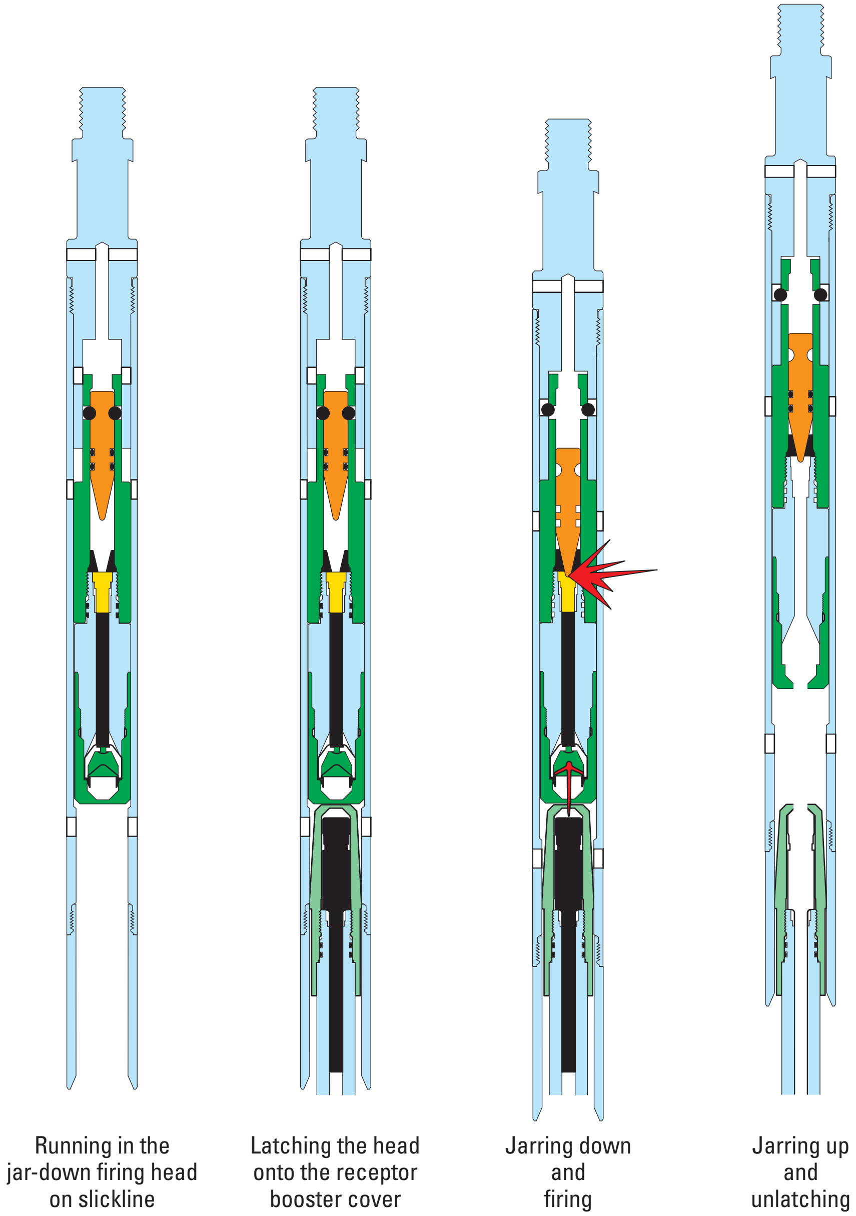

Figure 245. Jar down–activated TCF firing head principle of operation.

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Drop bar–activated TCF head

The drop bar–activated TCF system (Fig. 246 and Table 122) consists of a TCF head run separately from the gun string, downhole fill sub assembly run with the gun string, and drop bar. The head is activated by dropping the bar.

A 1.55-in. no-go sub guides the drop bar onto the firing head but prevents passage of larger objects. The latch neck and drop bar are specifically designed so that only the shaped nose of the drop bar can reach the release sleeve. The string can be run with the firing head in place, and the head is retrievable.

Figure 246. Drop bar–activated TCF firing head.

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Table 122. Drop Bar–Activated TCF Specifications

Outside diameter (in.)	1.375
Max. OD after firing (in.)	1.40
Temperature range (°F [°C])	400 [204][†]
Pressure rating (psi)	20,000
Min. operating pressure (psi)	500
Overall length (in.)	19.5
Weight (lbm)	5.5
Max. unlatch pull (slow) (lbf)	15,000
H_2S service	No

[†] For temperatures above 400°F or extended operations, special seals and explosives are required. See Table 17 and Fig. 84 in the "Operating Environment and Engineering of Perforating Operations" chapter and consult with your Schlumberger representative if the temperature or time exposure exceeds the HMX curve.

Safety considerations

The drop bar–activated TCF system improves overall safety by allowing the gun string to be run unarmed and without primary explosives. The guns are armed only at shooting depth. The gun string can be disarmed by unlatching the firing head before pulling it to the surface.

The firing head cannot be activated at the surface because a minimum hydrostatic pressure of 150 psi is required to fire the percussion detonator.

Tubulars are protected while the firing head is running in: In the unlikely event that the jar-down mechanism is accidentally activated while spudding against debris, the shaped charge jet develops vertically along the axis of the tubing, which helps prevent damage. In addition, the well fluid dampens the jet before it reaches the bottom of the firing head housing.

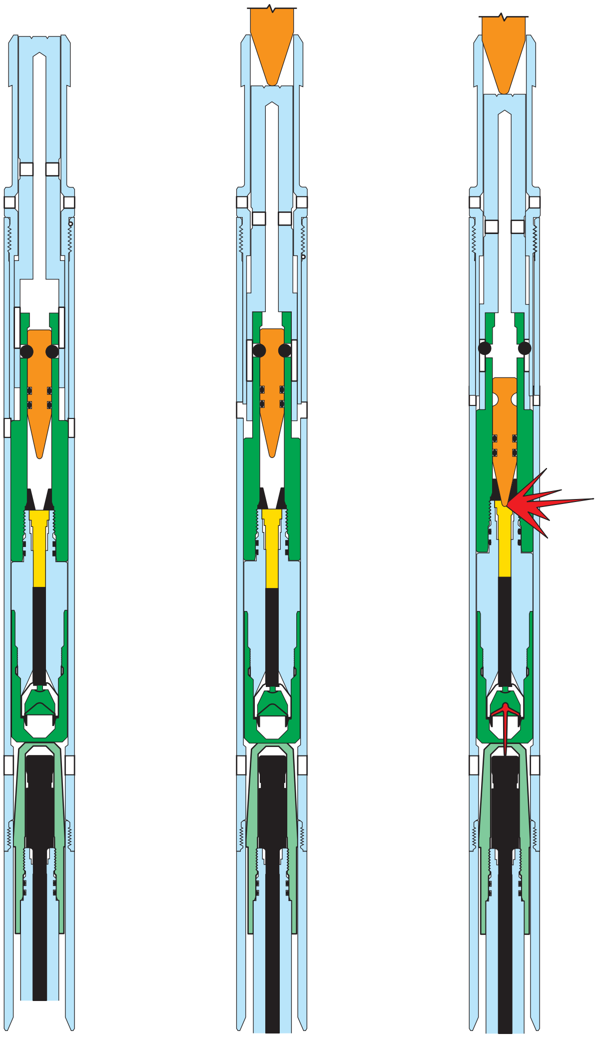
Drop bar–activated TCF operational procedures

The operating sequence involves latching the firing head, unlatching and retrieving the running tool, dropping the bar, and firing the guns. Once the gun string has been positioned at shooting depth, the drop bar–activated TCF head is connected to a slickline string with weights, jars, and a running tool. The assembly is lowered in the tubing and gently latched onto the downhole booster cover inside the fill sub. A light overpull is used to confirm latching (Fig. 247).

Once the firing head is latched, jarring down is used to unlatch the running tool from the firing head. The slickline tools are then pulled out while the firing head stays in position.

After the slickline assembly is removed, a drop bar with a special nose profile is dropped into the tubing. The bar passes through the no-go guide and hits the firing head release sleeve. Hydrostatic pressure drives the released firing pin into the percussion detonator, initiating the gun firing sequence: detonator, trigger charge, receptor booster, and guns.

The operational precautions for solid drop bars (see "Bar hydrostatic firing head" in this chapter) also apply to this system, especially when the bar is dropped in empty pipe.



Running in the drop bar head and latching onto the receptor booster cover

Bar strike releasing firing pin

Firing

Figure 247. Drop bar–activated TCF head principle of operation.

Absolute pressure–activated TCF head

The absolute pressure–activated TCF head (HDF with TCF head) is run separately from the gun string (Fig. 248 and Table 123). The downhole fill sub assembly is run with the gun string.

Safety considerations

The absolute pressure–activated TCF head increases confidence in the results and improves overall safety. Lower activating pressure is a major feature of a separately run, pressure-activated firing head. All pressure tests are performed before running the firing head, and the occurrence of overpressure while running in the hole is under control or not present because pressure tests have already been performed.

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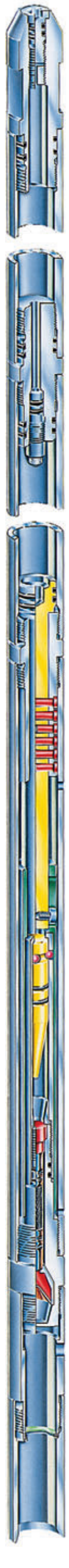

Figure 248. Absolute pressure–activated TCF head.

Table 123. Absolute Pressure–Activated TCF Specifications

Outside diameter (in.)	1.375
Temperature rating (°F [°C])	400 [204][†]
Pressure rating (psi)	25,000
Min. operating pressure (psi)	500
Makeup length (in.)	54
Weight (lbm)	16.6
Yield strength (lbf)	28,000
H_2S service	No

[†] For temperatures above 400°F or extended operations, special seals and explosives are required. See Table 17 and Fig. 84 in the "Operating Environment and Engineering of Perforating Operations" chapter and consult with your Schlumberger representative if the temperature or time exposure exceeds the HMX curve.

The system allows running the gun string unarmed and without primary explosives. The firing head is armed only at shooting depth. A shock absorber can be run with the head to avoid transmitting excessive shock to the shear pins when the head is released from the slickline tools after being engaged onto the gun string. If it is necessary to pull the string to surface, it can first be disarmed by unlatching the firing head. Because a minimum of 150-psi hydrostatic pressure is required to fire the percussion detonator, the firing head can not be activated at the surface.

Tubulars are protected while the firing head is running in. In the unlikely event that the firing head is accidentally activated while spudding against debris, the shaped charge jet develops vertically along the axis of the tubing, which helps prevent damage. In addition, the well fluid dampens the jet before it reaches the bottom of the firing head housing.

Absolute pressure–activated TCF operational procedures

The operating sequence involves latching the firing head, unlatching the running tool, and firing the guns. Once the gun string has been positioned at shooting depth, the TCF head is connected to the end of a slickline string with weights, jars, and running tool. The assembly is lowered in the tubing and gently latched onto the downhole receptor booster cover inside the fill sub. A light overpull is used to confirm latching (Fig. 249).

Once the firing head is latched, jarring down unlatches the running tool from the firing head. The slickline tools are pulled out while the firing head stays in position.

After the slickline assembly is removed, tubing pressure is increased to the calculated pressure to shear the traveling piston pins in the HDF head. An adjustable time delay is initiated before firing the guns. During this delay, tubing pressure is reduced to the desired underbalance.

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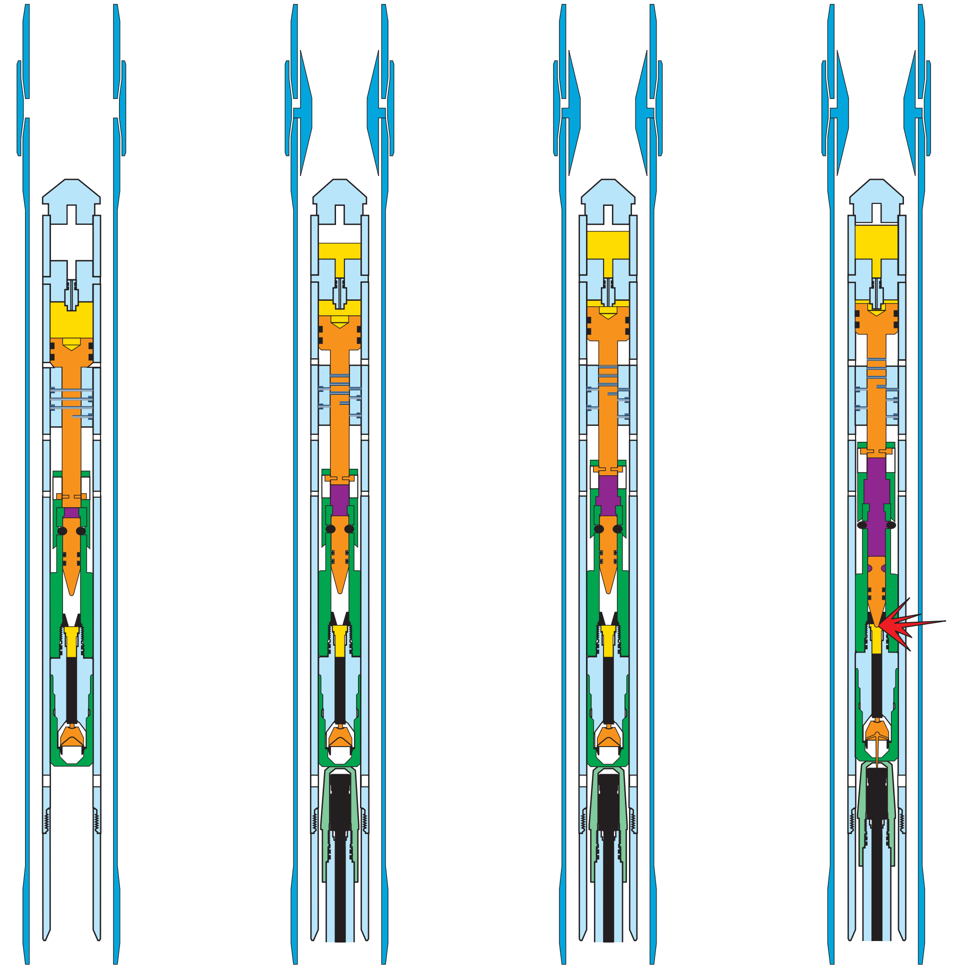

Running in the absolute pressure firing head on slickline

Pressuring tubing to initiate the firing delay

Delay

Firing after timed delay

Figure 249. Absolute pressure–activated TCF head principle of operation.

Timed pressure-activated TCF head

The timed pressure-activated TCF head is a variation of the absolute pressure–activated TCF head (HDF with TCF head) with the shear pins removed. As a result, no pumping is required to activate the head and the timer starts as soon as the head is exposed to pressure in the wellbore.

Safety considerations

Using the timed pressure-activated TCF system increases both confidence in the results and overall safety. Because the firing head is run separately, pressure does not have to be applied to the wellbore before firing.

As for all TCF heads, the running tool contains a minimal amount of explosives. If the running tool must be detonated before latching, the small shaped charge shoots downward to prevent damage to the tubulars.

The gun string can be run without primary explosives and is armed only at shooting depth. If necessary, the gun string can be disarmed by unlatching and retrieving the firing head. This allows the safe removal of the gun string from the well.

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Timed pressure-activated TCF operational procedures

Before the TCF assembly is run in the hole, the run speed, deviation, fluid density, and any other time constraints are calculated. The timer head is then set to allow for the time required to run the assembly into the hole, latch it, and retrieve the running tool (Fig. 250).

Once the gun string has been positioned at the shooting depth, the timed pressure-activated TCF head is connected to the end of a slickline string with weights, jars, and running tool. The assembly is lowered in the tubing and latched onto the downhole receptor booster cover inside the fill sub. A light overpull is used to confirm latching.

After the firing head is latched, jarring down unlatches the running tool from the firing head. The slickline tools are retrieved, and the firing head stays in position. The guns fire at the end of the time-delay period.

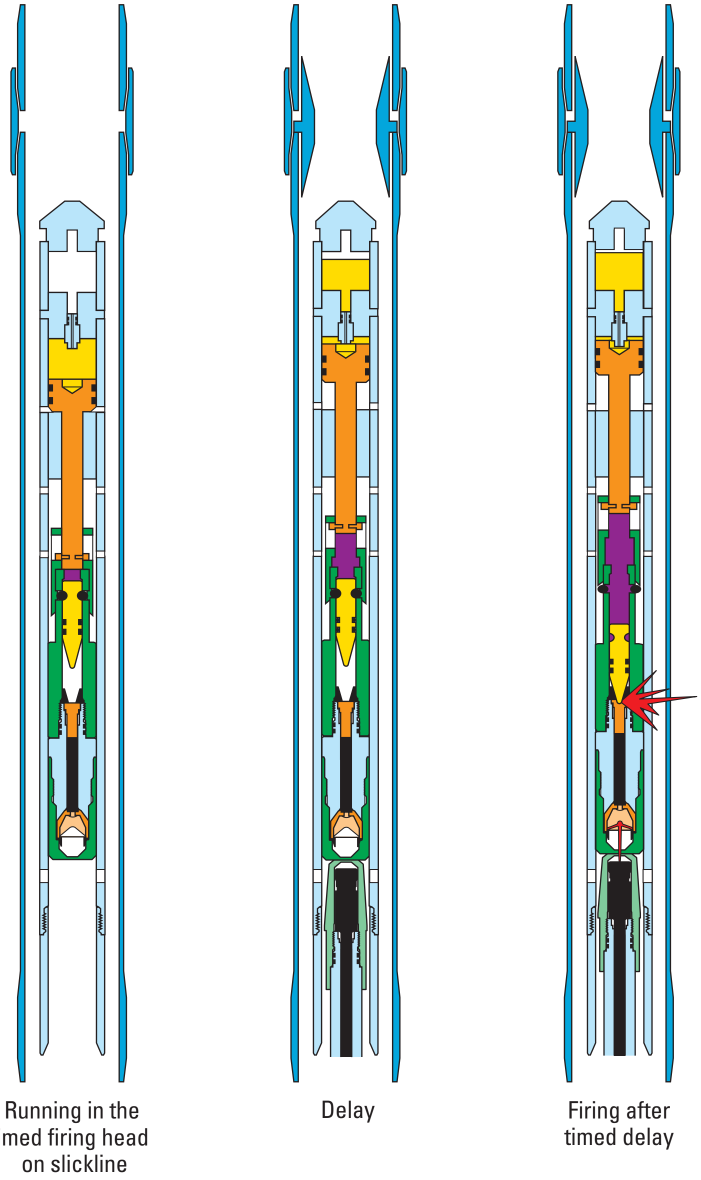

Figure 250. Timed pressure-activated TCF head principle of operation.

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Bar hydrostatic firing head

The Schlumberger BHF head is a bar-activated, hydrostatically fired firing head system (Fig. 251). The BHF system consists of a downhole fill sub with a no-go guide, firing head with an internal firing pin, and drop bar (Table 124). When the drop bar hits the release sleeve, it shears the retaining shear ring that secures the release mechanism and shifts the sleeve down. This movement releases the balls holding the firing pin. Once the firing pin is freed, hydrostatic pressure propels it into the percussion detonator (Fig. 252).

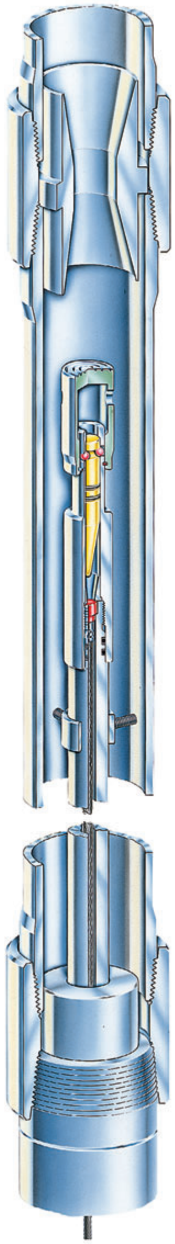

Figure 251. BHF head.

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Table 124. BHF Specifications

	BHF Head	
Outside diameter (in.)	1.25	
Temperature rating (°F [°C])	330 [165]	
Pressure rating (psi)	20,000	
Min. operating pressure (psi)	500	
H_2S service	No	
	End-to-End Fill Sub	
	3.06 in.	**3.68 in.**
Max. OD[†] (in.)	3.075	3.710
Min. ID (in.)	2.485	2.441
No-go and bar guide ID[†] (in.)	1.185	1.185
Temperature rating (°F [°C])	330 [165]	330 [165]
Pressure rating (psi)	20,000	20,000
Burst pressure (psi)	18,961	16,028
Collapse pressure (psi)	16,129	13,353
Makeup length[‡] (in.)	63.4	60.5
Weight[‡] (lbm)	60	77
Tensile strength (lbf)	234,919	229,027
H_2S service	No	No

[†] Dimensions include manufacturing tolerances.
[‡] For standard configuration

Features and benefits

- Debris protection—The firing head is mounted inside a fill sub on top of an extension housing. This configuration ensures that there is space for the drop bar to reach the head by providing sufficient volume to allow debris to settle around it.
- Simple and reliable—The BHF system has only a few components. One of the first firing head systems designed, the straightforward design of the BHF head has proved itself reliable.
- Dependable firing—The firing head is activated with minimal drop bar impact. After the firing head is activated, the firing pin is driven by hydrostatic pressure and does not depend on the intensity of the drop bar impact, which makes it suitable for use in moderately deviated wells.
- Compatible with jar-down operation—The BHF head is well-suited for use in jar-down operations because of the minimal impact requirement and use of hydrostatic pressure to drive the firing pin.
- Telltale feature—Circular grooves on the top of the release sleeve leave a recognizable pattern on the brass nose telltale of the drop bar.
- Operational flexibility—The BHF system can be run stand alone or in redundant configurations that provide a backup firing head for TCP operations (see “Redundant firing systems” in this chapter).

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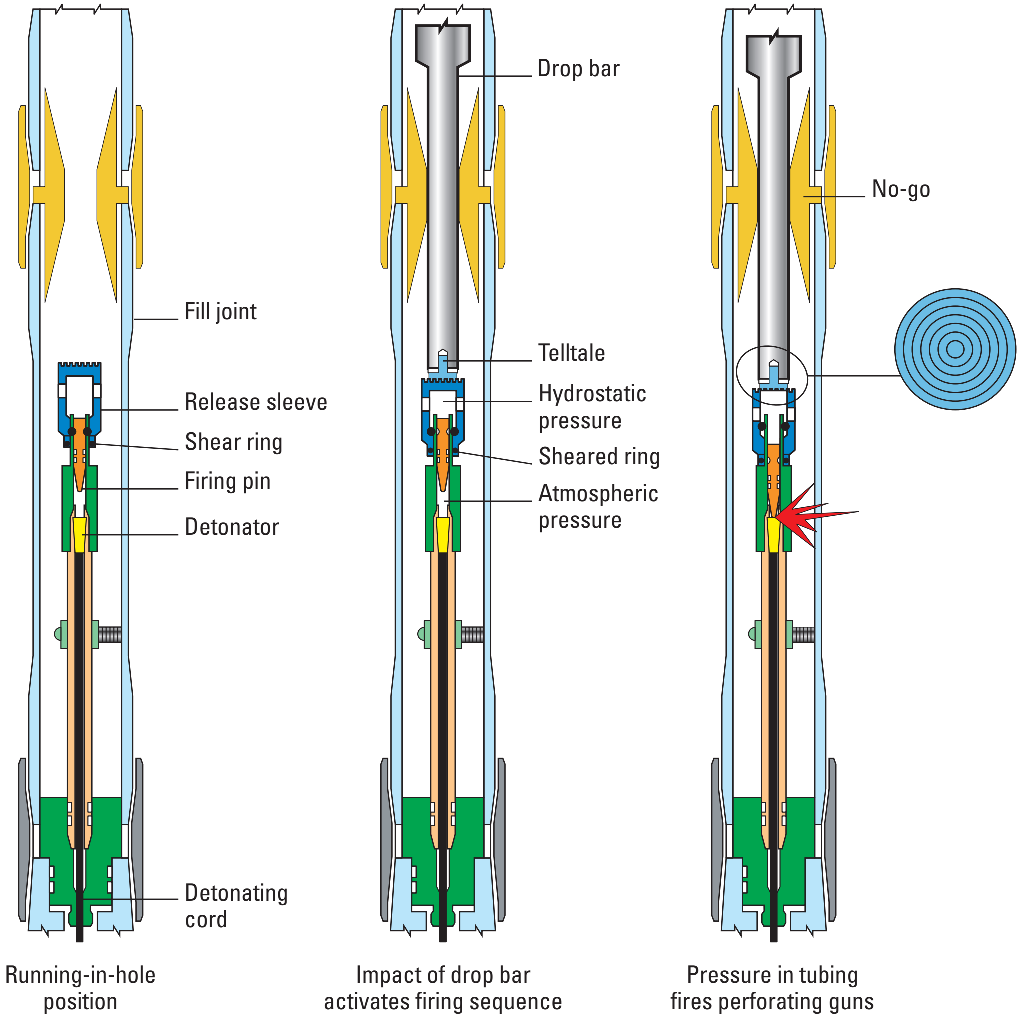

Figure 252. BHF principle of operation.

Safety considerations

For safety at the surface, the firing pin requires a minimum of 150-psi hydrostatic pressure to fire the percussion detonator. The no-go sub minimizes the possibility of accidental firing triggered by falling objects. If the guns flood, the pressure is balanced across the firing pin to prevent firing. The gun string remains sealed if a ballistic misfire occurs in the firing head.

Inclusion of a safety spacer is required (except for systems using the eFire electronic firing head) on top of the gun string to ensure that the guns are below the rig floor when the firing head is connected or disconnected. In case of trapped pressure in the safety spacer, a pressure vent in the firing head adapter is used to bleed off the pressure. Hardware to prevent trapped pressure is available and its use is recommended.

Applications

- Vertical wells—The BHF system is typically deployed in vertical wells because straight holes do not impede bar drop speed.
- Wells with deviation to 55°—Because operation of the drop bar relies on gravity, wellbore deviation is a critical consideration in selecting the BHF system. Although Schlumberger has performed jobs in wells deviated more than 55°, this deviation is still the cutoff to select other

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means to detonate the guns. In cases where other conditions prohibit the use of any other firing system, contact your Schlumberger representative for assistance in assessing mitigating measures and additional equipment that may allow use of the BHF system.

- Wells in which a partial fluid cushion is used to achieve underbalance—The BHF system does not require additional pressure from surface to detonate the guns, whereas hydraulic heads typically require nitrogen to increase the wellbore pressure to activate. Precautions to control the speed of the bar through very long empty sections might be required.

Drop bar

The drop bar is equipped with an upper fishing neck, lower extension nose, and brass impression block (telltale) (Table 125). Additional 5-ft extension weights can be added for deviated well applications. A one-piece drop bar is also available for upset tubing or significant changes in tubing ID.

The drop bar is always run on slickline if the pipe is dry. In dry pipe the bar can reach extremely high velocities and could cause damage to the completion string and also potentially damage the firing head and result in a misfire.

BHF operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, BHF system operations begin with thorough design and planning using the applicable flowchart, an abbreviated example of which is shown in Fig. 253.

Table 125. Drop Bar Specifications

	Standard Drop Bar	One-Piece Drop Bar
Outside diameter (in.)	1.25	1.75
Length (in.)	77†	72
Weight (lbm)	22†	42
Makeup length of extension (in.)	60	na
Weight of 1.25-in. extension (lbm)	21	na
Weight of 1.5-in. extension (lbm)	35	na
Fishing neck (in.)	1.1875	1.375

na = not applicable
† Includes one extension

Preparation

All job preparation, from the shop to at the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

Execution

The firing system typically is assembled at the wellsite. The detonator is placed in the assembly on the deck, away from the loaded guns. The system is considered armed only after the head is attached to the live gun string, with the following procedure:

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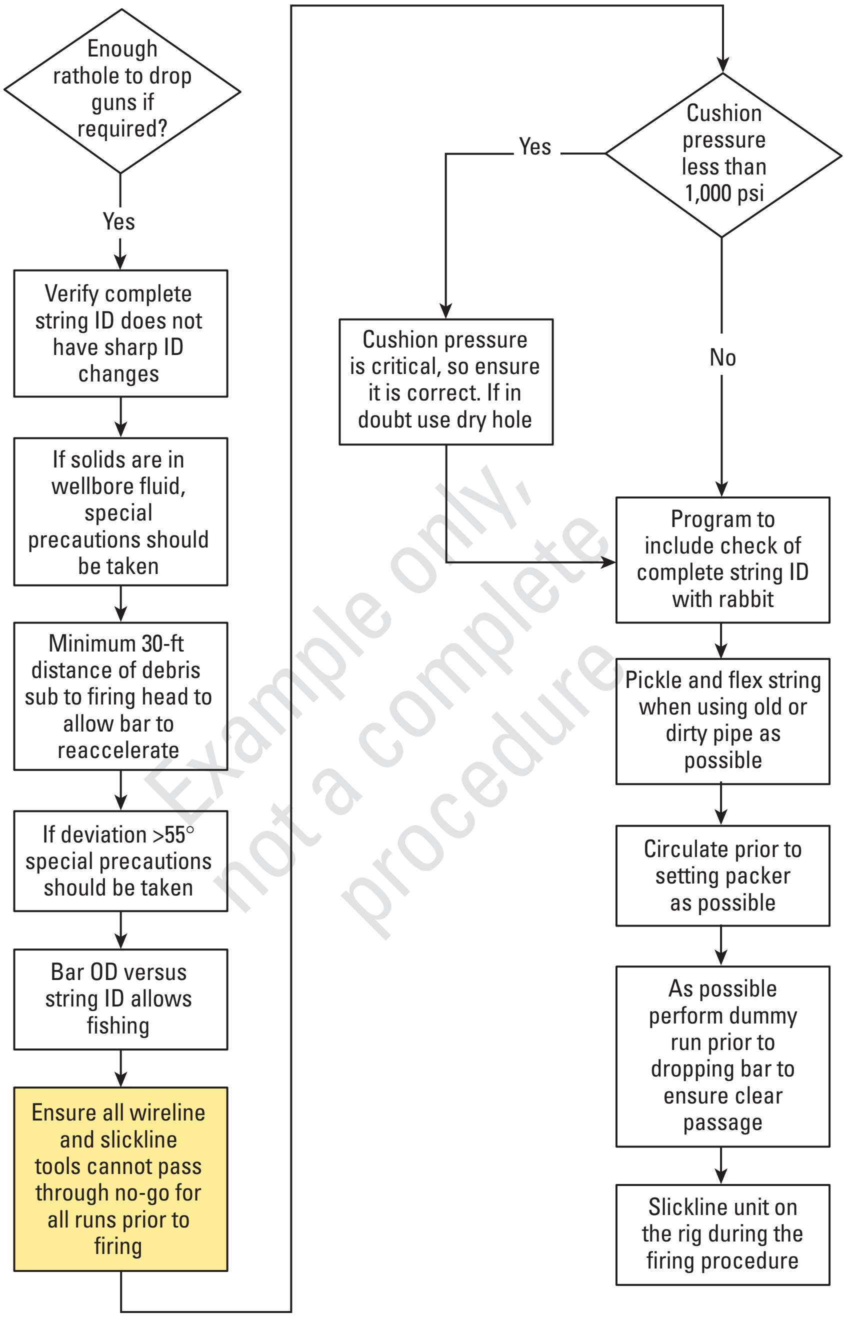

Figure 253. Excerpt of an example SDP design and planning flowchart for BHF operations.

1. Ensure that all guns are properly made up in the correct order and set the safety spacer in the slips with a safety clamp installed.
2. Pick up the firing head assembly with detonator installed and hang it in the blocks above the safety spacer.
3. Stab the firing system assembly into the safety spacer.
4. Tighten all connections to the proper torque.
5. Continue running in hole.

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Including a ceramic circulating-debris sub above the firing head is recommended to protect against debris interfering with the drop bar.

The firing procedure involves running the drop bar into the well by dropping it from the surface or on slickline. Slickline is recommended in wells that are deviated greater than 45°, strings with restrictions, empty strings, and strings with debris and gelled mud. Slickline is also used to provide greater firing control.

Figure 254 illustrates the wellsite setup for dropping the bar. With wellhead pressure control and shot detection equipment installed, the drop bar is placed in a short section of riser, including a fullbore valve at the bottom and a hydraulic head catcher at top. The tool catcher is pumped open to release the hanging drop bar.

The bar's fall time depends on many parameters, including well depth and deviation, type of fluid in the string, string ID, and bar length, density, and cross section. Typical fall speeds are 1,200 ft/min in 2⅞-in. tubing filled with heavy mud and 1,800 ft/min in 2⅞-in. tubing filled with clean brine. In empty pipe, fall speed can be 5 times faster within the usual range of free-fall depths.

Several fishing tool models are available to fish the drop bar. Before the bar is dropped, it is important to confirm that the available fishing tool is compatible with both the fishing neck of the drop bar and tubing restrictions.

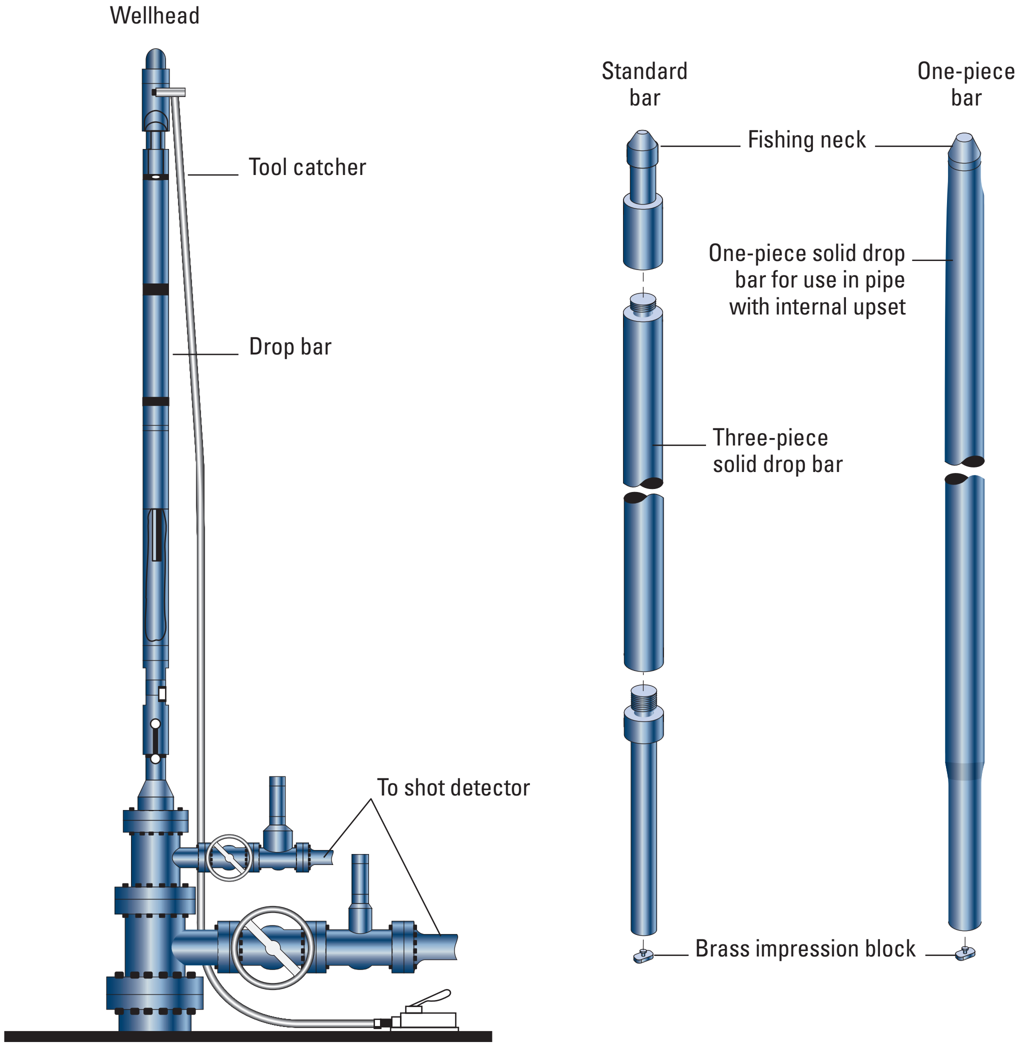

Figure 254. Wellsite setup for deploying the drop bar.

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ProFire programmable firing head

The ProFire programmable firing head uses hydromechanical technology to precisely control the firing time of the guns for performing multiple operations under pressure. The ProFire firing system consists of two main assemblies (Fig. 255 and Table 126):

- Hydraulic programmable actuator tool (HPAT)—The actuator controls the operating pressure rate and level and the number of pressure cycles that can be applied before firing.
- Hydraulic delay firing module (HDFM)—The firing head incorporates the delay mechanism and firing sections.

The ProFire head is ideally suited for underbalance operations, permanent completions requiring several pressure operations (packer setting, pressure testing, etc.), and long periods on bottom before perforating. The ProFire design prevents inadvertent or premature activation of the hydraulic firing head during operations.

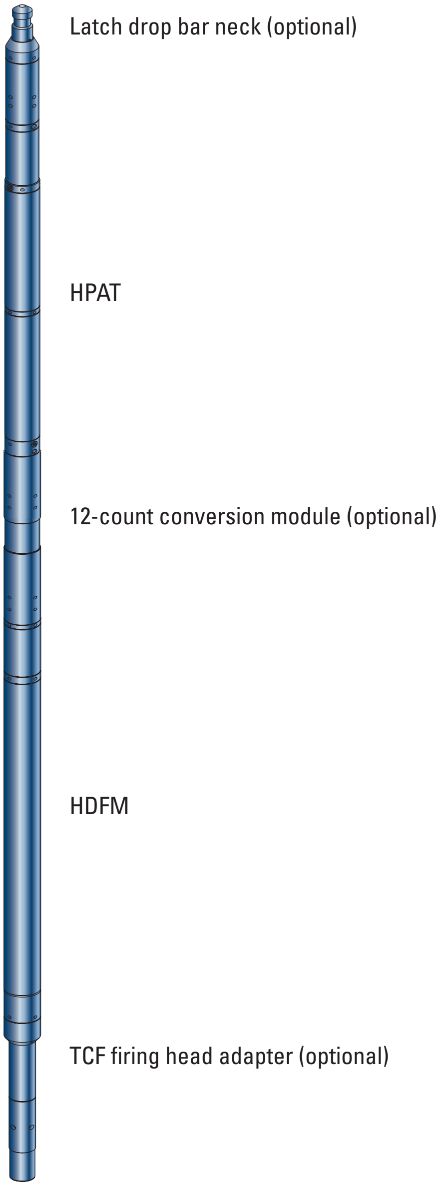

Figure 255. ProFire system key components.

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Table 126. ProFire Specifications

	ProFire System	ProFire II System
Outside diameter (in.)	2.00	2.11
Temperature rating[†] (°F [°C])	400 [204]	425 [218]
Pressure rating (psi)	20,000	30,000
Min. firing pressure (psi)	1,000	1,000
Length (in.)	193	193
Weight (lbm)	124	120
Minimum cycling command (psi)		
At 1,000 psi/min	3,500	2,000
At 65 psi/min	3,500	2,000
Hold time (min)	At max. pressure: 2	At max. pressure: 2
Max. number of cycles[‡]	12	12
H_2S service	No	No

[†] For temperatures above 400°F or extended operations, special seals and explosives are required. Refer to Table 17 and Fig. 84 in the "Operational Environment and Engineering of Perforating Operations" chapter and consult with your Schlumberger representative if the temperature or time exposure exceeds the HMX curve.

[‡] Typically run with 6 cycles; up to 12 cycles can be required for initiation by adding the optional 12-count module unit.

Features and benefits

- Absolute pressure triggering—The HPAT actuator cannot be operated until pressure is high enough to shear the pins. The adjustable, predictable activation pressure is a function of pressure changes over time rather than a function of absolute pressure.
- Adjustable and predictable delay time—The actuator allows up to 12 pressure cycles before initiating delayed firing. The multiple cycles provide time for establishing the desired underbalance. The last cycle unlocks the firing head and initiates the delay process. The programmable head provides an adjustable, predictable delay before firing the guns below.
- Pressure operations allowed—Because pressure operations can be performed before and after the completion and perforating string has been run, fewer runs are needed for completion operations. For example, the completion system can be pressure tested before firing.
- Compatibility—The ProFire firing head is compatible with gun accessory tools such as the CTXR, SXAR, MAXR, and GunStack stackable perforating gun system. It can also be used with electric submersible pumps where the eFire electronic firing system cannot be used.
- Reliable durability—Version II of the ProFire firing head is a proven performer for long-duration and HPHT operations. An interlock protects and isolates the head for pressure and wellbore fluids before activation.
- Redundant firing capability with all other firing systems—Any firing system can be combined with a ProFire head to make redundant firing systems.

Safety considerations

For safety at the surface, the firing pin requires a minimum hydrostatic pressure of 150 psi to fire the percussion detonator. The firing mechanism is not exposed and cannot be accidentally struck by falling debris in the string. The intrinsic safety of the design means that if the guns flood, pressure is balanced across the firing pin to prevent firing.

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Inclusion of a safety spacer is required on top of the gun string to ensure that the guns are below the rig floor when the firing head is connected or disconnected. In case of trapped pressure in the safety spacer, a pressure vent in the firing head adapter is used to bleed off the pressure. Hardware to prevent trapped pressure is available and its use is recommended.

Applications

- Perforating without killing the well—The perforated reservoir is not exposed to productivity-damaging kill fluids.
- Underbalanced perforating—The adjustable, predictable firing delay allows establishing underbalance.
- Multiple pressure-activated operations—Multiple pressure-activated operations can be performed in a well, such as pressure setting the production packer and pressure testing the completion string, prior to detonating the perforating guns that have been preinstalled downhole.
- Perforating in HPHT wells—The ProFire II head is proved to operate reliably and efficiently in extreme conditions.
- Highly deviated wells—Well deviation does not limit use of the ProFire head, which is also unaffected by heavy mud.

ProFire operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, ProFire system operations begin with thorough design and planning using the applicable flowchart.

Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

Execution

The HPAT actuator is usually built and function tested in the workshop. The remainder of the ProFire system is assembled at the wellsite. The detonator is placed in the assembly on the deck, away from the loaded guns. The system is considered armed only after the head is attached to the live gun string, with the following procedure:

1. Ensure that all guns are properly made up in the correct order and set the safety spacer in the slips with a safety clamp installed.
2. Pick up the firing head assembly with detonator installed and hang it in the blocks above the safety spacer.
3. Stab the firing system assembly into the safety spacer.
4. Tighten all connections to the proper torque.
5. Continue running in hole.

The first applied pressure cycle unlocks the ProFire firing head but does not initiate the firing sequence. The unlocking pressure is typically set between the packer setting pressure and the completion test pressure.

Up to 12 predetermined pressure and flow rate cycles are applied, with the last cycle triggering the delay and firing the guns.

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ProFire operational procedure example

The following operating sequence example is for three pressure cycles to activate the HDFM firing delay (Figs. 256 through 263). One cycle is required for each of the two C-rings and one cycle is then for the release sleeve.

During running in (Fig. 256), shear pins prevent the actuator lock piston from cycling. The HDFM is enclosed in an atmospheric chamber to protect it from hydrostatic pressure.

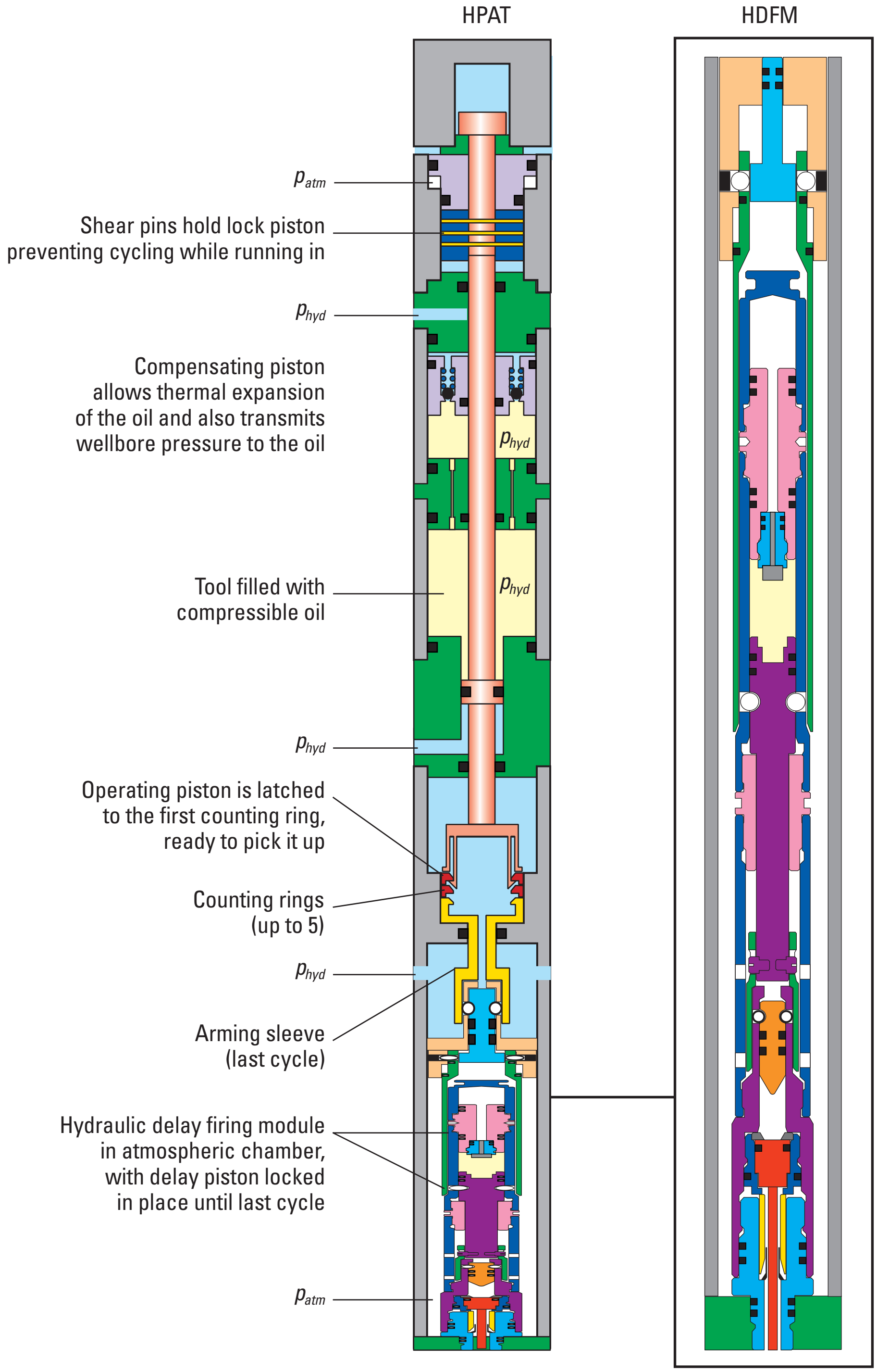

Figure 256. Running in the ProFire system. p_{hyd} = hydrostatic pressure, p_{atm} = atmospheric pressure.

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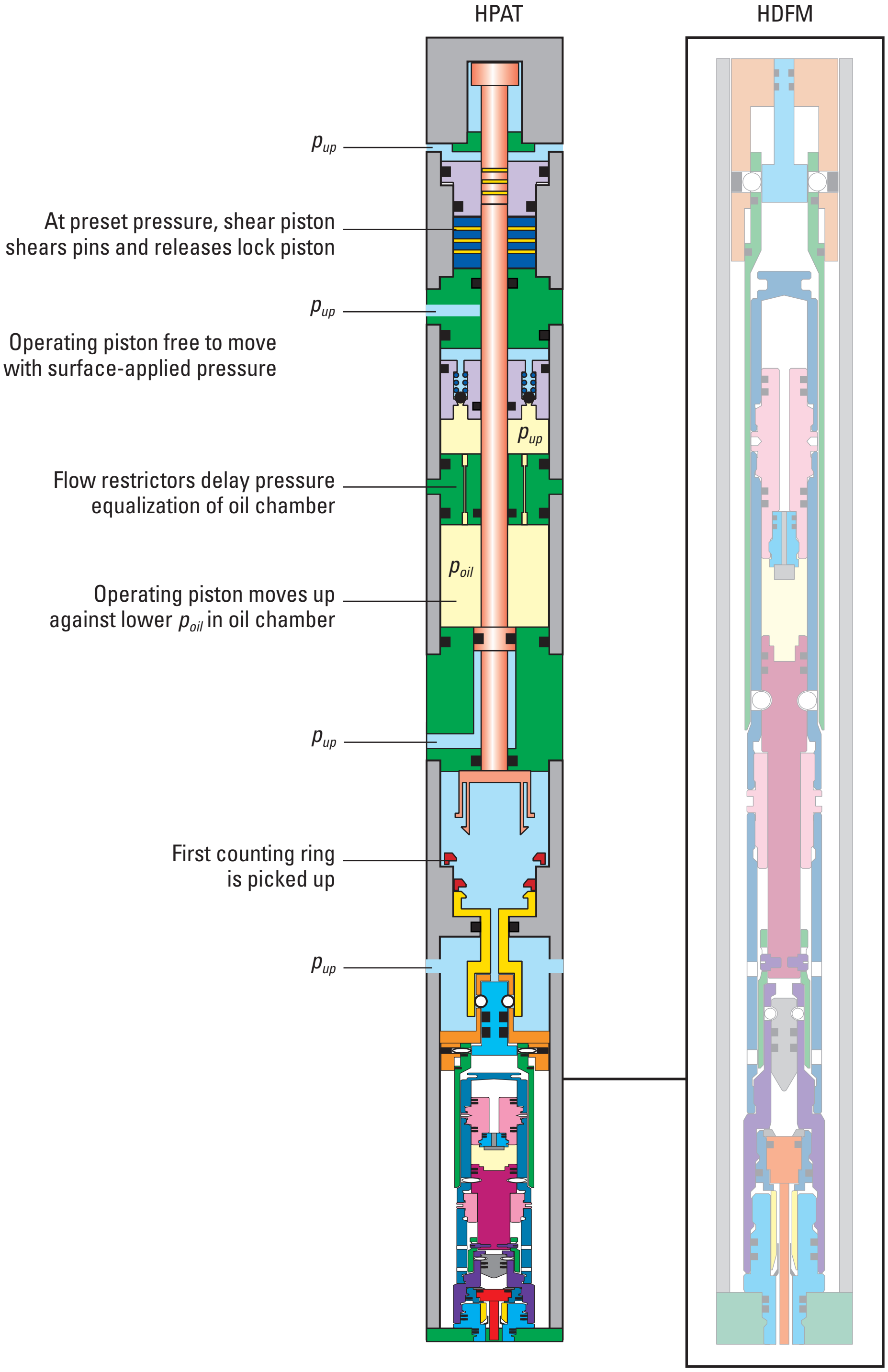
The first pressure cycle is shown in Figs. 257 and 258. Once the preset pressure level is reached, the shear piston shears the pins and releases the lock piston. This action allows the operating piston to pick up the first of the counting rings and release it from the ratchet grip. Up to five counting rings can be used (or up to 11 if the optional 12-count module unit is used); the



At preset pressure, shear piston shears pins and releases lock piston

Operating piston free to move with surface-applied pressure

Flow restrictors delay pressure equalization of oil chamber

Operating piston moves up against lower p_{oil} in oil chamber

First counting ring is picked up

Figure 257. The first pressure-up cycle shears pins. p_{up} = high-side shear pin pressure, p_{oil} = oil pressure in chamber of tool.

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number depends on the type of pressure operations. Reducing the applied pressure allows the operating piston to move down and engage the next counting ring. This pressure cycle has no effect on the delay module.

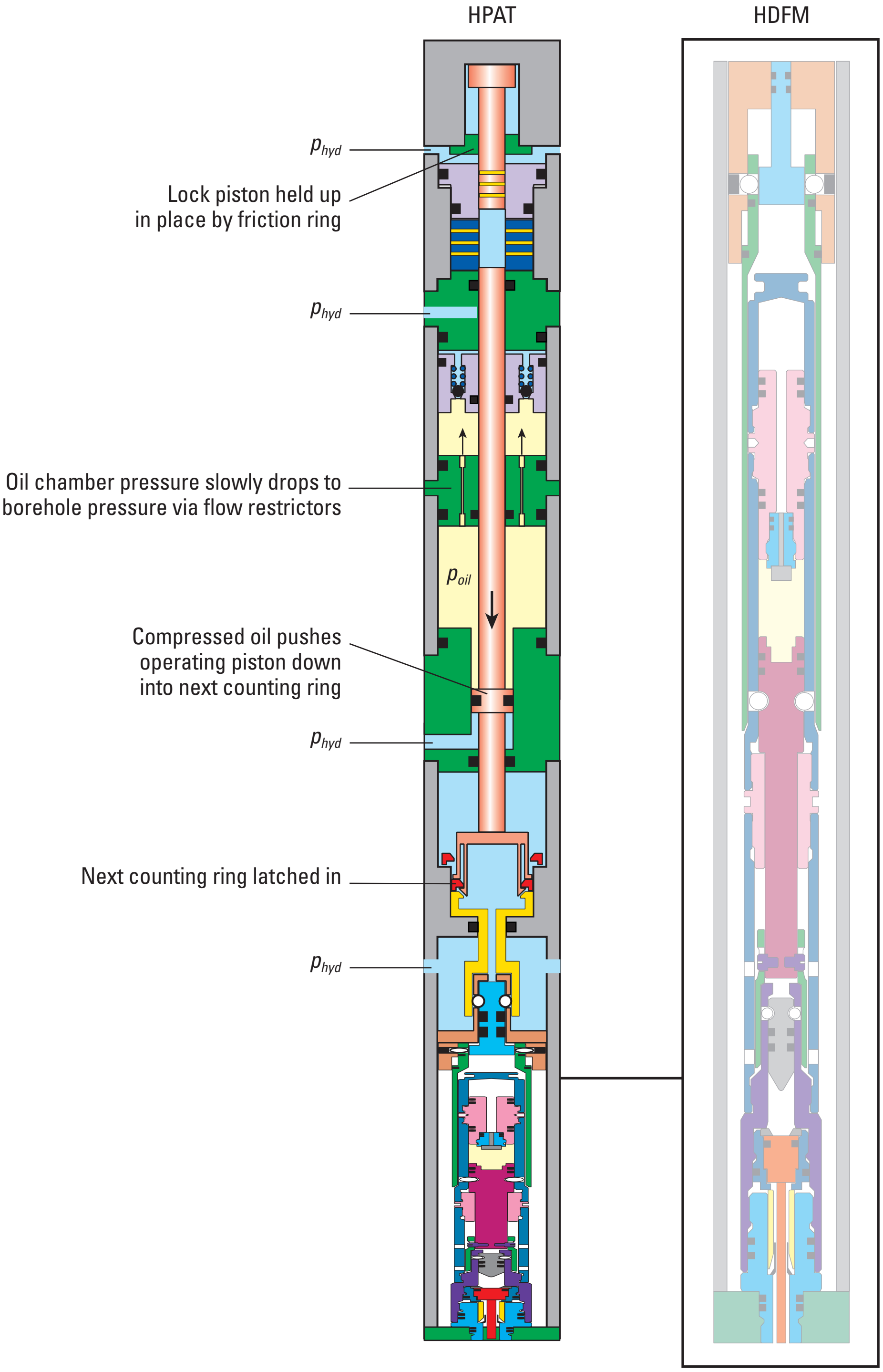

Figure 258. Pressure-down cycle latches the next ring.

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A second pressure cycle (Figs. 259 and 260) repeats the process but picks up the second and last counting rings. After the pressure has been reduced, the operating piston engages the arming sleeve connected to the release sleeve operator. Again, this pressure cycle has no effect on the HDFM.

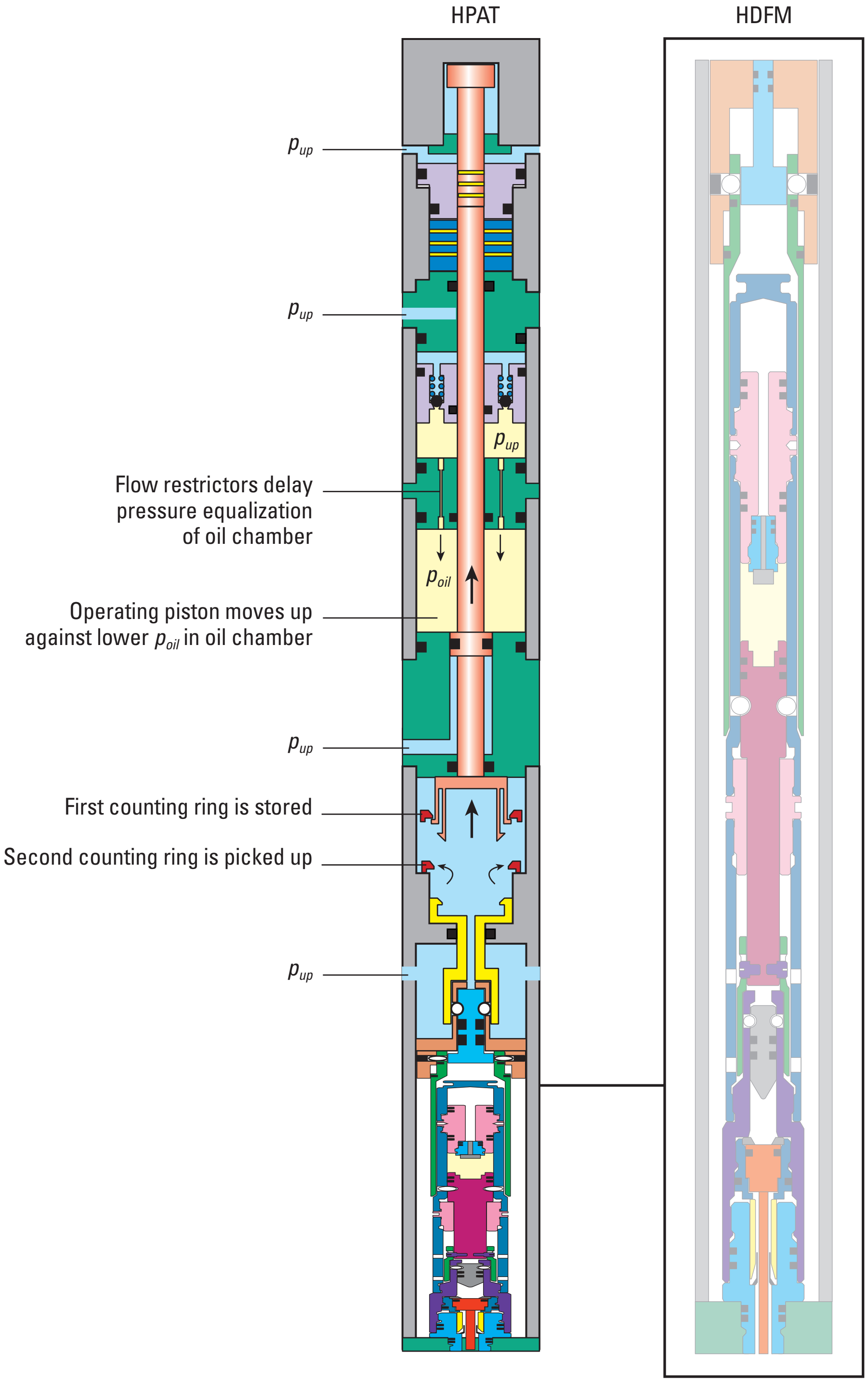

Figure 259. Second pressure cycle picks up second ring.

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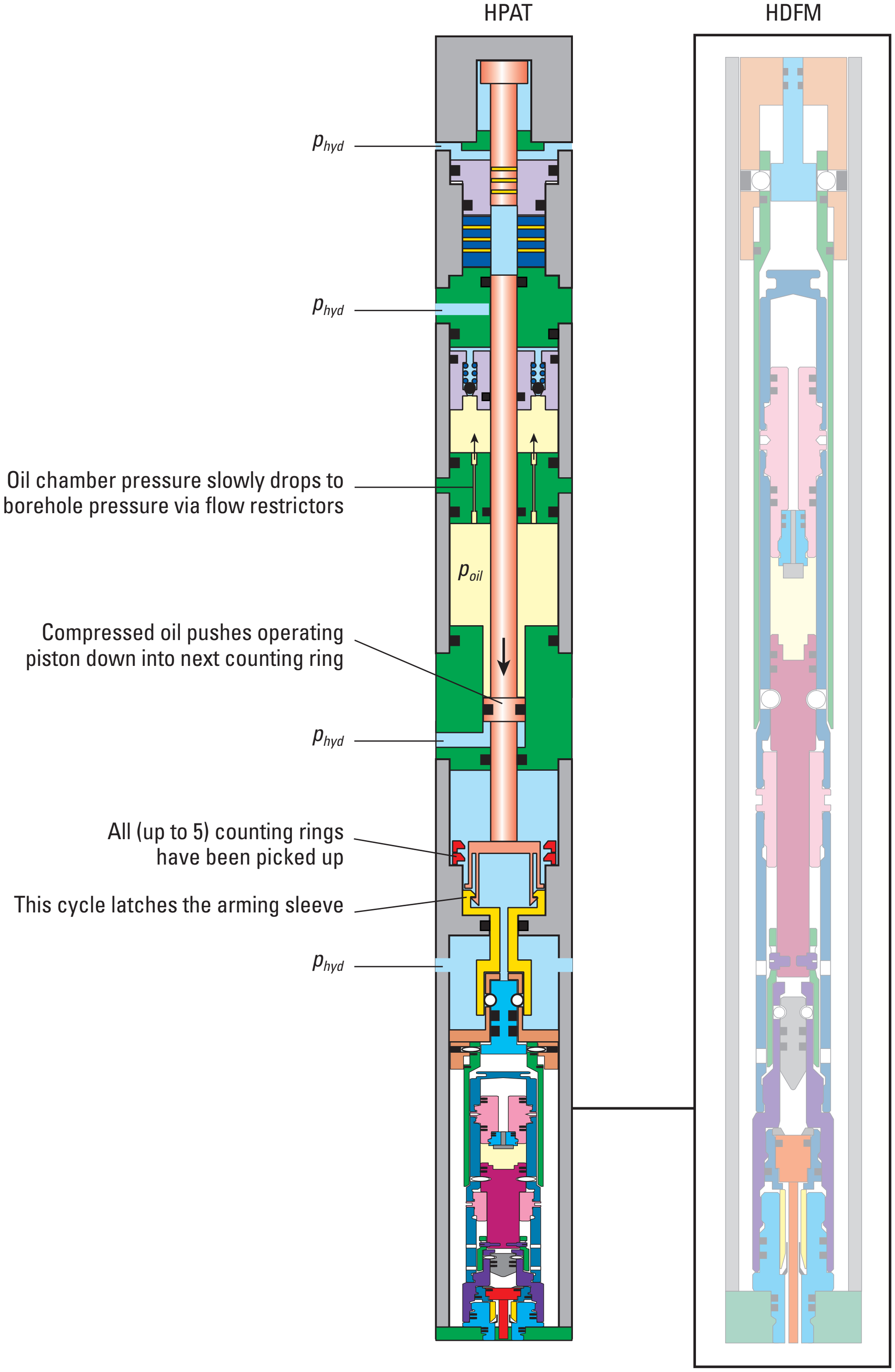

Figure 260. Pressure-down cycle latches next ring.

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The last pressure cycle (Figs. 261 and 262) causes the operating piston to pull the arming sleeve up and release the locking balls. The release of the locking balls enables the fluid pressure to push the release sleeve piston down, flooding the delay module chamber. At the same time, the release sleeve piston releases a second set of locking balls to allow fluid pressure to push the lock release sleeve up. This action unlocks the module and starts the metering.

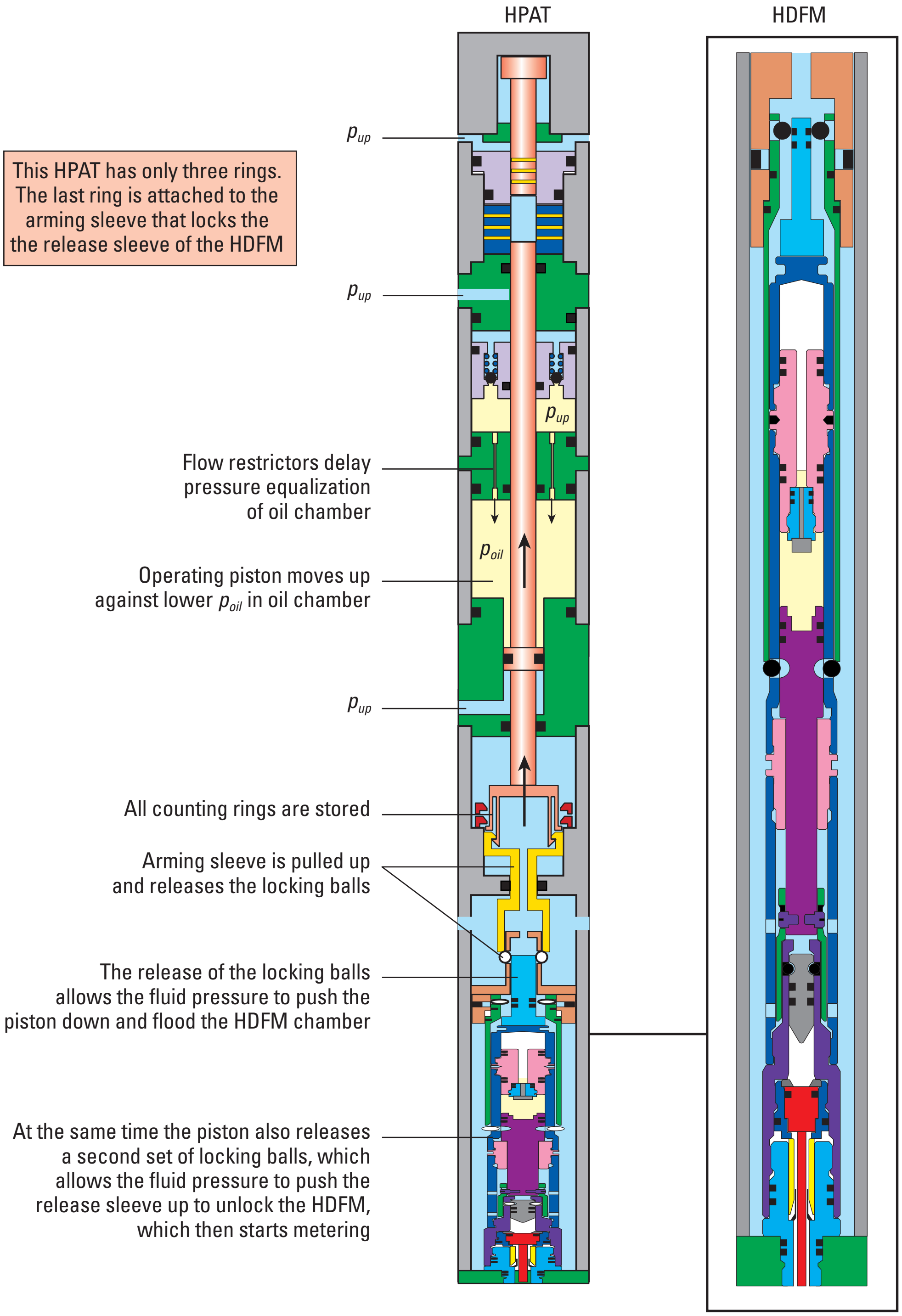

Figure 261. Next pressure-up cycle picks up the arming sleeve.

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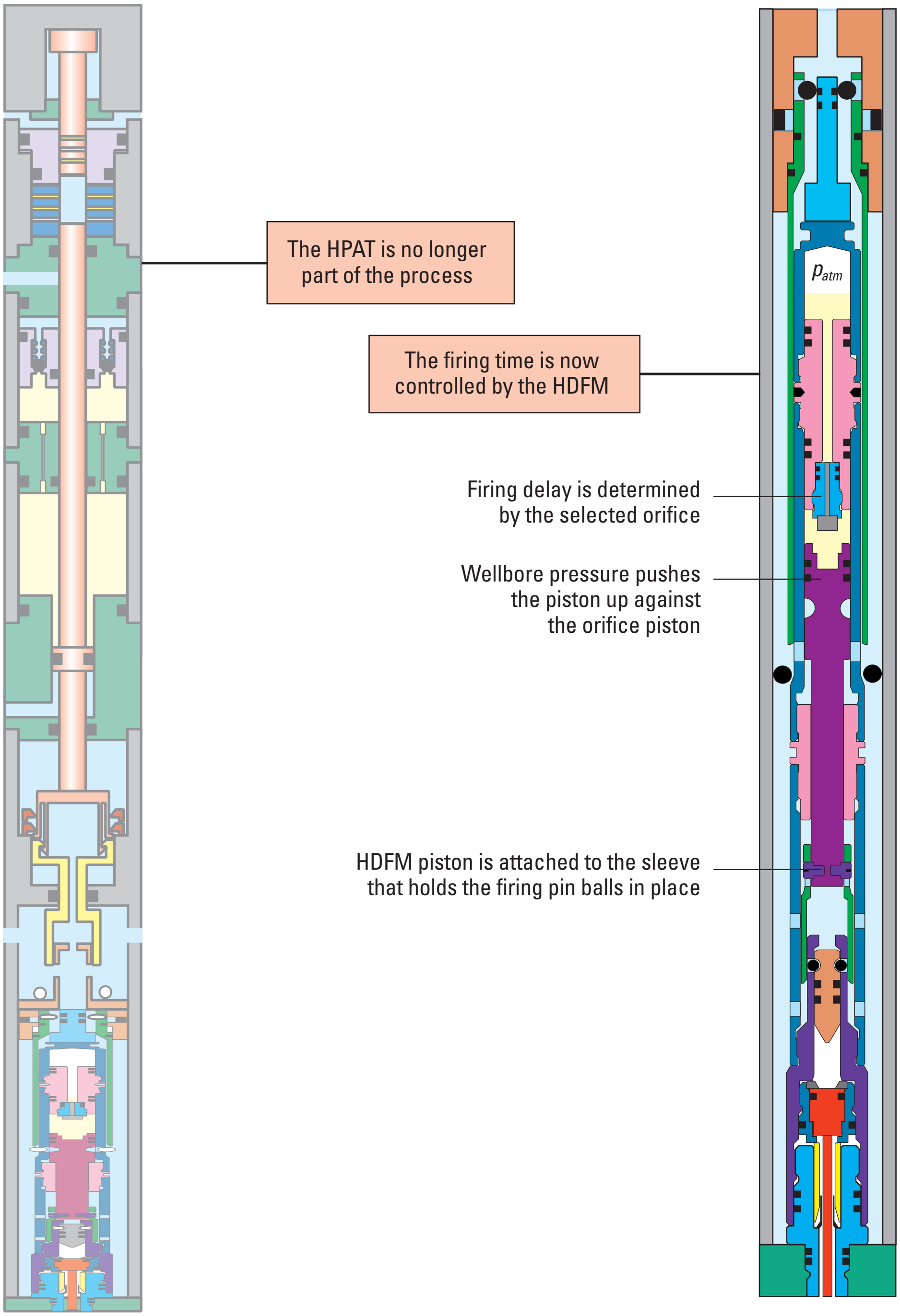

The HPAT is no longer part of the process

The firing time is now controlled by the HDFM

Firing delay is determined by the selected orifice

Wellbore pressure pushes the piston up against the orifice piston

HDFM piston is attached to the sleeve that holds the firing pin balls in place

Figure 262. Last pressure-up cycle starts the firing delay process.

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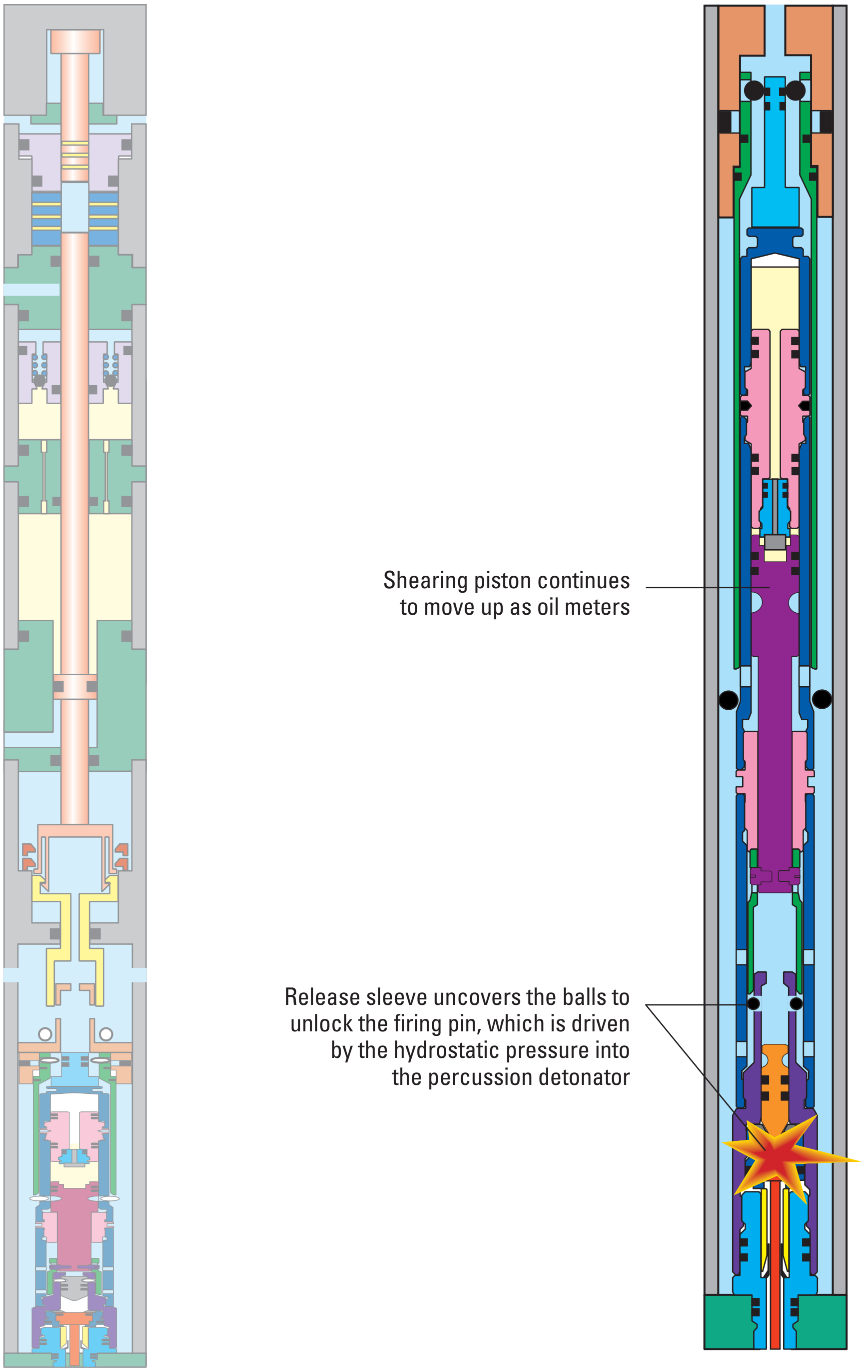
Last, the guns are fired (Fig. 263). The orifice selected determines the delay module metering. The unlocking of the firing pin and subsequent detonation are similar to those of the HDF head. Once the metering action starts, the actuator is no longer involved in the process.



Shearing piston continues to move up as oil meters

Release sleeve uncovers the balls to unlock the firing pin, which is driven by the hydrostatic pressure into the percussion detonator

Figure 263. Guns fire when the time delay is completed.

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The evolution of the pressure inside the tool is depicted in Fig. 264. The transient pressure (purple curve) is built in the main oil chamber as a result of the flow restrictors. For proper functionality a minimum of 1,000-psi differential pressure (difference between compensating oil chamber pressure and main oil chamber pressure) must be achieved. This is done by ensuring that the pump rate is above 1,000 psi/min for high-flow-rate configuration or above 60 psi/min for low-flow-rate configuration.

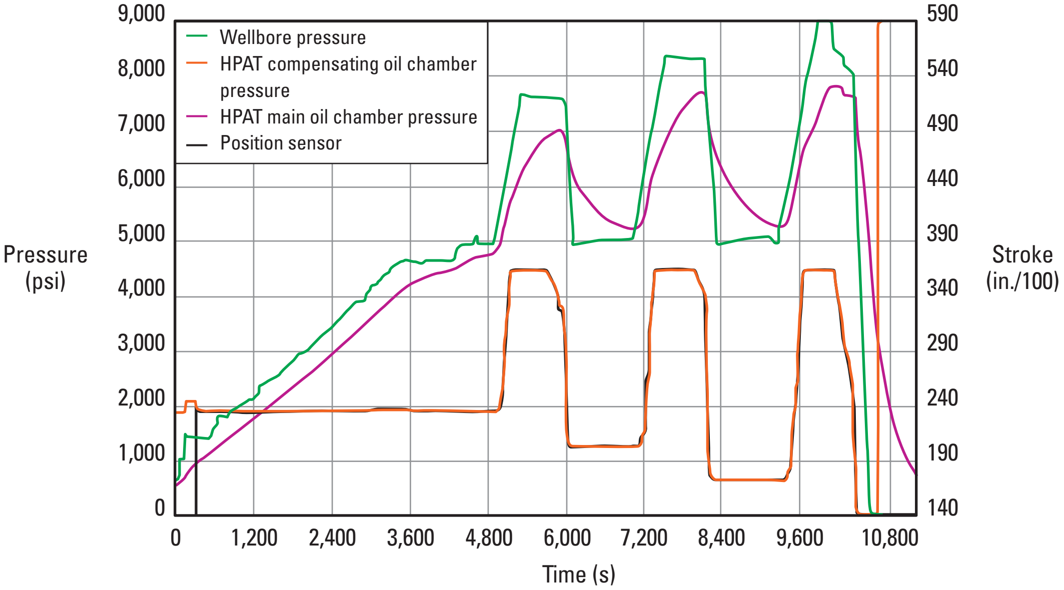

Figure 264. Example profile of a ProFire pressure cycle.

Differential pressure firing system

The differential pressure firing system (DFS) activates the DPF head by using the differential pressure created between the annulus pressure above the packer and the cushion or sump pressure below the packer (Fig. 265 and Table 127). The fullbore packer conversion system routes annulus pressure through the packer to the DPF head. An additional firing head can be installed for redundancy.

The DFS is designed to work with a DST string and can be used with other completion types as well. The combination of the DFS and a fullbore redundant firing system can be used for one-trip underbalanced perforating and completion operations.

The pressure-transfer assembly and flow tube route the hydrostatic pressure above the packer through either a Schlumberger PosiTrieve or FlexPac (Fig. 266) high-performance packer and then down an integral flow path in the debris sub and spacer pipe to the DPF head. The oil piston automatically closes to prevent formation pressure from entering the annulus after the packer has been set and the guns fired.

The DPF head detonates the perforating guns when the required pressure differential across the packer is generated. Firing can be accomplished in several ways, depending on job design and the other downhole tools used, including

- firing immediately on test valve opening, as rathole pressure drops to the tubing cushion pressure
- firing after test valve opening as cushion backpressure is reduced
- firing after test valve opening as pressure increases on the annulus

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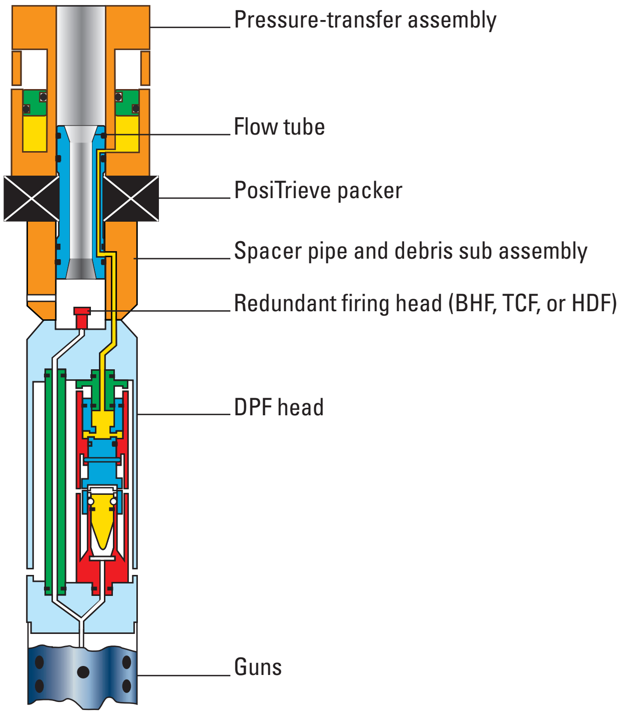

Figure 265. DFS incorporating a PosiTrieve packer.

Table 127. DFS Specifications

Outside diameter	
Pressure transfer assembly (in.)	5
Spacer pipes (in.)	4.62
DFS fullbore redundant head (in.)	4.62
Inside diameter	
PosiTrieve packer (in.)	1.53
FlexPac packer (in.)	2.25
Top connection	3½ IF box
Casing size (in.)	>7
Temperature rating (°F [°C])	400 [204][†]
Min. operating pressure (psi)	500
Differential pressure rating (psi)	10,000
Shear pins average pressure range	
Short hollow (psi)	310 to 335
Short (psi)	625 to 665
Long (psi)	1,250 to 1,325
Tensile strength[‡] (lbf)	215,000
H_2S service	Yes

[†] For temperatures above 400°F or extended operations, special seals and explosives are required. See Table 17 and Fig. 84 in the "Operating Environment and Engineering of Perforating Operations" chapter and consult with your Schlumberger representative if the temperature or time exposure exceeds the HMX curve.

[‡] At minimum yield (ambient temperature per material certification)

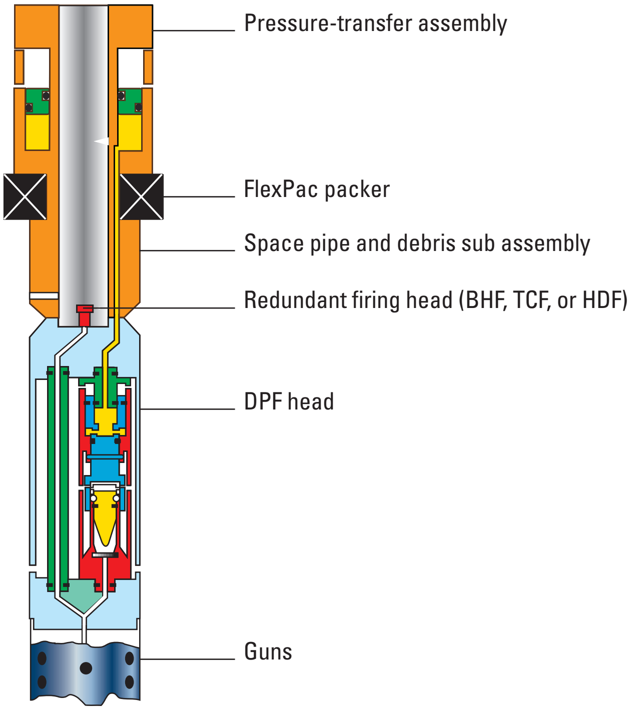

Figure 266. DFS incorporating a FlexPac packer.

- firing without a test valve by displacing a light fluid cushion, setting the packer, and reducing cushion backpressure or applying pressure to the annulus or both.

A redundant firing head, such as a BHF, HDF, or TCF head, can also be used with the DPF head.

Differential pressure firing head

The pressure-operated DPF head includes four main components (Fig. 267a) that function in the following sequence:

- Piston—The piston is exposed to annulus pressure and below-packer pressure.
- Shear pins—These pins determine the firing pressure differential. The annulus pressure must be higher than the tubing pressure for the head to fire.
- Release sleeve—The sleeve and ball bearings lock the firing pin in safety position while running in the hole. Below-packer pressure cannot act on the firing pin until the release sleeve is moved upward.
- Firing pin—When released by upward travel of the piston and release sleeve, the firing pin is driven down by below-packer pressure. The percussion detonator begins the gun detonation train upon impact by the firing pin.

When the differential pressure across the packer exceeds the shear pin rating of the DPF head, the piston moves up, shearing the pins and pulling the release sleeve up to uncover the ball bearings (Fig. 267b). The below-packer pressure then forces the firing pin down into the percussion detonator, initiating detonation of the gun string (Fig. 267c).

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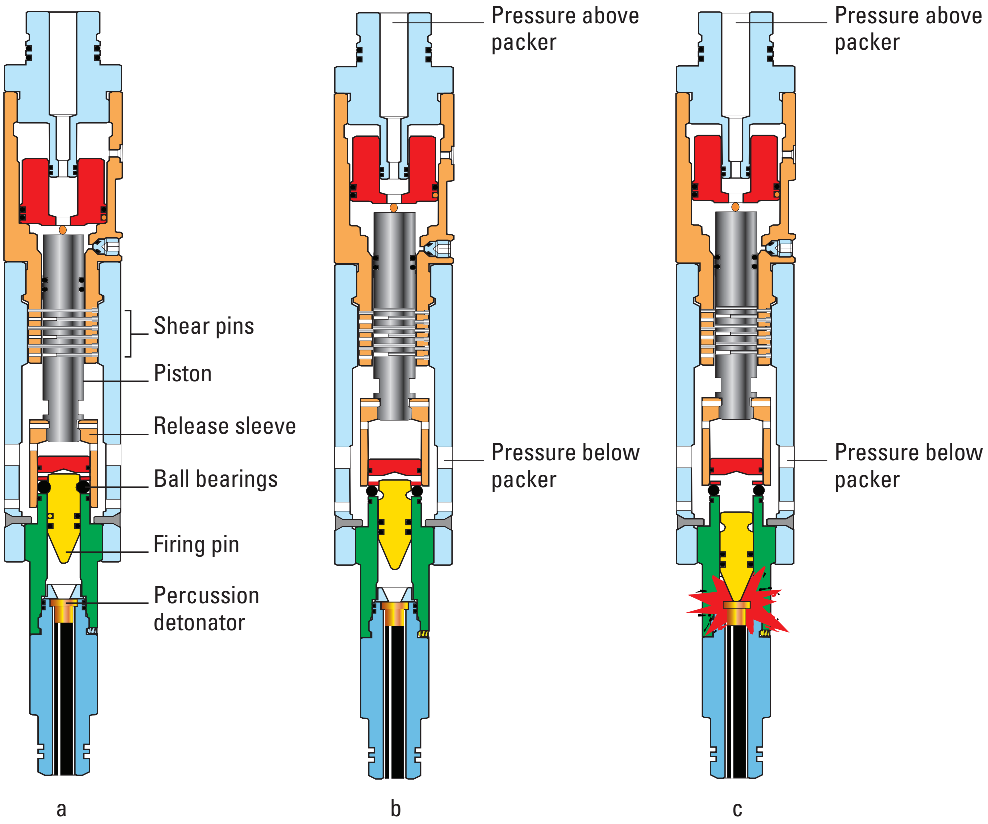

Figure 267. (a) Pressure-operated DPF head before firing. (b) DPF head with pins sheared. (c) DPF head detonation.

Features and benefits

- Differential pressure control—Differential pressure across the packer activates the firing head. When the packer is correctly set, the pressure difference can be obtained by pressuring the annulus, reducing tubing pressure, opening a test valve, or by doing some combination of these procedures. When the differential pressure exceeds the predetermined value, the shear pins break, releasing the ball bearings that secure the firing pin.
- Rathole pressure firing—Pressure in the rathole propels the released firing pin down onto the percussion detonator. A minimum pressure is required to fire the percussion detonator (Table 127).
- Adjustable operating pressure—The firing head shear pins can be selected to operate at differential pressures ranging from 500 to 10,000 psi in nominal increments of 300 to 1,200 psi.
- Compatibility with well testing and pressure testing—Adjustable operation of the DPF head makes it compatible with other pressure-operated equipment such as DST tools. The firing head also allows pressure testing of the casing and test string before perforating.
- Controlled tension release (CTR)—The CTR can be installed in the gun string to enable removal of the completion string if the guns become sanded in and stuck. The guns can then be fished separately.

Safety considerations

For safety at the surface, the DPF head requires a minimum rathole pressure of 150 psi to drive the firing pin into the percussion detonator. The release piston is protected and thus cannot be accidentally struck by falling debris inside or outside the string. If the guns flood, the pressure is

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balanced across the firing pin to prevent firing. The gun string remains sealed if a ballistic misfire occurs in the firing head.

Unless the packer is properly set, differential pressure cannot be built up, and the shear pins cannot be sheared. This firing system was specifically designed for combination with DST operations. Communication between the formation and the annulus through the pressure transfer assembly is prevented by the oil piston.

Inclusion of a safety spacer is required on top of the gun string to ensure that the guns are below the rig floor when the firing head is connected or disconnected (Fig. 268). In case of trapped pressure in the safety spacer, a pressure vent in the firing head adapter is used to bleed off the pressure. Hardware to prevent trapped pressure is available and its use is recommended.

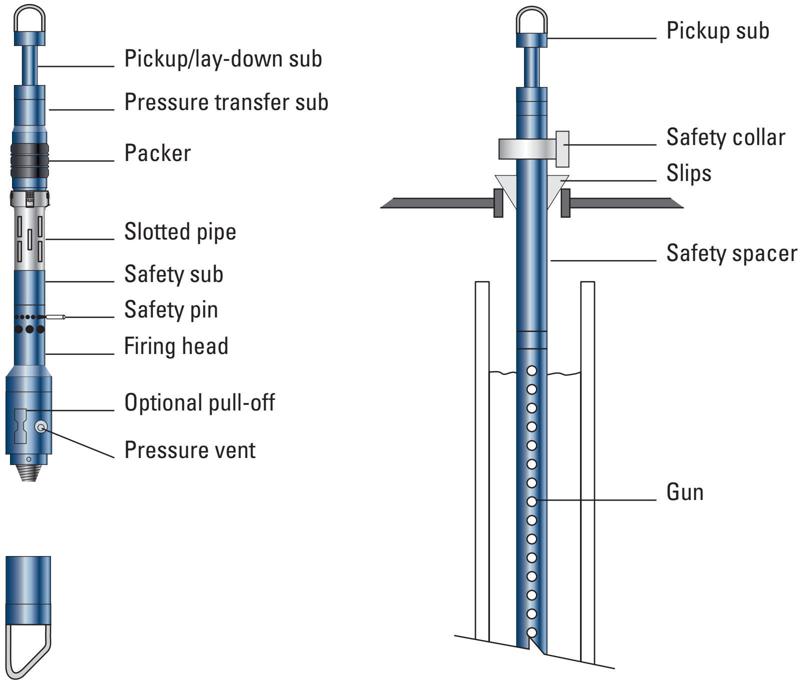

Figure 268. The guns are well below the rig floor when the firing head is connected.

Applications

- Impulse tests and DSTs—The DFS is ideal for impulse tests and DSTs where guns are run below a downhole test valve. The system operates at any deviation and is practically immune to debris.
- Existing open perforations—Opening the test valve while simultaneously firing the guns is an option for applications when there are open perforations in the well.
- Firing redundancy—The HDF head can be used as a redundant firing head with full fluid columns or nitrogen application from the surface. Redundant BHF, HDF, or TCF heads can also be used with the DPF head.
- Underbalanced operations—Underbalance can be established as a closed system with the downhole test valve. Alternatively, underbalance can be established as an open system by circulating light fluid through the packer bypass or by displacing the tubing fluid with nitrogen.
- Deviated wells—Well deviation does not limit use of the DPF head, which is also unaffected by heavy mud or tubing restrictions.

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DFS operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, DFS operations begin with thorough design and planning using the applicable flowchart.

Design and planning

Successful jobs using the DPF head require careful calculation of the pressure in the well when the guns fire. The shear pins are selected on the basis of the pressure calculation to ensure that the head fires at the correct time. The packer in the DFS is set to create a differential pressure across the piston in the firing head that holds the release sleeve. To achieve the differential between higher pressure above the packer (in the annulus) and lower pressure below the packer (in the rathole), either the annulus is pressured up, the pressure in the rathole is lowered, or both methods are combined.

The DPF head calculation is used to guide the pressure calculations, which include the annulus pressure (hydrostatic pressure plus applied pump pressure) and rathole pressure at the time the guns fire:

$$p_t = p_h + p_a + p_{ra}, \tag{19}$$

where

p_t = total activating pressure

p_h = hydrostatic pressure in the annulus above the packer

p_{ra} = rathole pressure at the depth of the firing head at the time of firing

p_a = maximum additional pressure that may be applied during the operation before firing.

The additional pressure p_a is included in the calculations to avoid premature firing. This pressure could be induced by circulating valve operation, casing test, packer setting or stabbing in, packer test, overpressure to break circulation, water hammer, DST tool string maximum operating pressure, and other operations.

The rathole pressure p_{ra} usually decreases when the DST valve is opened. After the DST valve is opened, the rathole pressure is the hydrostatic pressure of the fluid in the pipe string.

After the differential pressure and the most suitable pins are determined (Fig. 269), the upper and lower pressure limits (±5% of the shear pin value) are calculated and confirmed that they can be achieved safely (Fig. 270).

Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

Execution

The firing system typically is assembled at the wellsite. The detonator is placed in the assembly on the deck, away from the loaded guns. The system is considered armed only after the head is attached to the live gun string, with the following procedure:

1. Ensure that all guns are properly made up in the correct order and set the safety spacer in the slips with a safety clamp installed.
2. Pick up the pressure-transfer assembly, packer, and firing head assembly and hang it in the blocks above the safety spacer.
3. Stab the assembly into the safety spacer.
4. Tighten all connections to the proper torque.
5. Continue running in hole.

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Number of long pins $= \dfrac{p_t}{1.34 \times G \times 0.95 \times \text{TVL}} =$ ____________

To find the correct shear pin combination:
If decimal portion is ≥ 0.75, add a long pin.
If decimal portion is ≤ 0.75 but ≥ 0.5, add a short pin and a hollow short pin.
If decimal portion is ≤ 0.5 but ≥ 0.25, add a short pin.
If decimal portion is ≤ 0.25 but ≥ 0, add a hollow short pin.

Number of long pins used = A
Number of short pints used = B
Number of hollow short pins = B_H

p_t = Total activating pressure
1.34 = Correction factor for HDF shear pins when used in the DPF head
G = Temperature correction factor from chart
0.95 = Nominal shear pin value for 5% tolerance
TVL = True value of long shear pins
TVS = True value of short shear pins
TVH = True value of hollow short shear pins

The true shear value (psi) is indicated on the shear pin package.

Discard pin if true value is unknown.

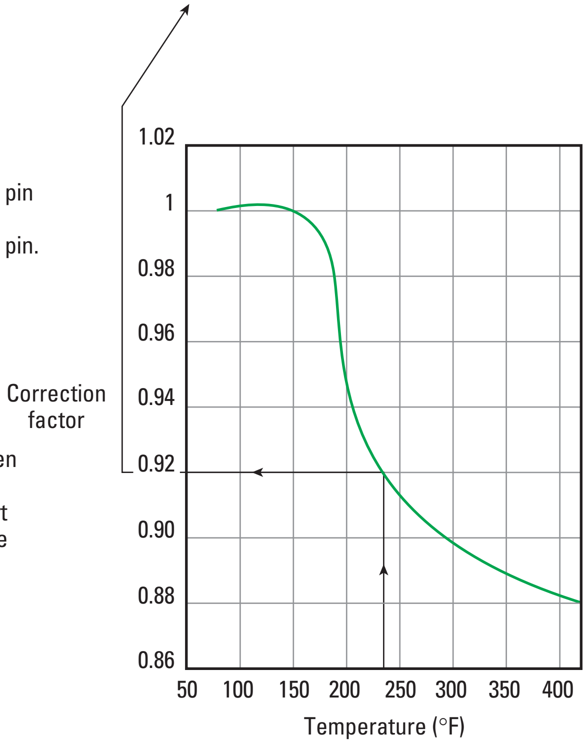

Figure 269. DPF pin calculation worksheet.

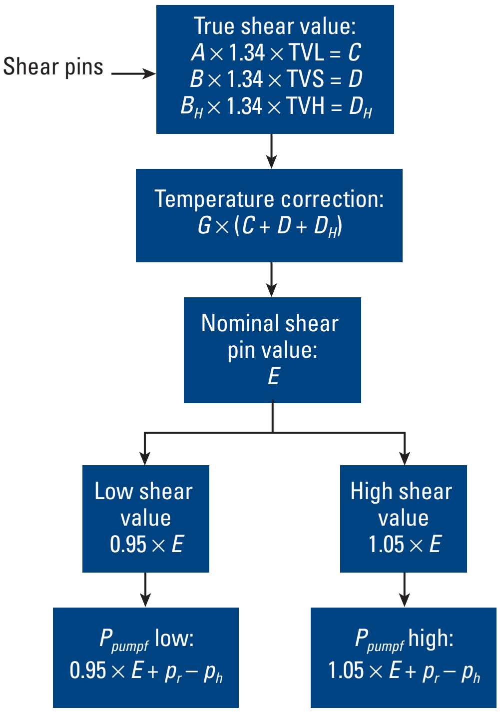

Figure 270. DPF shear pin verification. To the pump pressure p_{pumpf} is added 500 psi to ensure firing.

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The firing procedure involves activating the firing head by using the differential pressure between the annulus and the rathole, with three basic firing methods available:

- Pressure up the annulus—Using an open-ended workstring (without a test valve) or a test string (with a test valve), the packer is set and pressure applied to the annulus to create sufficient differential to shear the pins.
- Reduce rathole pressure—Using a test valve, the packer is set, the cushion is pressured up to hydrostatic pressure, and the test valve is then opened to reduce the cushion at the surface to shear the pins.
- Combination method—The workstring is displaced with a light cushion, the packer is set, the cushion pressure is then reduced, and pressure is applied to the annulus to shear the pins.

DFS operational procedure example

The example in Fig. 271 illustrates a combination of pressuring up the annulus to open the downhole valve and then reducing down the nitrogen cushion to fire the guns. Symbols labeled on the figure and their values are listed in Table 128.

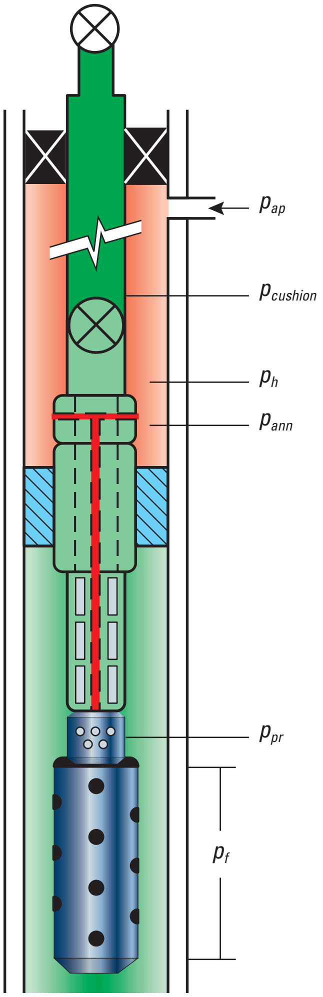

Figure 271. DPF head and TCP assembly.

Table 128. Symbols in Figs. 271 and 272

Symbol	Definition
p_h	Hydrostatic annulus pressure (transmitted to the firing head)
p_f	Formation pressure
p_u	Desired underbalance pressure
$p_{cushion}$	Cushion pressure at gun firing = $(p_f - p_u)$
p_{ra}	Rathole pressure = $p_{cushion}$ (after opening the PCT* Pressure Controlled Tester valve and reducing the nitrogen cushion)
p_{ap}	Pressure applied at surface to the annulus
p_{ann}	Annulus pressure = $p_h + p_{ap}$
$p_{ann} - p_{ra}$	Differential pressure sensed by the firing head

1. Run in with test string dry or partially dry (Fig. 272):

$$p_{ann} = p_{ra}.$$

   The values of p_{ann} and p_{ra} increase with p_h as the test string is run into the well.
2. Set the packer. Pressure up the tubing string with nitrogen gas to increase downhole pressure to approximately 1,000 psi above the desired value for the cushion pressure $p_{cushion}$ at gun firing:

$$p_{ann} = p_{ra} = p_h.$$

3. Open test valve by applying 900 psi to the annulus:

$$p_{ap} = 900 \text{ psi}.$$

   The value of p_{ann} increases to p_h + 900 psi.

   As the test valve opens, p_{ra} decreases from p_h (neglecting the rathole fluid compression) to $p_{cushion}$ + 1,000 psi. The annulus pressure holds steady, verifying that the packer is set.
4. Reduce the nitrogen to fire the guns. The value of p_{ra} decreases as the nitrogen is reduced from ($p_{cushion}$ + 1,000 psi) to $p_{cushion}$. The differential pressure increase from ($p_{ann} - p_{cushion}$ – 1,000 psi) to ($p_{ann} - p_{cushion}$) is transmitted to the shear pins of the firing head.
5. Fire the guns. The guns fire when the differential pressure reaches the value $p_{ann} - p_{cushion}$:

$$p_{ra} = p_{cushion}.$$

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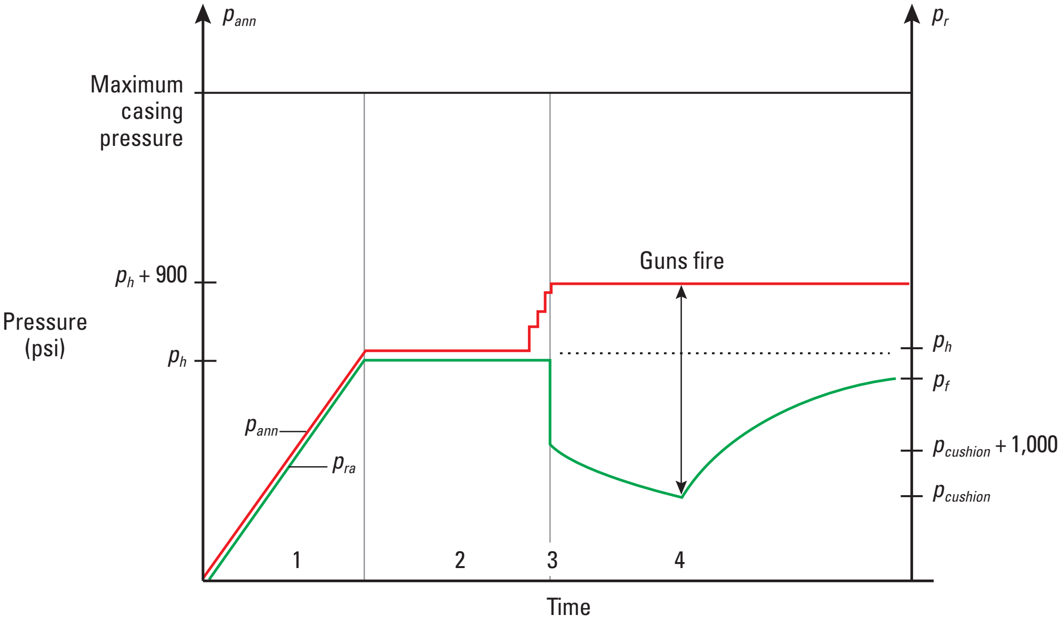

Figure 272. Sequence of events to fire DPF head.

Ball-activated and circulation ball drop–activated firing heads

The ball-activated firing (BCF) and circulation ball drop–activated firing (CBF) heads are designed for coiled tubing operations (Fig. 273). They allow circulation before and after firing the guns or other explosive devices, such as cutters. The CBF head (Fig. 274 and Table 129) was originally designed for well abandonment with coiled tubing to perform multiple operations during one trip in the hole, such as circulating for cleanup, perforating, and spotting a cement plug. Coiled tubing is now used mainly as a conveyor for perforating strings in highly deviated wells where cable cannot reach or if the total string weight is beyond the cable capacity, and the BCF and CBF heads enable multiple perforating techniques and the combination of other deployment systems.

The heads use the same hydrostatic firing mechanism as TCP firing heads, requiring a minimum hydrostatic pressure to fire. The initiation of the downhole detonation is controlled from the surface by first circulating a ball down to the BCF or CBF head. When the ball reaches the head and closes the circulating path by sealing the ball seat, the firing mechanism is activated by the differential pressure buildup across the operating piston, rather than by the absolute bottomhole pressure. For this reason, a well can be perforated in overbalanced or underbalanced condition. Because the operating piston must move upward in the CBF head (a feature not available with the BCF head) to release the firing pin, it is unaffected by water hammer effects and insensitive to vertical drops.

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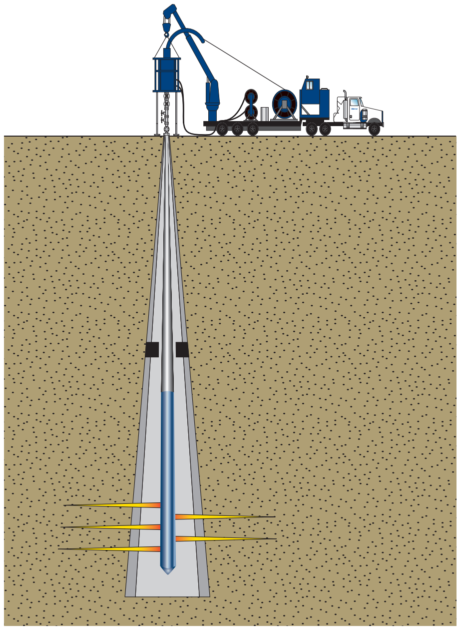
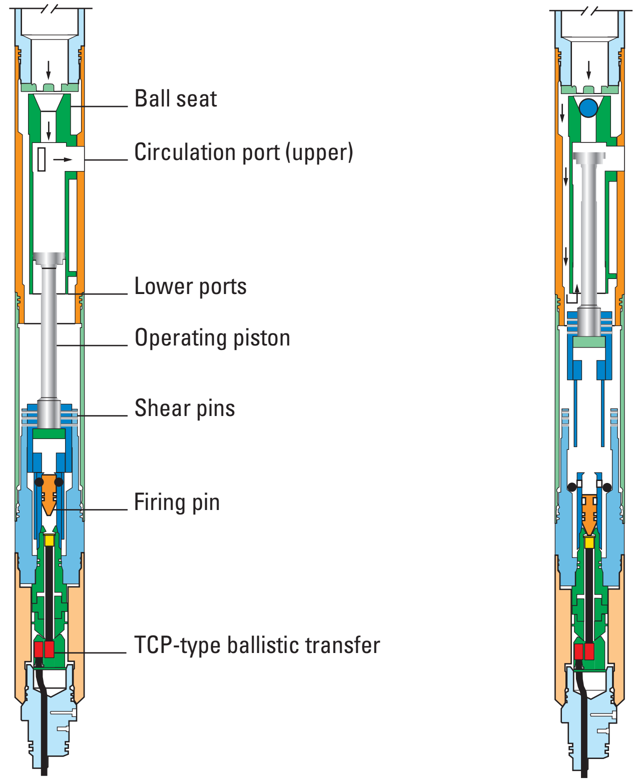


Figure 273. Coiled tubing perforating.



Circulation path

Pressure path to fire guns

Figure 274. 2.125-in. CBF head.

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Table 129. BCF and CBF Specifications

	BCF	CBF
Outside diameter (in.)	1.69	2.135
Temperature rating (°F [°C])	330 [165]	330 [165]
Pressure rating (psi)	20,000	25,000
Min. operating pressure (psi)	500	500
Min. shear pin setting (psi)	500	500
Max. shear pin setting (psi)	5,000	6,000
Max. differential pressure (psi)	na	8,500
Makeup length (in.)	23.41	30.34
Tensile strength at min. yield (lbf)	43,000	51,500
H_2S service	No	No
Flow area through firing head before firing		
⅝-in.-diameter ball seat (in.^{2})	0.248	0.233
½-in.-diameter ball seat (in.^{2})	na	0.162
Flow area through firing head after firing (in.^{2})	0.785	0.619

na = not applicable

Coiled tubing perforating operations with the BCF or CBF head can also employ techniques such as dropping guns or perforating without killing the well to minimize formation damage.

CBF heads are available in two sizes with multiple adapters to accommodate the various coiled tubing dimensions and gun sizes. CBF fill subs are also available to isolate the CBF from the tensile strength of the conveyor string. In this application, the fill sub carries the load while the CBF functions purely as a firing head (Fig. 275 and Table 130).

The BCF head (Fig. 276) was designed for applications requiring a firing head with a smaller OD. It is recommended for gun sizes of 2 in. or smaller.

Table 130. CBF Fill Sub Specifications

Hollow Carrier Gun OD (in.)	2.88	3.50	4.50
Max. OD† (in.)	2.895	3.515	4.535
Temperature rating‡ (°F [°C])	330 [165]	330 [165]	330 [165]
Pressure range (psi)	20,000	15,000	15,000
Collapse pressure (psi)	22,550	18,100	18,100
Differential pressure (psi)	8,500	8,500	8,500
Makeup length§ (in.)	46.0	44.1	44.1
Weight (lbm)	41.5	41.5	41.5
Tensile strength at min. yield (lbf)	222,000	374,000	374,000
H_2S service	No	No	No

† Dimensions include manufacturing tolerances.
‡ Limited by elastomers and explosives
§ Without gun adapter

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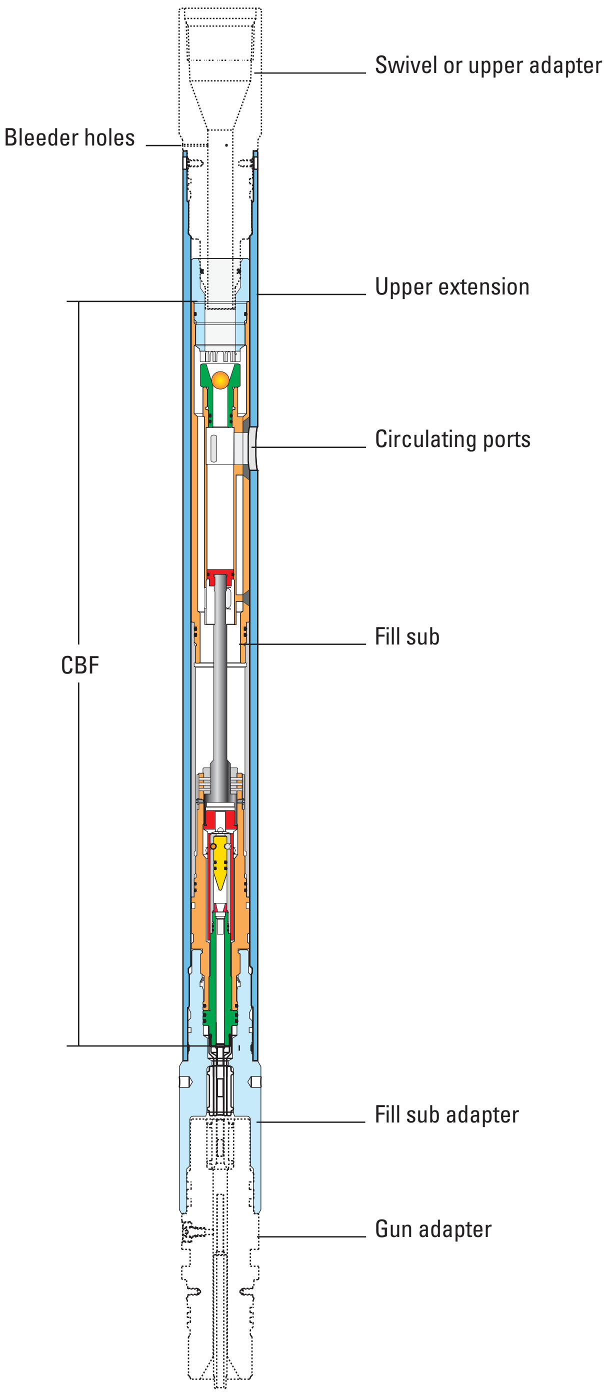

Figure 275. CBF fill sub.

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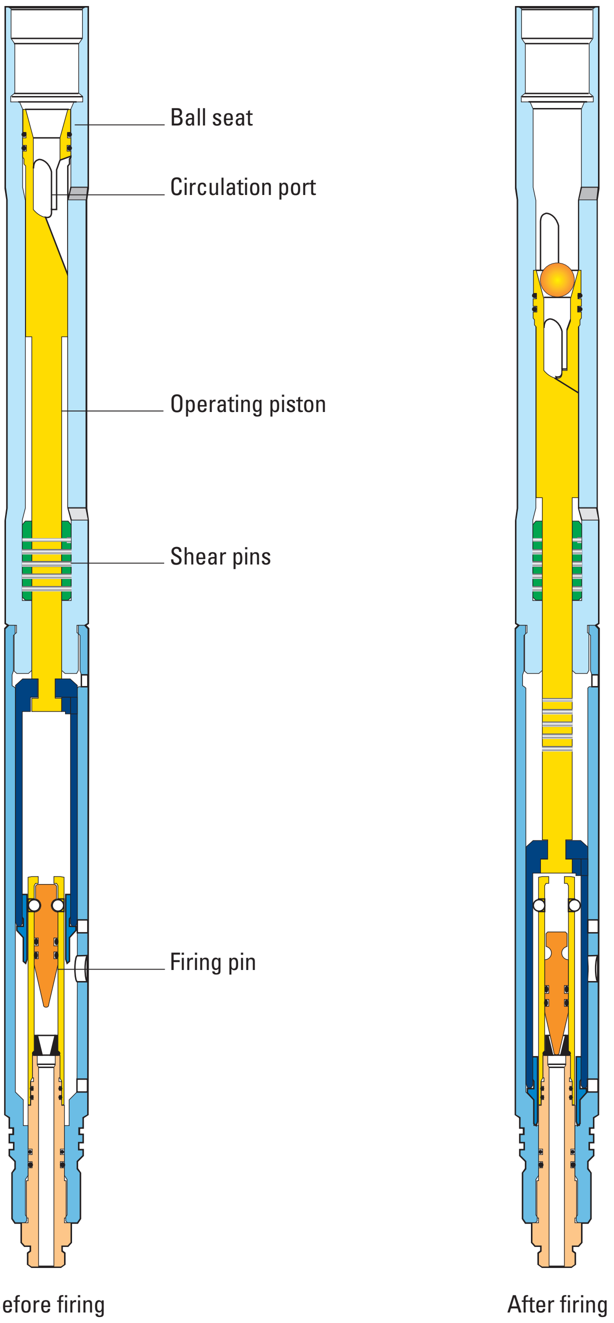

Figure 276. 1.6875-in. BCF head.

Features and benefits

- Circulation flexibility—Circulation is allowed in both directions prior to firing the guns. Underbalanced perforating conditions are easily established. The BCF and CBF heads also provide the ability to circulate after firing the guns.
- Pressure-balanced system—The CBF head is insensitive to water-hammer effects and vertical drops.
- Coiled tubing compatibility—The BCF and CBF heads can be connected to any coiled tubing string.

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Safety considerations

The firing head has a minimum hydrostatic pressure of 500 psi; however, caution is required when the guns are retrieved unfired. There must be no pressure in the surface wellhead equipment.

Schlumberger coiled tubing incorporates a BHA that eliminates accidental release and includes an all-purpose release joint for coiled tubing perforating. The assembly is a two-stage release mechanism that is not affected by pump or wellbore pressure.

The CBF head is also available for HPHT applications; contact your Schlumberger representative for more information.

Applications

- Highly deviated wells—Well deviation does not limit use of the BCF and CBF heads. The CBF head is also insensitive to water-hammer effects and vertical drops.
- Perforating long intervals in a single trip—Running on coiled tubing provides additional perforating capability and flexibility over other conveyance systems, including retrieving the gun strings under pressure while the well can produce at higher rates.
- Underbalance or overbalance, perforating, and treatment applications—Because differential pressure—rather than the absolute bottomhole pressure—is used to activate the firing mechanism, a well can be perforated in overbalanced or underbalanced condition.
- Single-trip well abandonment—Multiple operations can be performed during one trip, such as circulating and spotting a cement plug.
- Rigless operations—The CBF head is run on drillpipe and coiled tubing.

BCF and CBF operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, BCF and CBF head operations begin with thorough design and planning using the applicable flowchart, an abbreviated example of which is shown in Fig. 277.

Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and recorded in the RITE system.

Execution

The firing system typically is assembled at the wellsite. The detonator is placed in the assembly on the deck, away from the loaded guns. The system is considered armed only after the head is attached to the live gun string, with the following procedure:

1. Pressure-test the head to a value higher than the wellhead pressure before connecting to the guns.
2. Ensure that all guns are properly made up in the correct order and set the safety spacer in the slips with a safety clamp installed.
3. Rig up the coiled tubing surface equipment.
4. Break circulation to ensure that the tubing is free of obstructions. Make sure that the coiled tubing was cleaned and pigged or gauged before hooking up the head.
5. Pick up the head and its fill sub with the coiled tubing; connect it to the safety spacer. The system is now armed.

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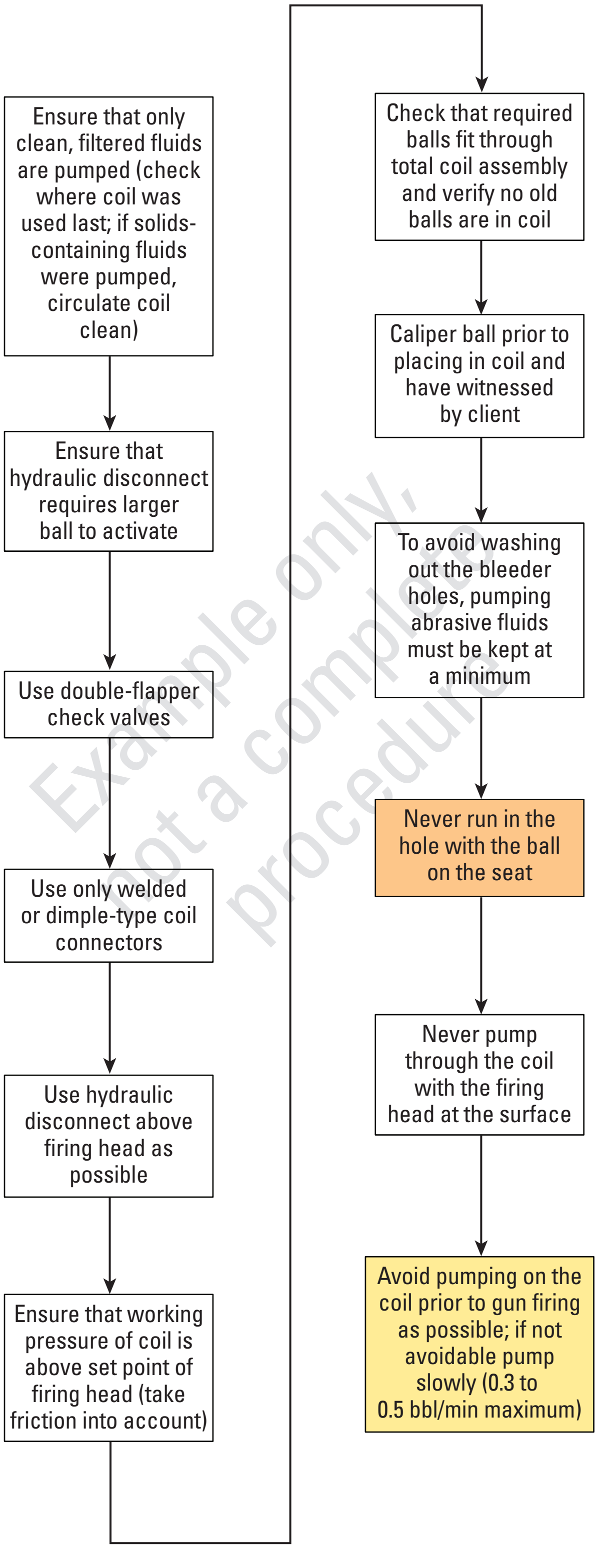

Figure 277. Excerpt of an example SDP design and planning flowchart for CBF operations.

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The coiled tubing surface equipment is then made up and the coiled tubing injected into the well. The guns are fired using the following procedure to introduce a ball into the coiled tubing and pump until it seats in the firing head.

1. Establish circulation by pumping into the coiled tubing and checking the returns.
2. Insert the firing head ball and pump slowly until the ball seats in the firing head. Seating is evident from the increased pumping pressure.
3. Increase the pump pressure until a sudden drop in pressure is noted. The guns should fire without any delay. Resuming circulation is possible after firing.

Universal setting tool with propellant

The universal setting tool with propellant (USTP) combines standard TCP firing heads (HDF, BHF, EOF, and coiled tubing heads) and propellant setting tools such as the casing packer setting tool (CPST) (Table 131). The USTP is used to set downhole equipment such as packers, bridge plugs, and the MAXR automatic release anchor on drillpipe, coiled tubing, slickline, or wireline. Other operations include TCP-style firing of chemical cutters and other propellant tools. The USTP configuration using a drop bar is shown in Fig. 278. A percussion igniter fits into the firing head. The system contains no explosives, yet is activated by the firing pin just as in conventional TCP gun firing. The flame generated by the propellant igniter upon activation ignites the power charge in the setting tool below. The flame can travel across a gap as large as 4 in. Adapters are available to connect conventional TCP firing systems to the Schlumberger CPST (see “Casing packer setting tool” in the “Wireline Perforating Techniques” chapter) and other models of setting tools and all sizes of chemical cutters.

Features and benefits

- Operational versatility—The USTP combines TCP firing head technology with setting tools and chemical cutters.
- Multiple conveyance modes—USTP operations can be conducted on drillpipe, coiled tubing, slickline, or electric line.

Applications

- Setting downhole equipment—Equipment such as packers, bridge plugs, and the MAXR are set using the USTP on drillpipe, coiled tubing, slickline, or wireline.
- Propellant operations—The USTP is used for TCP-style firing of chemical cutters and other propellant tools.

Table 131. USTP Specifications

Thread[†] (EUE)	2⅞
Outside diameter (in.)	3.68
Temperature rating (°F [°C])	350 [177]
Pressure rating (psi)	20,000

[†] Other sizes and thread types are available on request.

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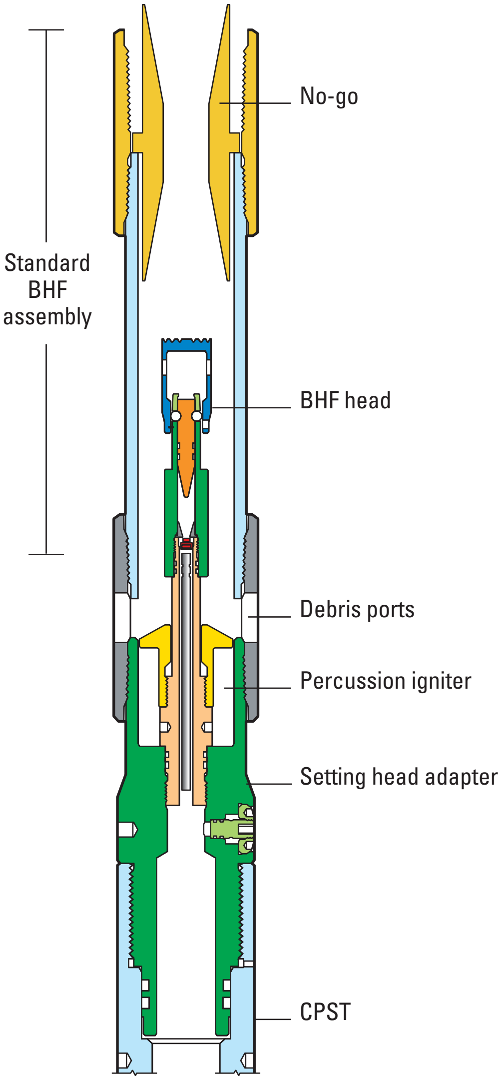

Figure 278. USTP configuration with drop bar.

Redundant firing systems

Two firing heads can be combined at the top of a gun string to provide backup firing capability (Fig. 279). For greater safety, both firing heads are positioned above the perforating guns and spaced apart from the guns with a safety spacer.

All individual safety features of the two redundant firing heads are preserved. No technical constraints dictate which firing head is activated first. Because the standard arrangement has an absolute pressure–activated firing head such as the HDF head as one of the systems, it is generally preferable to use this head as the primary firing head. If the primary head is a mechanical or electronic type and no shot is detected, pressuring the string to fire the secondary HDF could squeeze the formation of the primary head fired. The standard arrangement allows installation or removal of firing heads with the top shot below the rig floor.

The redundant fill sub configuration typically consists of the firing heads stacked one on top of the other in the same housing. The pressure-activated head is always installed on the bottom. If two pressure-activated heads are used, the primary head for firing should be installed on the bottom. Typical arrangements are BHF and HDF, TCF and HDF, and two HDF heads. Redundant

Figure 279. Redundant TCP firing heads.

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systems also include the ProFire and eFire firing systems. Some specific applications require installation of the firing head after installing the completion equipment. In these situations, the preferred method is to install the HDF in TCF mode by well intervention methods (i.e., slickline or wireline).

Any head can be used as the upper head, but if a drop bar or TCF head assembly is used then the string must be fullbore to provide mechanical access to the upper firing head. The minimum ID of the string must be sufficiently large to allow dropping the drop bar to the BHF head or for TCF conveyance. The lower firing heads can be any of the eFire, HDF, ProFire, or DPF heads. The DPF head is used by combining the DFS with the fullbore redundant firing system.

Configurations of three firing heads are available when additional redundancy is important, such as in permanent completions. For example, two ProFire heads can be combined with a TCF head (Fig. 280). The ProFire heads, run in place, are connected to a ballistic junction that propagates the detonation from the firing head simultaneously to X-Tools automatic releases such as the MAXR or SXAR above and to the gun string below. The TCF is used only as necessary before pulling the completion.

Several redundant head configurations are included in the “TCP Applications” chapter.

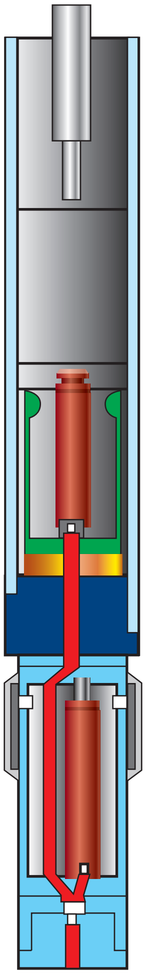

Figure 280. Two ProFire heads in conjunction with a TCF head.

Redundant configurations

Some of the redundant configurations are as follows:

- eFire and HDF heads
- two eFire heads
- BHF and HDF heads
- TCF and HDF heads
- two HDF heads
- DPF and HDF heads
- TCF and DPF heads
- two ProFire heads
- ProFire and TCF heads (HDF, jar down, or drop bar)
- ProFire and eFire heads.

Depending on the well environment and the job characteristics, other combinations and different sizes and threads can be designed on request. Contact your Schlumberger representative.

Selective and simultaneous firing

The use of multiple firing systems enables the selective perforating of two zones separated by a long interval. The lower zone is usually tested first and perforated using an HDF head. After the perforated lower zone is tested, the top zone can be perforated using any firing head except a pressure-activated head because of the following reasons:

- With another HDF head, the pressure increase on the tubing or rathole may not be possible to achieve with open perforations lower in the well.
- Rathole pressure may not be easy to predict for setting up the DPF head prior to running into the well.

Another possibility is to simultaneously perforate the two zones if pressure compatibility and produced fluids enable commingling. HDF heads are used for both zones. The HDF delay times are the same, and both zones are perforated at approximately the same time within the precision of the delays.

For perforating more than two zones, an HDF head can be used for each gun section. This technique is particularly useful and reliable where there are long intervals between multiple zones. It is preferred to the alternative of using one firing head, or a redundant firing system, and connecting long intervals with blank perforating guns. This alternative method, with its added complexity of multiple ballistic transfers, may not be technically practical or cost effective.

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Completion Perforating Equipment

A variety of equipment is necessary for a TCP completion. The objectives of the completion operation determine whether the equipment is run singly or in combination with other equipment. This chapter describes completion perforating equipment developed and provided by Schlumberger, grouped into the following categories:

- debris prevention
- gun release systems
- radioactive marker sub
- production and isolation valves
- shock absorbers
- sealed ballistic transfer
- orienting equipment
- dual and selective multiple-completion hardware
- pump-over perforating guns.

Debris prevention

Schlumberger debris-prevention equipment for TCP operations comprises the long-slot debris-circulating sub and fluid and debris-isolation sub.

Long-slot debris-circulating sub

The long-slot debris-circulating sub (LSDS) consists of a ceramic cone seated in a ported sub (Fig. 281 and Table 132). The sub is positioned between the packer and the guns, typically 30 ft above the firing head. The space below the sub is filled with a clean fluid. Before the packer is set, the assembly above the sub can be circulated with wellbore fluid to remove any debris that may have settled inside the sub. The long circulation slots allow relatively large debris to fall out into the annulus and not accumulate on the ceramic cone.

A debris-circulating sub is often used with BHF systems to prevent debris from settling on the downhole firing head. The drop bar easily breaks the frangible cone before reaching the firing head. Caution is necessary when breaking the cone by running the trigger charge, however, because debris can become trapped inside the lower housing of these assemblies. Breaking the cone after the correlation GR-CCL run or during a separate wireline or slickline run is sometimes preferable.

The LSDS can be customized to match the completion specification and metallurgy; contact your Schlumberger representative for more information.

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Figure 281. LSDS.

Table 132. LSDS Specifications

Thread[†] (8 RD, EUE)	2⅜	2⅞	3½
Outside diameter (in.)	3.06	3.67	4.50
Min. ID (in.)	2.00	2.44	2.99
Length (in.)	23.0	23.0	23.0
Flow area through valve (in.^{2})	3.25	4.68	7.02
Number of ports	3	3	3
Ports flow area (in.^{2})	17.35	17.35	17.35
Yield strength (lbf)	172,000	235,000	344,500
H_2S service		Available on request	

[†] Other sizes and thread types are available on request.

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Applications

- Debris protection—The cone prevents debris from settling on the firing head. The conical shape allows debris to exit through the sub ports into the annular space.
- Establishing underbalance—Before the packer is set, a lighter fluid can be circulated through the tubing to create the required underbalance condition.
- Perforated nipple for production—After the guns are fired, the ports of the sub allow formation fluid to flow to the surface through the tubing. Ports are sized to provide an unrestricted flow area greater than the tubing flow area.

LSDS operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, LSDS operations begin with thorough design and planning using the applicable flowchart, an abbreviated example of which is shown in Fig. 282.

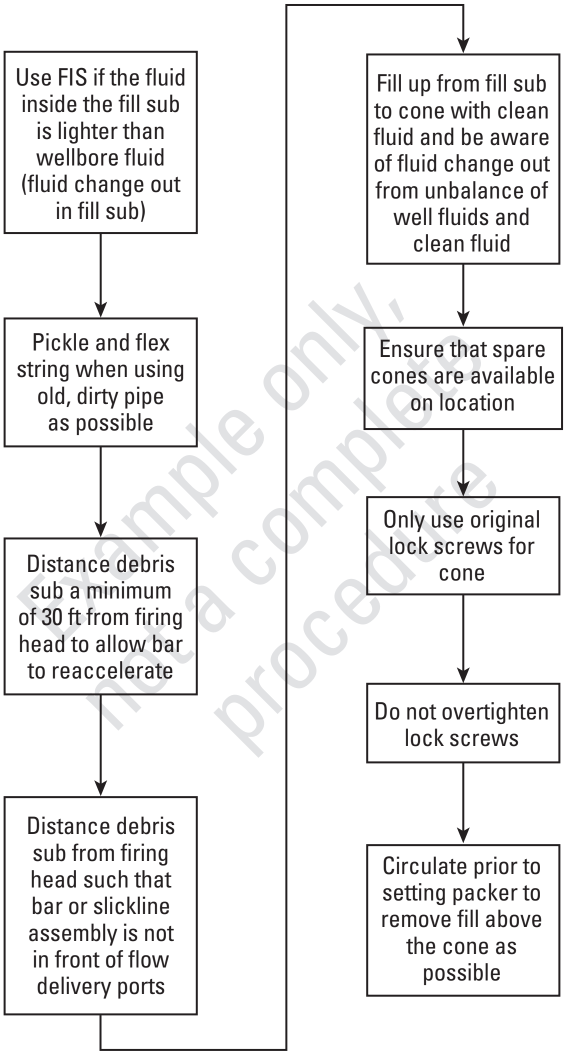

Figure 282. Excerpt of an example SDP design and planning flowchart for LSDS operations.

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Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

Execution

As possible, dirty strings should be circulated periodically on the way down. Circulation prevents debris accumulation that often results in plugged tubing above the cone. The frequency of circulation depends on the initial cleanliness of the string. At least one tubing volume should be circulated before the packer is set. A typical pump rate is 2 bbl/min. If plugging occurs, reverse circulation may unclog the ports.

Fluid and debris-isolation sub

The fluid and debris-isolation sub (FIS) adds a fluid-isolation function to the standard cone-type debris-circulating sub (Fig. 283 and Table 133). The FIS is used as an alternative to the LSDS in heavy mud environments or where large amounts of debris are expected.

The long circulation slots allow relatively large debris to exit to the annulus, avoiding accumulation on the ceramic cone. The heavier annulus fluid traps the lighter clean fluid in the space between the cone and the firing head. The lighter fluid cannot be displaced by the heavier annulus fluid. Firing head operation is therefore unaffected by mud and debris.

Applications

- Operations with large amounts of debris or heavy mud—The FIS is recommended for operations in which larger amounts of debris are expected and when heavy muds are used. The fluid-isolation feature keeps clean fluid around the firing head, ensuring reliable operation.
- Debris protection—The cone prevents debris from settling on the firing head. The conical shape allows debris to exit through the sub ports into the annular space.
- Establishing underbalance—Before the packer is set, a lighter fluid can be circulated through the tubing to create the required underbalance condition.
- Perforated nipple for production—After the guns are fired, the ports of the sub allow formation fluid to flow to the surface through the tubing. Ports are sized to provide an unrestricted flow area greater than the tubing flow area.
- Completion operations—The FIS is typically made with premium tubing threads to fit the completion string. The material for the FIS can be selected to fit the completion string. Larger sizes are usually custom made to fit the completion.

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Figure 283. FIS.

Table 133. FIS Specifications

Thread† (8 RD, EUE)	2⅜	2⅞	3½
Outside diameter (in.)	3.06	3.67	4.50
Min. ID (in.)	2.00	2.44	2.99
Length (in.)	27.0	27.0	27.0
Flow area through valve (in.^{2})	3.25	4.68	7.02
Number of ports	3	3	3
Ports flow area (in.^{2})	17.35	17.35	17.35
Yield strength (lbf)	137,000	198,000	272,000
H_2S service	Available on request		

† Other sizes and thread types are available on request.

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FIS operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, FIS operations begin with thorough design and planning using the applicable flowchart, an abbreviated example of which is shown in Fig. 284.

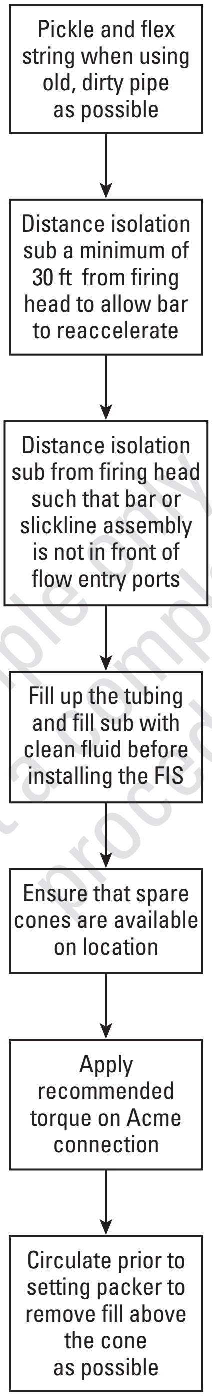

Figure 284. Excerpt of an example SDP design and planning flowchart for FIS operations.

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Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

Gun release systems

X-Tools gun-activated automatic release

The X-Tools automatic release mechanism developed by Schlumberger achieves extremely fast release times because it is closely linked to the detonating process. Figure 285 depicts the timing of various responses initiated by activation of the firing head. X-Tools release tools operate immediately after the guns fire but before the wellbore reacts. By contrast, a mechanically or pressure-activated device reacts only after wellbore effects have taken place. When dropping guns, the speed of activation is crucial to effects such as sanding. The speed of activation is also critical when dropping guns in highly deviated wells. Firing the guns creates very short dynamic movements that reduce friction and help convey the guns to the bottom of the well. For this dynamic movement to take place, however, release must occur at the instant of firing.

Schlumberger has developed a range of automatic gun release systems incorporating perforating gun–activated X-Tools technology. The closed tubing automatic gun release (CTXR) and automatic gun release (SXAR) are in this chapter; the monobore automatic release anchor (MAXR) and wireline-conveyed X-Tools automatic release (WXAR) are covered in detail in the following “Completion Perforating Without Killing the Well” chapter.

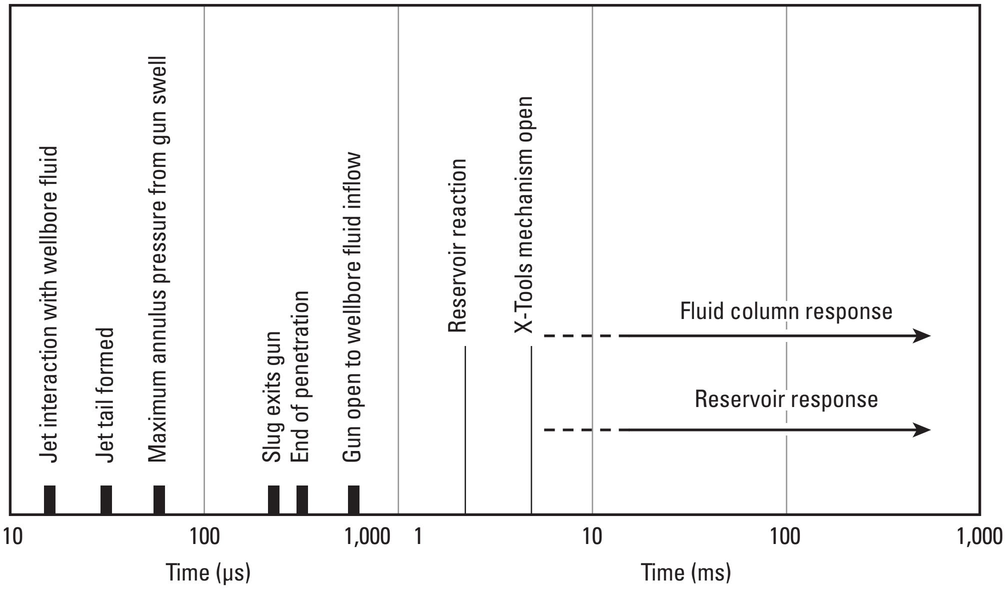

Figure 285. Timing of perforating events after charge initiation.

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Closed tubing automatic gun release

The closed tubing automatic gun release (CTXR) (Fig. 286 and Table 134) uses reliable X-Tools technology to automatically disconnect TCP guns in both open and closed tubing systems, including closed systems in which the tubing pressure is less than the wellbore pressure, such as PURE operations for clean perforations.

Automatically dropping the perforating guns to the bottom of the well at the instant of the high-order detonation of the detonating cord prevents the gun string from becoming stuck or sanded-up in unconsolidated sand formations. It allows access to the perforated zone for production logging and other remedial wireline operations. The need for slickline or pressure-activated drop-off after the shot is eliminated.

The CTXR is compatible with a range of firing heads, including eFire, BHF, HDF, TCF, and ProFire heads. Full tubing opening is provided after dropping the gun string, and the release housing attached to the tubing incorporates a wireline entry guide.

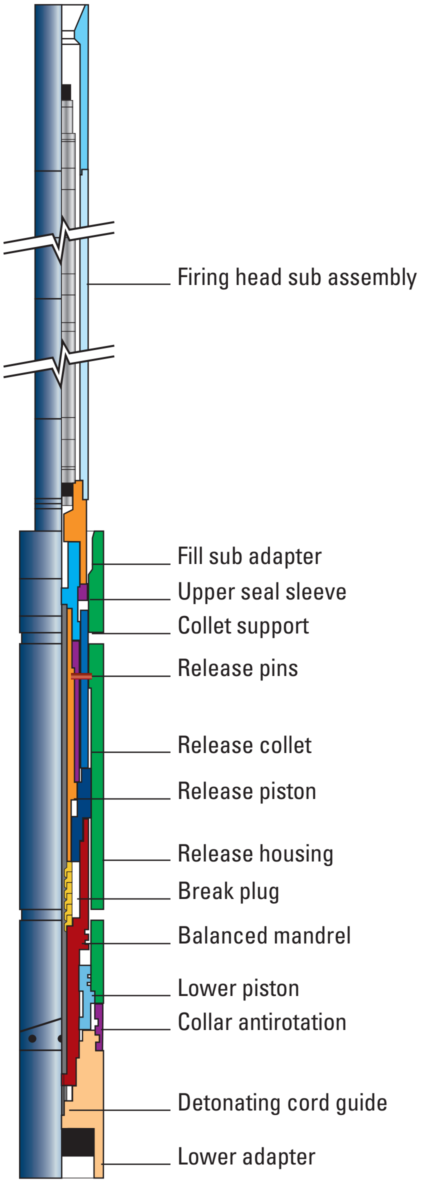

Figure 286. CTXR.

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Table 134. CTXR Specifications

Outside diameter[†] (in.)	3.69	5.2
ID (in.)	2.4	3.87
Temperature rating (°F [°C])	330 [165]	330 [165]
Maximum differential pressure (psi)	10,000	7,500
Maximum hydrostatic pressure (psi)	15,000	15,000
Minimum activation pressure (psi)	300	500
Min. weight required to drop guns (lbm)	300	500
Tensile strength (lbf)	113,371	200,000
H_2S service	Available on request	

Note: Additional sizes, threads, and housing materials for special applications are available on request. Contact your Schlumberger representative.

[†] Outside diameter can vary with the material.

The CTXR consists the three sections: release section, pressure-balance section, and gun adapter. Because the CTXR is internally pressure balanced, the guns automatically drop even in a closed system in which the tubing pressure is less than the pressure below the packer in the rathole. Without the pressure balancing, the upward force created by the pressure differential prevents gun drop and can force the guns upward. The CTXR system requires only the minimum 300-lbm weight of the perforating assembly to automatically initiate gun drop (Fig. 287).

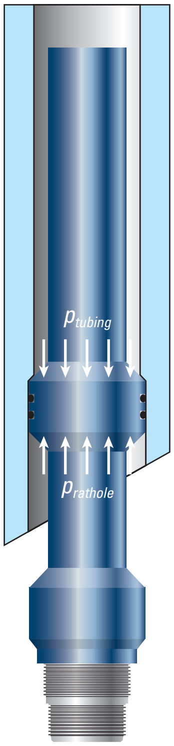

Figure 287. Because the CTXR is internally pressure balanced, in all applications the minimum required weight of the perforating assembly to initiate gun drop is 300 lbm. For the conventional release system shown here, if the tubing pressure is less than the rathole pressure ($p_{tubing} < p_{rathole}$), gun drop cannot be initiated unless the weight of the perforating assembly is greater than the net upward force.

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Features and benefits

- Fast, reliable activation—Reliable X-Tools gun-activated technology is used to automatically and instantly drop the perforating guns. Sanding-in of the guns is prevented.
- Compatibility—The CTXR is compatible with eFire, BHF, HDF, TCF, and ProFire heads.
- Closed system operability—The internally pressure-balanced CTXR is immune to pressure differentials.
- Operational flexibility—Automatic gun drop subs perform in higher well deviations than standard release subs. Automatic gun drop also requires less rathole than standard gun drop techniques.
- Improved perforation cleanup—The CTXR automatic release quickly removes the guns from the perforated zone to allow unrestricted flow.
- Full tubing opening—Upon gun dropping, the tubing is fully open and incorporates a standard wireline reentry guide (mule shoe) profile. Removal of the gun assembly opens the flow path through the bottom of the string and allows production logging and stimulation.
- Time-saving efficiency—No extra runs are required to drop the guns and the need for slickline intervention is effectively minimized.

Safety considerations

Trapped pressure must be taken into consideration, irrespective of the conveyance method. Dropping the guns eliminates this concern. If gun retrieval is later required, contact your Schlumberger representative to ensure that Schlumberger personnel are on site for the operation.

Applications

- Deviated wells—Gun release during detonation can be effective in wells deviated up to 80°.
- Wells with future production logging and stimulation operations—Gun removal provides full tubing access for production logging and stimulation.
- Extreme conditions—CTXR versions for H_2S environments are available on request.
- Wells with sanding potential—Quick removal of the guns prevents their sanding in.
- Closed-chamber perforating design and PURE perforating—The internally pressure-balanced CTXR serves as a plug in the end of the tubing to optimize job execution, unconstrained by tool function.

CTXR operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, CTXR operations begin with thorough design and planning using the applicable flowchart, an abbreviated example of which is shown in Fig. 288. Because of the broad compatibility of the CTXR, the firing system must be specified when the release is ordered.

Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

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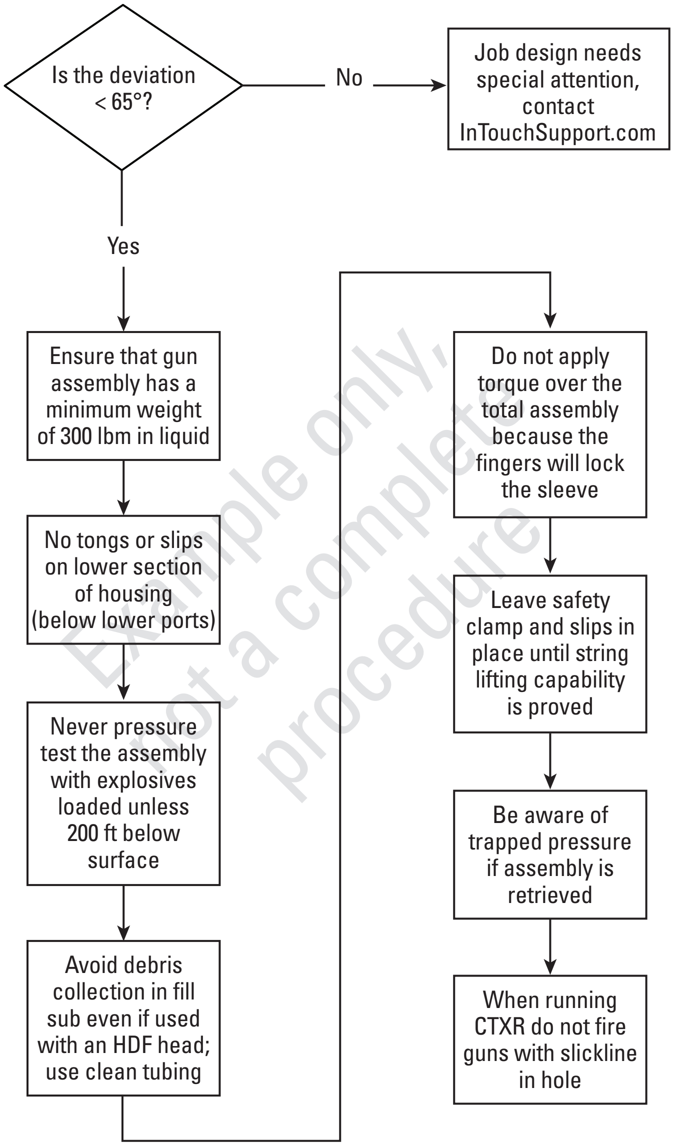

Figure 288. Excerpt of an example SDP design and planning flowchart for CTXR operations. All design and job checks for the selected firing head also apply.

Execution

When the firing head is activated, the high-order detonation causes the break plug of the CTXR to disintegrate, in turn allowing the release piston to shift and disengage the release pin and release fingers. Until this moment, the release fingers are held against a matching profile in the release housing. Release and dropping of the guns take place the instant detonation occurs. The guns, internal components of the CTXR, and firing head all drop to the bottom of the well. The upper part of the CTXR, now consisting only of the release housing and its mule shoe, remains at the end of the completion string. Its internal diameter is at least as large as the completion string above. The wireline or coiled tubing equipment is retrieved through the pressure control equipment without any attached guns.

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Automatic gun release

The SXAR automatic gun release (Fig. 289 and Table 135) incorporates X-Tools perforating gun–activated completion tools technology to automatically drop TCP guns to the bottom of the well the instant the guns fire. Automatic release is particularly important in unconsolidated formations where sanding is a problem and in highly deviated wells where drop-off must be initiated quickly to start the string moving downward.

The tubing is fully open after the gun string is dropped, and the tail pipe incorporates a mule shoe. The firing heads and no-gos are dropped as one piece for easy retrieval as required. The compatibility of the SXAR with a wide range of firing heads, including eFire, BHF, HDF, TCF, and ProFire heads, enables running additional firing heads below the SXAR.

Features and benefits

- Instant, reliable gun release—Using X-Tools gun-activated technology to drop the guns automatically at the instant of detonation initiates movement of the string and prevents sanding-in of the guns.
- Firing head compatibility—The SXAR is compatible with eFire, BHF, HDF, TCF, and ProFire firing heads.
- Operational flexibility—Automatic gun drop subs perform in higher well deviations that standard release subs. Automatic gun drop also requires less rathole than standard gun drop techniques.
- Improved perforation cleanup—The guns are quickly removed from the perforated zone to allow unrestricted flow.
- Time-saving efficiency—No extra runs are required to drop the guns.
- Full tubing opening—Upon gun dropping, the tubing is fully open and incorporates a mule shoe profile. The flow path is open through the bottom of the string to allow production logging and stimulation.

Safety considerations

Trapped pressure must be taken into consideration, irrespective of the conveyance method. Dropping the guns eliminates this concern. If gun retrieval is later required, contact your Schlumberger representative to ensure that Schlumberger personnel are on site for the operation.

Applications

- Deviated wells—Gun release during detonation can be effective in wells deviated up to 80°.
- Wells with future production logging and stimulation operations—Gun removal provides full tubing access for production logging and stimulation.
- Extreme conditions—SXAR versions for H_2S environments and HPHT are available on request.
- Wells with sanding potential—Quick removal of the guns prevents their sanding in.
- Open systems—Sufficient weight is required to overcome the differential pressure in closed systems.

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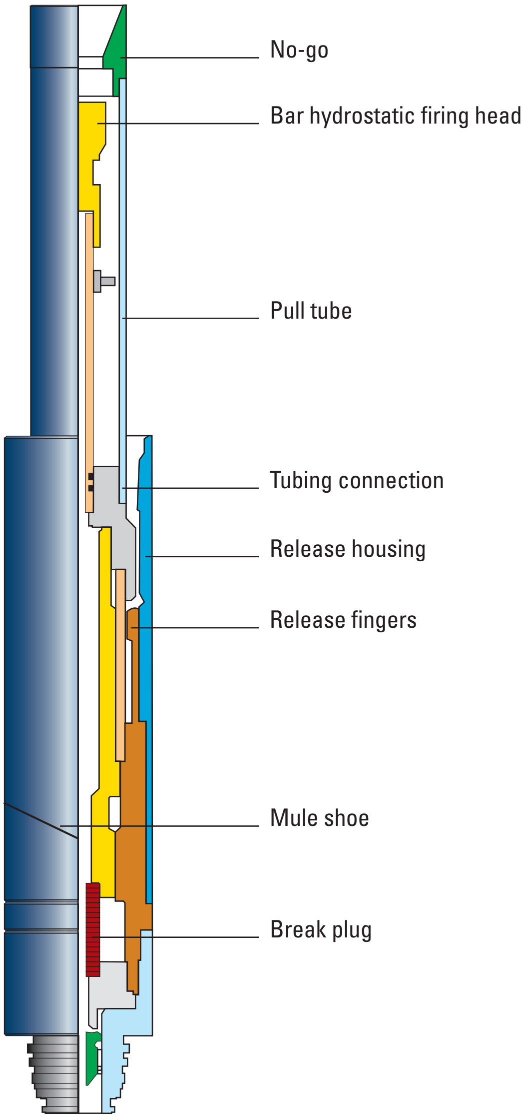

Figure 289. SXAR.

Table 135. SXAR Specifications

Tubing size (in.)	2⅜	2⅞	3½	4½	5½	7
Outside diameter (in.)	3.06	3.68	4.5	5.2	6.07	7.43
ID (in.)	2.5	2.75	2.965	4.0	4.768	6.28
Temperature rating (°F [°C])	400 [204]	400 [204]	400 [204]	400 [204]	375 [191]	400 [204]
Maximum differential pressure (psi)	8,500	8,300	9,000	10,000	7,900	8,000
Maximum hydrostatic pressure (psi)	20,000	20,000	20,000	15,000	15,000	15,000
Minimum pressure to activate (psi)	300	300	300	300	300	300
Minimum weight required below (lbm)	200	200	200	500	500	1,000
Tensile strength at 75% min. yield (lbf)	71,000	5,000	75,000	181,000	195,000	340,000

Note: Additional sizes, threads, and housing materials for special applications are available on request. Specifications may vary depending on configuration. Contact your Schlumberger representative.

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SXAR operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, SXAR operations begin with thorough design and planning using the applicable flowchart, an abbreviated example of which is shown in Fig. 290. Because of the broad compatibility of the SXAR, the firing system must be specified when the release is ordered.

Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

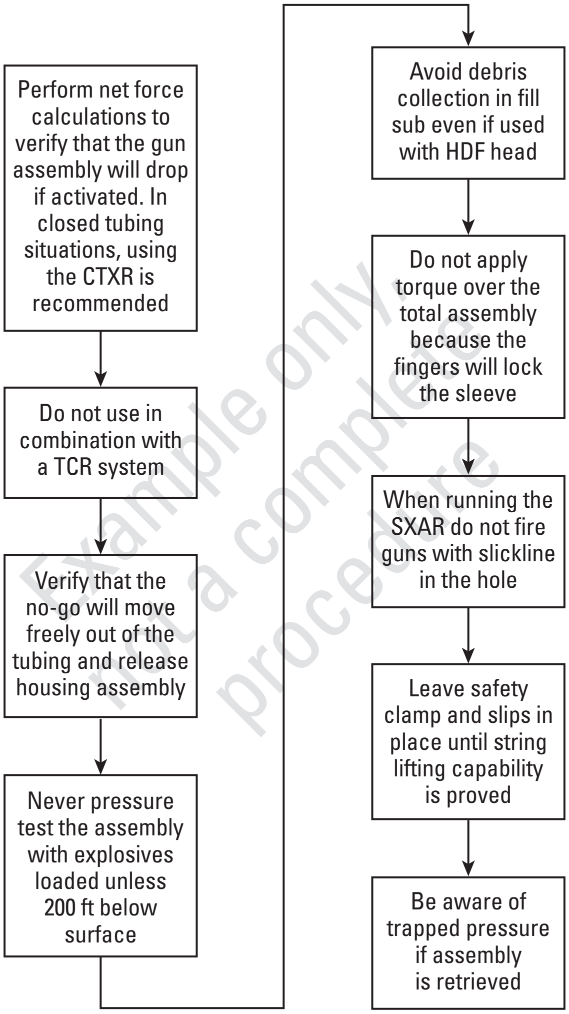

Figure 290. Excerpt of an example SDP design and planning flowchart for SXAR operations. All design and job checks for the selected firing head also apply.

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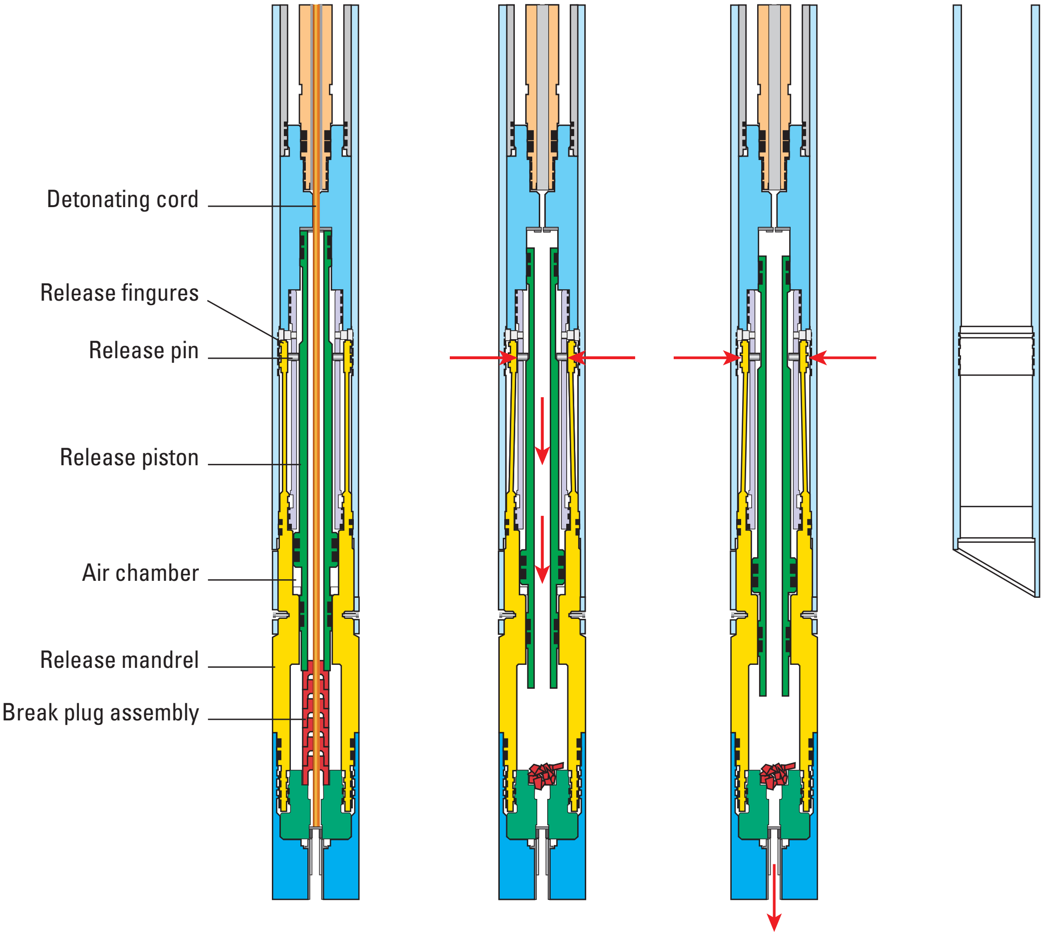
Execution

Figure 291 illustrates the release process. The SXAR gun release and the firing head are placed between the guns below the bottom of the completion string. The completion is run into the well, and the setting depth is determined by correlation or tagging bottom. Less rathole is needed for the automatic gun drop than for conventional release methods.

The packer is set and underbalance created. When the firing head is activated, the high-order detonation causes the break plug of the SXAR to disintegrate, in turn allowing the release piston to shift and disengage the release pin and release fingers. Until this moment, the release fingers are held against a matching profile in the release housing. Release and dropping of the guns take place the instant detonation occurs. The guns, internal components of the SXAR, and firing head all drop to the bottom of the well. The upper part of the SXAR, now consisting only of the release housing and its mule shoe, remains at the end of the completion string. Its internal diameter is at least as large as the completion string above. The wireline or coiled tubing equipment is retrieved through the pressure control equipment without any attached guns.



SXAR Assembly
Run in hole

Fired
Break plugs
shatter and
release piston
is forced down

Releasing
Release pins retract
Finders collapse
Gun string starts
dropping

After Release
Mule shoe

Figure 291. SXAR principle of operation.

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Tubing-conveyed gun release

The TCR system is used to drop perforating guns to the bottom of the well to provide access to the perforated zone for stimulation, squeezing, production logging, or additional perforating (Fig. 292 and Table 136). The TCR system is activated mechanically by using a slickline shifting tool or hydraulically by applying tubing pressure after dropping a testing tool or ball. After the guns are dropped with the lower part of the sub, the upper part of the sub becomes a tubing reentry guide. An additional after-release feature is a single-fish assembly.

The TCR is appropriate for wells without high deviation or other geometry that would interfere with proper functioning. The hydraulic-release TCR should be placed at least 30 ft above the circulation sub or slotted pipe to prevent possible clogging by debris. To prevent clogging of the mechanical-release TCR, debris-circulating subs are spaced at least 30 ft above and below the TCR.

If future production logging is a possibility in a high-flow-rate well, the TCR should be located at least 60 ft above the perforations as a precaution.

Safety considerations

For operations in which the TCR is used with a BHF head, a spacer must be installed to prevent accidental release when the bar is dropped. Tubing pressure activation cannot be used for this deployment.

Applications

- Permanent completions—TCR release of the gun string provides access for wireline or coiled tubing operations.
- Operations with expected sanding—When severe sanding problems are expected, the TCR sub can serve as a releasable weakpoint to free the packer assembly if the string gets sanded in.
- Drillstem testing—The TCR system can be used to drop the gun string during DST operations to allow through-tubing perforating of subsequent layers in a multilayer test or to provide access for production logging and sampling tools.

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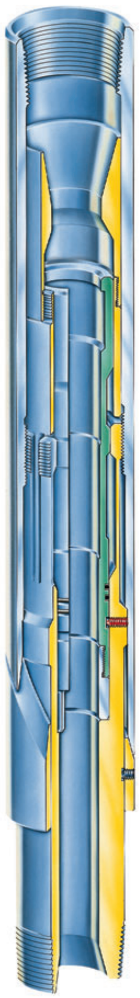

Figure 292. TCR.

Table 136. TCR Specifications

Tubing size[†] (in.)	2⅜	2⅜	2⅞	3½	4½
Outside diameter (in.)	3.06	3.62	3.62	3.75	5.20
Min. ID before drop (in.)	1.60	1.791	1.791	1.791	2.725
Min. ID after drop (in.)	2.31	2	2.750	2.965	4
Drop ball size (in.)	1.75	1.812	1.812	1.812	na
Temperature (°F [°C])	400 [204]	400 [204]	400 [204]	400 [204]	400 [204]
Maximum differential pressure (psi)	8,500	8,300	8,300	9,000	10,000
Length (in.)	33	42.6	32.25	35.9	41.3
Weight (lbm)	40	63.5	50	65.5	125
Tensile strength at 75% min. yield (lbf)	71,250	82,000	82,000	82,000	181,500
H_2S service[‡]	Available on request				

na = not applicable

[†] Other sizes and thread types, release sleeves, and profiles are available on request.

[‡] Corrosion-resistant alloys are available for hostile environments.

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TCR operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, TCR operations begin with thorough design and planning using the applicable flowchart, an abbreviated example of which is shown in Fig. 293.

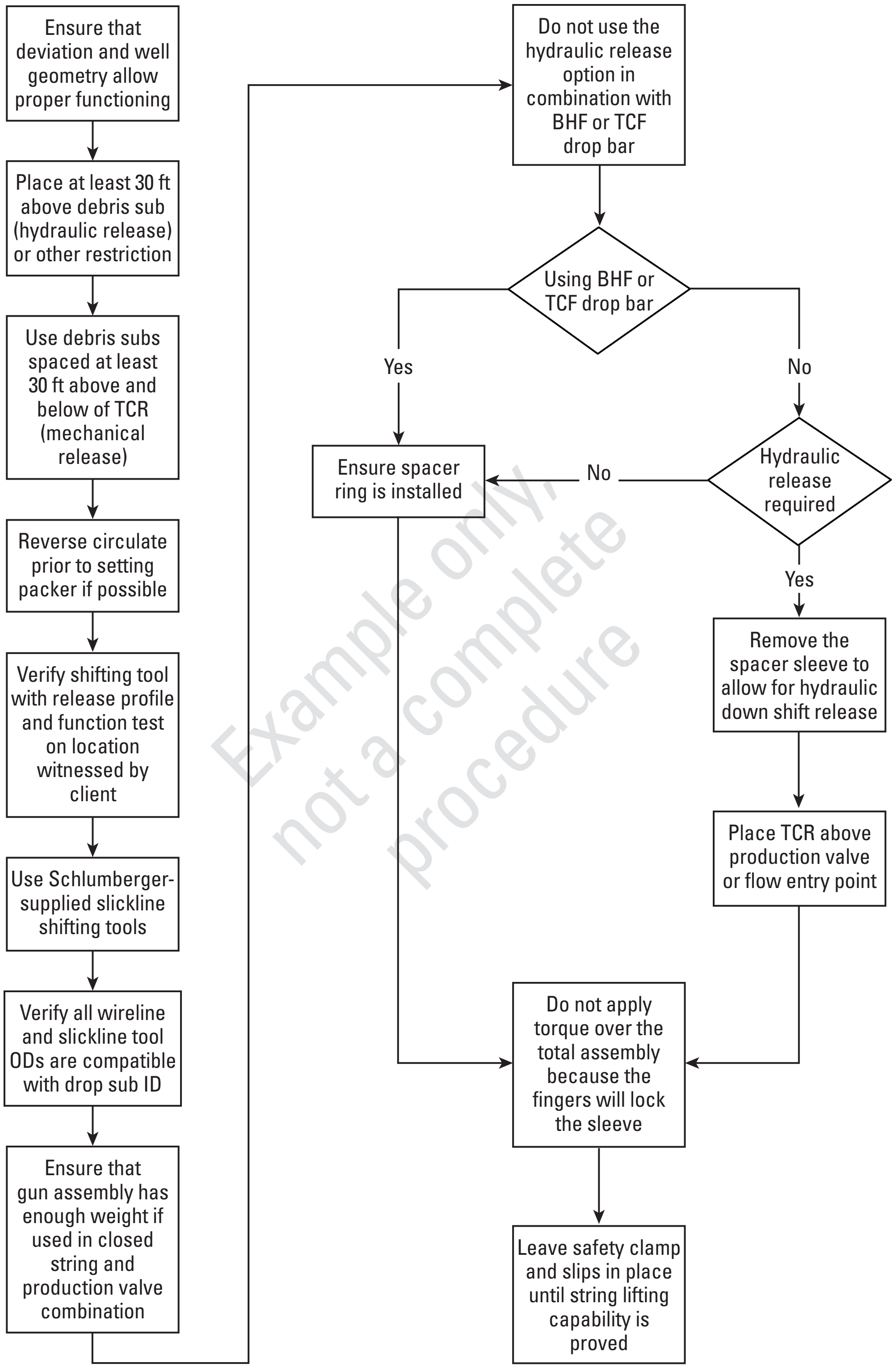

Figure 293. Excerpt of an example SDP design and planning flowchart for TCR operations.

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Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

Execution

The TCR is used in mechanical-release mode in wells with small angles of deviation in which a slickline shifting tool can operate reliably or where the TCP guns will be fired with a drop bar firing head. The gun release includes an optional spacer that prevents the release sleeve from shifting downward (Fig. 294).

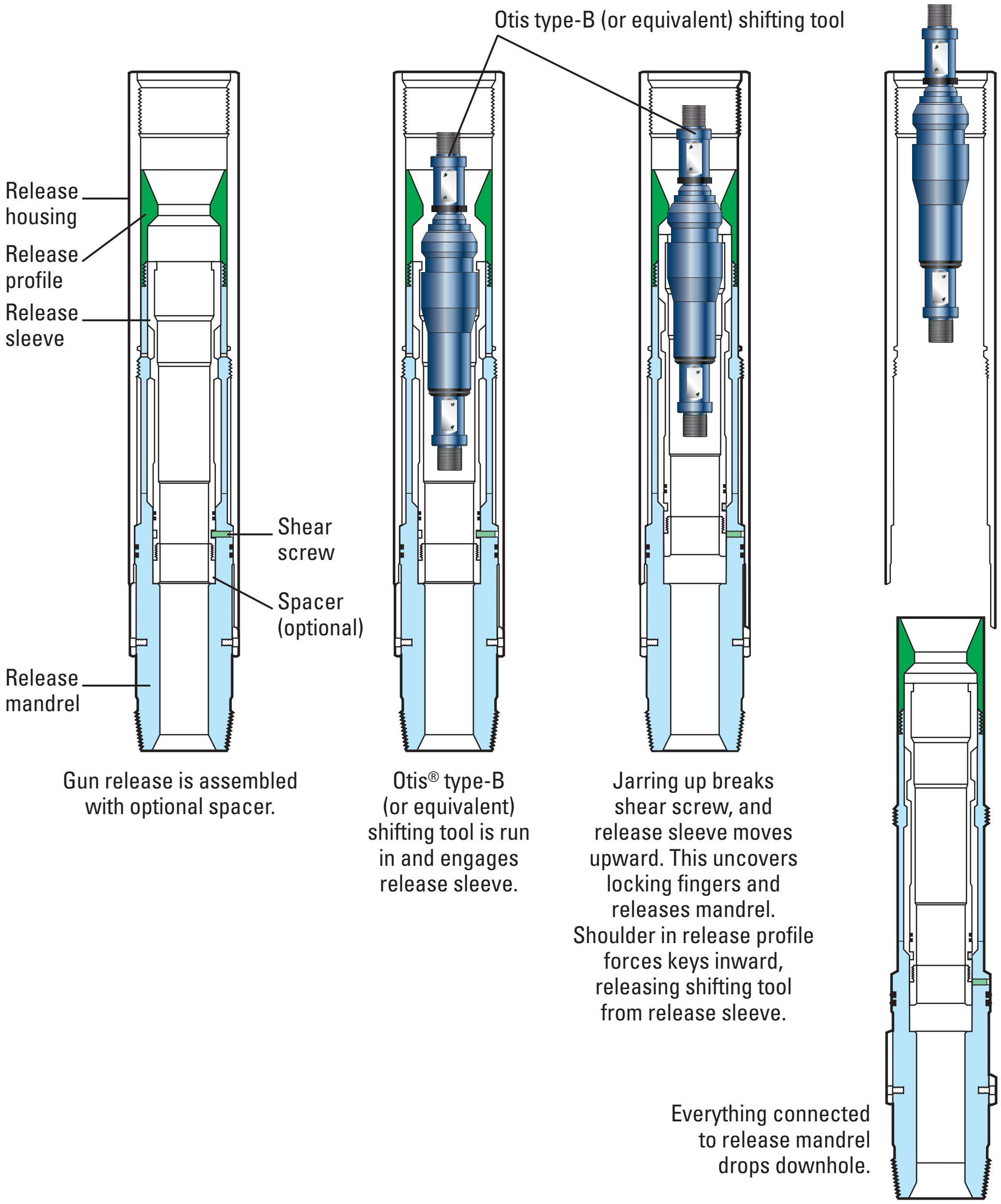

Figure 294. TCR mechanical-release mode.

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To activate, the shifting tool engages the release sleeve, which is secured to the release mandrel by a shear screw. Jarring up breaks the shear screw and pulls the sleeve upward. This action retracts the threaded locking fingers and releases the mandrel and all the TCP components below it. The shifting tool is disengaged from the release sleeve by a shoulder in the release profile. The mechanical-release mode also allows activation of the gun release by jarring down, but jarring down is normally used only as a backup procedure for pressure activation.

The TCR is used in pressure-release mode if well deviation is high or the use of slickline tools is not appropriate (Fig. 295). The TCR is run without a spacer to allow for hydraulic-down shift release. To activate the sub, a testing tool is run in (or a steel ball is dropped from the surface) to seat in the release sleeve, which is secured to the release mandrel by a shear screw.

Additional tubing pressure of 550 to 1,200 psi is required to break the shear screw, depending on the tool model and the hanging load (Fig. 296). Breaking the shear screw shifts the release sleeve downward, retracting the threaded locking fingers, and releases the mandrel and the assembly connected below it.

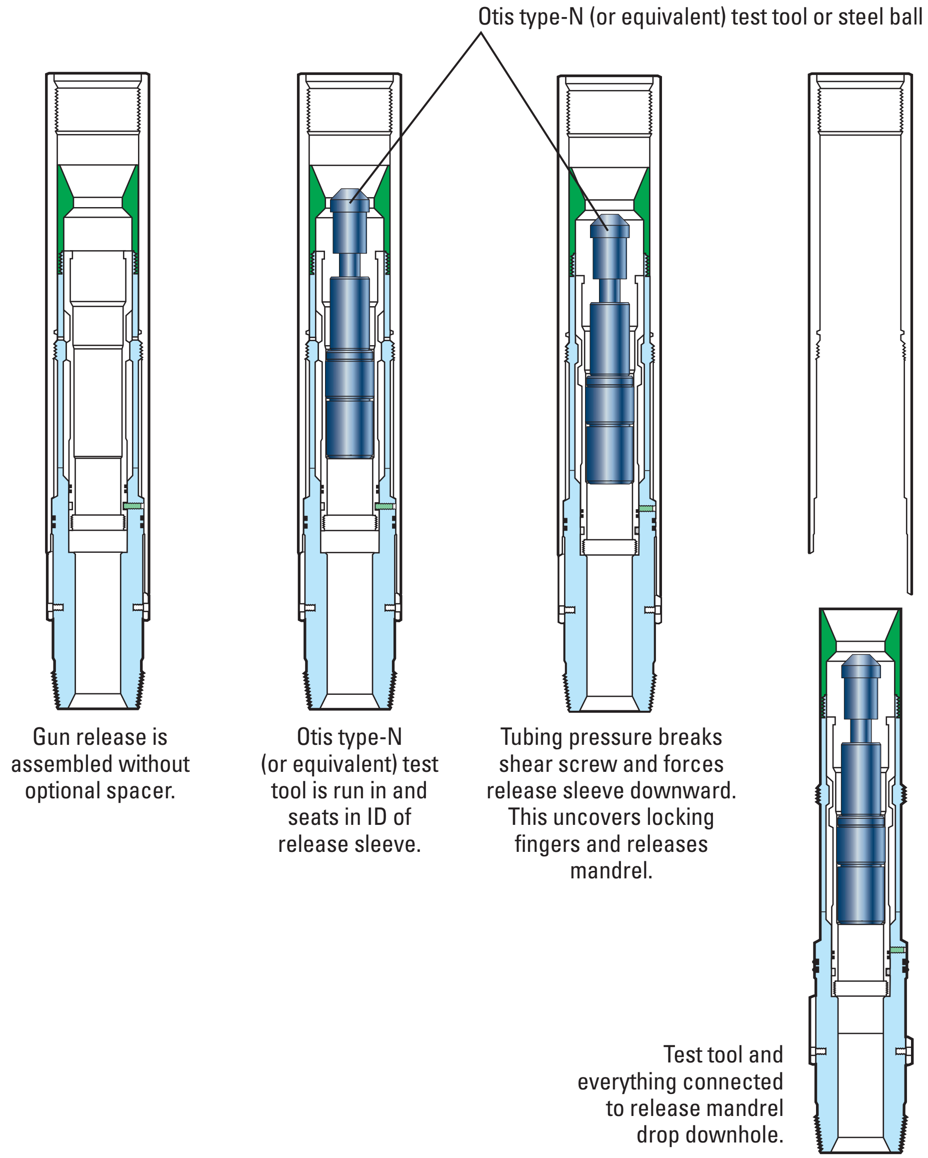

Figure 295. TCR pressure-release mode.

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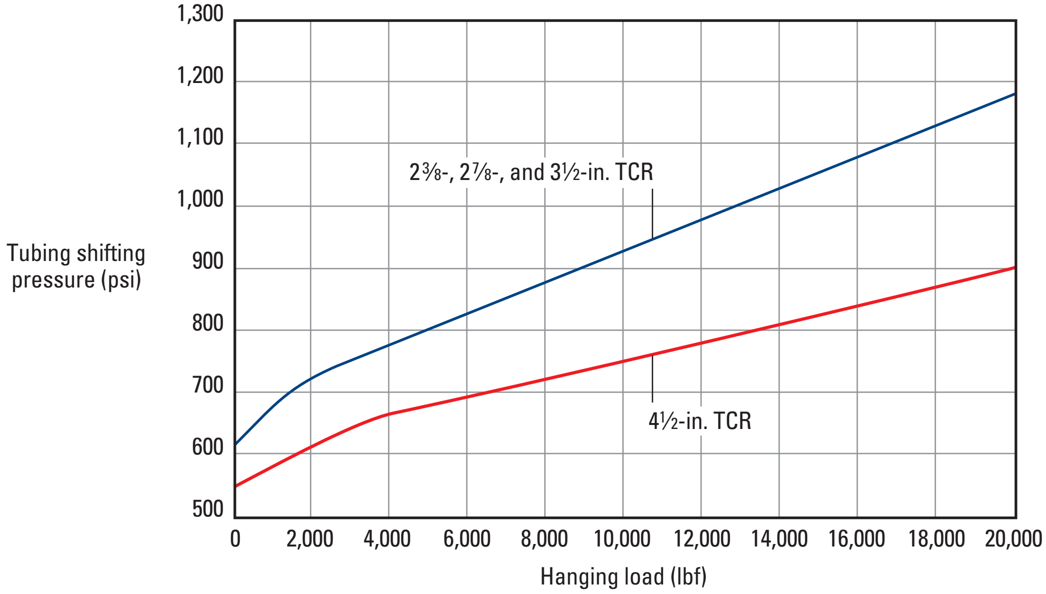

Figure 296. TCR shifting pressures chart.

Controlled tension release

The CTR tool is a fullbore safety release device designed for TCP operations (Fig. 297 and Table 137). The CTR tool is typically placed between the TCP guns and the packer. A unique CTR feature is that the tool cannot be activated by an accidental short overpull or by the shock of the TCP guns firing. The tension load of the CTR is supported by a crushable metal element and two oil chambers that open to the tool ID via a flow restrictor that provides a 5- to 15-min delay. Because the pulling load must be maintained on the CTR until sufficient oil has been displaced for the CTR to disconnect, accidental activation cannot take place.

If the guns become stuck, the remainder of the running assembly can be retrieved by activating the CTR. As previously described, activation is accomplished by pulling on the string with a predetermined amount of tension and holding this pull for a predetermined time. The required pull depends on the crushable element selected (50,000 lbf, 75,000 lbf, or 100,000 lbf nominal). The required time to disconnect depends on the flow restrictor orifice selected and the amount of overpull (5 to 15 min).

After release, the bottom sub of the tool becomes the top of the fish left downhole. It can be engaged for retrieval by using the threaded fishing tool provided with each CTR.

Safety considerations

The CTR cannot be accidentally activated by a short overpull or by the shock of the TCP guns firing; disconnection occurs only after a sustained pulling load on the release element. Because the tool design is pressure balanced, the disconnect load is independent of the differential pressure across the tool.

Applications

- Safety overpull release for TCP operations—The CTR is used to release the string from the guns.

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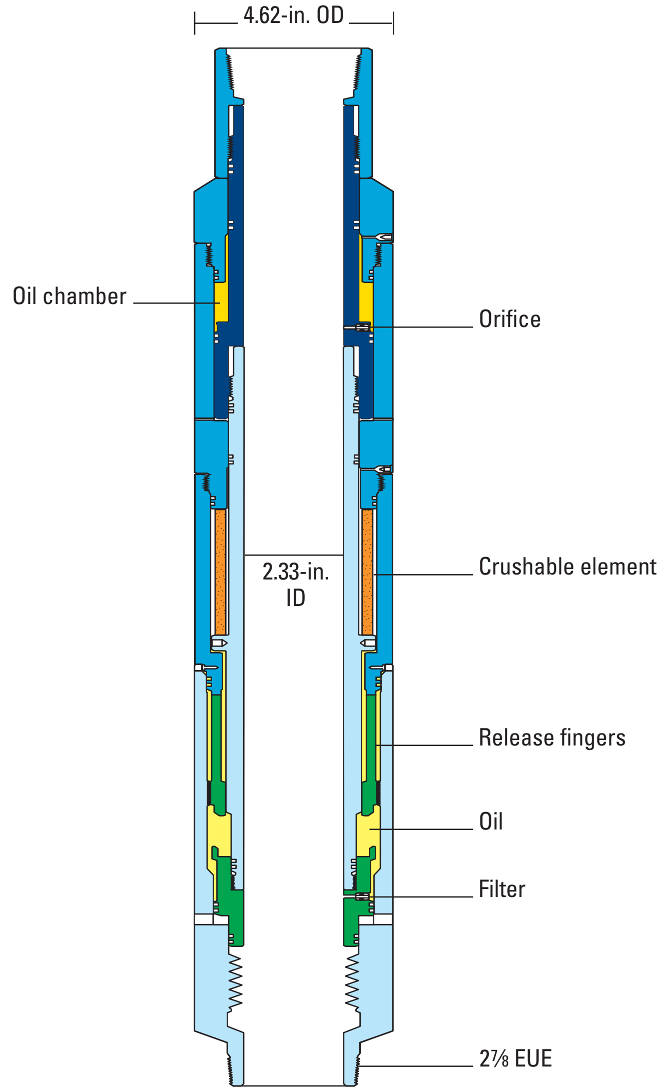

Figure 297. CTR.

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Table 137. CTR Specifications

Outside diameter (in.)	4.62
Inside diameter (in.)	2.33
Connections	
CTR top	2⅞ EUE box
CTR bottom	2⅞ EUE pin
Fishing tool top	3½ IF
Fishing tool bottom	3-2 Acme pin
Temperature rating (°F [°C])	400 [204]
Pressure rating	
Hydrostatic (psi)	20,000
Differential (psi)	10,000
Release element load	
50,000-lbf element (lbf)	55,000
75,000-lbf element (lbf)	85,000
100,000-lbf element (lbf)	115,000
Length (in.)	69.47
Weight (lbm)	200
Tensile strength[†] (lbf)	260,000
Tensile strength of fingers at 75% yield (lbf)	168,000

[†] After release

CTR operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, CTR operations begin with thorough design and planning using the applicable flowchart, an abbreviated example of which is shown in Fig. 298.

Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

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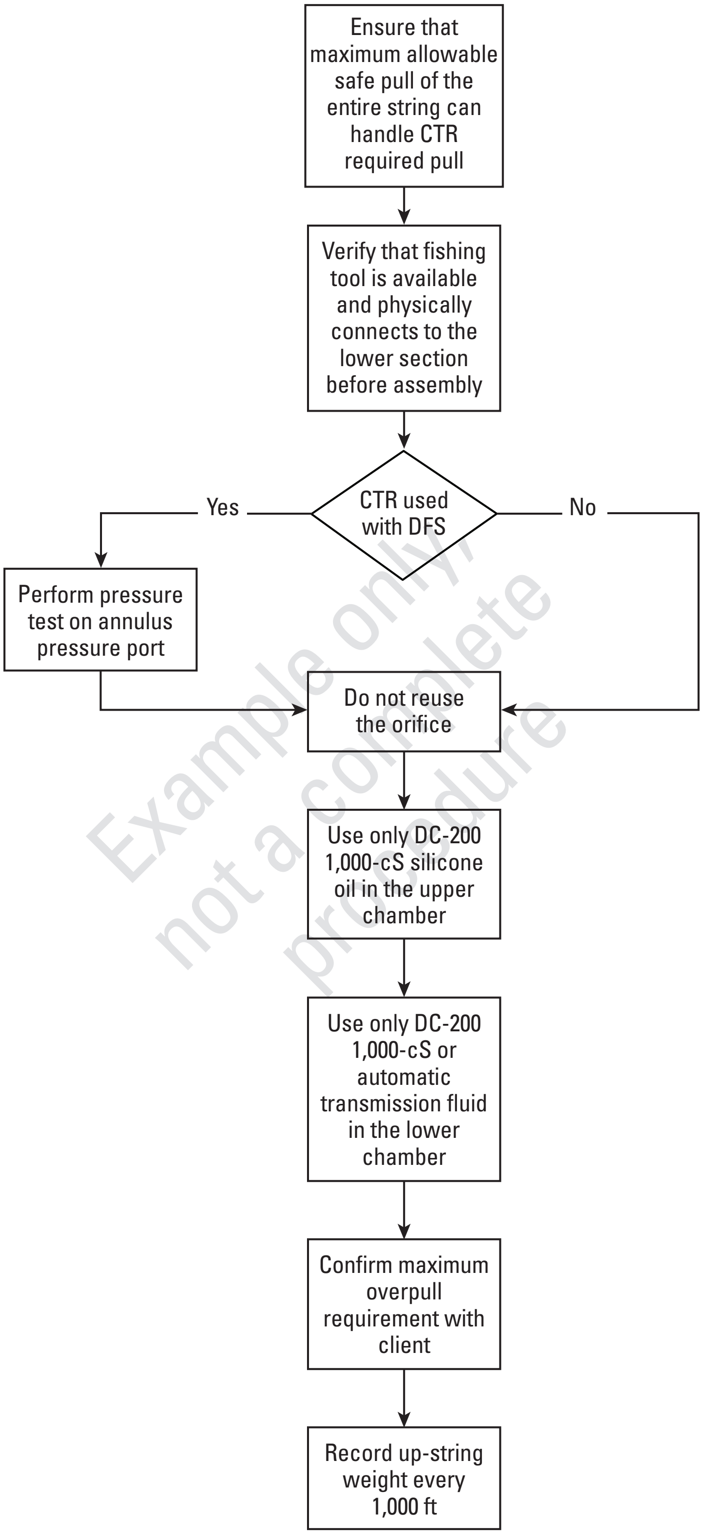

Figure 298. Excerpt of an example SDP design and planning flowchart for CTR operations.

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Radioactive marker sub

The radioactive marker sub (Fig. 299 and Table 138) is run in line with the workstring above the packer. It serves as a tubing collar or drillpipe tool joint, with one or two small cavities drilled and threaded to receive a sealing plug. A radioactive pip tag is installed in each cavity. A pip tag (Fig. 300) is a weak gamma ray source (1 µCi of cobalt-60). All radioactive material is fully recovered when the string is pulled.

Applications

- Accurate gun depth positioning—A through-tubing gamma ray log is used for depth correlation of the pip tag with the earlier openhole gamma ray log. Because the distance from the pip tag to the top shot was measured previously, the gun can be accurately positioned on depth (Fig. 301).

Figure 299. Radioactive marker sub.

Table 138. Radioactive Marker Sub Specifications

Size and rating	Matches the corresponding tubing or drillpipe thread connection
Half-life	Cobalt-60: 5.2 years Optional zinc-65: 240 days
Radiation level (mrem/hr at 1 ft)	1-µCi pip tag: 0.014

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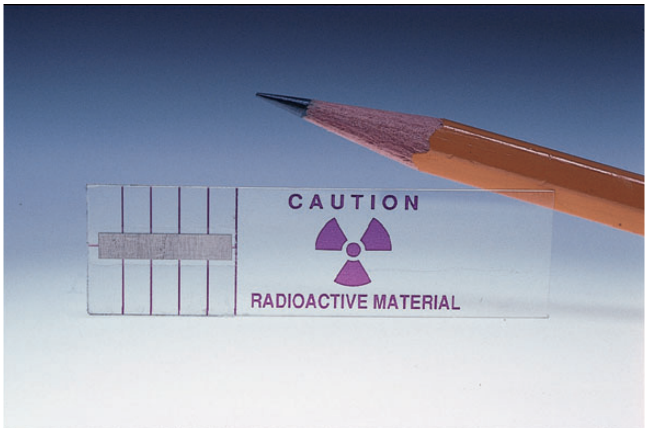

Figure 300. Pip tag.

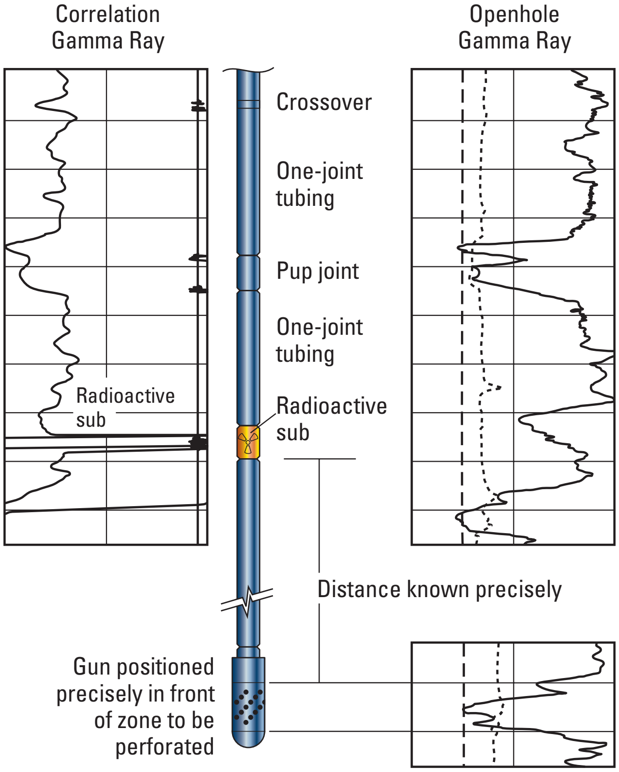

Figure 301. A through-tubing gamma ray log is used for depth correlation of the radioactive marker sub with the openhole gamma ray log.

Production and isolation valves

Production valves (run between the packer and the guns) are often required as part of a TCP string. Production valves are used

- to run a completion or testing string containing a lighter column of fluid to create an underbalance when perforating
- if existing perforations or leaks below the packer may cause difficulty in establishing the required underbalance before perforating
- to keep the tubing string sealed and allow the use of pressure-set packers, tubing hangers, and other pressure-operated tools such as TCP firing heads
- to keep high pressure away from the casing until perforation is completed for operations with extreme overbalance.

Automatic production valve

The automatic production valve (SXPV) incorporates perforating gun–activated X-Tools technology to provide all the advantages of conventional production valves with the added feature that the valve opens automatically as soon as and only when the guns fire (Fig. 302 and Table 139). Automatic opening at the time of gun firing allows almost instantaneous flow from the reservoir.

The SXPV is run between the packer and firing head of a TCP gun string (Fig. 303). The production ports of the SXPV are situated above the firing head and are isolated by a sleeve. Although hydrostatic pressure constantly pushes down on this sleeve, it cannot move in response to the tubing pressure. The sleeve is held in place by the breakup assembly, located below the firing head. When the firing head is activated, the breakup assembly shatters and the sleeve keeping the ports closed is shifted down, opening the ports.

The SXPV is beneficial for TCP jobs using the extreme overbalance perforating technique and for activation of the HDF head. In these situations, if the casing is leaking it would prevent pressuring up to fire the TCP guns.

Table 139. SXPV Specifications

	SXPV-AA	SXPV-BA
Tubing size (in.)	2⅜	2⅞
Outside diameter (in.)	3.06	3.68
Effective ID through ports after opening (in.)	2.5	2.5
Temperature rating (°F [°C])	350 [177]	350 [177]
Tubing pressure rating (psi)	20,000	20,000
Rathole pressure rating (psi)	20,000	30,000
Burst pressure (psi)	14,000	14,000
Collapse pressure (psi)	13,000	13,000
Tensile strength at 75% min. yield (lbf)	130,000	175,000

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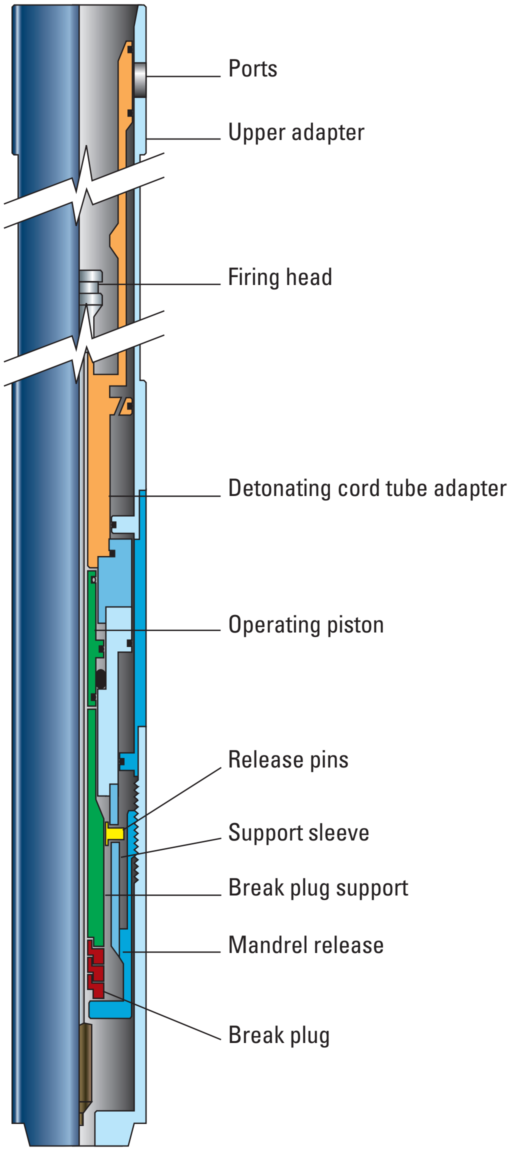

Figure 302. SXPV.

Applications

- Underbalance perforating—The SXPV can be run in a completion or formation test string with a lighter column of fluid in the tubing to create an underbalance for perforating operations. It is also ideal for jobs with existing perforations or leaks below the packer that would make it difficult to establish underbalance.
- PURE system for clean perforations—The closed system for PURE perforating operations can be established by using the SXPV.
- Extreme overbalance perforating—Excess pressure on the casing is prevented by the synchronized timing between gun system firing and SXPV opening.
- Existing perforations or leaking casing—The SXPV allows establishing underbalance and can also be used to activate an HDF head in conditions that would prevent pressure management in the tubing.

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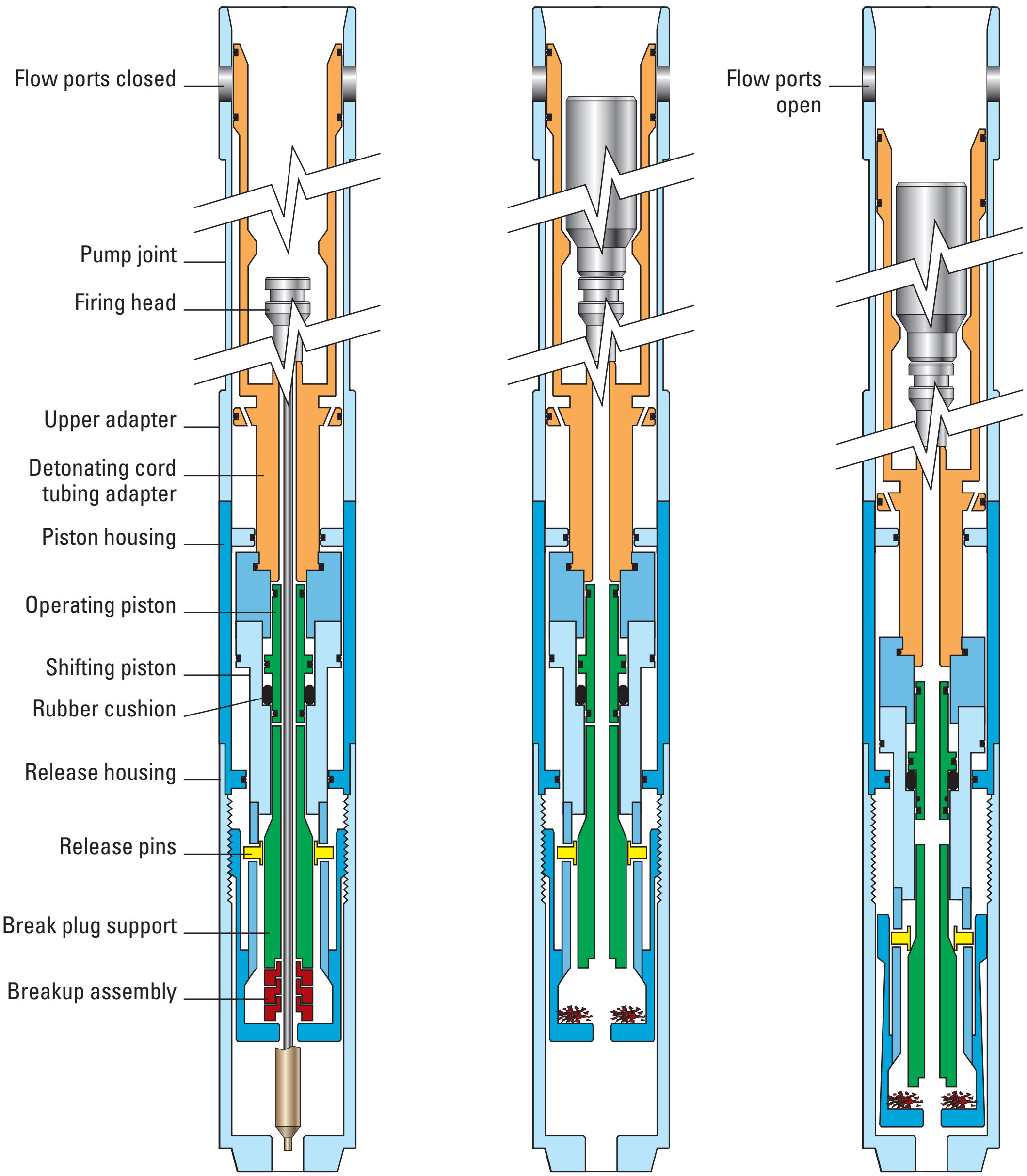

Figure 303. SXPV principle of operation.

Pressure-operated underbalance valve

The pressure-operated underbalance valve (POUV) is a production valve run in completions in which pressuring up the tubing is necessary to set tools such as packers and liner hangers (Fig. 304 and Table 140). Positioned between the packer and the perforating gun to seal off the tubing from the annulus, the POUV consists of a shear-pinned sliding sleeve inside a main housing.

The POUV keeps the system closed until it is time to open the valve and establish the desired underbalance. The valve is opened by applying pressure to the tubing at the surface. When the pressure inside the POUV exceeds the external pressure (rathole or hydrostatic pressure) by the value of the shear pins, sleeve is pushed up to expose the ports. The POUV is similar to the tubing fill-up valve (FLUP) and is available in standard and high-performance versions.

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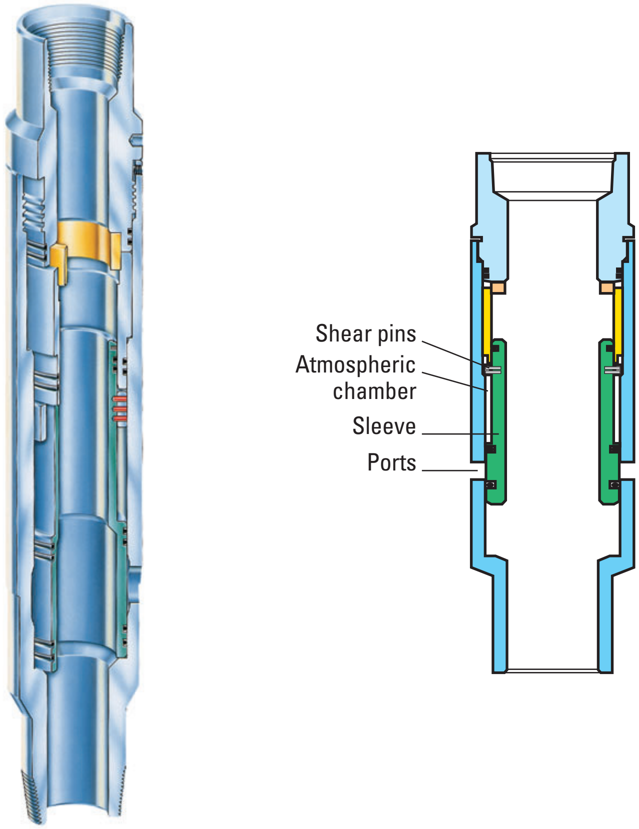

Figure 304. POUV.

Table 140. POUV Specifications

Tubing size (in.)	2⅜	2⅜	2⅞	3½
Service	Standard	High performance	Standard	Standard
Thread† (8 RD, EUE)	2⅜	2⅜	2⅞	3½
Outside diameter (in.)	3.63	3.63	4.00	4.50
Min. ID (in.)	1.88	1.88	2.25	2.75
Temperature rating (°F [°C])	350 [177]	425 [218]	350 [177]	350 [177]
Pressure rating (psi)	15,000	20,000	10,000	7,500
Max. differential pressure (psi)	5,000	5,000	5,000	5,000
Min. operating pressure (psi)	500	500	500	500
Weight (lbm)	54	49	64	78
Makeup length (in.)	34.67	32.34	34.67	34.67
Flow area through valve (in.^{2})	2.68	2.68	3.97	5.90
Tensile strength (lbf)	130,000	246,000	190,000	270,000
H_2S service	Available on request			

† Other thread types are available on request.

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Applications

- Establishing underbalance— Because there is no circulation before gun firing, the tubing is run with a clean cushion fluid to obtain the desired underbalance. Nitrogen is required to open the valve when the fluid does not reach the surface.
- Perforated nipple for production—When open, the valve allows for production, offering the same or larger flow area than that of the tubing.
- Hydraulic packer setting—The valve allows a hydraulic packer to be set without any additional equipment, ball, or plug. Typically, the valve shear screws are set at 1,000 psi above the packer setting pressure.
- Packer testing—After the packer is set and the valve opens, the packer can be pressure-tested through the annulus or tubing.
- Tubing testing—The tubing can be pressure-tested during its descent downhole; however, pressure testing generally is not done when running a hydraulic packer.
- Wells with existing perforations—The POUV enables establishing underbalance in wells with old open perforations.
- Casing in unknown condition—In older wells where the integrity and condition of the casing are not known, using the POUV allows isolating the pressure in the tubing from the pressure in the annulus.

Drop bar–activated tubing- or rathole-pressure-operated valve

The DTRV is a production valve used in TCP operations to isolate the rathole from the tubing (Fig. 305 and Table 141). A drop bar activates the DTRV by rupturing a break plug inside the valve on its way down to the firing head to detonate the guns. Then, the rathole pressure or tubing pressure, whichever is higher, opens the DTRV to apply underbalance or extreme overbalance conditions in the rathole at the time of firing the guns. The large flow area of the ports enables efficient surge in either operation. The DTRV does not require modification to operate in either rathole or tubing mode. The operating mode can be changed at any time, even after the perforating string is already in the hole.

Applications

- Underbalanced perforating—Operated in rathole-pressure mode, the DTRV maintains underbalance in the tubing until the break plug is broken by the drop bar.
- Wells with existing perforations—Using the DTRV allows a lighter fluid or partial cushion to be run when there are existing perforations. In rathole-pressure mode the DTRV allows establishing underbalance in casing with existing perforations.
- Extreme overbalance perforating—Operated in tubing-pressure mode, the DTRV enables perforating using extreme overbalance pressure. The pressure can exceed the rating of the casing because the valve isolates the casing from the pressure before gun detonation.

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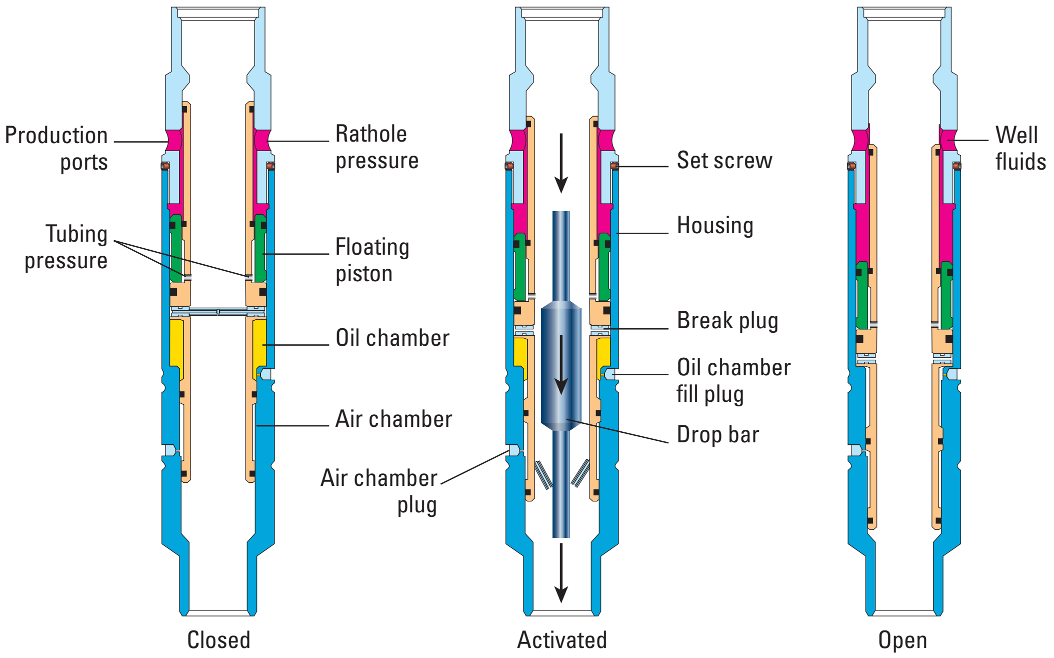
Rathole Pressure > Tubing Pressure



Tubing Pressure > Rathole Pressure

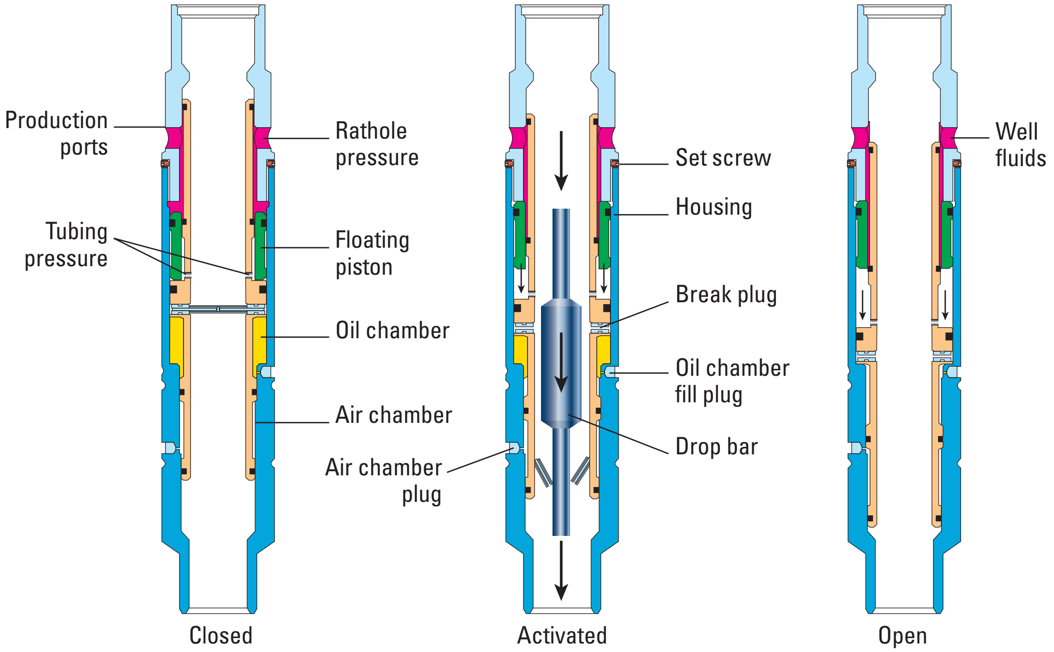


Figure 305. DTRV principle of operation.

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Table 141. DTRV Specifications

Tubing size (in.)	2⅜	2⅞	3½
Thread† (EUE)	2⅜	2⅞	3½
Outside diameter (in.)	3.63	4.00	4.50
Inside diameter (in.)	1.88	2.25	2.75
Flow area through valve (in.^{2})	2.68	3.97	5.90
Temperature rating (°F [°C])	350 [177]	350 [177]	350 [177]
Pressure rating at 80% min. yield			
Differential (psi)	10,000	10,000	10,000
Hydrostatic (psi)	15,000	13,000	11,000
Min. pressure to activate (psi)	500	500	1,000
Makeup length (in.)	25.52	25.82	32.3
Weight (lbm)	30	50	79
Tensile strength (lbf)	130,000	190,000	270,000

† Other thread types are available on request.

DTRV operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, DTRV operations begin with thorough design and planning using the applicable flowchart, an abbreviated example of which is shown in Fig. 306. Operational procedures specific to the firing head also apply.

Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

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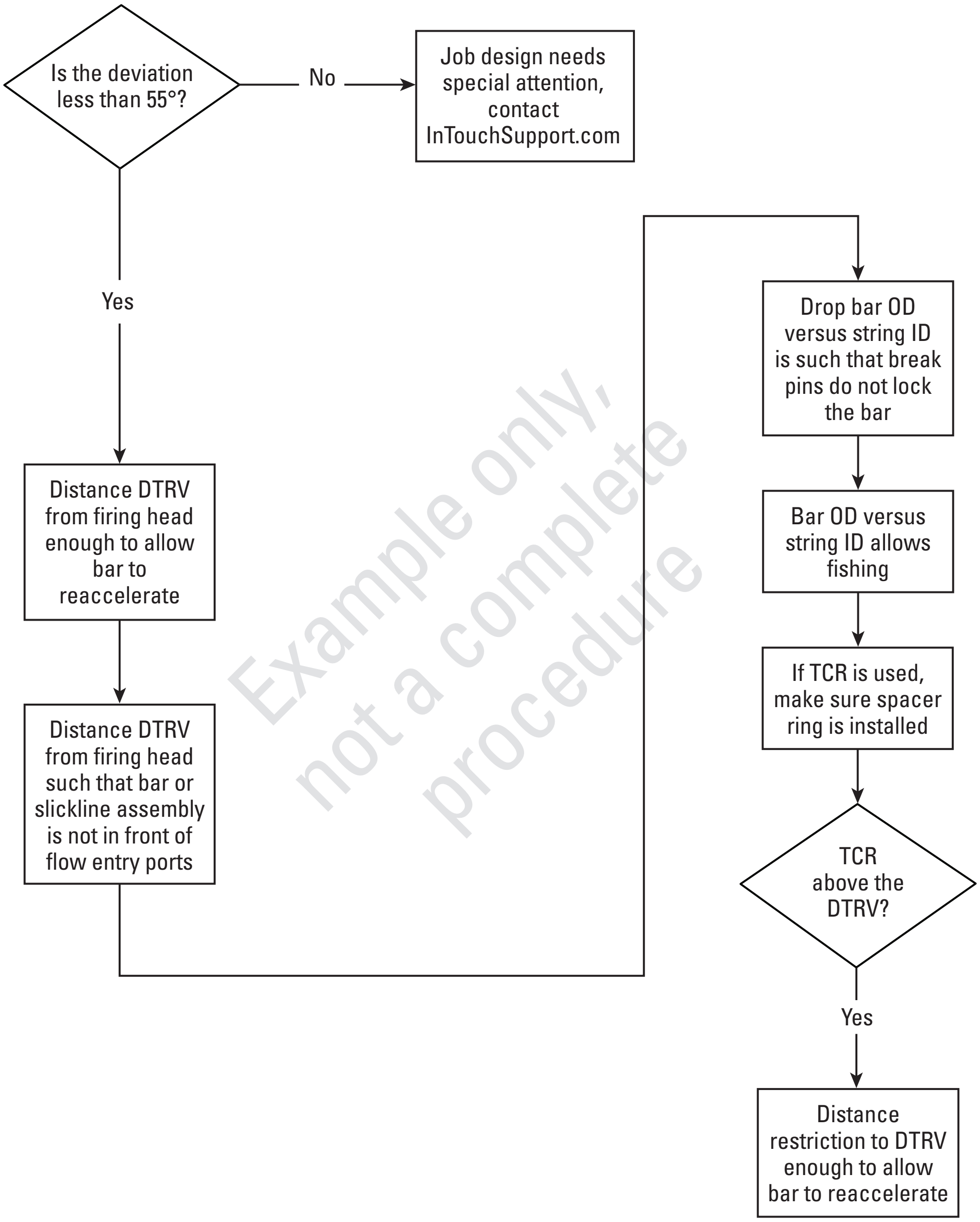

Figure 306. Excerpt of an example SDP design and planning flowchart for DTRV operations. All design and job checks for the selected firing head also apply.

Tubing fill-up valve

The FLUP improves the efficiency of running a completion or test string that requires a partial cushion (Fig. 307 and Table 142).

The FLUP stays open while running in the hole until it is exposed to a hydrostatic pressure that overcomes the shear pins and closes the valve. The number of shear pins can be varied to regulate the amount of pipe filled with fluid, and thus specify the underbalance, before going in the hole.

Figure 307. FLUP.

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Table 142. FLUP Specifications

Tubing size[†] (in.)	2⅜	2⅜	2⅞	3½
Service	Standard	High performance	Standard	Standard
Outside diameter (in.)	3.63	3.63	4.00	4.50
Inside diameter (in.)	1.88	1.88	2.25	2.75
Temperature rating (°F [°C])	350 [177]	425 [218]	350 [177]	350 [177]
Pressure rating				
Differential (psi)	5,000	5,000	5,000	5,000
Maximum hydrostatic (psi)	15,000	20,000	10,000	7,500
Min. operating pressure (psi)	500	500	500	500
Weight (lbm)	56	51	67	81
Flow area through valve (in.^{2})	2.68	2.68	3.97	5.90
Tensile strength (lbf)	130,000	246,000	190,000	270,000
H_2S service	Available on request			

[†] The standard thread is 8 RD EUE, with other connections available on request.

Applications

- Tubing fill-up for a partial cushion—The FLUP saves time by alleviating the need to fill the pipe from the surface as it is being run into the hole. The tubing automatically fills through the production ports. The valve can be closed at any predetermined depth by increasing the total pressure above the shear pin value. The FLUP is typically used in conjunction with another valve, such as the DTRV, POUV, or SXPV, to provide a flow path for production.
- Hydraulic packer setting—The valve also allows automatic fill-up and cleanup, with the capability to circulate a light fluid, before a hydraulic packer is set.

FLUP operational procedures

As described in "Service delivery procedure" in the "Tubing-Conveyed Perforating Completion Techniques" chapter, FLUP operations begin with thorough design and planning using the applicable flowchart, an abbreviated example of which is shown in Fig. 308.

Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

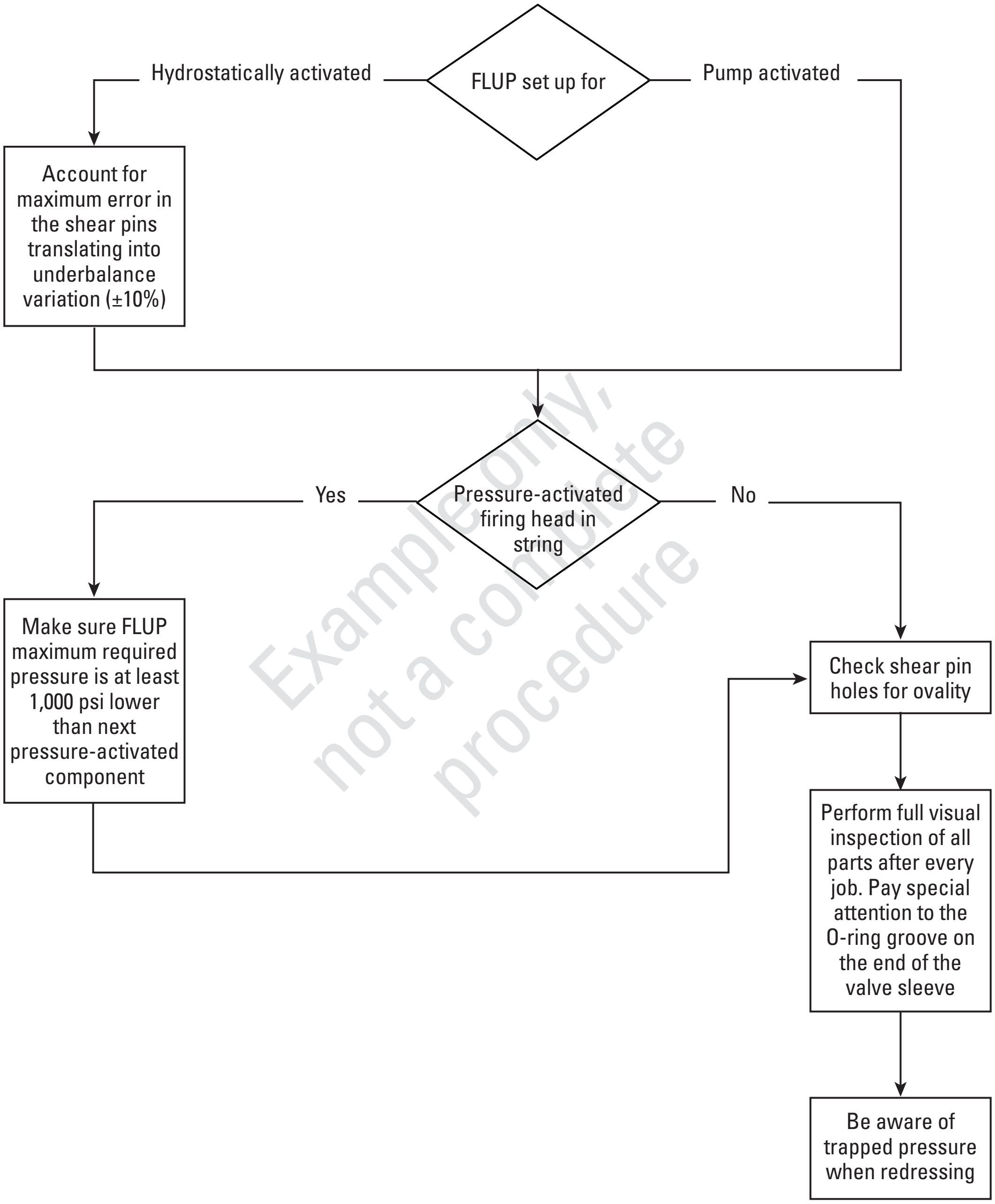

Figure 308. Excerpt of an example SDP design and planning flowchart for FLUP operations.

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Shock absorbers

The gun string is subjected to high transient shock from firing that can result in large shock loads to other equipment in the string. Shock absorbers are used to attenuate shock loads resulting from gun firing.

Automatic shock absorber

The automatic shock absorber (SXVA) is the first true shock absorber introduced into the TCP market (Fig. 309 and Table 143). In the past, rubber elements or steel washers were used to dampen the shock resulting from the guns firing. The SXVA elements instead absorb the shock, preventing damage to other elements in the string such as packers, gauges, and adjacent gun strings.

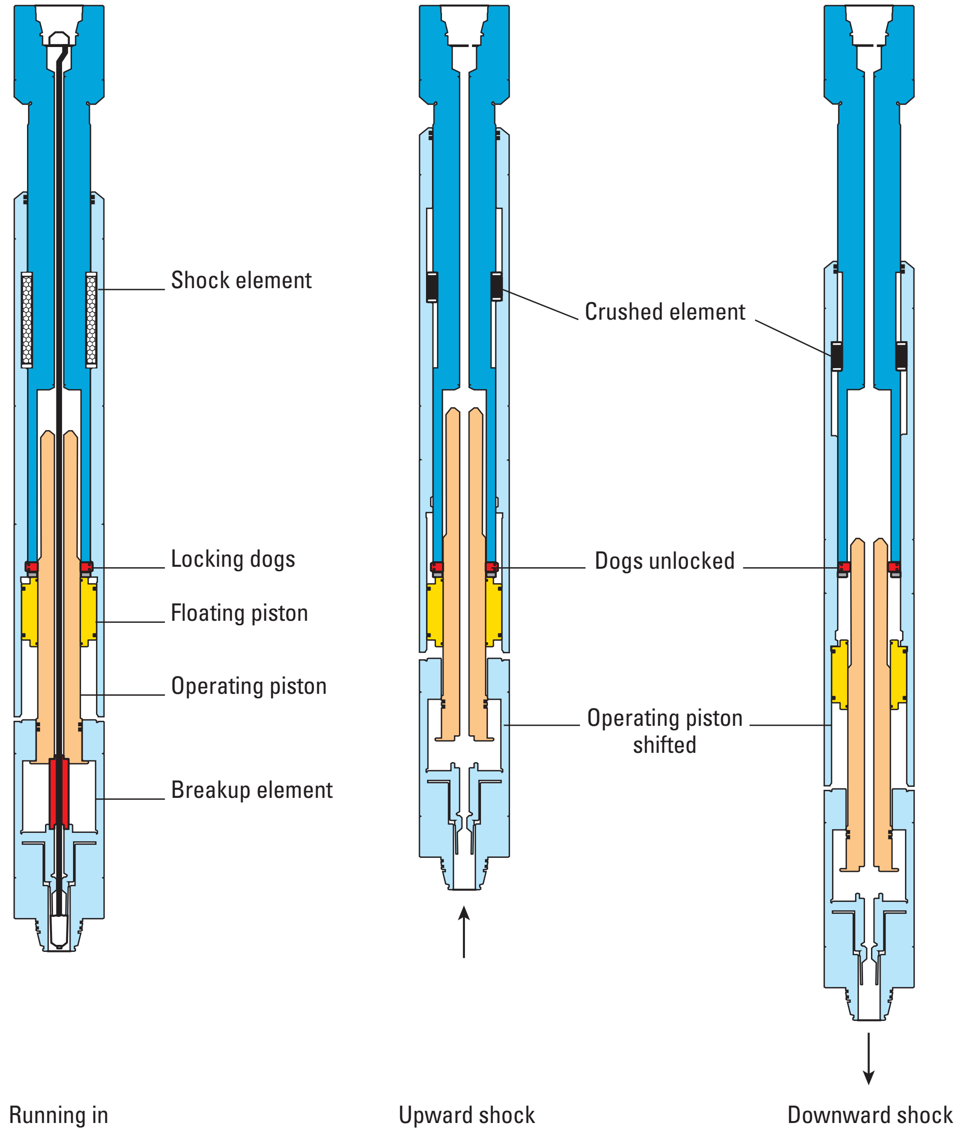

Figure 309. SXVA.

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Table 143. SXVA Specifications

Max. outside diameter (in.)	3.075	3.075	4.635	6.635
Detonation transfer type	Side by side	End to end	Side by side	End to end
Temperature rating (°F [°C])	350 [177]	350 [177]	350 [177]	350 [177]
Pressure rating (psi)	15,000	15,000	12,000	12,000
Collapse pressure (psi)	18,000	18,000	13,800	13,800
Makeup length (in.)	98	100	96.3	107.1
Weight in air (lbm)	163	173	375	477
Max. tensile load before firing (lbf)	21,576	21,576	115,261	115,261
Max. tensile load after firing (lbf)	77,000	77,000	200,000	289,000

Designed for placement at the top of the gun string, the SXVA is long enough to act as a safety spacer. It stays rigid while running in the hole. At the instant the guns fire, the SXVA is transformed from a rigid tube into an active shock absorber that uses the X-Tools gun-activation technology. The crushable element absorbs shock from above and below. It converts the kinetic energy of the shock wave into heat, dissipating the shock load over a very short time period.

Applications

- TCP operations in which high shock could occur—The SXVA prevents damage to the string, gauges, and packers.

Sealed ballistic transfer

The reliability of a continuous high-order detonation over a long interval unavoidably decreases as the length of the gun string increases. To offset the risk of disabling part of the gun string as a result of a gun failure, bulkheads are used to make sealed ballistic transfers (SBTs). The bulkhead equipment provides a pressure seal between guns and uses a ballistic transfer (Fig. 310 and Table 144) to breach the sealed bulkhead and propagate the detonation through the gun string.

Explosive bulkheads use monodirectional (diode) ballistic transfer so that high-order detonation is transferred only from top to bottom. No detonation can be transferred from the bottom up, which also reduces the risk of low-order transfer from the top down.

Integral SBT equipment is used with redundant HDF heads. The sealed detonating cord tubes are installed either end to end or side by side in ported adapters with sealed explosive bulkhead housings at the top. They are mounted at regular intervals along the gun string. All heads are activated together but have different delay times. The primary head at the top fires first. In normal operation, the top primary firing head fires the complete gun string. If both top redundant firing

Table 144. SBT Specifications

Outside diameter (in.)	2.12 to 4.80
Temperature rating (°F [°C])	330 [165] HPHT version: 450 [232]
Pressure rating (psi)	20,000 HPHT version: 22,000

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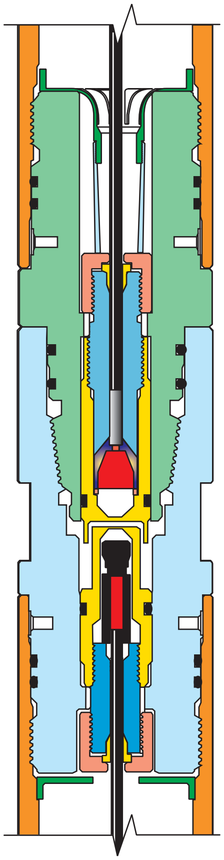

Figure 310. Bulkhead with ballistic transfer.

heads fail and the interval is only partially shot in a redundant operation, the remainder of the gun string is not flooded and can be fired by the next firing head down the string.

SBTs are also used alone, spaced through a long gun string at 500 to 800 ft apart. With this configuration, only part of the gun system floods if there is a leak in the gun string.

Applications

- TCP operations with multiple guns—Using SBTs protects against total gun string flooding and reduces the risk of propagation of low-order detonation.

Orienting equipment

Gun swivels

A gun swivel allows the gun string to rotate with respect to the tubing string. Asymmetrically loaded guns and special spacers orient themselves because of the well deviation and their own weight (nonaxial center of gravity). Roller adapters aid rotation.

Swivels can be located in the tubing string above the firing head, below the firing head, or between the guns. Axial and radial loads are supported by the use of both thrust and journal bearings.

Orienting adapters between guns align the guns with respect to one another.

Tubing gun swivels

Various sizes and ratings of tubing gun swivels are available based on the gun system used and the well conditions.

Intragun swivels

Intragun swivels incorporating detonation transfer components are available for use with long gun strings (Fig. 311).

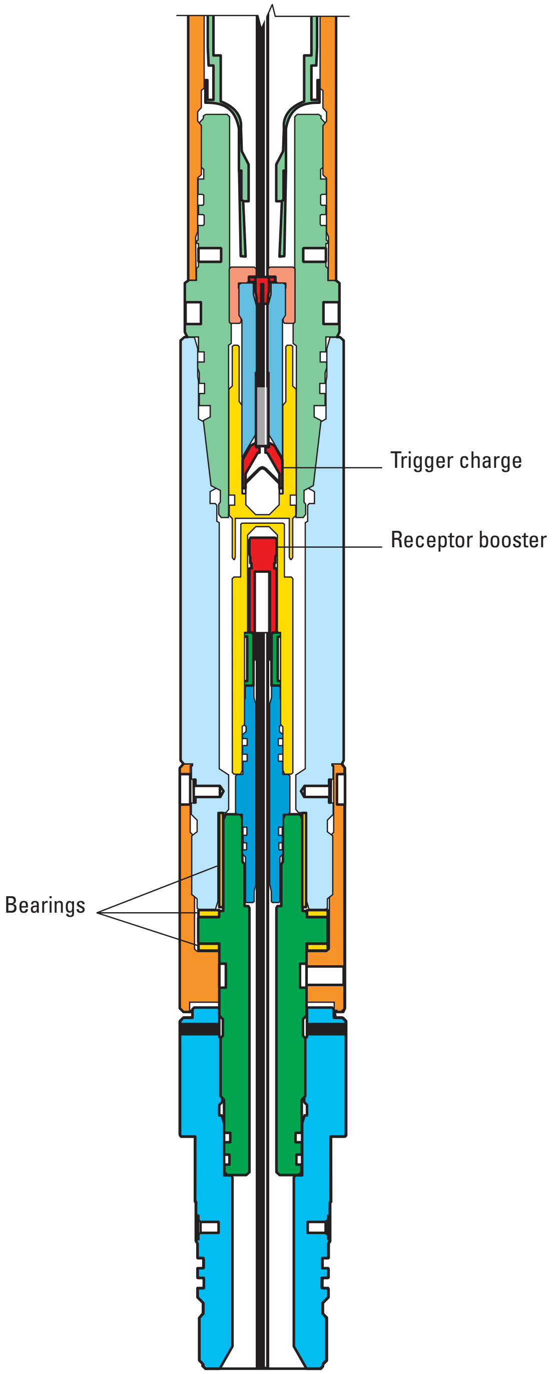

Figure 311. Intragun ballistic gun swivels.

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Modular and high-load-capacity swivels

Modular swivels are used in deviated wells to allow the gun string to rotate with respect to the tubing string. Through use of the gun string weight (gravity), the guns are correctly positioned with respect to the low side of the well.

The axial load is supported by roller thrust bearings in either tension or compression. The bending load is supported by a radial needle roller bearing. The upper adapter is changed to connect the swivel either below the firing head or between guns (intragun).

Both end-to-end transfer and SBT are incorporated in the modular swivel. End-to-end transfer allows positioning the intergun modular swivel between any guns or weighted spacers. SBT allows the swivel to rotate, and the ballistic transfer breaches the sealed bulkheads and propagates the detonation through the gun string. Transfer requires use of TCF charges along with TCF receptor boosters. Swivels are typically installed in a gun string every 1,640 ft.

Special swivels with high load capacity are required for string weights above 50 tons. These special swivels incorporate a patented feature to protect the roller bearings from damage resulting from the high loading of the heavy gun string during entry to and exit from the well. In the horizontal section, the undamaged swivel is free to rotate at a low coefficient of friction.

Applications

- Hydraulic fracturing—For both hard- and soft-rock reservoirs, gun swivels are used to orient the guns to shoot in the preferred fracture plane.
- Sand prevention—In weakly consolidated rocks, swivels orient the guns to shoot in the direction of maximum perforation stability.
- Increased productivity in laminated reservoirs with a high ratio of horizontal to vertical permeability—The swivels are used to orient the guns to shoot across bedding planes to increase productivity.
- Deviated and horizontal wells—The modular swivel aligns the guns in nonvertical wells.
- Operations with heavy string weight—The high-load-capacity swivel operates reliably despite the string weight.

Gun rollers

Gun rollers (Fig. 312 and Table 145) considerably improve gun transportability in highly deviated or horizontal wells by decreasing the gun friction on the casing. They allow shooting-range alignment between guns and optimize the gun clearance for big hole charges.

Applications

- Highly deviated wells—Gun alignment rollers improve the ease of conveying guns to shooting depth in highly deviated wells and then dropping the gun string at release depth. Gun orientation is also more reliable for shooting the low side of the hole.
- Oriented perforating—Positive alignment between guns within a gun string is provided by rollers for oriented perforating applications.

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Figure 312. Gun alignment rollers.

Table 145. Gun Roller Specifications

Gun size (in.)	2⅞	3⅜	4½
Outside diameter (in.)	2.75	3.375	4.438
OD with rollers (in.)	3.09	3.715	4.778
Length (in.)	15.0	15.0	15.0

Orienting spacers

Oriented TCP guns are used in highly deviated or horizontal wells. Orienting spacers are weighted for use in conjunction with swivels and rollers to orient the gun string. The orienting spacer consists of a section of gun body fitted with a weighted insert instead of a loading tube. The weight lies on one side of the spacer and is fixed to it so that gravity tends to rotate the spacer until the weighted side points down. As the gun string is run in the hole, movement and gravity continuously adjust the gun string. Thus, the orienting spacer maintains the same relative position. The gun phasing is dictated by the application, such as fracturing, sand prevention, or productivity enhancement.

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OrientXact tubing-conveyed oriented perforating system

The Schlumberger OrientXact oriented perforating system (Fig. 313 and Table 146) improves well productivity and can prevent sand production in horizontal and highly deviated wells. The system is configured with passive orienting weights and assembled in sections of 1,000 ft or longer, with high-load-capacity roller-bearing swivels at each end. This design provides an overall orientation accuracy of ±10° in the wellbore, independent of length or tortuosity. The OrientXact system has been qualified for dogleg severity as great as 10° per 100 ft of wellbore length at the SRC test facility in Rosharon, Texas, USA.

The aligning and orienting hardware uses weighted spacers and aligning adapters to lock individual components to each other in the desired configuration:

- Aligning and locking adapters—Adapters lock carriers to each other and eliminate all rotational clearances from manufacturing tolerances in the locking features.
- Carriers, loading tubes, and weighted spacers—Carriers and spacers are manufactured to be independent of the different trajectories of the wellbore for aligned and oriented perforating. The carriers and weighted spacers bend uniformly in dogleg severities of more than 10° per 100 ft of wellbore length. The weighted spacer design eliminates any tendency for these com-

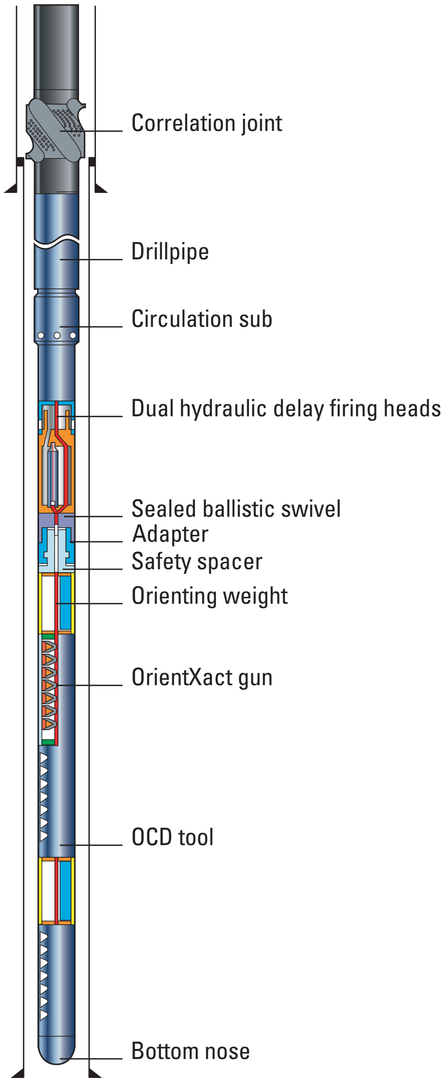

Figure 313. OrientXact tubing-conveyed perforating gun system.

Table 146. OrientXact Specifications

Outside diameter (in.)	2.88	3.38	3.50	4.50	4.72
Hollow carrier guns					
Shot density (spf), phasing (°)	4, 0/180 ± 10	4, 10/350	4, 10, 350	4, 10/350	4, 10/350
	5, 10/350	5, 10/350	5, 10/350	4, 0/180	4, 0/180
	5, 0/180	5, 0/180	5, 0/180	4, 0/180 ± 10	4, 0/180 ± 10
Shot spacing (in.)	4 spf: 3	4 spf: 3	4 spf: 3	3	3
	5 spf: 2.4	5 spf: 2.4	5 spf: 2.4		
Temperature rating[†] (°F [°C])	330 [165]	330 [165]	330 [165]	330 [165]	330 [165]
Pressure rating[‡] (psi)	20,000	20,000	20,000	10,000	20,000
Min. casing size (in.)	5½	5½	5½	7	7
Max. diameter including burrs, shot in liquid/gas (in.)	3.19/3.20	na/3.78	na/4.04	4.74/4.77	4.99/5.01
Max. gun length (ft)	10, 20, 30	10, 20, 30	10, 20, 30	10, 20, 30	10, 20, 30
Interval missed between guns (in.)	5 spf: 25.4	5 spf: 25.4	5 spf: 25.4	26.1	26.1
Weight of loaded in air (lbm)					
10-ft gun	166	246	250	325	397
20-ft gun	296	438	444	650	795
30-ft gun	426	629	638	975	1,193
Bend trajectory increments[§] (°)	30	30	30	30	30
Max. tensile load (lbf)					
Bend angle	na	170,000	na	240,000	375,000
No bend	124,000	na	165,000	165,000	na
Weighted spacers					
Max. OD (in.)	2.90	3.605	3.605	4.68	4.93
Length (ft)	10	10	10	10	10
Weight (lbm)	231	327	330	555	590

na = not available
[†] For 100 hr
[‡] At 400°F [204°C]
[§] From 0°F to 330°F [–17°C to 165°C]

ponents to try to rotate the string off axis when the string is bent. After the shot, the weighted spacer assemblies continue to provide orientation torque. This keeps the carrier exit holes along the top side of the assembly and minimizes the likelihood of debris inside the carriers falling out during retrieval of the string.

- Swivels—To improve orienting performance, a new swivel was developed to provide very low torsional friction while under simultaneous bending and compressive or tensile loading. Test results demonstrate that the string provides the necessary torque to overcome swivel resistance with tension and compression loads to 55,000 lbf and simultaneous bending to 10° per 100 ft.

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The unique OCD Orientation Confirmation Device of the OrientXact system verifies the orientation of the perforation cavities to an accuracy of ±1°. This critical data is available immediately after retrieving the gun string.

Applications

- Horizontal and highly deviated wells, regardless of dogleg severity or tortuosity—OrientXact orientation performs independently of tortuosity and is qualified for dogleg severity to 10° per 100 ft of wellbore length.
- Oriented perforating in long horizontal wells—Deployment on tubing, coiled tubing, or drillpipe enables underbalanced perforating of long intervals simultaneously.
- Oriented perforating in weak reservoirs—The stability of the perforation cavities is enhanced by perforating in the direction of the maximum stress, and sand production can be prevented or delayed by oriented perforating. In normally stressed horizontal wellbores, this optimal perforating orientation is vertical, which means the best perforation stability is achieved by shooting upward or downward. Shooting upward is preferred, however, because the gun clearance ensures optimum perforation cleanup and most of the perforating debris stays in the gun.

Remote operated OrientXact system

The remote operated OrientXact (ROOX) system (Fig. 314 and Table 147) is an oriented gun system with connectors designed for using a remote operated handling system. No personnel are required for gun handling on the drill floor.

The upper ROOX gun adapter (green on Fig. 315a) has a lifting profile that fits a hydraulically activated elevator with inserts modified to allow for gun swell. This integral lifting profile allows handling of the gun system without using any form of external lift sub. Once stabbed, the threaded coupling (yellow in Fig. 315b) is made up to the upper adapter on the gun below.

The tapered profile ensures the correct alignment between each gun assembly to maintain OrientXact orientation accuracy. There are no external seals on the ROOX gun connector that can be damaged during the handling and makeup procedure, and any torque transmitted through the gun string is absorbed by the tapered profiles on the adapters, not by the threaded coupling. Further operational reliability is provided by the SBT between each gun for rugged and pressure-tight explosive transfer that is not affected by liquid entry.

Applications

- Horizontal and highly deviated wells, regardless of dogleg severity or tortuosity—ROOX orientation performs independently of tortuosity and is qualified for dogleg severity to 10° per 100 ft of wellbore length.
- Oriented perforating in long horizontal wells—Deployment on tubing, coiled tubing, or drillpipe enables underbalanced perforating of long intervals simultaneously.
- Oriented perforating in weak reservoirs—Oriented perforating can enhance the stability of the perforating cavity and also prevent or delay sand production.

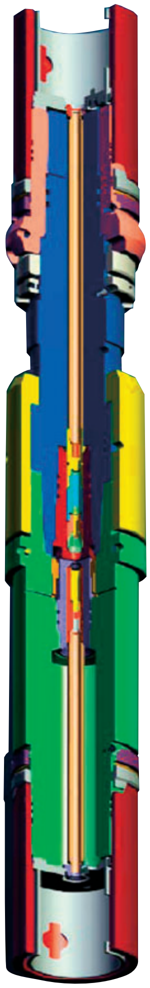

Figure 314. ROOX.

Table 147. ROOX Specifications[†]

Outside diameter (in.)	5.06
Temperature rating[‡] (°F [°C])	300 [149]
Pressure rating (psi)	20,000
Tensile strength at 67% of min. yield (lbf)	375,000

[†] Contact your Schlumberger representative for the availability of other sizes and ratings.
[‡] HMX explosives at 100 hr.

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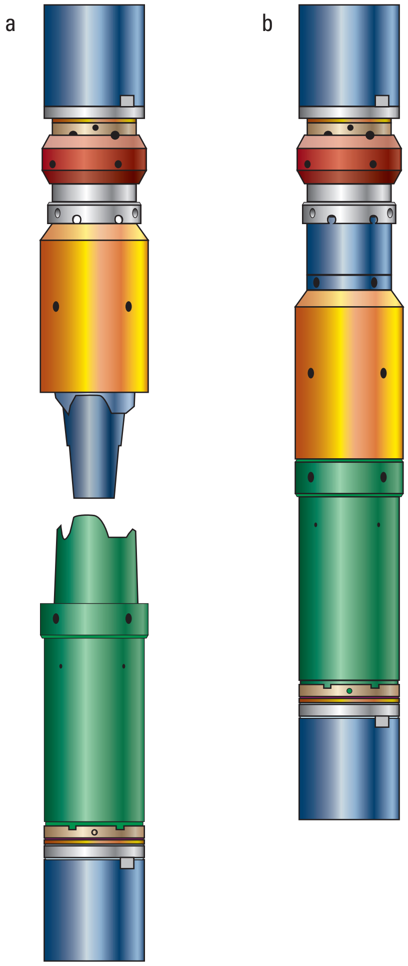

Figure 315. ROOX adapter (a) being stabbed and (b) fully made up.

Dual and selective multiple-completion hardware

Dual-string completions are perforated with TCP guns and special hardware (Fig. 316) to orient short-string guns below the dual packer, directing all shots away from the long string. The gun string can be suspended from a gun hanger built into the long string or connected directly from the short string. Special orienting Y-block hardware is also available to place guns alongside the tubing between two packers. This technique is useful for selective completions with multiple packers and zones. A sliding sleeve enables pressure-firing of the guns and production or isolation of intervals. Example strings are in the "TCP Applications" chapter.

Applications

- Guns suspended from a short string—To preserve correct orientation of the short-string guns with respect to the long-string blast joints, cast blocks are available as orienting hardware. Cast blocks are also preferred for smaller tubing in relatively large casings (for example, 2⅜ in. or 2⅞ in. inside 9⅝-in. casing). Cast blocks are sized according to the casing ID and blast joint OD. For example, in a 9⅝-in. casing, 3⅜-in. guns (60° phasing, 4 spf, providing 180° perforation coverage) can be run next to 3½-in. connection blast joints. Figure 317 illustrates the only possible relative position of a blast joint and a gun string section with a welded cast block.

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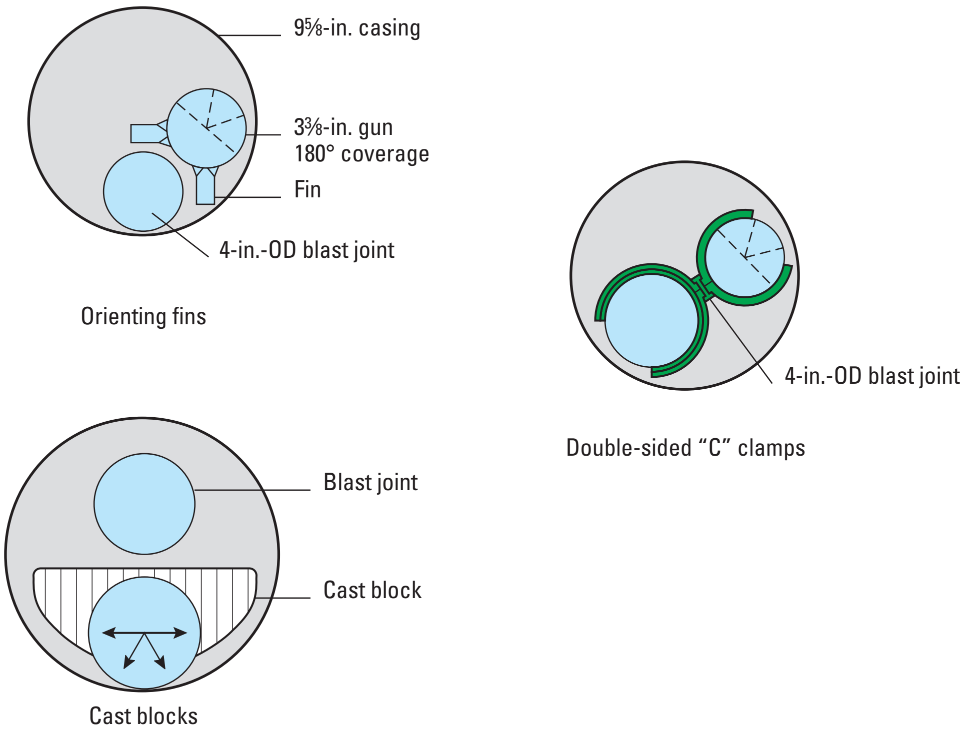

Orienting fins

Double-sided “C” clamps

Cast blocks

Figure 316. Dual- and multiple-completion hardware.

Double-sided C clamps or fins or both may be used instead of cast blocks. Positioned at gun interconnections and tightened on the gun string, they allow the long string to move vertically with respect to the short string.

The short string is made up to the bottom of the dual packer with an adjustable union incorporating a swivel and a short telescopic section. After the dual packer is made up to the long string, the swivel allows makeup to the short string without turning either string. The telescopic part allows the short-string gun top to be spaced out. If more spacing is required, a pup joint is added or removed. A drop bar, trigger charge, hydraulic delay, or eFire firing system can be used on either string. A redundant firing system can also be included.

- Guns suspended from a gun hanger—A gun hanger is a mechanical device run in line with the long string. An offset allows the guns to be suspended from the gun hanger and positioned alongside the long string. Fins or cast blocks are used for the shot orientation. The hanger technique is used between two hydraulic packers isolating the target zone. A sliding sleeve in the long string enables commingled production or zone isolation. When gun positioning is not critical, more than one perforating string can be positioned in the same long string, depending on the number of isolation packers used.

  An HDF system, which may be redundant, is used to fire the guns. Tubing pressure is applied from the surface into the long string and to the firing head through the sliding sleeve.

  As an extra precaution, radioactive pip tags in the top and bottom shots of the short-string or Y-block guns can be used. A GR-CCL is run in the long string to check the correct depth of the guns before setting the hydraulic packers. Another GR-CCL run is used to verify firing because the two large radioactive peaks are considerably attenuated.

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- Guns suspended from a Y-block with a side pocket—A Y-block with a side pocket mandrel (SPM) is a mechanical device run in line with the long string. An offset allows guns to be positioned alongside the long string, hanging below the Y-block. Special orienting clamps are used for the shot orientation. The clamps restrict rotation of the guns but allow them to slide down and up the blast joints. This type of installation includes two hydraulic packers isolating the target zone. A sliding sleeve on the long string enables commingled production or zone isolation. Several Y-blocks can be positioned in the long string, depending on the number of zones being isolated. The Y-block with an SPM is designed for firing the guns with the BHF system. A kick-over tool run on slickline activates the BHF head by jarring down.

Side-mounted perforating gun system

Side-mounted gun (SMG) completions are perforated with TCP guns and special hardware that orients the short-string guns below the packer to direct all shots away from the production tubing. The dual oriented perforating guns are clamped to the outside of the production tubing. Each gun section has dual HDF heads that are activated at the same time by the direct application of pressure to the production tubing; the eFire electronic firing system can also be used.

These customized systems are made available by request to the RapidResponse product development group at SRC.

Applications

- Operations in wells with production tubing—SMGs orient short-string guns below the packer to direct all shots away from the production tubing.
- Dual-zone perforation with selective gas lift—SMGs can be used to perforate an upper gas zone to activate a gas lift mandrel and produce from a lower perforated zone.

Pump-over gun

The circulate before and after (CBAP) pump-over gun system is a hollow carrier gun that allows fluid circulation through the gun body before and after perforating (Fig. 317). The charges are packaged and sealed as in a conventional short-section hollow carrier gun. A combination of ported upper and lower subs and an outer sleeve enable pumping fluid from above the gun to between the outer sleeve and the gun body and finally out through the lower sub. These customized systems are made available by request to the RapidResponse product development group at SRC. Charge size, phasing, and orientation depend on the job.

The CBAP gun system was developed by Schlumberger for use in coiled tubing operations in wells that require fracturing, wellbore cleanout, and perforating. With this equipment combination, high-rate solids cleanout and perforating can be combined in one coiled tubing run. This capability avoids separate cleanout runs on coiled tubing between each perforating run.

Applications

- Coiled tubing fracturing operations with proppant placement—The CBAP combination of proven firing systems and hollow carrier technology provides flexibility in perforating design and orientation to prevent proppant bridging, with same-trip maximum debris removal through the ability to circulate through the tool at high rates.

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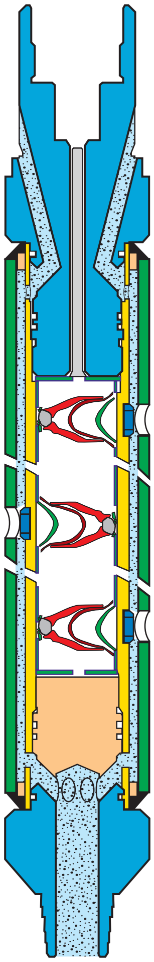

Figure 317. CBAP pump-over gun.

CBAP operational procedures

Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

Execution

A typical CBAP operation begins with running in the well with the pump-over gun system attached to coiled tubing. After the first interval is perforated, the wellbore is circulated clean. The CBAP gun is then pulled above the perforations and a fracture treatment is conducted. Proppant or sand is then placed as a protective plug above the interval, and the well is again circulated clean before pulling out of the hole. Pumping through the CBAP assembly means that circulation takes place at the very end of the coiled tubing string both before and after perforating.

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TCP Applications

There are many possible designs for TCP strings; the correct choice depends on the completion objective. This section gives the components found in common strings for various TCP applications and describes each component, its purpose, and method of activation. Many possible combinations of this equipment are not noted here. Always check with your Schlumberger representative for advice on the most efficient string configuration for your application.

Temporary completions

Permanent completions

Workover completions

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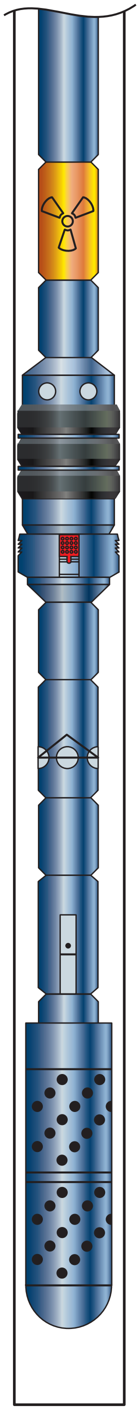
Temporary completion: Basic TCP string with tubing filled to surface

This basic TCP string is used for shoot-and-test operations where an underbalance is created by circulating a lighter fluid through the circulating sub before setting the packer.



String Component	Method of Activation	Purpose of Component
Radioactive marker sub		Allows depth control
Retrievable packer	Mechanical rotate and reciprocate	Seals, supports string, provides hold-down
Fluid and debris-isolation sub		Protects firing heads from debris and provides a flow path
Firing head	See firing head table below	
Safety spacer		Safety at surface
Hollow carrier guns		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X	X	X	X	X	X

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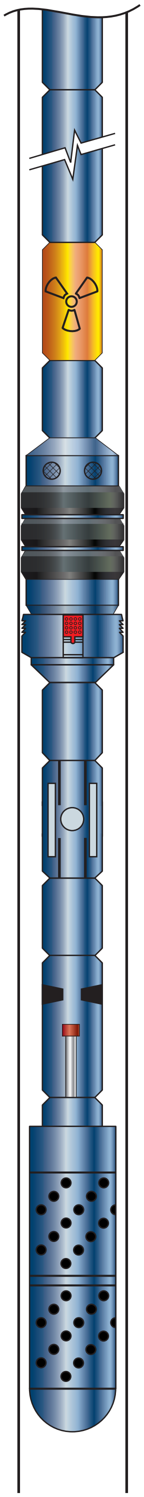
Temporary completion: Basic TCP string with tubing partially empty

This basic TCP string is used for shoot-and-test operations where an underbalance is created by running the tubing partially empty. The production valve is activated just before gun firing.



String Component	Method of Activation	Purpose of Component
Radioactive marker sub		Allows depth control
Retrievable packer	Mechanical rotate and reciprocate	Seals, supports string, provides hold-down
Production valve	Drop bar or absolute pressure	Maintains underbalance and provides a flow path
Firing head		
Safety spacer		Safety at surface
Hollow carrier guns		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X	X	X[†]	X		X

[†] Activated with N_2 or via annulus.

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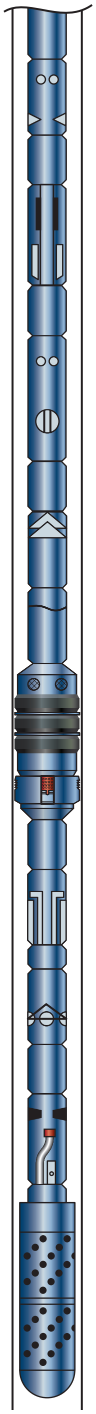
Temporary completion: DST-TCP with redundant firing and nitrogen cushion

The guns are fired with nitrogen in the tubing. The time delay of the HDF head allows firing the guns after the nitrogen has been bled down to the desired underbalance pressure. The circulating valve in the IRIS dual-valve tool allows displacement of the completion fluids to reach the correct underbalance pressure after the nitrogen pressure is removed. The redundant drop bar head is also available.



String Component	Method of Activation	Purpose of Component
SHORT reversing valve	Annulus pressure	Acts as secondary reversing valve
DataLatch* downhole recorder and transmitter		Provides surface readout pressure recording and retrieval through the LINC* Latched Inductive Coupling tool
IRIS dual valve	Annulus pressure pulses	Acts as a test valve and primary circulating valve
Jar	Tension	
Safety joint	Left-hand torque	
PosiTest* or PosiTrieve retrievable packer	Mechanical rotate and reciprocate	Seals, supports string, provides hold-down
Gun drop sub	Slickline	Releases guns if required
Fluid and debris-isolation sub		Protects firing head from debris and provides a flow path
Redundant firing heads		
Safety spacer		Safety at surface
Hollow carrier guns		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
	X	X	X[†]	X	
Optional redundant combinations					

[†] Jar down, drop bar, and absolute pressure

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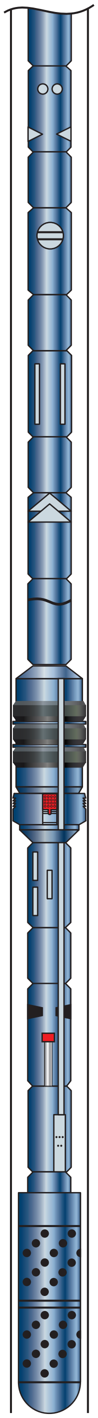
Temporary completion: Sand control, shoot and surge

The shoot-and-surge technique allows creating an underbalance by opening an underbalancing valve below a partially empty string after the packer is set. This procedure minimizes sand production by allowing the formation to surge a predetermined amount into the well.



String Component	Method of Activation	Purpose of Component
SHORT reversing valve	Annulus pressure	Acts as secondary reversing valve
Underbalancing valve (SBSV or IRIS)	Annulus pressure	Isolates string during run in hole, creates underbalance when opened
Gauge carrier		Holds and protects pressure gauges
Jar	Tension	
Safety joint	Left-hand torque	
PosiTest or PosiTrieve retrievable packer	Mechanical rotate and reciprocate	Seals, supports string; bypass offers primary method of reverse circulating
Slotted pipe		Provides a flow path
Secondary firing head		
Primary firing head		
Safety spacer		Safety at surface
Hollow carrier guns		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X	X	X	X	X	
Optional redundant combinations					

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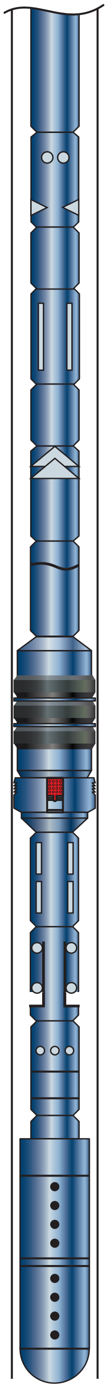
Temporary completion: Sand control, oriented perforating

To perforate highly deviated wells for gravel-packed completions, oriented perforating is preferred, usually horizontally to minimize sand production through the poorer gravel-packed sections normally found on the high and low sides of the casing. The underbalance is created by circulating lighter fluids through the packer bypass.



<table>
<tr><th>String Component</th><th>Method of Activation</th><th>Purpose of Component</th></tr>
<tr><td>SHORT reversing valve</td><td>Annulus pressure</td><td>Provides a secondary method of reverse circulating</td></tr>
<tr><td>Gauge carrier</td><td></td><td>Holds and protects pressure gauges</td></tr>
<tr><td>Jar</td><td>Tension</td><td></td></tr>
<tr><td>Safety joint</td><td>Left-hand torque</td><td></td></tr>
<tr><td>Retrievable PosiTest long-stroke packer</td><td>Mechanical vertical motion only</td><td>Allows packer to be set in highly deviated hole without pipe rotation, includes bypass for circulation</td></tr>
<tr><td>Slotted pipe</td><td></td><td>Provides a flow path</td></tr>
<tr><td>Swivel</td><td></td><td>Allows gun rotation</td></tr>
<tr><td>Firing head</td><td colspan="2"><table>
<tr><td>Electronic</td><td>Drop Bar</td><td>Time-Delay Absolute Pressure</td><td>Trigger Charge</td><td>Differential Pressure</td><td>Time-Delay Hydraulic</td></tr>
<tr><td>eFire</td><td>BHF</td><td>HDF</td><td>TCF</td><td>DFS</td><td>ProFire</td></tr>
<tr><td>X</td><td></td><td>X</td><td></td><td></td><td>X</td></tr>
<tr><td colspan="6">Optional redundant combinations</td></tr>
</table></td></tr>
<tr><td>Safety spacer</td><td></td><td>Safety at surface</td></tr>
<tr><td>Hollow carrier guns with big hole charges and orienting hardware</td><td></td><td>Low-side-loaded gun shoots the lower 180° of the casing</td></tr>
</table>

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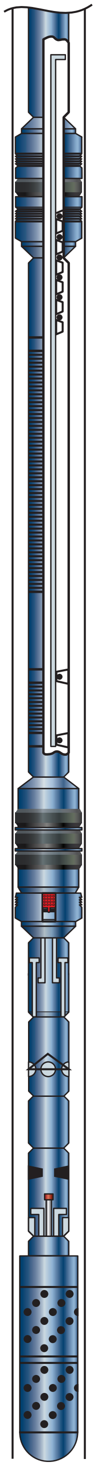
Temporary completion: Single-trip perforate and gravel pack

This string allows single-trip perforating, surging, and gravel packing. Underbalance is created by circulating a lighter fluid through the IRDV circulating valve, which is positioned above the QUANTUM packer.



String Component	Method of Activation	Purpose of Component
QUANTUM gravel-pack packer	Tubing pressure	Gravel-pack operation
Screen		
Lower telltale		
Retrievable PosiTest long-stroke packer	Vertical motion	Sets packer without rotating string
Shock absorber		Protects string
Debris-circulating sub		Protects head from debris and provides a flow path

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X		X	X		X

String Component	Method of Activation	Purpose of Component
Firing head		
Automatic gun drop	Guns firing	Primary gun release
Safety spacer		Safety at surface
Hollow carrier guns		

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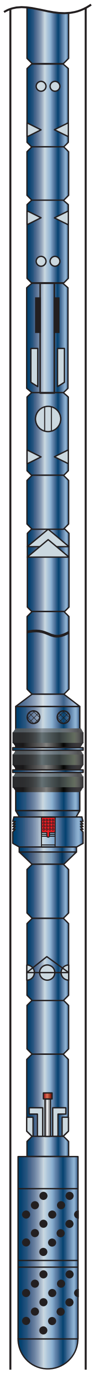
Temporary completion: Single-trip perforate, acidize, test

This string allows perforating, testing for skin, acidizing, and additional testing with data retrieval between tests through the DataLatch tool. Underbalance is created by spotting nitrogen using the IRDV circulating valve. The guns are released to allow subsequent production logging and wireline perforating.



String Component	Method of Activation	Purpose of Component
Annular reversing valve (SHRV)	Annulus pressure	Acts as a primary reversing valve
Multicycle circulating valve (MCVL)	Tubing pressure	Spots nitrogen, provides a secondary reversing valve
DataLatch downhole recorder and transmitter		Provides pressure recording and retrieval through the LINC tool
Fullbore tester valve	Annulus pressure	Acts as DST valve
Jar	Tension	
Safety joint	Left-hand torque	
Hydraulic retrievable packer	Pressure set	Seals, supports string, provides hold-down
Debris-circulating sub		Protects head from debris and provides a flow path
Firing head		
Automatic gun drop	Guns firing	Primary gun release
Safety spacer		Safety at surface
Hollow carrier guns		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X	X	X	X	X	X
Optional redundant combinations					

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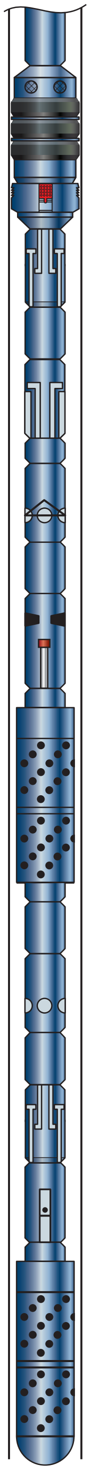
Temporary completion: Single-string selective firing–commingled production

This string allows production from two separately perforated zones. Underbalance for the bottom zone is created by circulating a lighter fluid; for the top zone, it is dictated by the formation pressure of the bottom zone. The guns are fired selectively, bottom gun first.



String Component	Method of Activation	Purpose of Component
HiPack* hydraulic retrievable packer	Pressure set, pull release	Seals, supports string, provides hold-down
Shock absorber		Protects packer and string
Gun drop sub	Slickline or hydraulic	Releases guns, if required
Fluid and debris-isolation sub		Protects firing head from debris, provides a flow path
Top-zone firing head		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
	X		X		
Optional redundant combinations					

Safety spacer		Safety at surface
Hollow carrier guns		
Spacer(s)		Space out
Ported sub		Allows pressure to reach lower firing head
Shock absorber		Protects upper string
Bottom-zone firing head		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X		X			X
Optional redundant combinations					

Safety spacer		Safety at surface
Hollow carrier guns		

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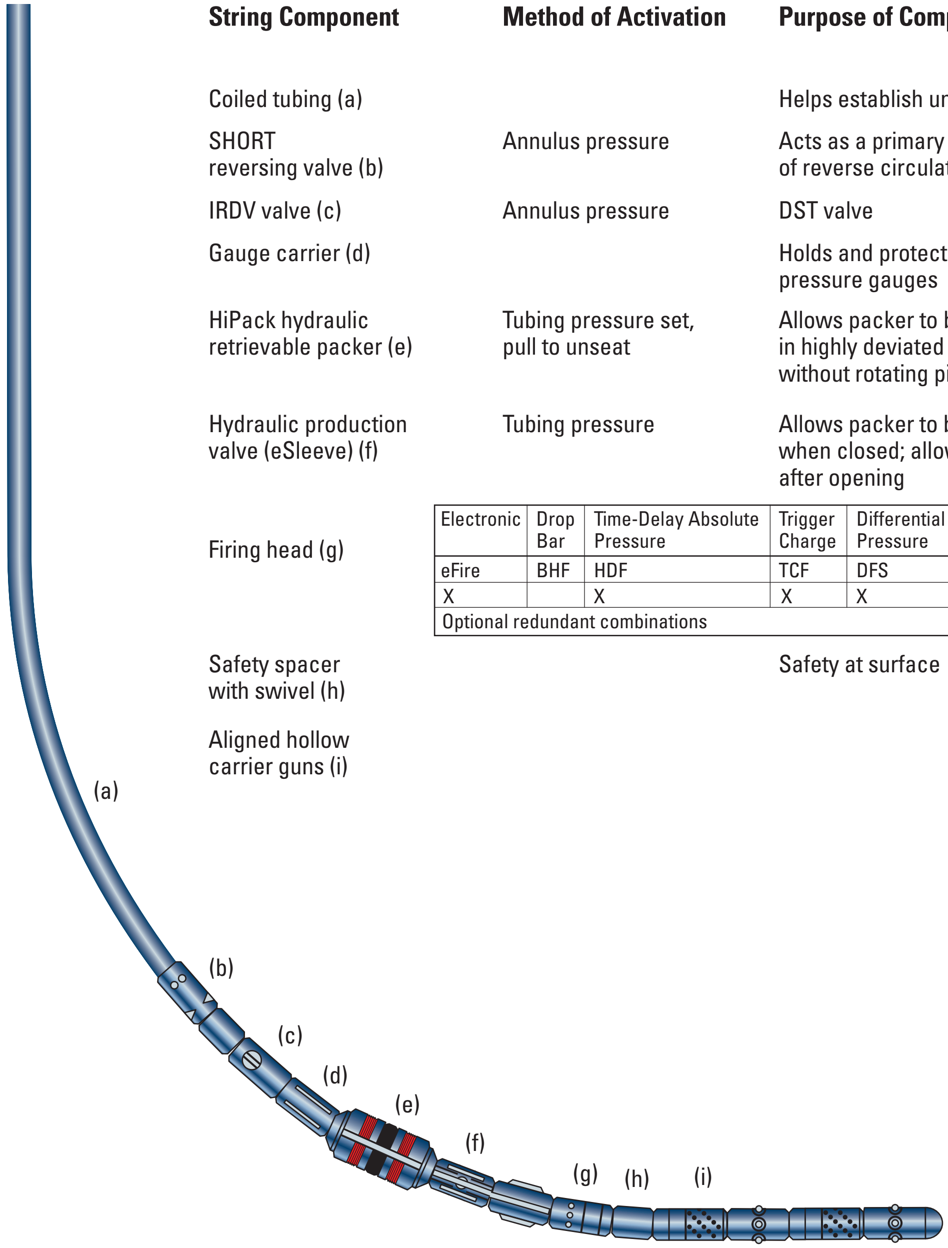
Temporary completion: DST-TCP in horizontal well

Horizontal wells can be perforated with a string including a retrievable hydraulic packer and hydraulic production valve. Special horizontal hardware is used to aid the string in reaching bottom. The underbalance is created by displacing clean fluid with nitrogen through coiled tubing.



<table>
<tr><th>String Component</th><th>Method of Activation</th><th>Purpose of Component</th></tr>
<tr><td>Coiled tubing (a)</td><td></td><td>Helps establish underbalance</td></tr>
<tr><td>SHORT reversing valve (b)</td><td>Annulus pressure</td><td>Acts as a primary method of reverse circulating</td></tr>
<tr><td>IRDV valve (c)</td><td>Annulus pressure</td><td>DST valve</td></tr>
<tr><td>Gauge carrier (d)</td><td></td><td>Holds and protects pressure gauges</td></tr>
<tr><td>HiPack hydraulic retrievable packer (e)</td><td>Tubing pressure set, pull to unseat</td><td>Allows packer to be set in highly deviated holes without rotating pipe</td></tr>
<tr><td>Hydraulic production valve (eSleeve) (f)</td><td>Tubing pressure</td><td>Allows packer to be set when closed; allows flow after opening</td></tr>
<tr><td>Firing head (g)</td><td colspan="2">
<table>
<tr><td>Electronic</td><td>Drop Bar</td><td>Time-Delay Absolute Pressure</td><td>Trigger Charge</td><td>Differential Pressure</td><td>Time-Delay Hydraulic</td></tr>
<tr><td>eFire</td><td>BHF</td><td>HDF</td><td>TCF</td><td>DFS</td><td>ProFire</td></tr>
<tr><td>X</td><td></td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td colspan="6">Optional redundant combinations</td></tr>
</table>
</td></tr>
<tr><td>Safety spacer with swivel (h)</td><td></td><td>Safety at surface</td></tr>
<tr><td>Aligned hollow carrier guns (i)</td><td></td><td></td></tr>
</table>

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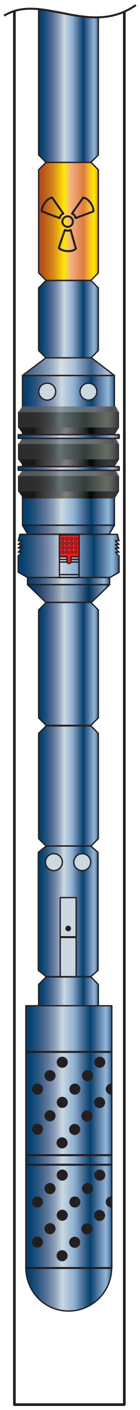
Temporary completion: Extreme overbalance perforating

This string incorporates a production valve that stays closed until the guns fire. This allows the tubing to be pressured up to the extreme overbalance, protecting the casing. The instant the guns fire, the valve opens, allowing the pressure to reach the perforations.



String Component	Method of Activation	Purpose of Component
Radioactive marker sub		Allows depth control
Packer	Mechanical or hydraulic	Seals, supports string, provides hold-down
Automatic production valve	Opens the instant guns fire	Seals tubing string until open
Firing head		
Safety spacer		Safety at surface
Hollow carrier guns		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X	X	X	X	X	

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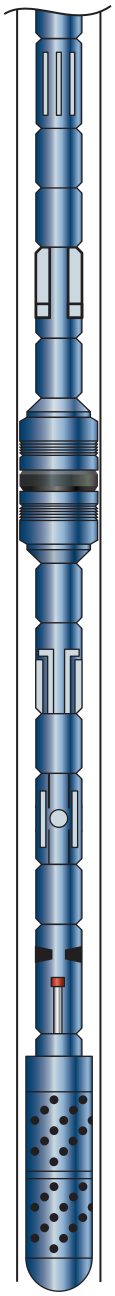
Permanent completion: Hydraulic packer and hydraulic production valve

The hydraulic packer can be set before creating the underbalance by displacing lighter fluids through the sliding sleeve, running down with a liquid cushion in place or with gas lift. The hydraulic production valve is then opened with tubing pressure.



String Component	Method of Activation	Purpose of Component
Sliding sleeve	Slickline	Circulating fluid
Expansion joint		Allows for string movement
Hydraulic packer	Tubing pressure	Seals and supports string
Gun drop sub	Slickline or hydraulic	Releases guns if required
Hydraulic production valve (POUV)	Tubing pressure	Seals string and provides a flow path
Firing head		
Safety spacer		Safety at surface
Hollow carrier guns		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X	X	X	X		X

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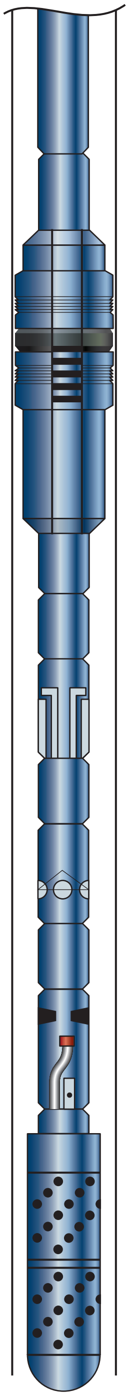
Permanent completion: Sting-through completion

In this string a packer with a sealbore assembly is set on wireline and the guns are stung through. Underbalance is created by circulating through the ported sub before stinging into the packer.



String Component	Method of Activation	Purpose of Component
Permanent packer with sealbore extension	Electric wireline	Seals string from annulus
Gun drop sub	Slickline or hydraulic	Releases guns if required
Debris-circulating sub		Protects firing head from debris and provides a flow path
Redundant firing heads		
Safety spacer		Safety at surface
Hollow carrier guns		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X	X	X	X		X
Optional redundant combinations					

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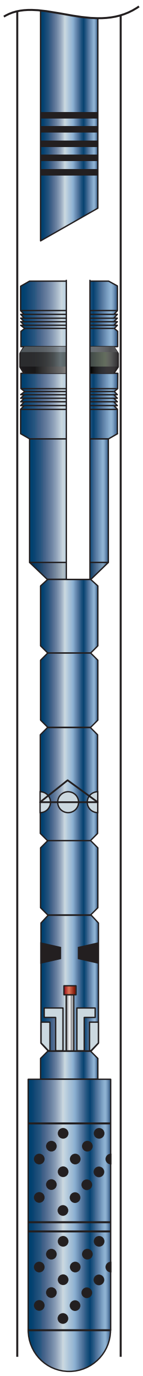
Permanent completion: Stab-in completion

In this string the packer and gun string are run and set on depth by drillpipe or wireline, and the completion string is stabbed into the packer before firing. Underbalance is achieved by circulating lighter fluid before stabbing into the packer.



String Component	Method of Activation	Purpose of Component
Seal assembly		Seals production string from annulus
Permanent packer and sealbore extension	Electric wireline	Seals string from annulus
Debris-circulating sub		Protects firing head from debris and provides a flow path
Redundant firing heads		
Automatic gun drop	Guns firing	Primary gun release
Safety spacer		Safety at surface
Hollow carrier guns		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X	X	X	X		X
Optional redundant combinations					

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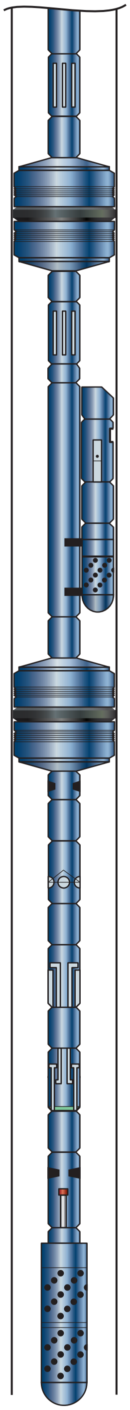
Permanent completion: Single-string selective completion

Two zones can be perforated with one tubing string. The upper zone guns are attached to and oriented away from the long string of tubing. The lower zone underbalance can be created by circulating lighter fluid through the tubing before the packers are set. The underbalance in the upper zone is established by circulating lighter fluid through a sliding sleeve above the upper packer. After both packers are set, the upper zone gun is fired by tubing pressure and the lower zone is fired by drop bar. Isolation between the zones is achieved by setting a plug in the seating nipple.



String Component	Method of Activation	Purpose of Component
Sliding sleeve	Slickline	Circulates above top packer
Hydraulic packer	Tubing pressure	
Sliding sleeve	Slickline	Isolates top zone, allows production
Y-block		Supports gun
Upper firing heads		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X		X			X

Hollow carrier guns (oriented)		Shoot away from production string
Hydraulic packer	Tubing pressure	
Seating nipple	Set plug in	Seals off lower zone
Fluid and debris-isolation sub		Protects firing head from debris and provides a flow path
Gun drop sub	Slickline or hydraulic	Releases guns if required
Shock absorber		Isolates packer from the shock of gun firing
Lower firing head		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X	X	X	X		X

Safety spacer		Safety at surface
Hollow carrier guns		

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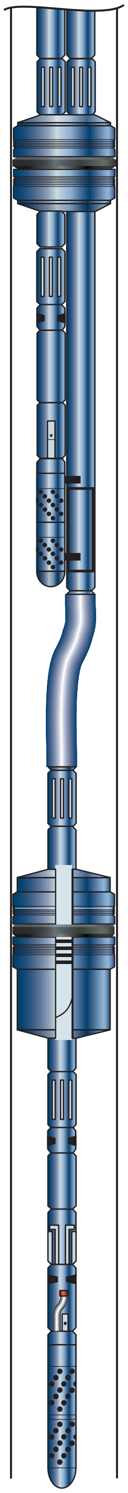
Permanent completion: Dual-string completion (sting-through)

Two zones can be selectively completed with a dual string. The guns for both strings are spaced below the dual packer and run with the long tubing string. The long string guns are stung through a permanent packer; then, the dual packer is set. The underbalance is created by circulating lighter fluids through the sliding sleeve into the long string and out of the short string.



String Component	Method of Activation	Purpose of Component
Dual packer	Tubing pressure	
Swivel		Orients the guns relative to the long string and aids makeup
Sliding sleeve	Slickline	Provides flow path
Landing nipple	Set plug in	Pressure tests string, isolates zone
Upper firing head		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X	X	X	X		X
Optional redundant combinations					

String Component	Method of Activation	Purpose of Component
Safety spacer		Safety at surface
Radioactive pip tags		Allows check of gun depth and verifies firing
Hollow carrier guns (oriented)		Shoot away from long string
Sliding sleeve	Slickline	Circulates underbalance fluid
Permanent packer and sealbore assembly	Electric wireline	
Sliding sleeve	Slickline	Provides flow path
Landing nipple		
Gun drop sub	Slickline	Releases guns if required
Lower firing head		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X	X	X	X		X
Optional redundant combinations					

String Component	Method of Activation	Purpose of Component
Safety spacer		Safety at surface
Hollow carrier guns		

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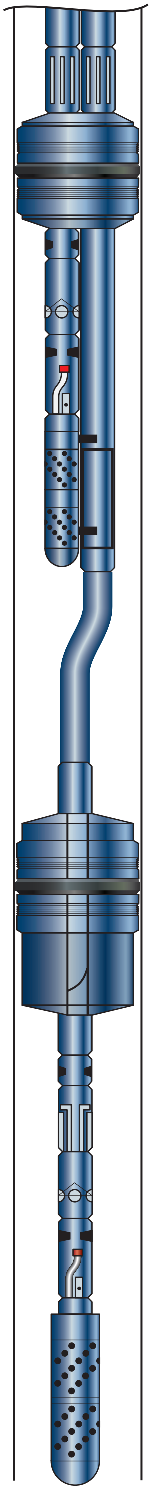
Permanent completion: Dual-string completion (stab-in)

Two zones can be selectively completed with a dual string. The long string guns are run below a permanently set packer. The short string guns are run below a dual packer, and the long string tubing is stung into the lower packer. The underbalance is created by circulating lighter fluids through the long string before the dual packer is set or by swabbing.



String Component	Method of Activation	Purpose of Component
Dual packer	Tubing pressure	
Swivel		Orients the guns relative to the long string and aids makeup
Landing nipple	Set plug in	Pressure tests string, isolates zone
Fluid and debris-isolation sub		Protects firing head from debris and provides a flow path
Upper firing head		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X	X	X	X		X
Optional redundant combinations					

Safety spacer		Safety at surface
Hollow carrier guns (oriented)		Shoot away from long string
Permanent packer and sealbore	Electric wireline	
Landing nipple		
Gun drop sub	Slickline	Releases guns if required
Debris-circulating sub		Protects head from debris and provides a flow path
Lower firing head		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X	X	X	X		X
Optional redundant combinations					

Safety spacer		Safety at surface
Hollow carrier guns		

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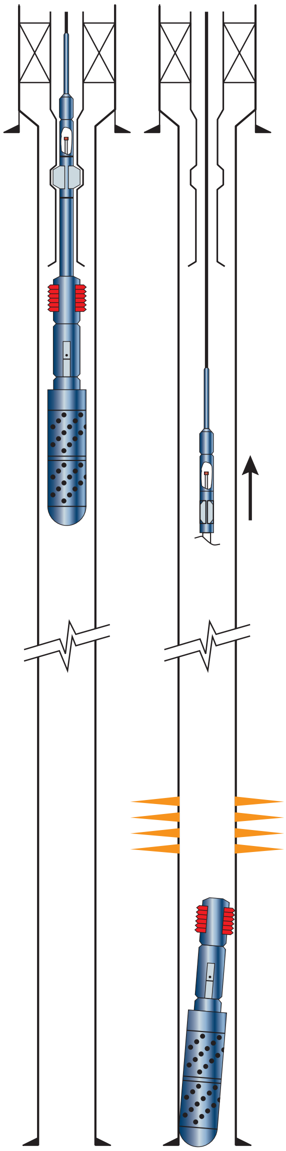
Permanent completion: Tubing- and wireline-conveyed perforating completion

Completion of deep, high-temperature wells with long sections of liner is possible by conveying the guns on tubing, hanging them at a depth where the temperature is low enough for prolonged exposure, and then latching in with wireline and lowering the guns to the perforation depth. Once on depth the guns are anchored, wireline is removed, and the guns pressure-fired. The underbalance is created by circulating lighter fluids before the packer is set.



String Component	Method of Activation	Purpose of Component
Wireline latch and	Wireline	Activates neutral release
neutral release	Mechanical	Releases the gun string gently
Inductive coupler and	Wireline	Triggers the anchor-setting tool
anchor-setting tool	Wireline	Sets the anchor section and separates running tools
Anchor and release section	Set by setting tool, released by slickline	Anchors the gun and releases the gun string
Firing head		
Safety spacer		Safety at surface
Hollow carrier guns		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X		X			X
Optional redundant combinations					

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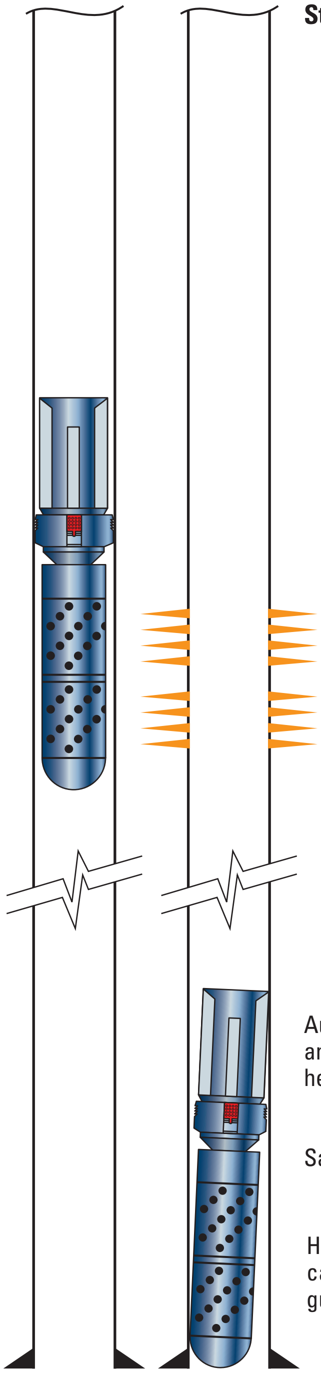
Permanent completion: Gun string anchored in casing

Anchoring a gun string in casing provides the advantages of a TCP gun string shot underbalance in a monobore completion. This completion method is also useful when the gun string must be separate from a conventional completion assembly. The anchor releases the instant the guns fire, dropping the assembly to bottom. After the assembly drops, the well is fullbore.



String Component	Method of Activation	Purpose of Component
Automatic release anchor with firing head	Mechanically set on wireline or pipe, released when guns fired	Anchors guns in position
Safety spacer		Safety at surface
Hollow carrier guns		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X		X	X		X

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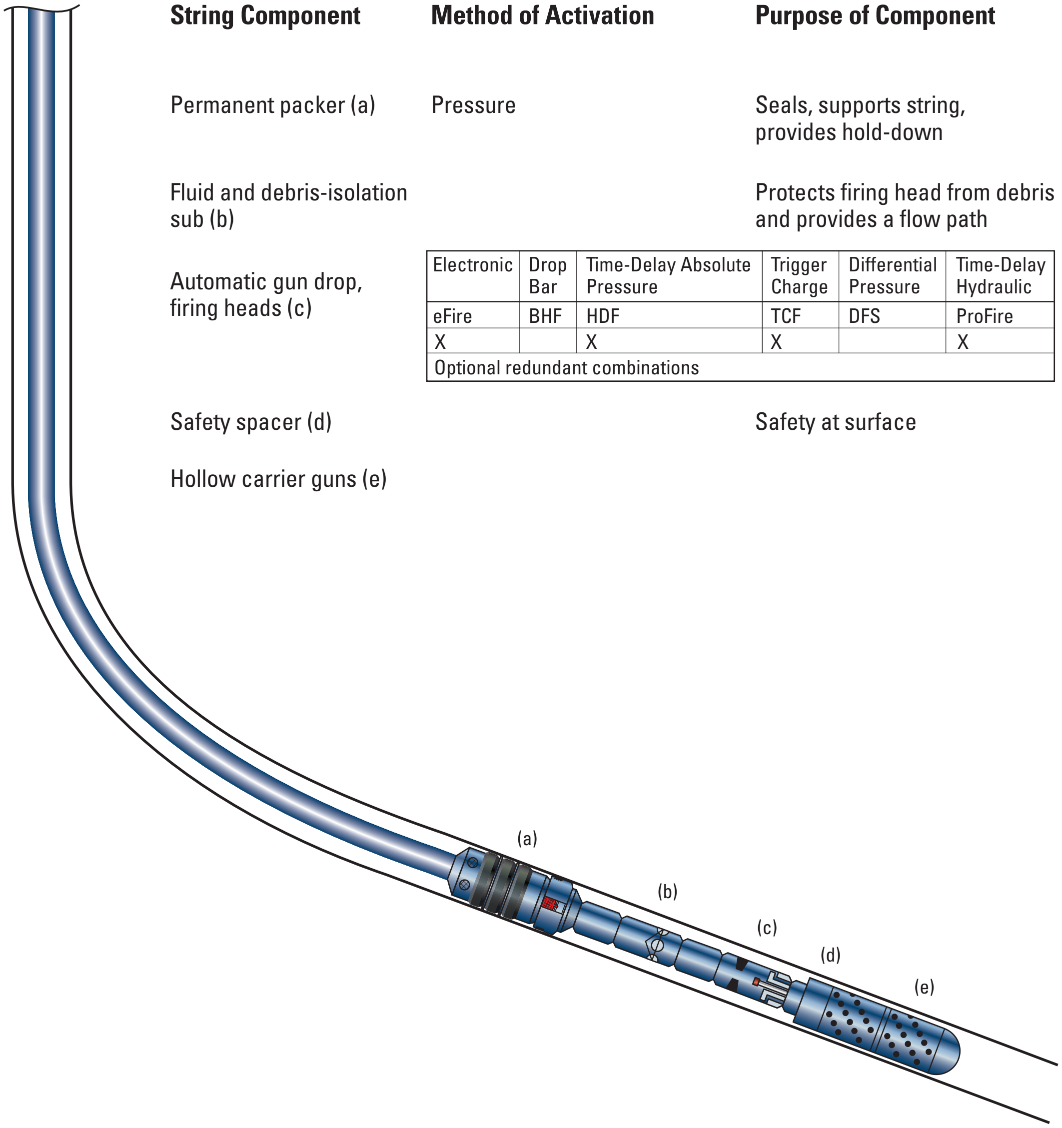
Permanent completion: TCP with automatic gun drop in highly deviated wells

Automatic gun drop is required when guns must be dropped in deviations greater than 45°. Guns have been dropped in deviations up to 80° with this system. The guns stay attached to the gun string until they fire. At firing they are released to fall to the bottom of the well.

String Component	Method of Activation	Purpose of Component
Permanent packer (a)	Pressure	Seals, supports string, provides hold-down
Fluid and debris-isolation sub (b)		Protects firing head from debris and provides a flow path
Automatic gun drop, firing heads (c)		
Safety spacer (d)		Safety at surface
Hollow carrier guns (e)		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X		X	X		X
Optional redundant combinations					



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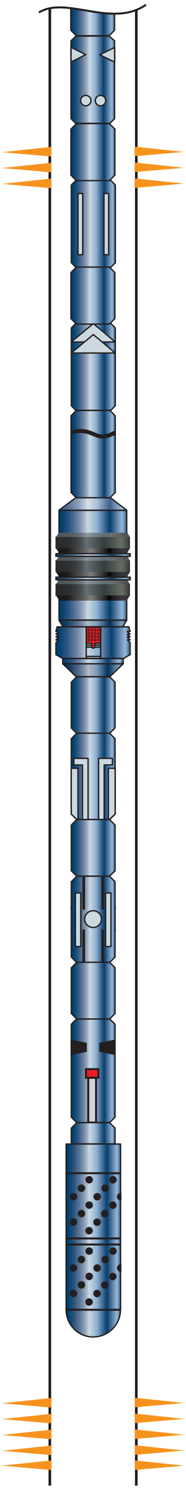
Workover completion: Reperforating with packer set between existing perforations

A new zone can be perforated or an existing one reperforated in the presence of open perforations with underbalance. The underbalance is created by opening an annular production valve an instant before firing; the string is run partially filled and closed.



String Component	Method of Activation	Purpose of Component
Mechanical reversing valve (MRV)	Rotate to open, reciprocate to close	Acts as a secondary reversing valve
Squeezed-off perforations		
Gauge carrier		Holds and protects pressure gauges
Jar	Tension	
Safety joint	Left-hand torque	
PosiTrieve retrievable packer	Mechanical rotate and reciprocate	Includes bypass for reversing out
Gun drop sub	Slickline or hydraulic	Releases guns if required
Production valve	Drop bar or pressure	Isolates tubing, provides flow path
Firing head		
Safety spacer		Safety at surface
Hollow carrier guns		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
X	X	X	X[†]		X
Optional redundant combinations					

[†] Jar down, drop bar, and timed pressure

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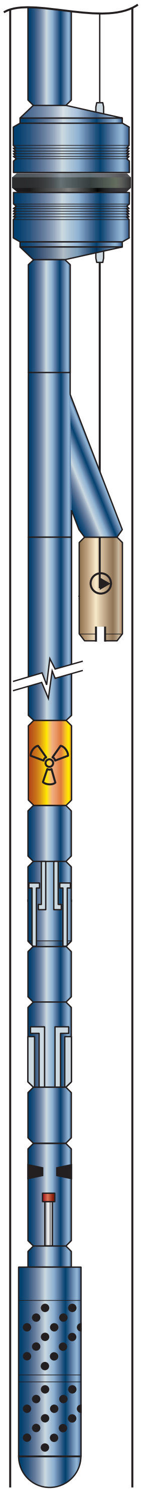
Workover completion: Pumped well recompletion

This string allows recompletion of a pumped well in a depleted reservoir using a Y-tool and a TCP string. A dynamic underbalance is created by operating the pump.



String Component	Method of Activation	Purpose of Component
Dual packer	Tubing pressure	
Y-tool		Branches to pump
Submersible pump	Electrical	Pumps fluid
Radioactive marker sub		Provides depth correlation
Shock absorber		Protects pump and string
Gun drop sub	Slickline or hydraulic	Releases guns if required
Firing head		
Safety spacer		Safety at surface
Hollow carrier guns		

Electronic	Drop Bar	Time-Delay Absolute Pressure	Trigger Charge	Differential Pressure	Time-Delay Hydraulic
eFire	BHF	HDF	TCF	DFS	ProFire
	X		X†		

† Jar down and drop bar

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Completion Perforating Without Killing the Well

Killing the well—stopping it from flowing or having the ability to flow into the wellbore—before or after perforating diminishes the performance of new or existing perforations. The damage can have long-lasting effects, and performance cannot usually be restored to the original, undamaged state.

Completion without killing the well results in a perforation-to-production process that does not expose the formation to kill fluids. This process enables underbalanced perforating of the entire interval. Removing the guns from in front of the producing interval allows unrestricted flow and provides access for evaluation and treatment.

Virtually all perforating jobs performed with hollow carrier gun systems conveyed on tubing or wireline can be performed without killing the well. The advantages are numerous:

- ability to retrieve long gun strings after perforating
- perforating and reperforating long horizontal sections
- running and retrieving guns using coiled tubing
- running and retrieving guns using slickline
- no limitation resulting from the weight or total length of the gun string
- automatic release of the gun string upon firing
- perforating and sand control in one trip
- incorporating guns in a permanent completion with a choice of either dropping or retrieving them.

Schlumberger has developed techniques and equipment for safer and more efficient perforating without killing the well. Figure 318 lists some of the reservoir, economic, and technical benefits provided by the techniques described in this chapter. The PERFPAC sand control method, which is not included in the figure, is discussed later in this chapter.

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Reservoir Economics Technique

	Remove guns without controlling (killing) well	Fast gun removal to surge all perforations	Optimum perforation cleanup	Shoot pay zone underbalanced in one run	Never shut in well	High-angle wells	Reperforate without killing the well	Reperforate while producing	No additional drilling (rathole) required	No rig required to perforate	New well	Best gun (size, spf, penetration, hole size)	Horizontal wells	Workovers
Through tubing	✓						✓		✓	✓	✓			✓
CTXR	✓	✓	✓	✓	✓	✓				✓[1]	(✓)	✓		
SXAR	✓	✓	✓	✓	✓	✓				✓[1]	(✓)	✓		
MAXR	✓	✓	✓	✓	✓	✓				✓[1]	✓[2]	✓	(✓)	
WXAR	✓	✓	✓	✓	✓	✓	✓			✓	✓	(✓)		✓
FIV	✓		✓[3]	✓		✓	✓		✓	✓[1]	✓		✓	
Wireline CIRP	✓		✓[3]	✓			✓		✓	✓	✓			✓
Coiled tubing CIRP	✓		✓[3]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
GunStack	✓	(✓)	✓[3]	✓		✓[4]	✓	✓[4]	✓	✓	✓	✓	✓[4]	✓

✓ Advantage

(✓) Limitations

[1] Rig required for installation, but not for perforating

[2] Best in monobores

[3] Guns are in place impeding cleanup

[4] Requires suitable conveyor

Figure 318. Advantages of completion perforating without killing the well.

X-Tools gun-activated automatic release

The X-Tools automatic release mechanism developed by Schlumberger achieves extremely fast release times because it is closely linked to the detonating process. Figure 319 depicts the timing of various responses initiated by activation of the firing head. X-Tools release tools operate immediately after the guns fire but before the wellbore reacts. By contrast, a mechanically or pressure-activated device reacts only after wellbore effects have taken place. When dropping guns, the speed of activation is crucial to effects such as sanding. The speed of activation is also critical when dropping guns in highly deviated wells. Firing the guns creates very short dynamic movements that reduce friction and help convey the guns to the bottom of the well. For this dynamic movement to take place, however, release must occur at the instant of firing.

Schlumberger has developed a range of automatic gun release systems incorporating perforating gun–activated X-Tools technology. The monobore automatic release anchor (MAXR) and wireline-conveyed X-Tools automatic release (WXAR) are in this chapter; the closed tubing automatic gun release (CTXR) and automatic gun release (SXAR) are detailed in the preceding “Completion Perforating Equipment” chapter.

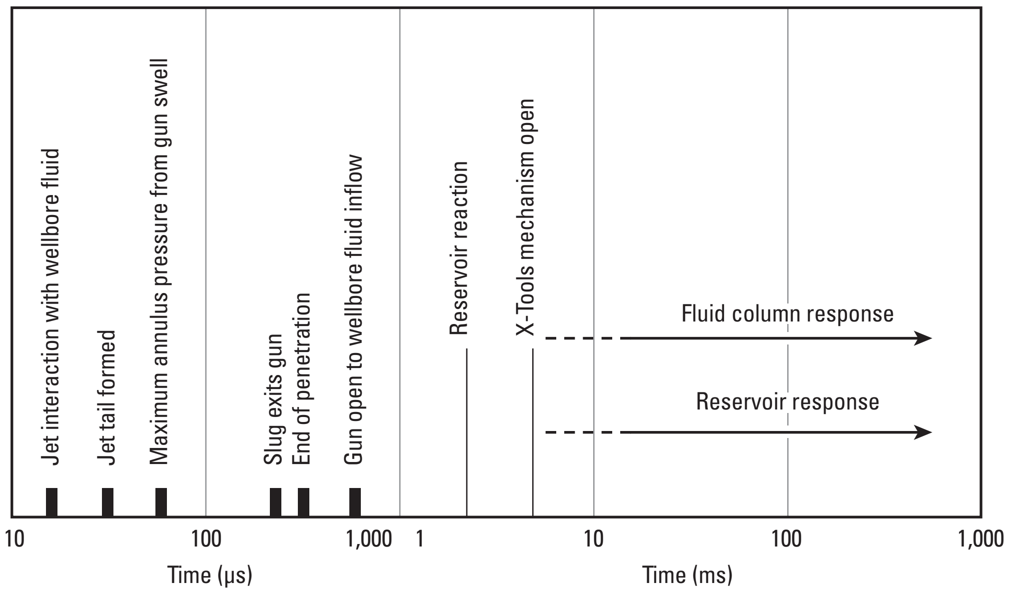

Figure 319. Timing of perforating events after charge initiation.

Monobore automatic release anchor

The monobore automatic release anchor (MAXR) is used to anchor perforating guns in completions and then automatically drop them off at the instant of detonation through the use of X-Tools gun-activated technology (Fig. 320 and Table 148). The primary application of the MAXR is to anchor hollow carrier gun strings in monobore wells. As shown in the operating sequence in Figure 321, the MAXR is run into the hole using wireline, pipe, or coiled tubing and set with standard equipment, such as that used for a packer or bridge plug.

The MAXR is also used in conventional completions in which the guns are run into the well before the completion string. This method allows the gun and firing head assembly to be independent of the completion string assembly. Therefore, the end of the completion string can be located well above the guns.

The MAXR housing replaces the firing head fill joint; the HDF or TCF firing head fits inside this housing. A wide variety of redundant firing systems that can be used depending on the job design. When the firing head is activated and detonates the detonating cord through the MAXR, the X-Tool release mechanism automatically power-retracts the slips. The anchor and gun string drop to the bottom, leaving a fullbore flowpath.

A secondary mechanical backup release is available to drop the guns. The mechanical release can be actuated by slickline at any time during the operation.

Another MAXR application is as a gun stacking platform (Fig. 322). The MAXR is run and set below, and guns are run on top of the MAXR. After firing, the MAXR is released and drops into the hole with the guns.

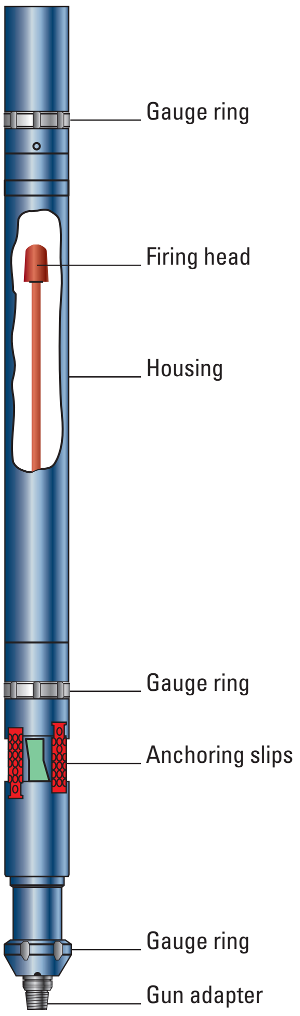

Figure 320. MAXR.

Table 148. MAXR Specifications†

Casing size (in.)	3½	4½–5	5½	7	7⅝	9⅝
Casing weight (lbm/ft)	9.20–15.50	4½ in.: 9.50–12.60 5 in.: 18–23.2	20–26	26–32	29.7–39	29.3–53.5
Outside diameter (in.)	2.38	4½ in.: 3.62 5 in.: 3.75	4.25	5.50	5.50	7.62
Temperature rating (ºF [ºC])	375 [191]	400 [204]	400 [204]	400 [204]	400 [204]	375 [191]
Pressure rating‡ (psi)	17,000	20,000	20,000	20,000	20,000	15,000
Makeup length (in.)	128.98	115.38	115.98	114.10	114.02	136.36
Weight (lbm)	90	195	210	450	500	900
Tensile strength‡ (lbf)	23,000	62,000	62,000	115,000	115,000	168,000

† Contact your Schlumberger representative for special-order 4½-, 5-, 5½-, and 7-in. sizes.
‡ At 80% min. yield

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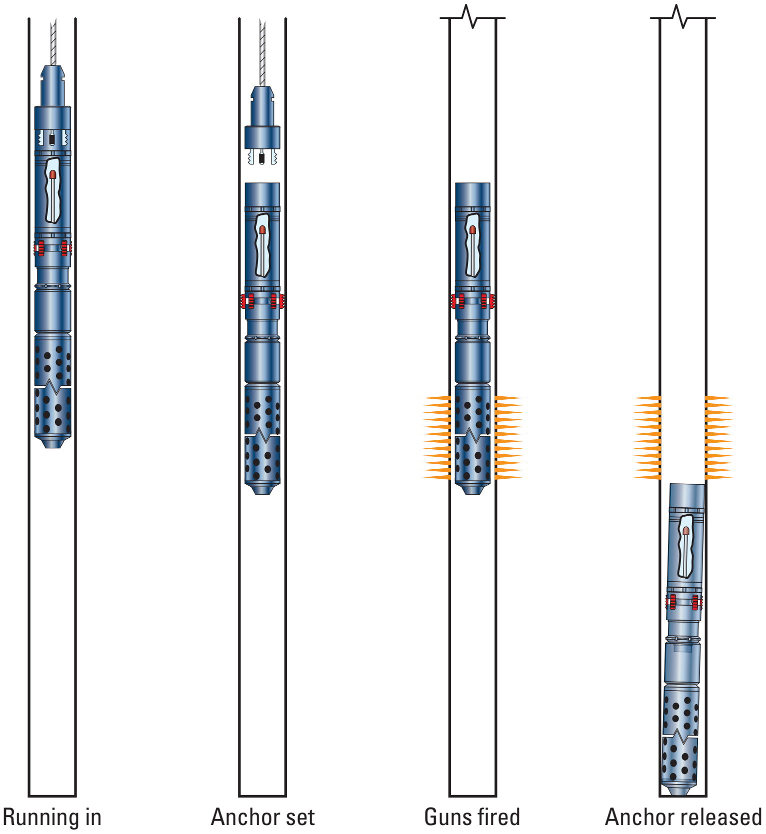

Figure 321. MAXR principle of operation.

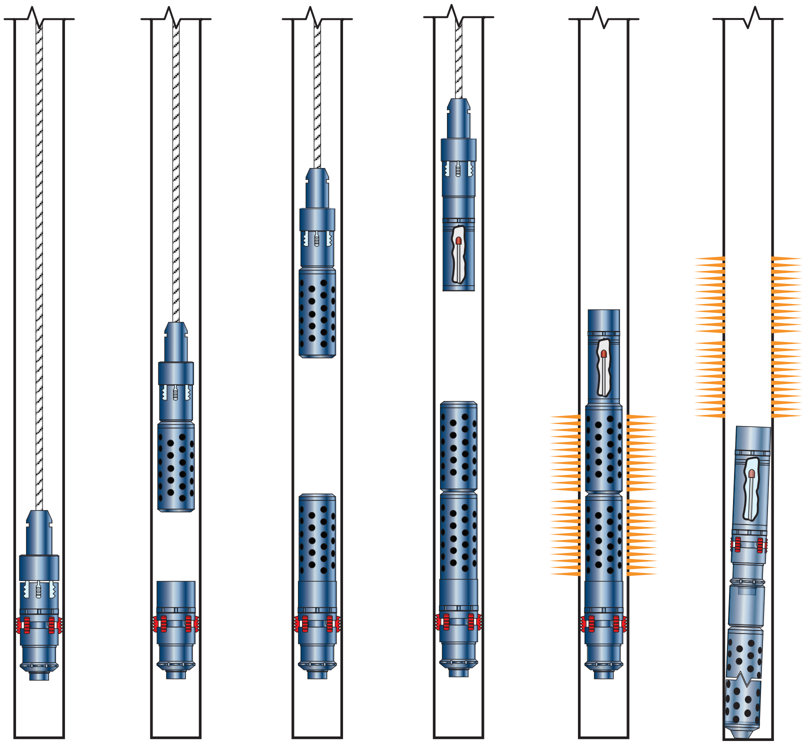

Figure 322. MAXR application as a gun stacking platform.

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Features and benefits

- Reliable and proven—The MAXR uses a slip design based on the PosiTrieve packer and the X-Tools release mechanism that is also used in the SXAR, CTXR, SXPV, and SXVA.
- Conveyance flexibility—The MAXR is used with wireline, tubing, drillpipe, and coiled tubing.
- Operational simplicity—No string rotation or set-down weight is required for setting or releasing. The anchor position on top of the gun string provides easy access to the release and firing head. Automatic gun drop requires less rathole than conventional gun drop techniques.
- Instant gun release—Dropping the guns automatically at the instant of perforation prevents sanding in.
- Designed for retrieval—A special tool can be used for release and retrieval before shooting and dropping.
- Firing head compatibility—The MAXR is compatible with a wide variety of firing heads. Depending on the completion, the firing heads can be run in TCF mode after the MAXR is set on depth. Redundant firing systems can be placed below, enclosed in a fluid isolation sub. Dual-zone independent firing is also enabled.

Safety considerations

Trapped pressure must be taken into consideration, irrespective of the conveyance method. Dropping the guns eliminates this concern. If gun retrieval is later required, contact your Schlumberger representative to ensure that Schlumberger personnel are on site for the operation.

Using the MAXR to release the guns decouples the shock of the guns firing from the completion.

Applications

- Monobore wells—The primary use for the MAXR is anchoring and releasing perforating guns in monobore completions.
- Completions in which the guns are installed before running the completion string—Using the MAXR allows introducing the gun and firing head assembly independently of the completion string assembly. The installation of completions several hundred feet above the anchored guns minimizes the rathole required.
- Underbalanced operations—For operations in which a large underbalance is applied, the MAXR is used to securely anchor the guns. Releasing the MAXR removes the anchor and attached guns.
- Wells with future production logging and stimulation operations—Gun removal also provides full tubing access for production logging and stimulation.
- Wells with sanding potential—Quick removal of the guns prevents their sanding in.

MAXR operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, MAXR system operations begin with thorough design and planning using the applicable flowchart, an abbreviated example of which is shown in Fig. 323. Because of the broad compatibility of the MAXR, the firing system must be specified when the MAXR is ordered.

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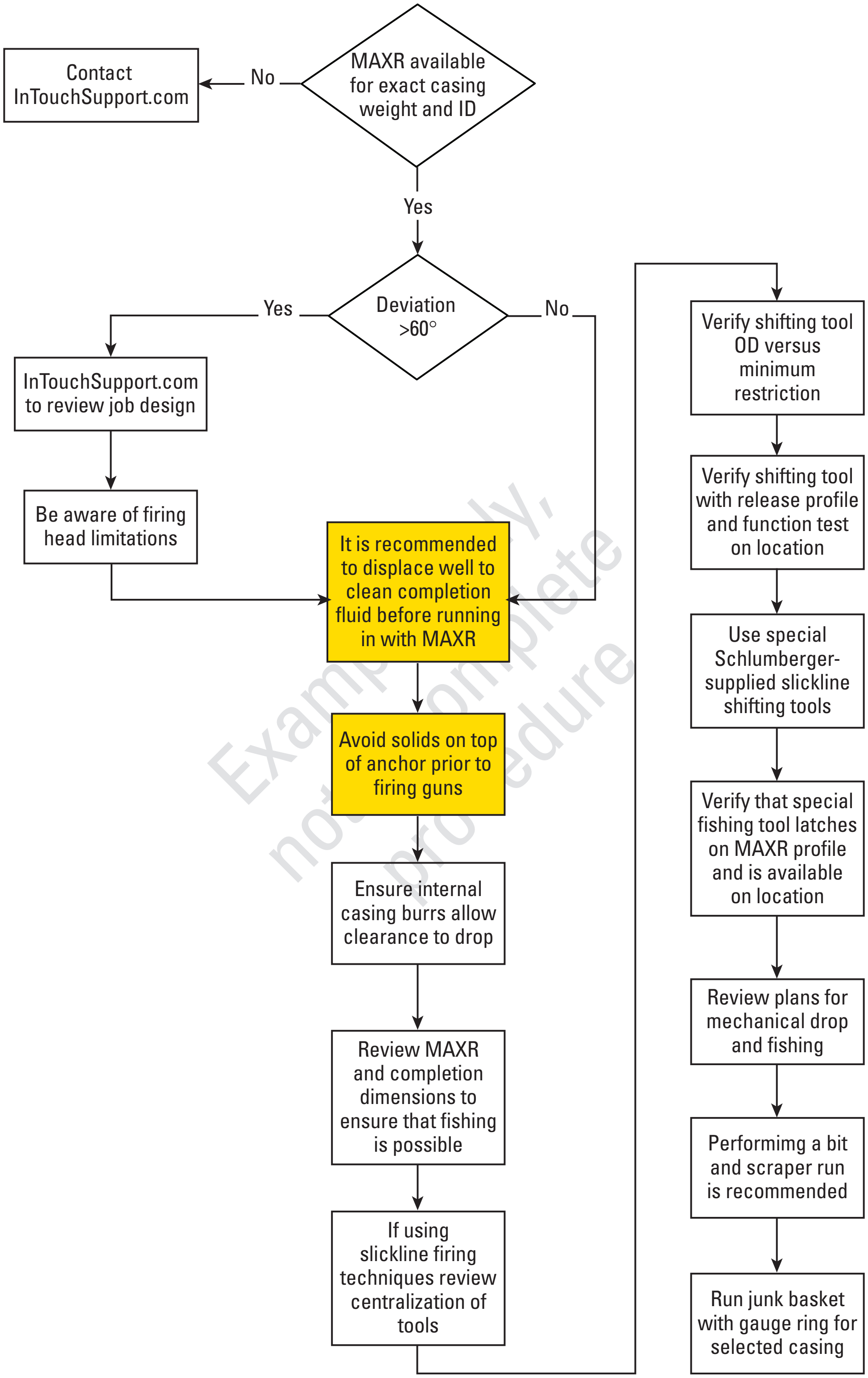

Figure 323. Excerpt of an example SDP design and planning flowchart for MAXR operations. All design and job checks for the selected firing head also apply.

Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

Execution

In a monobore completion (Fig. 324), the guns are run first on pipe or wireline. A MAXR and its setting tool are connected to the top of the gun string. Setting depth is determined by correlation or tagging bottom. Activating the setting tool sets the packer-like slips of the MAXR into the casing and disengages the setting tool, which is then retrieved.

The firing head usually is separately introduced later, as determined by the completion program. Separate introduction ensures wellbore integrity by minimizing the exposure of the head to downhole conditions. In addition, MAXR operations can be conducted in multiple wells at the same time for batch-completion programs.

Once the completion is run into the well, the packer is set and underbalance created. The MAXR releases automatically only when the firing head is detonated. It can also be released mechanically using slickline and a shifting tool.

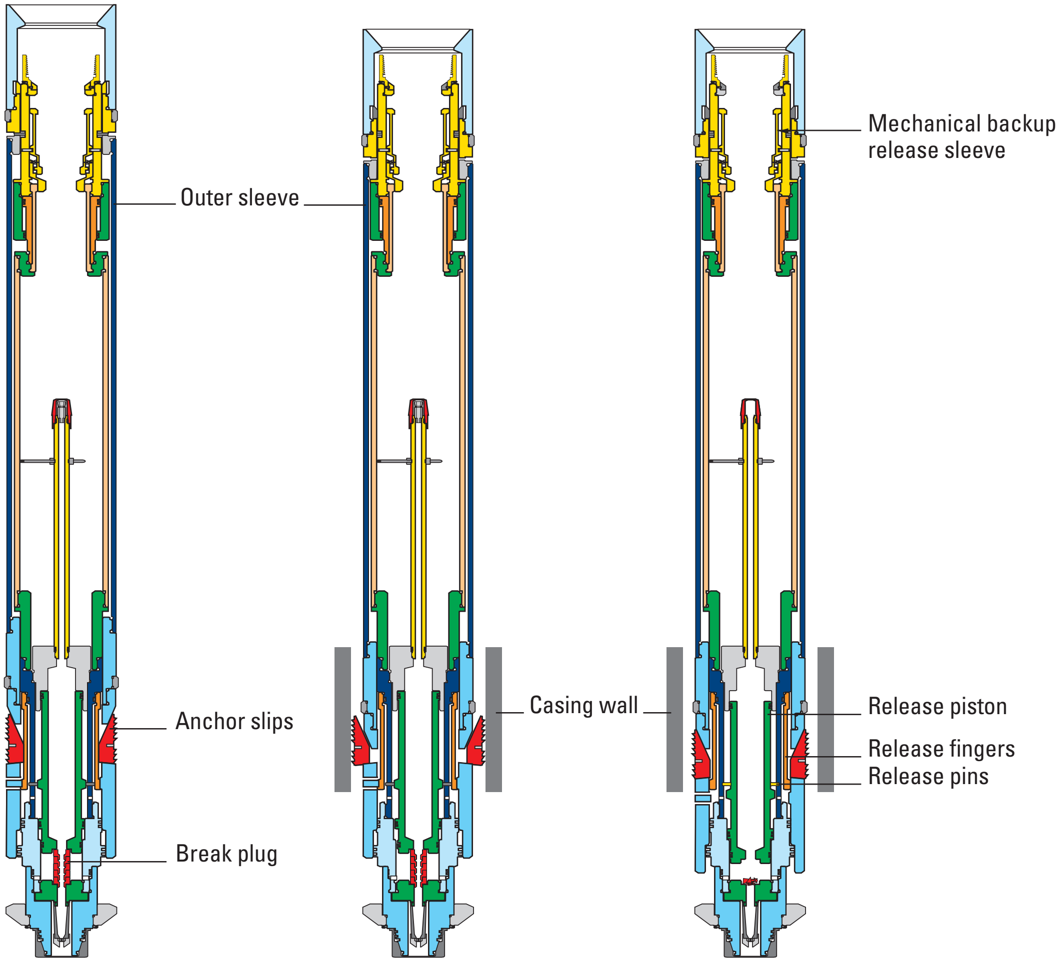

Figure 324. MAXR principle of operation.

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Wireline-conveyed X-Tools automatic release

The WXAR incorporates reliable X-Tools technology to automatically drop perforating guns to the bottom of the well at the instant of the high-order detonation (Fig. 325 and Table 149). The main application of the WAXR is to perforate long intervals at underbalanced pressure without killing the well. With the WAXR, gun strings can be used that are longer than the available wellhead pressure control equipment can accommodate. Hollow carrier gun strings longer than 300 ft (2⅞-in. guns) have been run using the WXAR to drop off the bottom portion of the gun string at the instant the guns fire. The bottom portion of the gun string falls to the bottom, and the remaining guns still attached to the wireline provide enough weight to be able to remove the guns from the well under pressure. The wireline assembly can then be rigged down with the surface pressure control equipment, with the WXAR and associated equipment brought back to the surface with the firing head. The WAXR can also be placed between guns to shorten the length of the gun string dropped in the rathole.

Because the WXAR is run in line with the gun system, it can be used with any firing system (Fig. 326) and also can be run on tubing, coiled tubing, or any other conveyance method. Adapters for the 3.06-in. tool are available for a wide size range of hollow carrier guns.

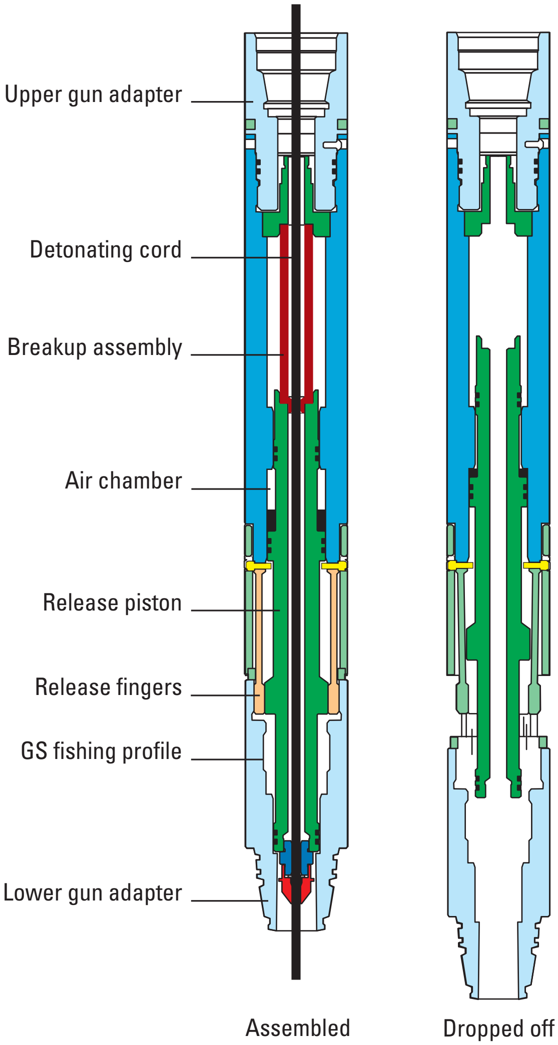

Figure 325. WXAR.

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Table 149. WXAR Specifications

Outside diameter (in.)	3.06	3.5
Temperature rating (°F [°C])	400 [204]	400 [204]
Pressure rating (psi)	20,000	20,000
Min. pressure to operate (psi)	500	500
Makeup length (in.)	35.9	35.9
Weight in air (lbm)	62	67
Min. weight below for release (in air) (lbm)	200	200
Tensile strength at 80% min. yield (lbf)	80,000	80,000

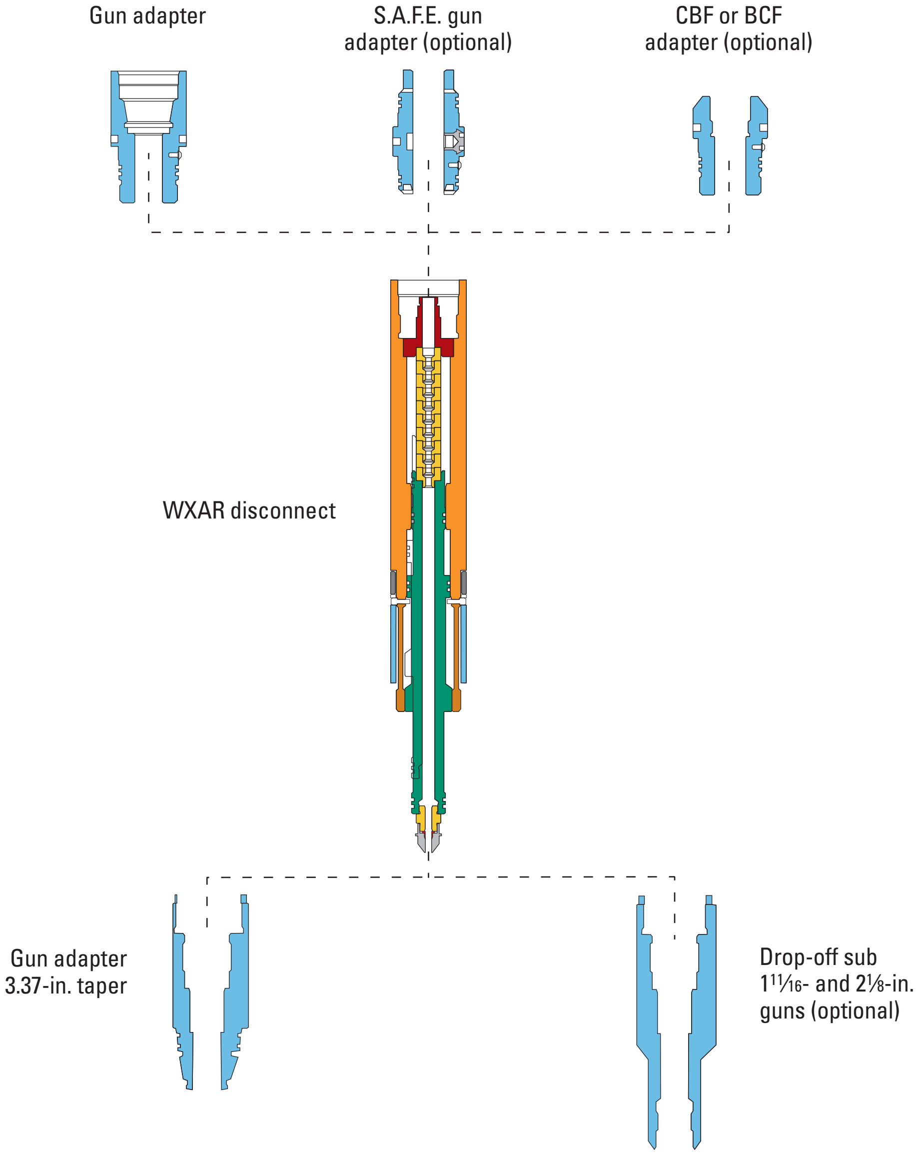

Figure 326. The WXAR is compatible with all firing heads and numerous gun systems in a range of sizes.

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Features and benefits

- Instant gun release—The X-Tools mechanism automatically drops the guns at the instant of detonation to prevent sticking or sanding in of the guns.
- Improved perforation cleanup—The WXAR release quickly removes the guns from the perforated zone.
- Time-saving efficiency—No extra runs are required to drop the guns.
- Full tubing opening—Upon gun dropping, the tubing is fully open. Gun removal also allows production logging and stimulation. A GS fishing profile is built in for recovery.
- Firing head, gun system, and conveyance compatibility—The WXAR is compatible with all firing heads and numerous gun systems in a range of sizes and can be conveyed on wireline, tubing, and coiled tubing.
- Operational flexibility—Automatic gun drop requires less rathole than standard gun drop techniques.

Safety considerations

Using the WXAR enables running and retrieving the firing heads separately from the guns. The wireline or coiled tubing string is not affected by mechanical shock.

Applications

- Long perforating intervals with a limited length of wellhead pressure control equipment—The WXAR extends the length of the gun string that can be conveyed into the well. Only the part of the string that fits inside the pressure control equipment can be recovered after release.
- Wells with future production logging and stimulation operations—Gun removal also provides full tubing access for production logging and stimulation.
- Wells with sanding potential—Quick removal of the guns prevents their sanding in.

WXAR operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, WXAR system operations begin with thorough design and planning using the applicable flowchart. Because of the broad compatibility of the WXAR, the firing system must be specified when the release is ordered.

Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

Execution

The WXAR is connected to the gun string with adapters (Fig. 326); the configuration depends on the guns and conveyance method. Pressure control equipment is used to ensure that the perforating equipment can be inserted and retrieved with pressure at the surface. The guns are run into the well, and the setting depth is determined by correlation, depth measurements, or tagging bottom. Underbalance is created by circulating a lighter fluid through the tubing or through the coiled tubing.

Firing is accomplished electrically if wireline or electric coiled tubing is used for conveyance, and pressure is used if conveyance is by coiled tubing only. The WXAR releases automatically

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when the guns fire, dropping the guns to the bottom. The WXAR uses the same principle of operation as the SXAR (see the "Completion Perforating Equipment" chapter). The high-order detonation that occurs upon activating the firing head causes the breakup plug to disintegrate, in turn allowing the release piston to shift up and disengage the release fingers. Until this point, the release fingers are held against a matching profile in the lower gun adapter. The release and dropping of the guns take place the instant detonation occurs.

CIRP Completion Insertion and Removal under Pressure

The CIRP system for completion, insertion, and removal under pressure (Fig. 327 and Table 150) is used to insert and retrieve long gun strings under wellhead pressure when the surface pressure control equipment, or lubricator, is shorter than the gun string. Using the CIRP system, a long interval can be perforated under the optimum underbalance condition, and then the guns can be retrieved without exposing the formation to damaging kill fluids. Wells can also be reperforated without killing, minimizing production loss and formation damage. Multiple perforating runs can be completed without killing the well between runs. On extended-reach wells, for example, the perforated interval may be longer than the maximum gun string that can be conveyed, mandating multiple runs.

The length of the surface lubricator determines the length of the gun string interval between two CIRP connectors. The CIRP system is compatible with all Schlumberger hollow carrier guns from 2 to 4½ in.

CIRP equipment consists of three main components:

- Connectors tie the gun sections together and provide sealed ballistic transfer.
- The deployment stack locks and unlocks connectors under pressure and supports and locks the disconnected string.
- Two gate valves isolate the lubricator from well pressure to contain well pressure while picking up or laying down short gun sections.

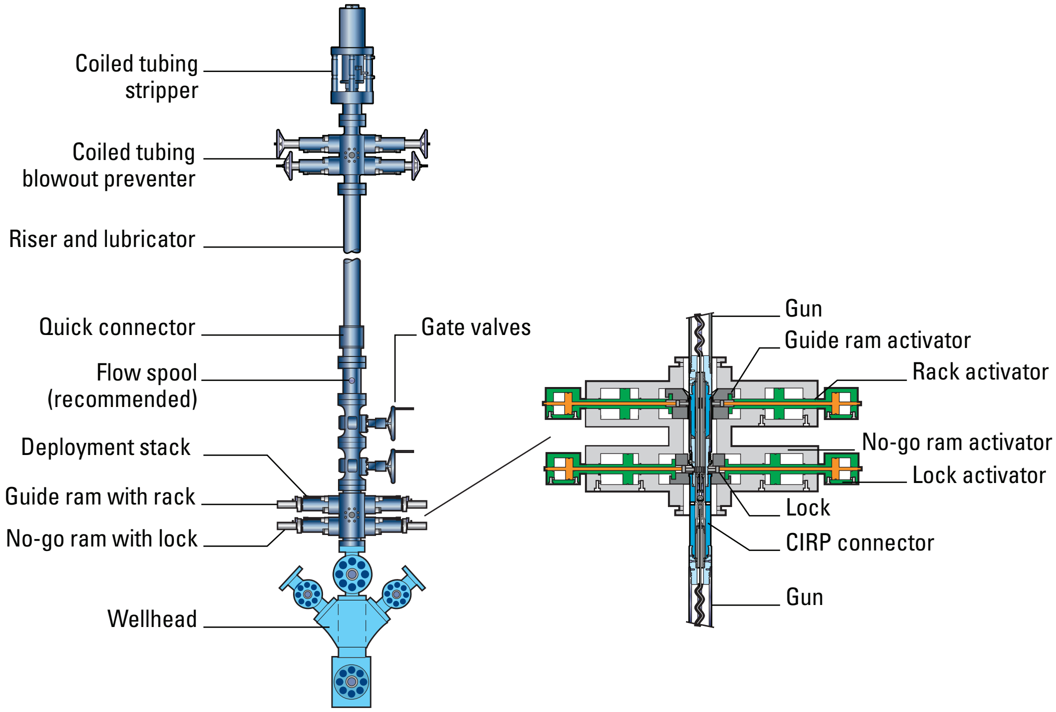

Figure 327. CIRP system for coiled tubing operations.

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Table 150. CIRP Specifications

Hollow Carrier Gun Size (in.)	2	2½	2⅞	3⅜	3½	4½
Connectors						
Outside diameter (in.)	2.25	2.25	2.80	2.80	2.80.	4.50
Temperature rating (°F [°C])	400 [204][†]	400 [204][†]	400 [204][†]	400 [204][†]	400 [204][†]	400 [204][†]
Collapse pressure[‡] (psi)	20,000	20,000	20,000	20,000	20,000	20,000
Shot-to-shot distance[§] (in.)	46	46	46	46	46	47
Make-up length (in.)	33.94	33.94	3.370	33.70	33.70	35.33
Slick joint length (in.)	12.00	12.00	11.84	11.84	11.84	12.00
Tensile strength[‡] (lbf)	60,000	60,000	145,000	145,000	145, 000	375,000
Compressive strength[‡] (lbf)	19,000	19,000	51,000	51,000	51,000	295,000
Nominal rotation of lock sleeve (°)	15	15	15	15	15	15
Rack and lock						
CIRP stacks (in.)	4.06 combi	4.06 combi	4.06 combi	4.06 combi	4.06 combi	5⅛ combi
ID (in.)	4.06	4.06	4.06	4.06	4.06	5.125
Working pressure (psi)	10,000	10,000	10,000	10,000	10,000	10,000
Ram space out, center to center (in.)	11.50	11.50	11.50	11.50	11.50	14.50
Max. downward load on no-go rams (lbf)	20,000	20,000	40,000	40,000	40,000	85,000
Max. upward pull on no-go rams (lbf)	20,000	20,000	40,000	40,000	40,000	85,000

Note: For additional sizes and special applications such as HPHT, contact your Schlumberger representative.

[†] For 100 hr. Temperature rating can be increased with special seals.

[‡] Collapse pressure rating is at 67% of yield strength; tensile and compressive strengths are at yield strength.

[§] Nominal shot-to-shot distance; exact distance depends on shot density and phasing option of gun.

The CIRP connector (Fig. 328) is the mechanical and ballistic link between the gun sections deployed in the lubricator. The lower section of the connector has a spring-loaded lock sleeve, which must be rotated to unlock the connector and disconnect the upper section (Fig. 329). The two sections are locked together when the sleeve is rotated back and held in the lock position by a torque spring (Fig. 330). Both sections have an SBT for the donor transfer on the top (trigger charge) and the receiver transfer on the bottom (receptor booster). A slick joint at the bottom of the connector has a landing shoulder for precise positioning in the deployment stack.

The CIRP deployment stack is installed at the bottom of the lubricator, below the gate valves. Hydraulically operated, it includes two sets of ram activators that activate the lower no-go rams with lock inserts and upper guide rams with rack inserts. The lower set of activators closes the no-go ram around the slick joint to provide a shoulder to land the gun string on. The connector is then landed in the ram and the lock inserts are activated to grip the connector. This assembly precisely locates the lock sleeve across the sleeve activator (rack) and locks the connector against rotation. The second set of activators closes the guide ram around a pinion profile on the lock sleeve. Then the rack inserts engage the lock sleeve and rotate it against a torque spring. The string can then be pulled up to disengage the upper section of the CIRP connector.

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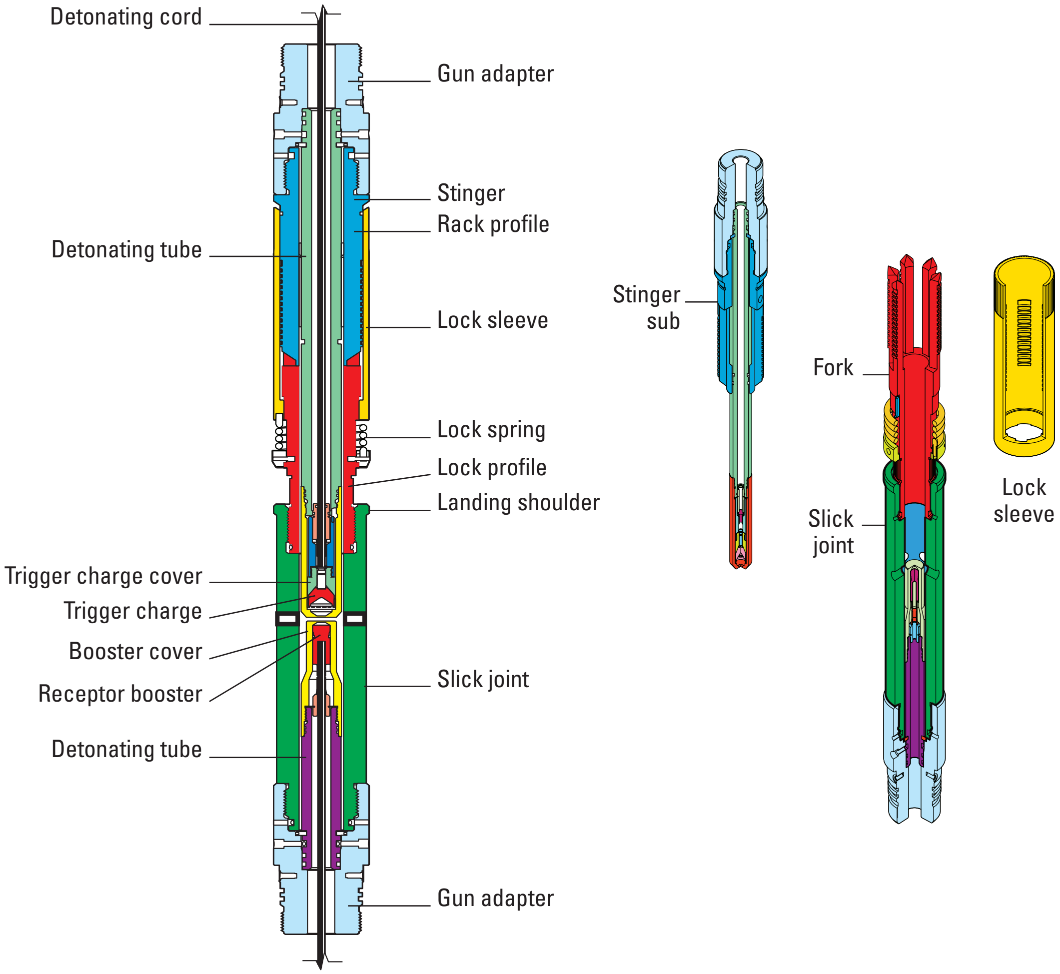

Figure 328. CIRP system with inset of a connector.

The lock and rack allows connection or disconnection of the connectors under pressure inside the lubricator assembly; gun string segments matching the lubricator length can be installed or removed. Closing the gate valve allows the pressure in the lubricator to be bled off. It can then be disconnected for insertion or removal of gun sections. At this point, bleeding off the pressure and opening the lubricator to insert or remove a gun segment is possible. The SBT seals the loaded guns before they are shot.

Features and benefits

- Deployment flexibility—The CIRP system can be used in coiled tubing, snubbing, wireline, and slickline operations requiring pressure control. The system is adaptable to existing coiled tubing BOPs.
- Pressure control—Insertion and retrieval of the gun string is made under pressure, including underbalance control.
- Gun system compatibility—2- to 4½-in. hollow carrier guns are used with the CIRP system.
- Remote operation in challenging well conditions—The CIRP system can be customized for HPHT operations and completely remote operation of the BOP stack.
- Debris tolerant—The CIRP system provides the ability to wash the connectors and clean them in the case of sand and debris.

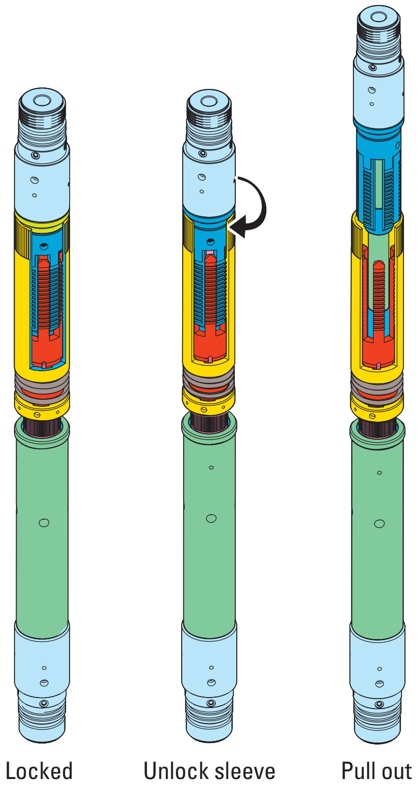

Figure 329. Disconnecting the CIRP connector.

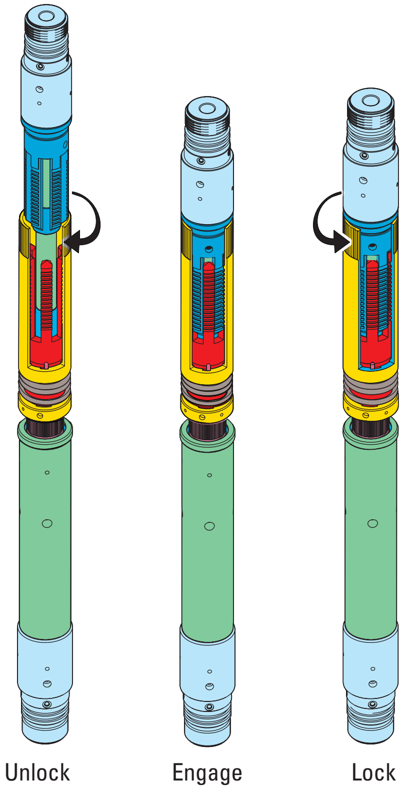

Figure 330. Connecting the CIRP connector.

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- No rathole drilling—No rathole below the perforated zone is necessary to allow the guns to be dropped.
- No formation damage from kill fluids and minimized production loss when reperforating—With the CIRP system, the well is not killed.

Safety considerations

In CIRP operations, the firing head is usually deployed separately, not attached to a gun, and then connected to the gun string with a CIRP connector. This is an important safety feature when deploying a pressure-activated firing head under pressure. In the unlikely event that the head goes off accidentally while the lubricator is being pressured up, it would initiate only the trigger charge and not the guns because they are not connected. The safety of electronic firing is also enhanced because only the detonation train from the detonator to the trigger charge would be initiated in case of accidental firing while connecting the head.

The latest versions of the CIRP system allow completely remote operation, minimizing personnel exposure.

In case of hydrate, the CIRP system provides the ability to circulate in glycol or methanol.

Applications

- Rigless perforating or reperforating—Rigless operations typically have only short lubricators, which would limit the length of the gun string deployed.
- Perforating long intervals with controlled underbalance—In a single trip, long gun strings can be inserted and removed under controlled pressure, even if the lubricator is shorter than the gun string.
- Multiple perforating runs—With the CIRP system, multiple runs are made without killing the well between runs.

CIRP operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, CIRP system operations begin with thorough design and planning using the applicable flowchart.

Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

Execution

The procedure for running the CIRP system into the well is as follows (Fig. 331):

1. Rig up the bottom gun section into the lubricator, close the lubricator, and equalize the pressure.
2. Open the gate valves and lower the gun down through the deployment stack. Stop when the connector is aligned with the no-go ram of the deployment stack. Close the no-go ram and land the gun in the no-go.
3. Close the lock to keep the connector from rotating. Close upper guide ram to centralize the gun string. Close the upper ram rack to rotate the lock sleeve and unlock the connection.

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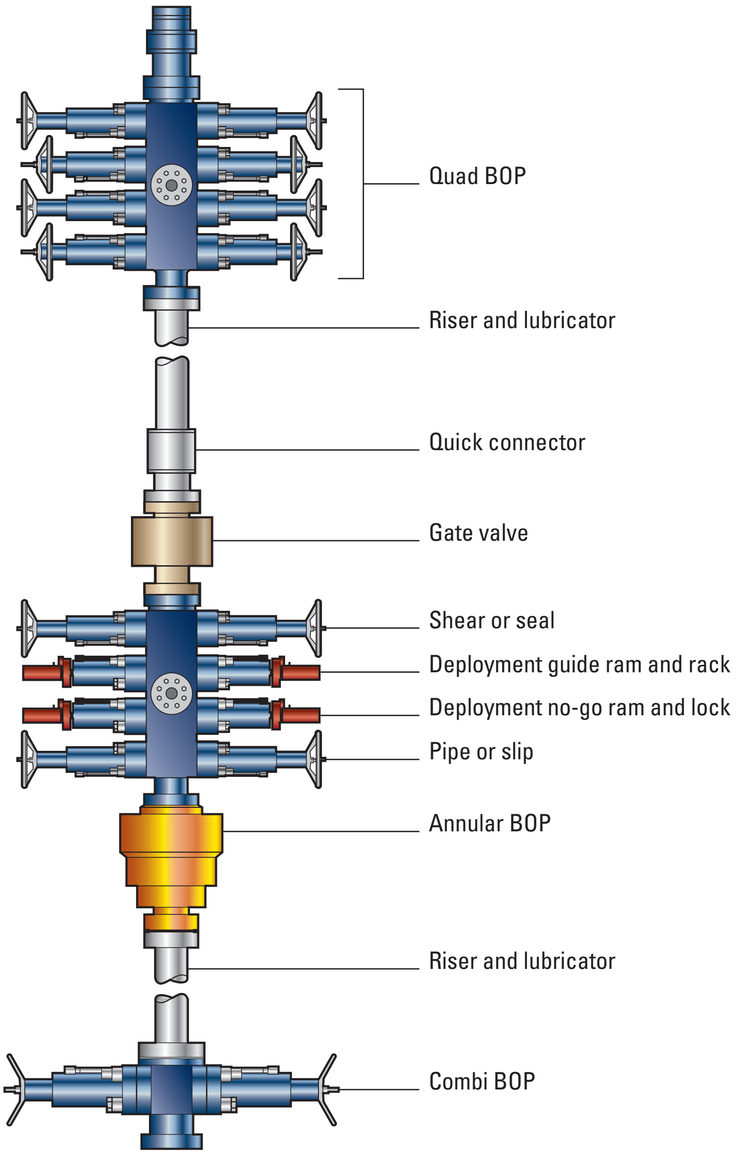

Figure 331. Typical wellhead installation using the CIRP system.

4. Pull the running tool into the lubricator and close the gate valves; bleed off the lubricator.
5. Disconnect the lubricator, pull the next gun section into it, and reconnect the lubricator.
6. Equalize the pressure, open the gate valve, and lower the gun to stab into the open connector.
7. Open the upper rack to lock the connector. Open the upper guide ram and pull-test to verify the connection.
8. Open the lower lock and run into the hole to the next connection; repeat the process.

After all the guns are inserted, the firing head is connected. Figure 332 shows a coiled tubing string example. The string is then run to perforating depth and fired. The process is reversed when retrieving the gun string.

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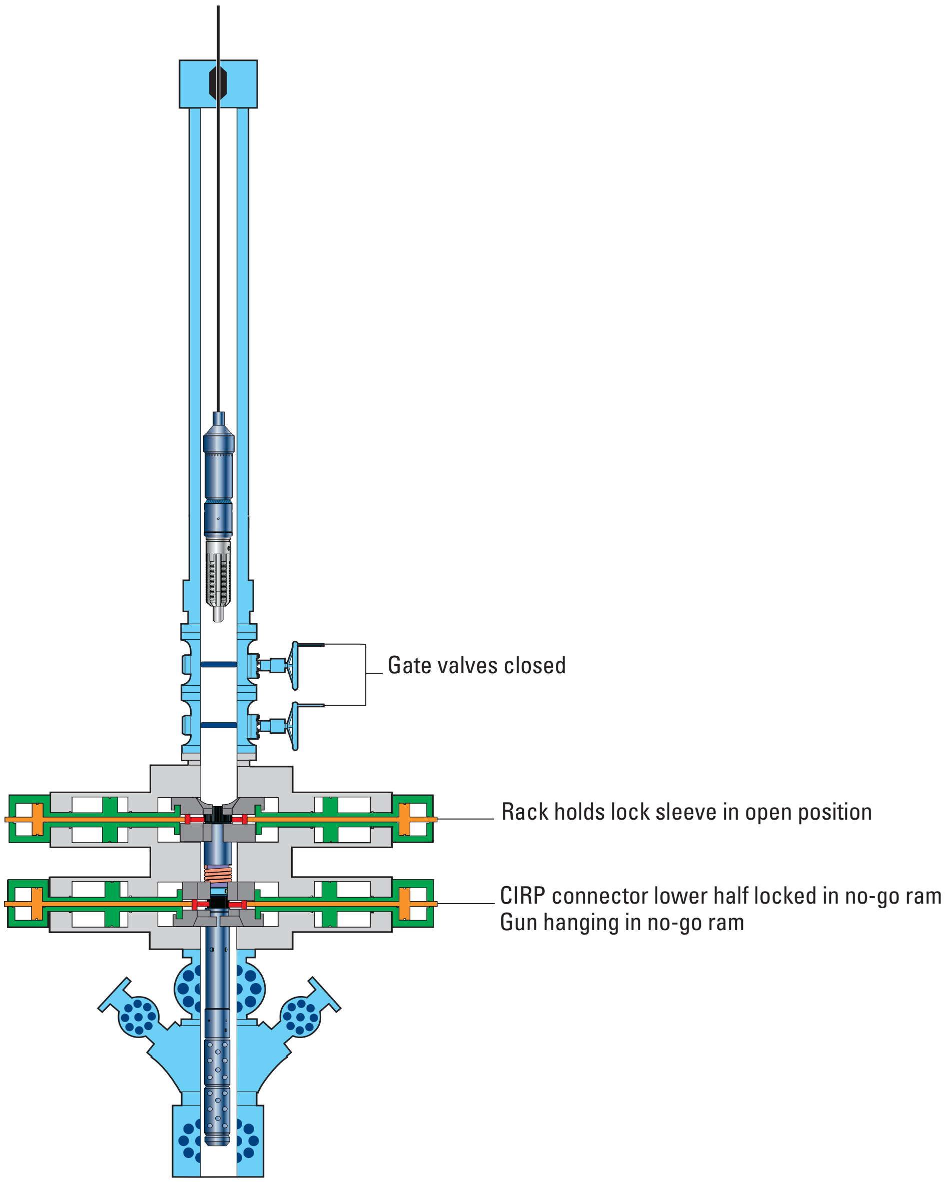

Figure 332. Running the CIRP assembly with a coiled tubing firing head.

GunStack stackable perforating gun system

The GunStack stackable perforating gun system (Fig. 333 and Table 151) enables installing, connecting, firing, and disconnecting perforating guns downhole under pressure. The system can be conveyed and retrieved on slickline, electric wireline, coiled tubing, or jointed pipe. Rather than having to run a gun string long enough for the entire shooting interval, operators use the GunStack system to run the guns in sections according to the available lubricator length.

This technique is ideal for perforating long intervals with rigless operations. The first gun section is run and latched to a downhole anchor. All consecutive sections are then assembled and latched downhole until the desired gun string length is achieved. After the guns have fired, they disconnect in sections following a short delay. The sections can be retrieved into the lubricator without killing the well. The GunStack system also allows retrieval of the gun string any time before or after shooting.

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The GunStack system consists of three main components:

- mechanical releasable anchor (MRA) or MAXR monobore automatic release anchor
- anchor latch adapter
- GunStack connector.

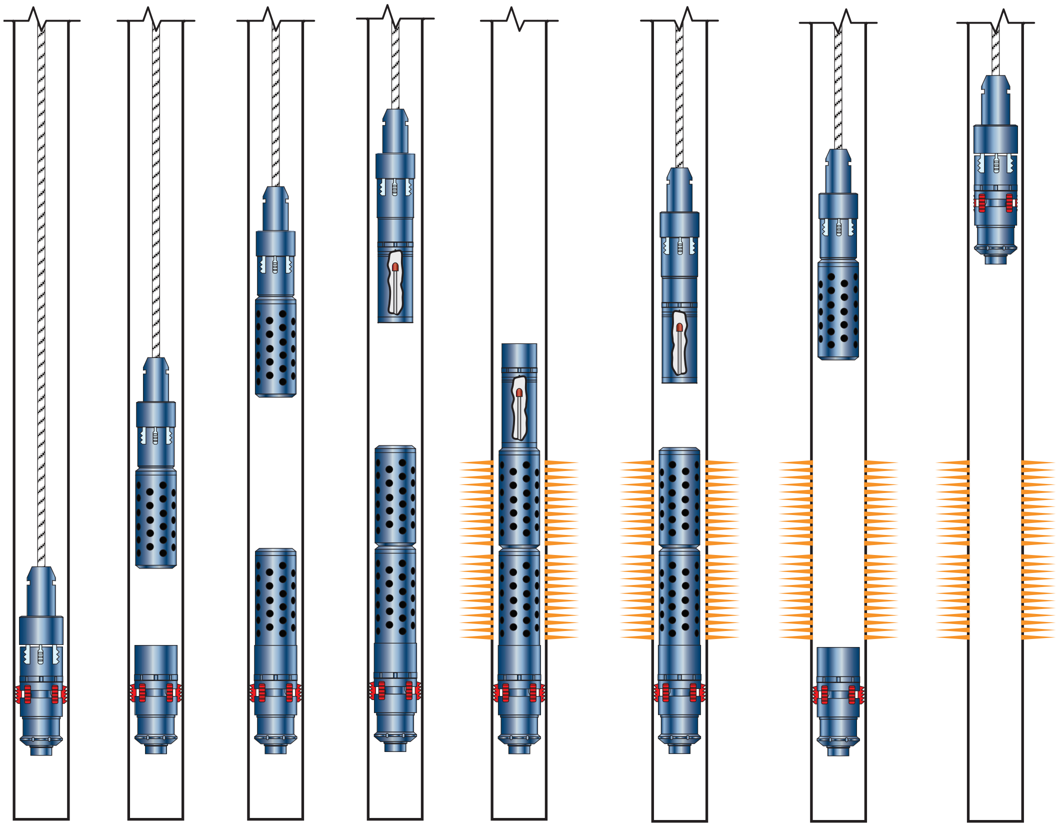

Figure 333. GunStack principle of operation with MRA.

Table 151. GunStack Specifications

Hollow Carrier Gun Size (in.)	**2.88**	**3.38**
Outside diameter[†] (in.)	2.88	3.38
Upper and lower connections	2.3483-6 SA M2 pin	2.9133-6 SA M2 pin
Temperature rating[‡] (°F [°C])	330 [165]	330 [165]
Max. operating pressure (psi)	20,000	20,000
Min. operating pressure (psi)	500	500
Makeup length (in.)	37.93	37.43
Weight in air (lbm)	68.0	71.9
H_2S service	No	No

[†] Different sizes are available upon request.

[‡] Temperature rating limited by elastomers and explosives. Time at maximum temperature is 100 hr at 15,000 psi. See Table 17 and Fig. 84 in the "Operating Environment and Engineering of Perforating Operations" chapter and consult with your Schlumberger representative if the temperature or time exposure exceeds the HMX curve.

The release anchor locates and supports the gun string and prevents movement of the guns in either direction until activation. The MRA (Fig. 334) is used when guns must be retrieved immediately after perforating. The MAXR (see "Monobore automatic release anchor" previously in this chapter) is used to drop the guns after perforation, with future retrieval possible.

The anchor latch adapter provides the means of latching and unlatching the first gun section to the anchor. The MRA or MAXR anchor is run, positioned, and set using electric wireline. The setting depth is determined by correlation or tagging bottom. Activation of the setting tool sets the anchor's packer-like slips into the casing and disengages the setting tool, which is then retrieved.

Slickline is used for all subsequent operations, such as running in, latching gun sections, and retrieving guns. The use of slickline saves time and is more cost effective than electric wireline. The MAXR automatically releases the guns only when they are fired. It can also be released mechanically using slickline and a shifting tool. The MRA is released and retrieved using slickline only after retrieving all the guns and the anchor latch. The anchor latch is run and set in the anchor and then retrieved using slickline. The latch has two index pins that engage and lock the first gun section to the anchor (Fig. 335).

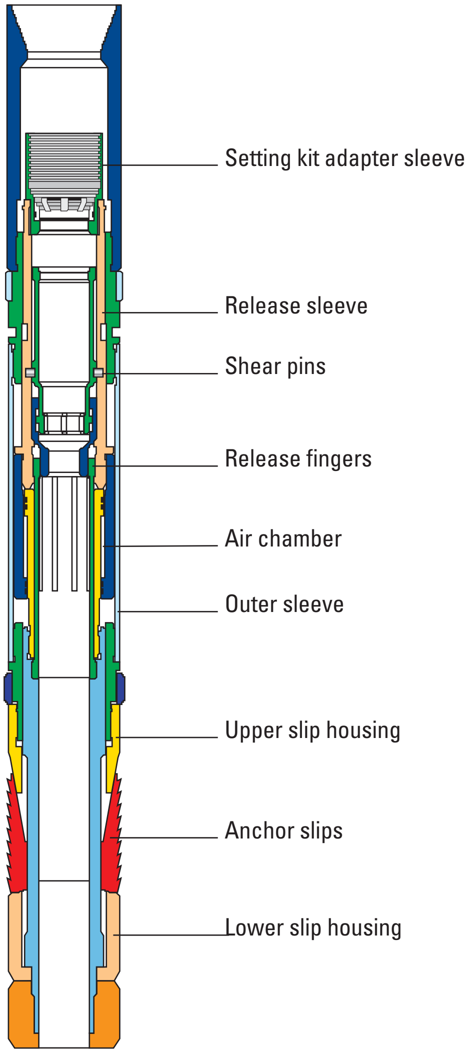

Figure 334. MRA.

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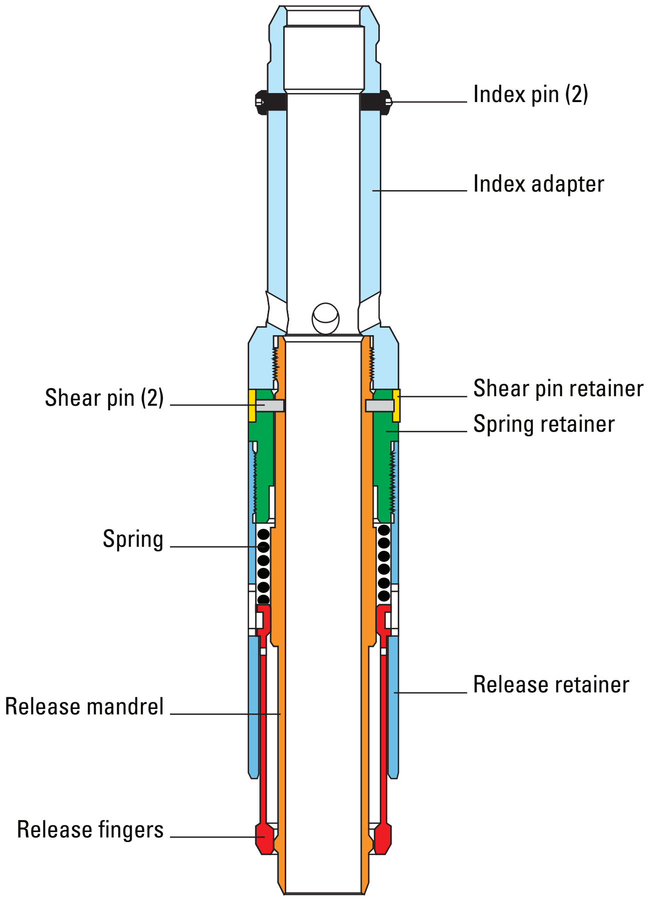

Figure 335. Anchor latch adapter.

The GunStack connector consists of two sections. The lower section, which is placed at the top of the gun section, contains two index pins and the SBT receptor booster. The upper section, placed at the bottom of the gun section, contains three components:

- Automatic release (Fig. 336)—When the guns fire, rathole pressure enters the gun and activates a hydraulic delay. After a predetermined time, the hydraulic delay causes the release fingers to disengage and separate the upper section from the mechanical connect-disconnect section.
- Mechanical connect-disconnect (Fig. 337)—When the lower part of the automatic release is introduced into the upper section, such as when connecting one gun to another, the index pins engage the index sleeve, locking the two sections together. Mechanical disconnect is performed by reciprocating the top gun until it disengages.
- SBT trigger charge—Detonation is transferred from gun to gun by using SBT.

Features and benefits

- Precise gun positioning—Using the GunStack system to assemble and disconnect multiple guns or gun sections downhole enables precisely depth matching of the gun string to the full reservoir thickness and perforating underbalanced.
- Gun control—The positive latch mechanism and time-delay disconnect of the guns prevent them from being blown uphole.

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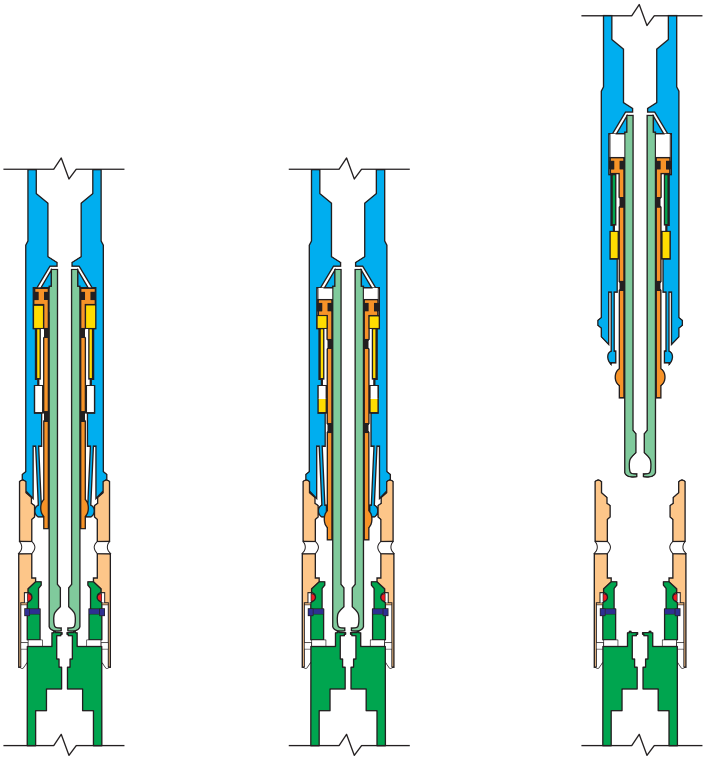
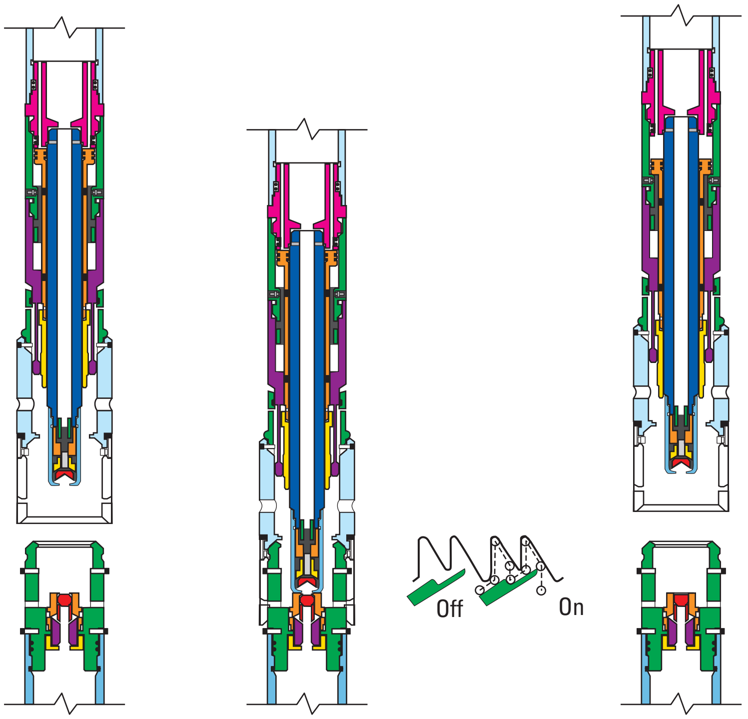


Fired

Delayed metering

Automatic disconnect

Figure 336. GunStack delayed disconnect.



Running in

Latched on

Unlatched mechanically

Figure 337. GunStack mechanical disconnect.

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- Conveyance flexibility—GunStack system can be conveyed on slickline, electric wireline, coiled tubing, or jointed pipe.
- Gun disconnect options—The MAXR can be used with the GunStack system to automatically release and drop the guns at the time of high-order detonation to prevent gun sanding in. The MRA option can be released mechanically using slickline and a shifting tool. Removing the guns from the producing interval does not restrict flow or subsequent evaluation or treatment.

Safety considerations

Ballastic arming of the gun sections and firing heads takes place downhole, away from personnel at the surface. The firing head is run in only after all guns are downhole. The positive latch mechanism prevents the guns from being blown uphole, and the mechanical latch allows disconnecting even if the guns have not been fired. Handling shorter sections of guns is also safer.

Applications

- Underbalanced perforating of long intervals—The GunStack system anchors long gun strings to withstand high underbalance and obtain optimum perforation cleanup.
- Wells with future production logging and stimulation operations—Gun removal provides access for production logging and stimulation.
- Rigless perforating or reperforating—The GunStack system is used to run the guns in sections according to the available lubricator length. No rathole is required.

GunStack operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, GunStack system operations begin with thorough design and planning using the applicable flowchart.

Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

Execution

Figure 333 illustrates the procedure to run the GunStack system in the well. The setting tool and anchor are run in, and the anchor is set just below the interval being perforated. The slickline unit is rigged up to run in the anchor latch adapter, which engages the anchor. The latch is released and the slickline pulled out. The first gun section is picked up and run in the well to engage the anchor latch adapter. Positive latching is ensured with an upward pull of 200 lbf. The slickline is released from the gun and pulled out. This procedure is repeated for all remaining sections of guns. Once all guns are installed, the firing head is picked up and latched to the top of the last gun section and then the slickline is pulled out

If the operation dictates retrieval of the guns after latching, each gun section is released mechanically by reciprocating the uppermost gun with the slickline retrieving tool. To perforate, the required underbalance is established and the guns then fired. On firing, the guns either drop to the bottom (if the MAXR is used) or remain in place (if the MRA is used). With either anchor, the automatic release at each gun section is activated after firing. The guns disconnect approximately 30 s later. To retrieve the guns, slickline and the retrieving tool are rigged up. Each gun section is pulled separately, finishing with the anchor latch adapter and finally the MRA.

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FIV Formation Isolation Valve tool

The FIV Formation Isolation Valve tool (Fig. 338 and Table 152) is a monobore completion valve normally run below a permanent completion packer. The tool acts as a downhole lubricator valve, isolating the formation while allowing long strings of guns to be run into and retrieved from the well.

After perforating, the guns are pulled above the tool, and the valve is closed by a shifting tool connected below the guns. Closing the valve allows the tubing pressure to bleed off. The guns can then be retrieved from the well. The valve is reopened for production by applying a predetermined number of tubing pressure cycles above the closed ball valve. Alternatively, the FIV tool can be opened mechanically with the shifting tool.

Available in a wide range of materials, sizes, and tubing connections, the FIV tool consists of three main sections: ball valve, latch, and Trip Saver one-trip operations feature.

The full-opening ball valve isolates the well from wellbore fluid above the FIV tool. The design is a larger version of the reliable Schlumberger HPHT DST ball valve with a gas-tight seal (Fig. 339). Turning in a fixed yoke, the ball valve seals in both directions to contain pressure both above and below the ball. This feature prevents debris interference to make the FIV tool highly tolerant of debris.

The ball valve is opened and closed mechanically or can be opened using tubing pressure cycles. It is mechanically operated simply by pushing (opening the ball) or pulling (closing the ball) using the shifting tool. A detent ring locks the ball in open or closed position, and a predetermined force is required to pull it out of that position. The force required to pull the ball valve closed is designed to be higher than the force required to open the ball valve. This safeguard prevents accidental closing of the ball when pulling guns or tools through the FIV tool. The force required to close the ball valve is a 3,000- to 5,000-lbf pull. The force to open is a 1,000- to 3,000-lbf push.

In perforating, the ball valve is closed with the shifting tool attached to the bottom of the gun string. The ball valve can also be opened by applying a set number of tubing pressure cycles (up to 10) using the Trip Saver feature.

The latch allows using a shifting tool to open or close the ball valve to control circulation through the FIV tool. It consists of latch collet and latch mandrel (Fig. 340) and is opened or closed when the correct shifting tool profile engages the collet. The shifting tool can be configured to open only or to open and close. A force of 2,500 lbf is required to pull the collet out of the detent, and the tool then disengages when the collet locks into the positive locking mechanism of the mandrel. Latch operation is not affected by changes in well pressure or differential pressure.

Table 152. FIV Specifications[†]

Casing (in.)	7	7 and 7⅝	9⅝	10¾
Outside diameter (in.)	5.35	5.515	8.00	9.34
ID (in.)	2.935	3.105	4.56	5.60
Temperature rating (°F [°C])	300 [149]	200 [93]	200 [93]	200 [93]
Body differential pressure rating (psi)	6,600	10,000	5,000	4,500
Ball differential pressure rating (psi)	5,900	5,000	5,000	5,000
Overall length (in.)	220	238	221	219
H_2S service	Yes	Yes	Yes	Yes

[†] The specifications listed are for typical FIV configurations. The FIV tool is custom designed for each completion. Tool dimensions are a function of the tubulars in the well. Pressure and temperature specifications depend on the application and reservoir parameters. Contact your Schlumberger representative to specify the FIV tool for your operation.

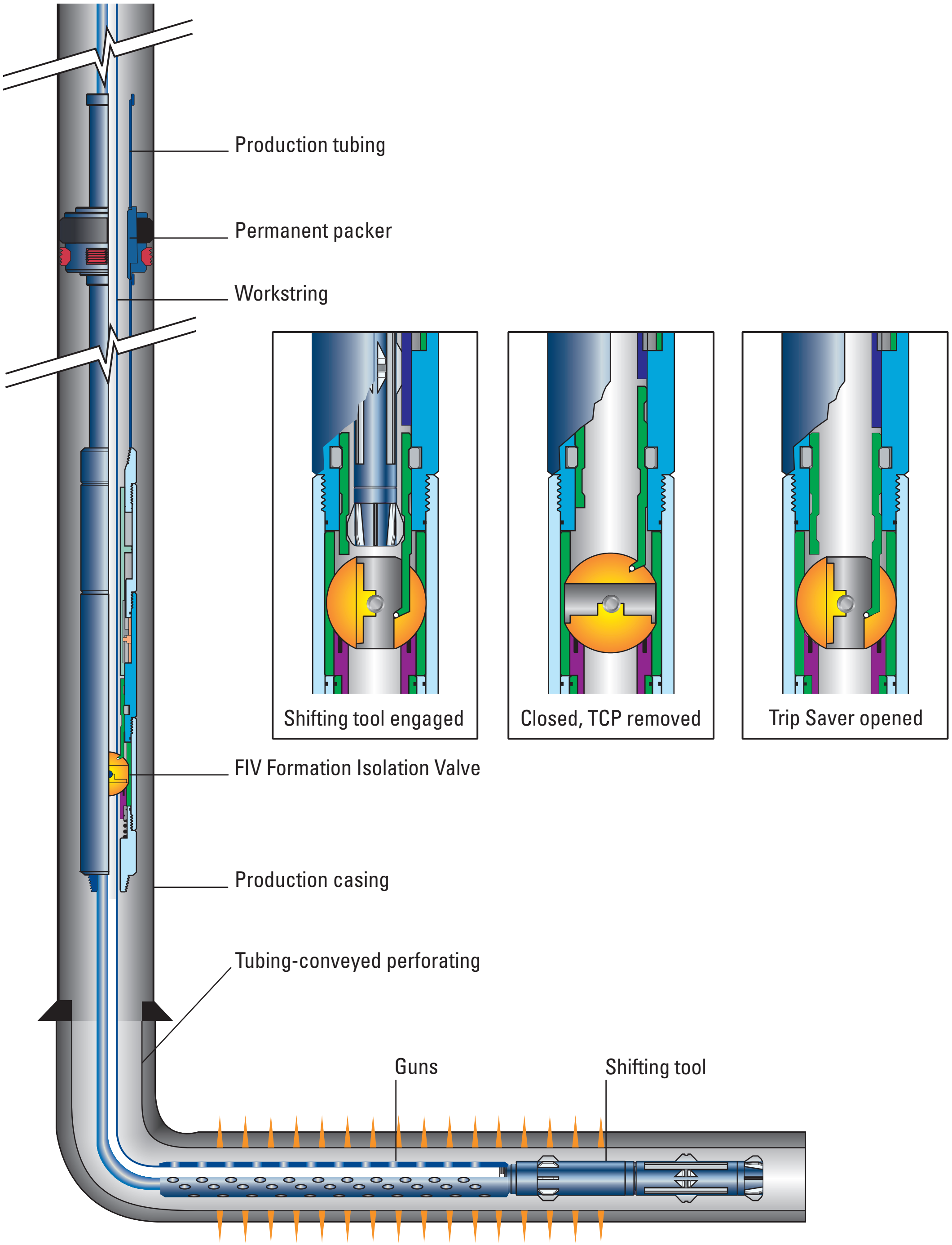

Figure 338. FIV tool.

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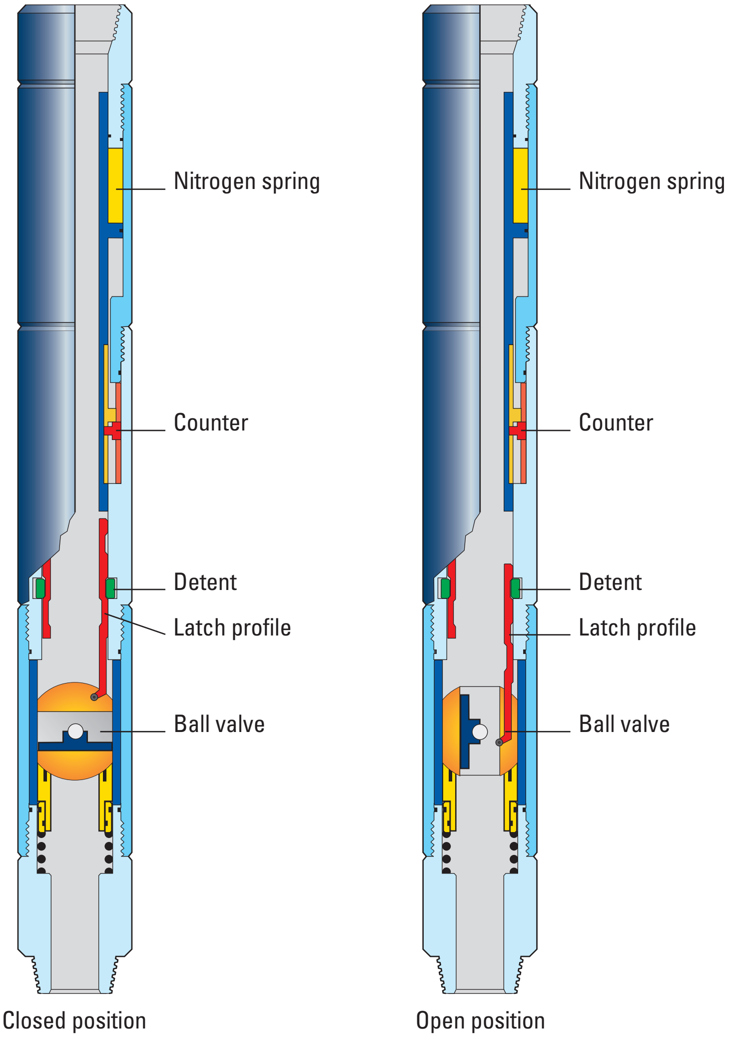

Figure 339. FIV ball valve.

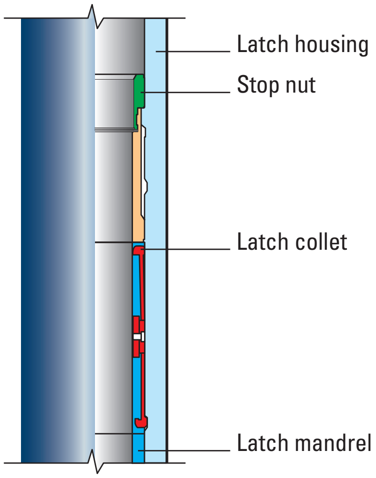

Figure 340. FIV latch.

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The FIV shifting tool (Fig. 341) is connected to the bottom of a perforating gun string, coiled tubing, or pipe string. The open-only setting allows opening the ball valve without closing it during retrieval. The open-close setting opens the FIV tool when it is run through the valve and closes it during shifting tool retrieval (Fig. 342). The shifting tool can also be circulated through.

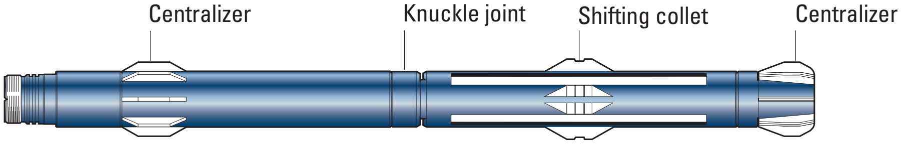

Figure 341. FIV shifting tool is used to open and close the ball valve mechanically.

Figure 342. FIV shifting tool positions.

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Trip Saver one-trip operations feature

The optional Trip Saver feature provides a way to reopen the ball valve with applied tubing pressure (Fig. 343). As the name implies, it can save a trip into the hole to reopen the ball valve using the shifting tool.

Located in the upper part of the FIV tool, the Trip Saver feature is a mandrel that can be cycled up by applying tubing pressure and returned back down by the force of a nitrogen spring (Fig. 339). During this up-and-down movement, the mandrel cycles through an indexing section with a maximum of 10 cycles (one cycle includes both the up and down movements; a 15-cycle option is available). Cycling is used to apply pressure against the FIV ball valve to test the tubing or set a packer without activating the Trip Saver feature to open the ball valve. On the final cycle, a spline on the mandrel aligns with a spline in the housing to enable the Trip Saver mandrel to push on the latch mandrel that opens the ball valve. The Trip Saver feature can be used to reopen the ball valve once.

An optional lock on the Trip Saver mandrel can be used to permanently lock the ball valve in the open position. Without the lock on the Trip Saver feature, the ball valve can be operated normally with the shifting tool after Trip Saver activation. As a contingency, the ball is made of a soft material, which enables milling the ball if it cannot be reopened.

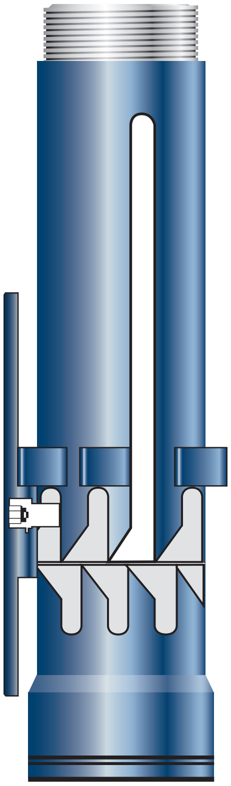

Figure 343. FIV optional Trip Saver feature.

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Features and benefits

- Reliable operations—With its design based on proven DST technology, the FIV valve is highly debris tolerant and suitable for HPHT operations.
- Trip Saver feature—Optional one-time nonintervention uses tubing pressure cycles.
- Pressure control—Bidirectional sealing holds pressure both above and below the valve.
- Formation protection—Formations are isolated without applying kill fluid.
- Completion placement versatility—The FIV tool is available in multiple versions, customized for each completion. Placed below the packer in a lower completion, the FIV tool maintains pressure integrity throughout the job. Placed above the packer, the FIV tool provides pressure integrity for the life of the completion. With short gun strings, the FIV tool can be placed near the surface, above the subsurface safety valve.

Safety considerations

Use of the FIV tool eliminates concerns about conveying or retrieving perforating guns with wellhead pressure. Placed in the completion string and below the packer, the FIV tool does not interfere with future through-tubing operations or become a source of leaks after use.

Applications

- Underbalanced perforating and horizontal wells—The FIV tool provides a two-way barrier, holding pressure both above and below it.
- Operations with debris, sanding, or using fluid-loss materials and friction-reducing products—The rotating-ball design of the FIV valve makes it highly debris tolerant.
- Multiple perforating runs—Using the FIV tool allows multiple perforating runs without killing the well and exposing the formations to damage from kill fluids. It serves as a downhole lubricator valve to allow long strings to be run and retrieved with complete formation isolation.

FIV operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, FIV operations begin with thorough design and planning using the applicable flowchart. Because the FIV tool is available in a wide range of materials, sizes, and tubing connections, these specifications must be made in advance.

Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

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Execution

The FIV tool is compatible with monobore completions where the internal diameter is consistent for the entire completion. Typically the FIV tool is run into the hole in the open position as part of the completion below the production packer.

To perforate long horizontal intervals, the guns must be conveyed on a snubbing or coiled tubing unit so that they can be moved after perforating without having to kill the well. The FIV shifting tool is connected to the bottom of the gun string. The shifting tool automatically closes the FIV tool when pulled through the latch profile connected to the ball valve mechanism. The well pressure above the FIV tool can then be bled to zero, and the guns can be pulled out of the hole.

When the completion includes a gas lift mandrel near the FIV tool, the mandrel can sometimes be used to kill the well above the FIV tool for added safety when pulling the guns out of the hole. Once the well is ready for production, the FIV tool can be reopened using the Trip Saver feature or by running in with the FIV shifting tool on pipe, coiled tubing, or slickline. The completion planning process should include verifying that all nipples and sleeves operated with a slickline shifting tool are compatible with the FIV shifting tool. The angle and spacing of the shifting collet profile can be custom-designed to fit the completion and application.

FIV series

Reliable, proven FIV technology is available in several variations (Fig. 344).

- HPHT FIV system is qualified to 15,000 psi differential pressure across the ball in high-temperature (425°F [218°C]) environments.
- AFIV annular-controlled FIV system uses a sleeve, not a ball, to isolate the tubing from the annulus. AFIV systems are used for multizone well control, intelligent completions, and on-and-off flow control.
- MFIV mechanical FIV system operates only mechanically because it does not include the optional Trip Saver section. There is no limit to the number of times the valve can be opened and closed with the shifting tool, and operation is unaffected by changes in well pressure or differential pressure.
- SFIV surface-controlled FIV system is a specialized surface-controlled version of the downhole lubricator valve for underbalanced drilling operations and perforating without killing. Set above the subsurface safety valve, it provides a bidirectional pressure barrier. Operation is with a single control line.

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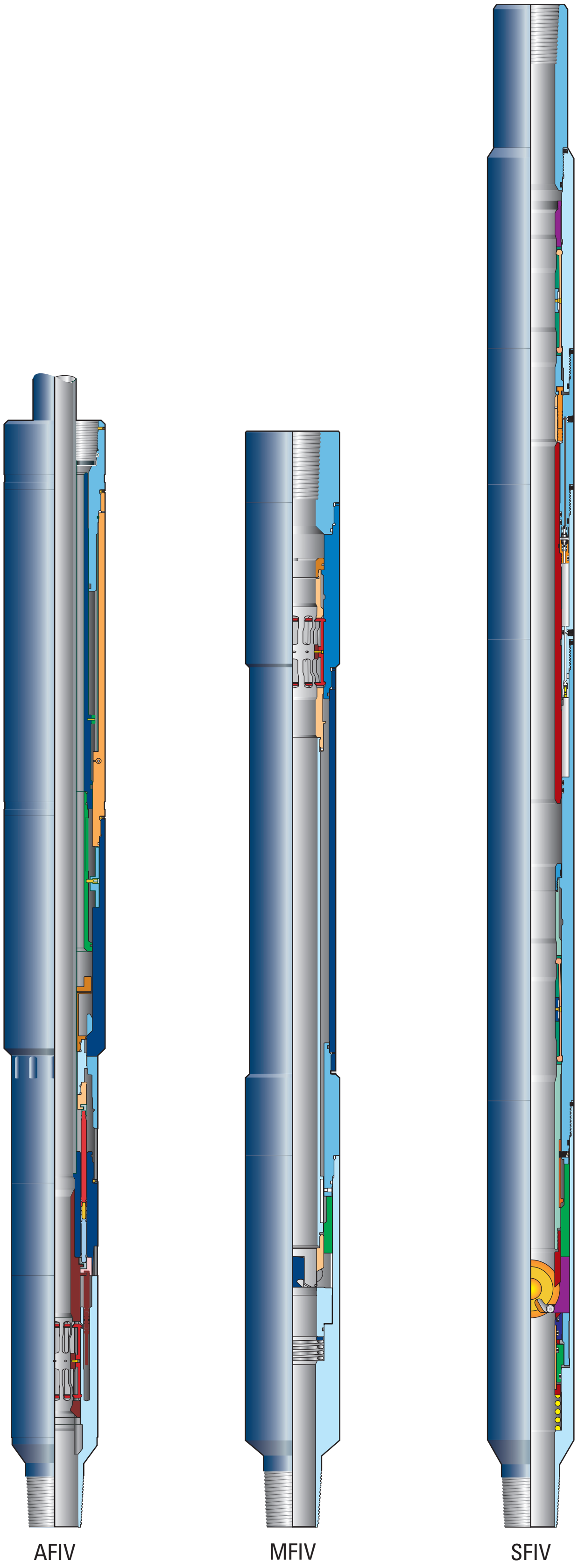

Figure 344. AFIV, MFIV, and SFIV systems.

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PERFPAC sand control method

PERFPAC sand control service provides perforating and gravel packing in a single trip that cuts fluid loss, reduces formation damage, and saves rig time (Fig. 345). Including a DST string allows single-trip well testing and cleanup, before and after sand control treatment.

The PERFPAC system consists of a TCP gun string, retrievable packer, sand control screen assembly, and DST string. This combination enables perforating the well underbalanced, followed by a well test to evaluate formation properties, such as permeability and damage.

The TCP gun string has hollow carrier guns with big hole charges and the SXAR automatic release. The SXAR drops the guns upon firing to prevent them from being sanded in.

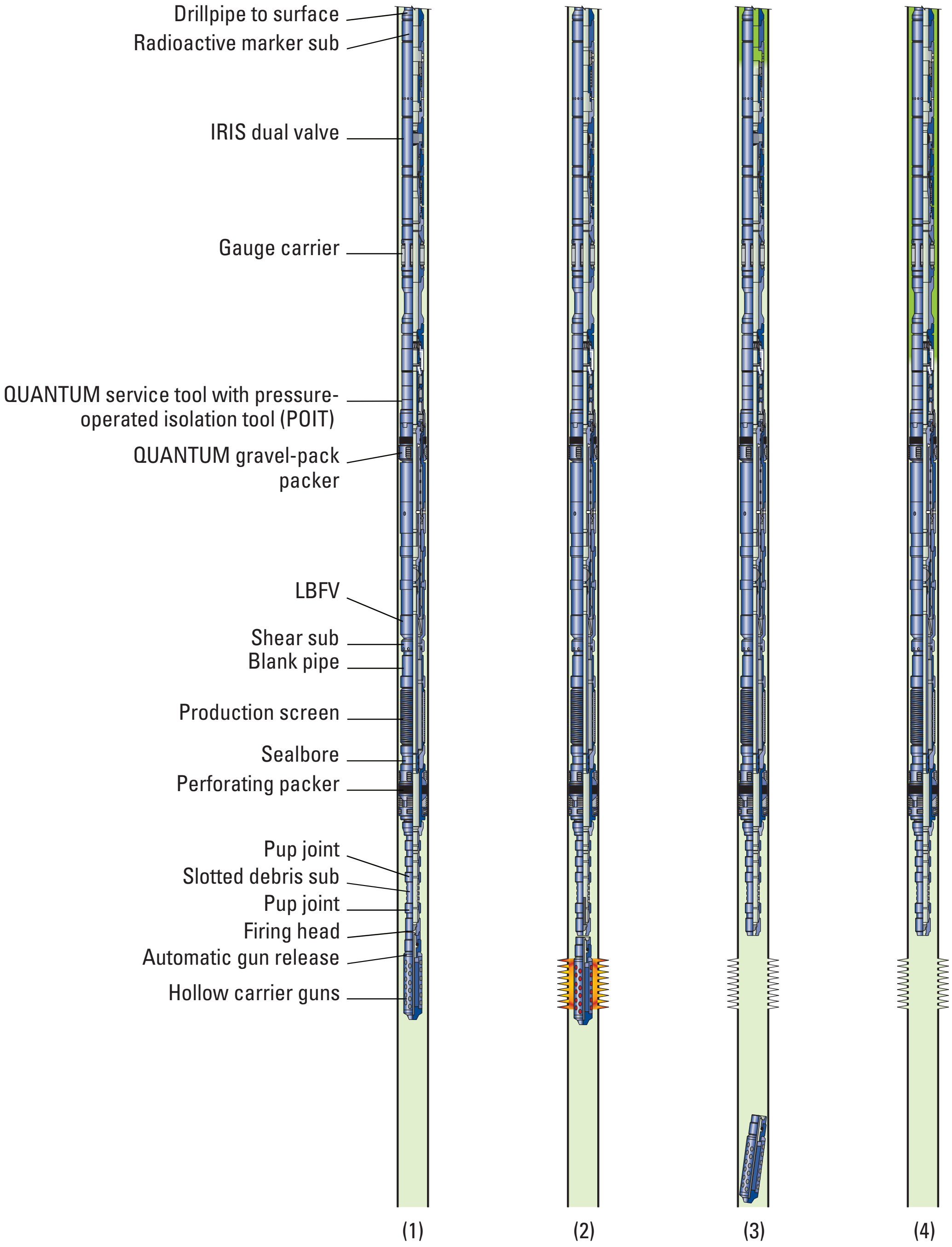

Figure 345. PERFPAC integrated perforating and gravel packing.

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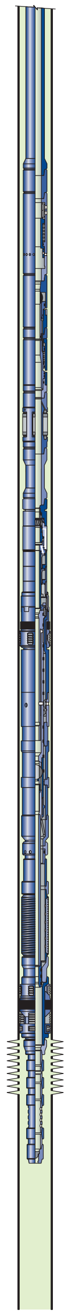
The retrievable packer provides isolation, underbalance, and support for perforating. It also acts as a sump packer for the gravel pack.

The sand control screen assembly is placed across the perforations to prevent sand influx into the wellbore.

The DST string includes the IRIS Intelligent Remote Implementation System dual valve (IRDV), UNIGAGE* pressure gauge system, and a safety joint. The IRDV is a compact fullbore testing tool with a multicycle test valve and a circulating valve. Operated by coded pressure pulses, it is completely insensitive to pressure fluctuations in the well during gravel-pack operations. The DST string can be used to retest the well at the conclusion of the gravel-pack operation.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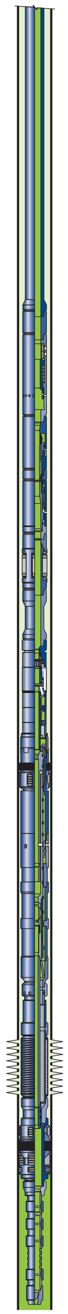
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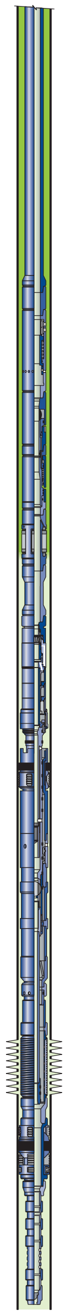
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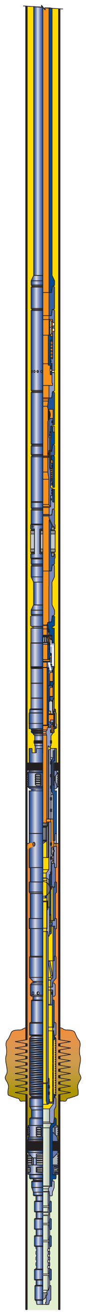
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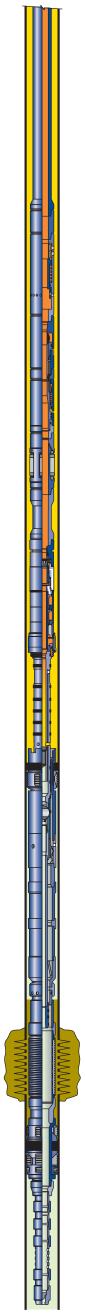
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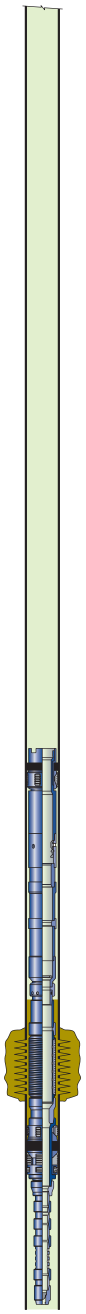
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QUANTUM gravel-pack packer

The QUANTUM* gravel-pack packer with a large-bore flapper valve (LBFV) is used with the PERFPAC system for sand control in the same one-trip operation. It remains in place with the completion packer.

The QUANTUM packer is set and operated after perforating the well and moving the retrievable packer down below the perforations, with the screen assembly positioned across the perforations. The QUANTUM running tool is then free to perform functions such as circulation, fluid injection, gravel placement, and isolating the gravel-packed annulus from the tubing.

When the gravel-pack operation is complete, the running tool is pulled out of the packer, automatically closing the LBFV. The LBFV prevents fluid above the QUANTUM packer from entering the gravel pack and damaging the pack and formation. It also prevents the loss of completion fluid to the formation. The tubing is then pulled out of the hole and replaced with the completion string. A mule shoe on the end of the completion string is used to break through the LBFV so the seal assembly can be landed in the sealbore receptacle of the QUANTUM packer.

Features and benefits

- Fast, efficient permanent completions—Perforating and gravel packing are accomplished in a single trip for significant time and cost savings.
- Protection from formation damage—Formation damage from fluid loss during the completion is minimized through reduced exposure without the use of potentially damaging lost-circulation-material pills.
- Intelligent completion capability—The PERFPAC system accommodates a full range of reliable testing tools, including the IRDV and UNIGAGE system.

Applications

- Single-trip perforating and gravel packing—The PERFPAC system combines perforating and gravel-packing services.
- Intelligent completions—Multiple testing tools can be combined with the PERFPAC system.
- Deepwater, deviated, and horizontal operations—The PERFPAC system can be run in wells deviated up to 75° in casing sizes greater than 7 in.
- Underbalance operations—Underbalance is achieved through automatic closure of the IRIS test valve while running into the well or by operating the IRIS circulating valve after setting the packer.
- Sand control—The QUANTUM gravel-pack system combines with PERFPAC service for wells where sand control is needed.

PERFPAC operational procedures

As described in “Service delivery procedure” in the “Tubing-Conveyed Perforating Completion Techniques” chapter, PERFPAC system operations begin with thorough design and planning using the applicable flowchart.

Preparation

All job preparation, from the shop to the rig, is done using standard Schlumberger systems and procedures. This includes the RITE maintenance control and tracking system to ensure that complete prejob and postjob as well as periodic maintenance is performed. All maintenance activities are recorded on check sheets and entered in the RITE system.

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Execution

Figure 345 shows the sequence of events for a typical PERFPAC operation:

1. The complete perforating and gravel-packing string is assembled and run into the well on tubing. Underbalance can be achieved by preprogramming the IRDV to automatically close the IRIS test valve while running into the well or by operating the IRIS circulating valve after setting the packer.
2. Correlation is made to ensure that the guns are on depth, and then the retrievable packer is set above the perforating zone. The guns are fired.
3. The guns are dropped automatically by the SXAR upon firing.
4. The well is stabilized above the retrievable packer and the IRIS tester valve is closed.
5. After stabilization, the IRDV PERFPAC command is sent and the retrievable packer is released and moved down to below the perforations. The IRDV allows equalizing by opening both the test valve and the circulating valve for a preprogrammed period
6. With the screen assembly positioned across the perforations, the test valve remains open and the circulating valve is automatically closed. The retrievable packer is then reset below the perforations as a sump packer. With the IRDV test valve open, the QUANTUM packer is set by dropping a ball and pressuring up on the tubing.
7. To create the flow path for the gravel-pack treatment, the VRX plug is dropped and the IRDV tool is cycled to the mechanical override position.
8. The tools are then positioned for the gravel-pack treatment. The running tool is set such that circulation can be established along a specific path—down the tubing to the annulus below the QUANTUM packer, through the gravel-pack screens, and back through the wash pipe. At the QUANTUM packer, the path crosses over to the annulus. Because the running tool can also be positioned to pump fluid into the formation, pumping specific treating fluids into the formation can be incorporated in the pre-gravel-pack treatment. The gravel pack is circulated behind the screen. An increase in the circulating pressure and amount of gravel pumped indicate successful completion of the pack.
9. The running tool is repositioned to allow excess gravel to be reverse-circulated out of the tubing.
10. The running tool is released from the QUANTUM packer and pulled out of the well with the DST string. The LBFV (not shown) closes automatically and prevents any completion fluid above the QUANTUM packer from entering the formation.

    After completion tubing is run into the well, the well is ready for production.

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Glossary, Symbols, and Abbreviations

3D

Three dimensional.

A

Number of long shear pins.

AC

Alternating current.

acid

Reactive treatment fluid pumped into the wellbore and formation to dissolve porous media.

acid frac

Hydraulic fracturing treatment performed in carbonate formations to etch the open faces of induced fractures using a hydrochloric acid treatment. When the treatment is complete and the fracture closes, the etched surface provides a high-conductivity path from the reservoir to the wellbore.

acidizing

The pumping of acid into the wellbore to remove near-well formation damage and other damaging substances. Acidizing treatment improves the formation permeability to enhance the production of reservoir fluids.

AFIV*

annular controlled FIV system. Uses a sleeve instead of a ball to isolate the tubing from the annulus.

AIT*

Array Induction Imager Tool.

alpha

Dynamic strength factor.

annulus

Space between the outside diameter of the tubing string and the inside diameter of the casing string or between the pipe and the wellbore.

AOF

Area open to flow. Calculated by multiplying the area of each perforation by the number of perforations and used to determine pressure drop and flow rate across the perforated completion.

API

American Petroleum Institute. Trade association for the oil and natural gas industry that publishes recommendations on generally accepted practices for the oil industry.

artificial lift

Systems such as rod pumping, gas lift, and electric submersible pumps that add energy to the fluid column in a wellbore with the objective of initiating and improving production from the well.

ASFS*

addressable-switch firing system. Smart gun system for selective perforating with a microprocessor-controlled electronic switch attached to each detonator.

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ASTM International

Originally known as the American Society for Testing and Materials.

autodetonation

The detonation of explosives in the absence of an intentional stimulus; usually the result of temperature and confinement.

B

Formation volume factor. Also, the number of short shear pins.

ballistic chain

The explosive sequence, consisting of the detonator, detonating cord, and shaped charges.

ballout

Ball sealers seal off a set of perforations to divert fluid to another perforated interval.

ball sealer

Small spherical seals incorporated in the treatment fluid and pumped with it into the well to close off certain perforations and divert flow to other perforations.

b_c

Perforation damage in Brooks's (1997) conceptual method for estimating the productivity of a natural completion.

BCF

Ball-activated firing. Firing head system for coiled tubing operations that allows circulation before and after firing.

B_H

Number of hollow short shear pins.

BHA

Bottomhole assembly. The equipment and tools assembled below the drillpipe and conveyed into the wellbore.

BHF

Bar hydrostatic firing. Bar-activated, hydrostatically fired firing head system.

big hole charge

Charge designed to provide the largest possible entrance hole in the casing, typically for sand control applications.

Bigshot 21*

gravel-pack gun system. Hollow carrier perforating gun system designed for gravel-pack operations.

biwing

Fracture propagation away from the wellbore in two fracture wings 180° apart.

booster

Auxiliary explosive charge installed on the end of a detonating cord to ensure reliable transmission of the detonating wave.

BOP

Blowout preventer. One or more large valves at the top of a well that can be closed to prevent the escape of pressure if the drilling crew loses control of the formation fluids.

Brinell

Scale of indentation hardness.

Bruceton test

Analysis of explosives sensitivity.

bullet

The initial development of perforating technology: a hardened steel bullet or projectile propelled by an explosive charge to create a perforation.

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burr
Ridges produced by the passage of the perforator jet on the outside of the gun carrier and on the inside surface of the casing.

cable head
Electromechanical device used to connect an electrical toolstring to a logging cable, electrical wireline, or coiled tubing string equipped with an electrical conductor.

capex
Capital expenditures.

capsule gun
Exposed perforating gun system with individual shaped charges mounted on a carrier strip or links that are exposed to the well environment.

carbonate
Sedimentary rocks such as limestone, dolomite, and chalk that consist primarily of calcium carbonate minerals, usually formed by organic or inorganic precipitation.

carrot
Debris produced by the fusing of particles of the shaped charge liner.

cased hole
Wellbore lined with a string of casing or liner.

casing gun
Perforating gun system used to perforate wells before the completion string has been run or after it is pulled.

cavity
Perforation hole in rock left after the passage of a perforator jet or bullet.

cavity effect
Ability of a shaped charge to perforate deeply into metals and rocks.

CBAP
Circulate before and after.

CBF
Circulation ball drop–activated firing. Firing head system for coiled tubing that allows circulation before and after firing.

CBM
Coalbed methane.

CCL
Casing collar locator. Downhole tool used for depth control by confirming or correlating known reference points on the casing string.

C_d
Dimensionless discharge coefficient.

CFE
Core-flow efficiency. A measure of perforation flow performance from the ratio of the measured postshot flow rate to an ideal rate based on preshot permeability.

charge standoff
The space between the shaped charge and the internal surface of the perforating gun body, which must be adequate to allow the shaped charge jet to form before exiting the gun body.

CIRP*
Completion Insertion and Removal under Pressure. System used to insert and retrieve long gun strings under wellhead pressure when the surface pressure control equipment is shorter than the gun string. Using the CIRP system, a long interval can be perforated under the optimum underbalance condition, and then the guns can be retrieved without exposing the formation to damaging kill fluids.

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CleanPACK*
debris-free perforating charge.

CleanSHOT*
debris-free perforating charge.

clearance
The distance between the external surface of the gun assembly and the internal surface of the casing or liner. Gun clearance depends on the position of the gun within the tubular and varies between phases of shots on any gun unless the gun assembly is centralized. Variation in clearance contributes to variable performance of the perforations.

closed chamber
Operations with the surface valve closed to create a closed, known volume into which the reservoir fluid can flow.

CO_2
Carbon dioxide.

completion
Operations performed after the openhole drilling phase of a well to prepare it for production or injection.

correlation
Comparison and correction of measured depths with known features on baseline logs of the wellbore tubulars and the surrounding formation.

CPST
Casing packer setting tool. Wireline setting method for bridge plugs, cement retainers, and packers.

crushed zone
Zone of altered permeability surrounding the perforation cavity in the rock.

CT
Coiled tubing. A long, continuous string of flexible steel pipe wound on a spool or reel. The pipe is straightened before it is pushed into a wellbore and rewound to coil the pipe back onto the transport and storage spool. As a well-intervention method, coiled tubing techniques improve operational safety under live well conditions because the continuous string enables pumping fluids at any time, regardless of the position or direction of travel.

CTR
Controlled tension release. Fullbore safety release for TCP operations that is activated by a predetermined tension held for a predetermined time, independent of the differential pressure across the tool.

CTXR
Closed tubing automatic gun release. Automatic gun release for both open and closed tubing systems that incorporates X-Tools perforating gun-activated technology to automatically drop TCP guns to the bottom of the well the instant the guns fire.

CV
IRDV circulating valve.

D
Perforation diameter in Brooks's (1997) conceptual method for estimating the productivity of a natural completion.

d
Diameter.

damaged zone
The area surrounding the wellbore that has been harmed by the drilling process, generally as a result of mud or cement-filtrate invasion altering permeability.

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Darcy flow

Fluid flow regime that follows Darcy's law, which assumes laminar flow in the formation.

DataLatch*

electrical wireline downhole recorder and transmitter. Combined downhole recording and surface readouts for well testing operations.

d_{cd}

Diameter of the shaped charge liner.

deep penetrating charge

Shaped charge designed to penetrate beyond the damaged zone with a medium-sized entrance hole.

d_{EH}

Diameter of the perforation entrance hole diameter for the particular grade of casing.

depth control

Procedures and equipment used to measure and correlate depth to ensure that a treatment is applied at the correct position within the wellbore.

DepthLOG*

CT depth correlation system. Real-time CCL correlation log for accurately correlating depth.

depth reference

Surface location, such as the kelly bushing or ground level, that all well measurements are based on.

detonating cord

Cord with a flexible outer sheath and inner core of explosive material used to transfer the detonation from the detonator to initiate shaped charges sequentially along the longitudinal axis of the perforating gun.

detonator

Perforating gun system component used to initiate explosion of the shaped charges.

deviation

Angle at which the wellbore diverges from vertical.

DFS

Differential pressure firing system. Activates the DPF head by using the differential pressure created between the annulus pressure above the packer and the cushion or sump pressure below the packer.

d_i

Diameter of invasion.

d_p

Diameter of the perforation entrance hole in casing.

DPF

Differential pressure firing. Firing head activated by differential pressure used in the DFS firing system.

drawdown

Pressure drop from the reservoir to the flowing bottomhole pressure in the wellbore.

drop bar

Bar dropped through the tubing or running string to fire the percussion detonator of a tubing-conveyed perforating gun assembly.

DSI*

Dipole Sheer Sonic Imager. Combines monopole and dipole sonic acquisition capabilities to obtain borehole shear measurements in both soft- and hard-rock formations.

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DST

Drillstem test. Procedure used to determine the productive capacity, pressure, permeability, and extent of a hydrocarbon reservoir. The zone of interest is isolated from the wellbore and valves are opened to produce the reservoir fluids through the drillpipe. The test goals and well conditions determine how long the well is allowed to flow. DSTs can involve multiple periods of flow and pressure buildup.

DTRV

Drop bar–activated tubing- or rathole-pressure-operated valve. Production valve used in TCP operations to isolate the rathole from the tubing.

E

Nominal shear pin value.

e

Fracture interval.

EFI

Exploding foil initiator. Detonating mechanism that contains no primary high explosives and is resistant to stray voltages because of the high currents required for detonation.

eFire*

electronic firing head system. Firing mechanism activated by precise coded signals that cannot be replicated randomly by environmental conditions at the surface or in the well, applied pressure, or shock.

eFire-CT*

electronic firing head system for coiled tubing deployment.

eFire-Slickline*

electronic firing head system for slickline deployment.

eFire-TCP*

electronic firing head system for tubing-conveyed perforating deployment.

electric line

Cable used in operations such as wireline, conductor slickline, and conductor line-equipped coiled tubing through which signals from the measurements are passed.

Enerjet*

expendable strip gun system. High-performance exposed capsule gun systems available in retrievable and expendable versions for through-tubing operations.

EnerjetExpress*

high-efficiency capsule perforating system.

entrance hole

Hole made in the casing ID as a result of the passage of a perforator jet or bullet.

EOB

Extreme overbalance. The application of pressure to the well that is significantly higher than that needed to fracture the formation.

EOF

Extreme overbalance firing. Simplified firing head, triggered by absolute pressure and without a hydraulic delay.

EPD

Electric potential difference.

ESIC

Electronic secondary initiating cartridge. RF-immune component of the S.A.F.E. detonating system.

eSleeve

Hydraulic production valve.

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ESP
Electric submersible pump.

EUE
External upset ends. Forged ends on API-specification tubing and drillpipe to provide additional thickness for strengthening connections.

exit hole
Hole made in the casing OD as a result of the passage of a perforator jet or bullet.

expendable
Perforating gun system designed to disintegrate upon detonation.

extreme overbalance
Condition in which the hydrostatic pressure inside the casing or liner is much greater than the reservoir pressure.

F
Decimal fraction of the reservoir interval that is perforated.

fill sub
TCP component that houses the firing head and collects debris (fill).

filtercake
The concentrated residue deposited on the borehole wall when a slurry, such as a drilling fluid, is forced against the formation next to the borehole.

filtrate
The liquid portion of the drilling fluid that passes through filtercake and invades porous and permeable formations next to the borehole.

fines
Very small particles, which can migrate suspended in the produced fluid to bridge the pore throats near the wellbore, reducing well productivity.

FIS
Fluid and debris-isolation sub. In addition to protecting against debris collection, the sub traps light, clean fluid to provide isolation from heavy annular mud.

fishing
Application of tools, equipment, and techniques for the removal of junk, debris, or lost or stuck equipment from a wellbore.

FIV*
Formation Isolation Valve. Full-opening ball valve that acts as a downhole lubricator valve, providing a two-way barrier to isolate formations against damage caused by fluid loss during completion operations.

FlexPac*
high-performance service packer.

FLUP
Tubing fill-up valve. Allows automatic filling of the tubing through production ports.

FMI*
Fullbore Formation MicroImager.

formation damage
The reduction in permeability to the near-wellbore area of a reservoir formation, typically induced by fluid invasion and fines migration.

Frac Gun*
perforating gun for low-deviation wells requiring fracture stimulation.

frac pack
Fracturing for production stimulation and gravel packing for well completion combined in one operation.

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G
Shear pin temperature correction factor.

G3
Fishing pulling profile.

gpf
Grains per foot, a measure of explosives.

GR
Gamma ray. Both the tool and logged measurement of the total natural radioactivity, which can be made in both open hole and through casing.

gravel pack
The process of placing gravel in the annulus between a screen in the wellbore and the formation to prevent sand production.

GS
Type of fishing profile.

gun phasing
The angular displacement between successive charges around the perforating gun axis.

GunStack*
stackable perforating gun system. Used to assemble, fire, and disconnect perforating guns downhole under pressure without killing the well. The guns are run in sections according to the available lubricator length.

H
Brinell hardness.

h
Height.

half-length
Radial distance from the wellbore to the outer tip of the propagated hydraulic fracture.

HARC
Hazard analysis and risk control. Formalized method for defining and understanding the risks to a process, and specifying the preventive and mitigation controls to be applied.

HCl
Hydrochloric acid.

HDF
Hydraulic delay firing head. Absolute pressure-triggered firing head with delay before firing occurs.

HDFM
Hydraulic delay firing module. ProFire firing head assembly incorporating the delay mechanism and firing sections.

HEC
Hydroxyethyl cellulose.

HEGS*
High-Efficiency Gun System. Expendable hollow carrier gun that shoots the charges through plugs in the carrier.

high explosive
Chemical explosive materials with an extremely high reaction rate that creates very high combustion pressures.

HiPack*
High-Performance Testing Packer. Hydraulic retrievable packer for drillstem testing with a built-in floating seal assembly that eliminates the need for drill collars and expansion-contraction joints.

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HMX
Cyclotetramethylene tetranitramine, an explosive compound.

HNS
Hexanitrostibene, an explosive compound.

hollow carrier
Perforating gun systems that use pressure-tight steel tubes to protect the charges and gun components from the well environment for improved performance and reduced debris.

hostile environment
Difficult well conditions that may detrimentally affect steel, elastomers, mud additives, electronics, or tools and their components. These conditions typically include high temperatures, the presence of acid gases (H_2S, CO_2), chlorides, high pressures, and extreme measured depths.

HPAT
Hydraulic programmable actuator tool. ProFire firing head assembly that controls the operating pressure and number of pressure cycles applied before firing.

HPHT
High pressure, high temperature.

H_2S
Hydrogen sulfide.

HSD*
High Shot Density gun system. Hollow carrier guns featuring increased shot density, optimum phasing patterns, and the largest high-performance changes available for natural, stimulated, or sand control completions.

HSV
High shear value.

hydraulic fracturing
The induction of fractures in the formation resulting from the application of hydraulic pressure causing fluid flow. The rate of flow must exceed the mechanical strength of the formation to initiate the fracture. Proppant is mixed with the treatment fluid to keep the fracture open when the treatment is complete. Hydraulic fracturing creates high-conductivity communication with a large area of the formation and bypasses damage that may exist in the near-wellbore area.

Hydrostone®
Registered trademark of United States Gypsum Corporation for a nonexpanding cement-mounting material.

HyperDome*
through-tubing carrier gun. Selective firing system.

HyperJet*
casing perforating charge. Charge designed for hollow carrier guns.

HyperPack*
big hole shaped charge. Charge designed for casing gun perforating.

ID
Inside diameter.

IF
Internally flush. API specification for threaded connections.

impulse test
Well testing procedure for analyzing the reservoir response following fluid injection or production of relatively short duration compared with the following shut-in interval.

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inhibitor
Chemical agent added to a fluid system to retard or prevent an undesirable reaction that occurs within the fluid or with the materials present in the surrounding environment.

injection
Introduction of fluid to, rather than the production from, a well.

InTouchSupport.com*
online support and knowledge management system.

IPR
Inflow performance relationship. Used to assess well performance by plotting the well production rate against the flowing bottomhole pressure.

IRDV
Intelligent Remote Dual Valve. IRIS combination of a multicycle test valve and circulation valve, operated independently by coded pressure pulses.

IRIS*
Intelligent Remote Implementation System. Compact fullbore testing tool with multicycle test and circulating valves operated by coded low-pressure pulses sent down the annulus and detected by the intelligent controller in the tool.

ISO
International Organization for Standardization.

jar
Mechanically or hydraulically activated device used downhole to deliver an impact load to another downhole component, especially when that component is stuck.

jet
The detonation of a shaped charge produces this extremely high pressure pulse of molten metallic plasma that perforates the casing or liner and penetrates into the reservoir formation.

k
Permeability.

k_c
Permeability of the crushed zone.

k_d
Permeability of the damaged zone.

k_h
Horizontal permeability.

kh
Permeability-thickness product.

kill
Stopping a well from flowing or having the ability to flow into the wellbore.

k_{sh}
Permeability of shale.

k_v
Vertical permeability.

L
Length.

laminar flow
Streamlined flow of single-phase fluids in which the fluid moves in parallel layers, or laminae.

LBFV
Large-bore flapper valve.

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LCM

Lost circulation material. Material intentionally introduced into a mud system to reduce and eventually prevent the flow of drilling fluid into a weak, fractured, or vugular formation.

limited entry

A completion with only a portion of the productive interval open to flow, either by design or as a result of damage. Limited entry also results from partial penetration, which occurs when the productive formation is only partly drilled.

LINC*

Latched Inductive Coupling tool. Mechanical latch and extract tool that also provides a bi-directional communications link.

liner

The metallic insert within a shaped charge. Also, a casing string in which the top does not extend to the surface but is suspended from inside the previous casing string.

LMS

Learning Management System. Schlumberger training and competency management tool.

ln

Natural logarithm function.

lower completion

Packer, liner hanger, and other downhole components of a permanent completion.

low explosive

Chemical explosive materials that have a low reaction rate and are commonly used as propellants.

LSDS

Long-slot debris-circulating sub. The long circulation slots of the sub allow debris to fall out into the annulus instead of settling in an assembly housing.

LSV

Low shear value.

lubricator

Surface pressure control equipment for introducing and removing tools from producing wells under pressure.

LWD

Logging while drilling.

m

Ratio of in situ penetration in SPAN analysis.

matrix

The finer grained, interstitial particles in sedimentary rocks that lie between larger particles or in which larger particles are embedded.

max.

Maximum.

MAXR

Monobore automatic release anchor. Used to anchor perforating guns in completions and then automatically drop them off at the instant of detonation through the use of X-Tools perforating gun–activated technology.

MCCV

Multicycle circulating valve. Reclosable valve operated by tubing pressure and used for spotting fluids and nitrogen.

MCM

Modular configuration MAXIS* PC-based platform for logging acquisition and imaging.

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MCVL

Multicycle circulating valve.

MDT*

Modular Formation Dynamics Tester. Wireline tool for pressure measurement and PVT-quality fluid sampling.

MEM

Mechanical earth model. A numerical representation of the state of stress and rock mechanical properties for a specific stratigraphic section in a field or basin.

MFIV*

mechanical FIV system. Operates only mechanically, unaffected by changes in well pressure or differential pressure.

microannulus

Narrow cement-sandface annulus.

min.

Minimum.

minimum restriction

The smallest diameter present in a wellbore through which a toolstring must pass to access the operating depth or zone of interest.

MPD

Magnetic positioning device. Orients perforating guns in the wellbore.

MPSU

Mechanical plugback tool setting unit. Contracts the PosiSet elastomer sealing assembly.

MRA

Mechanical releasable anchor. Locates and supports the perforating gun string and prevents movement of the guns until activation. The MRA is released and retrieved on slickline after the guns have been retrieved.

MRV

Mechanical reversing valve.

mule shoe

Wireline reentry guide sub.

N

Shot density in Brooks's (1997) conceptual method for estimating the productivity of a natural completion.

NACE International

Originally known as the National Association of Corrosion Engineers.

natural completion

A completion system designed to use the natural flow capability of the reservoir.

nipple

Completion component consisting of a short section of heavy-wall tubular threaded on both ends with a machined internal surface that provides a seal area and a locking profile.

NODAL*

production system analysis. Analytical tool used in forecasting the performance of the various elements of the completion and production system.

no-go

Precisely sized device lowered into a well to check the dimensions of well components and openings or a nipple with a reduced-diameter internal profile that provides a positive indication of seating by preventing the tool or device to be set from passing through the nipple.

NONA

Nonanitroterphenyl, an explosive compound.

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non-Darcy
Fluid flow that deviates from Darcy's law, which assumes laminar flow in the formation.

NPT
National Pipe Thread.

OCD*
Orientation Confirmation Device. Measures with an accuracy to 1° the actual orientation of the perforation tunnels produced with the OrientXact tubing-conveyed oriented perforating system.

OD
Outside diameter.

open hole
Uncased portion of a well.

OrientXact*
tubing-conveyed oriented perforating system. Perforating system that provides alignment accuracy and verification of charge orientation, ideally suited for long and high-deviation wells.

overbalance
Positive pressure differential in which the hydrostatic pressure inside the casing or liner is greater than the reservoir pressure.

P
Perforation penetration.

p
Pressure.

p_a
Additional applied pressure.

packer
Device run into the wellbore and then expanded from its original diameter to seal against the wellbore to hydraulically isolate the zones above and below the packer. A packer can also be set against the casing or liner to isolate the annulus from the production conduit, enabling controlled production, injection, or treatment.

p_{ann}
Annulus pressure downhole.

p_{ap}
Pressure applied at the surface to the annulus.

p_{atm}
Atmospheric pressure.

PCT*
Pressure Controlled Tester. Downhole valve operated by annulus pressure and used to control formation flows and shut-ins for applications that do not use the IRIS Intelligent Remote Implementation System.

$p_{cushion}$
Hydrostatic pressure from the fluid column.

p_{dr}
Downstream restriction pressure.

p_{dsc}
Pressure downstream of the surface choke.

p_{dsv}
Pressure downstream of the safety valve.

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p_e
Undisturbed reservoir pressure.

PEGS
Program to Evaluate Gun Systems.

PERF
Productivity Enhancement Research Facility at SRC, Rosharon, Texas, USA.

perforate
To create holes through the casing or liner and into the formation to achieve efficient communication between the reservoir and the wellbore.

perforating gun
Device used to perforate oil and gas wells in preparation for production.

perforation
The communication tunnel created through the casing or liner and continuing as a cavity into the reservoir formation, through which oil or gas is produced.

perforation damage
Reduced permeability of fluid flow through the perforation in comparison with an ideal perforation in an undisturbed formation with no effect on the rock permeability.

PERFPAC*
sand control method. Single-trip system for integrated perforating and gravel packing.

permeability
Measure of a rock's ability to transmit fluids.

permeability anisotropy
Difference between the vertical and horizontal permeability of a formation.

p_f
Formation pressure.

p_{firing}
Total downhole pressure to fire the firing head.

PFP
Preferred fracture plane. Plane that lies normal in the formation to the minimum far-field stress direction that contains the wellbore and the wellbore surface.

PFrac*
perforating charge for wells requiring fracture stimulation.

PGGT*
Powered Gun Gamma Tool. Records naturally occurring gamma rays in the formations for positioning and correlation.

p_h
Hydrostatic pressure.

p_{HDF}
Pressure sensed at the HDF head.

p_{hyd}
Hydrostatic pressure.

PI
Productivity index. Mathematical means of expressing the ability of a reservoir to deliver fluids to the wellbore and usually stated as the volume delivered per psi of drawdown at the sandface (bbl/psi).

p_i
Injection pressure.

p_{IRDV}
IRDV pressure.

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Pivot Gun*
perforating gun system. High-performance, nonretrievable exposed perforating gun.

PLC
Programmable logic controller.

PLMP
Product Lifecycle Management Process. Framework for the development of a product or service, followed by support of the commercial product or service until its eventual obsolescence.

P_o
Original penetration.

p_{oil}
Oil pressure in tool chamber.

POIT*
pressure-operated isolation tool. Used to completely isolate the release mechanism of the QUANTUM gravel-pack packer-setting tool during well operations to prevent premature packer setting caused by gun shock, underbalance pressure surges, and well control operations.

pore
A discrete void within a rock, which can contain air, water, hydrocarbon, or other fluids.

pore throat
In an intergranular rock, the small pore space at the point where two grains meet, which connects two larger pore volumes.

porosity
The percentage of pore volume or void space within rock or that volume within rock that can contain fluids. Effective porosity is the interconnected pore volume in a rock that contributes to fluid flow in a reservoir. It excludes isolated pores. Total porosity is the total void space in the rock whether or not it contributes to fluid flow.

Port Plug gun
Hollow carrier perforating gun system that shoots the charges through replaceable plugs in a reusable gun carrier.

PosiSet*
mechanical plugback tool. Drillable plug system used in rigless through-tubing recompletions.

PosiTest*
retrievable compression packer. Packer with integral bypass to equalize the pressure across the packer while running in and out, which prevents a swabbing effect.

PosiTrieve*
downhole retrievable packer with hold-down section. Compression-set packer designed for use in cased holes, which minimizes surge and swab effects when running or being pulled and resists being pumped out of the hole.

postshot flow
Second perforation cleanup period of semisteady-state flow.

POUV
Pressure-operated underbalance valve. Production valve that isolates the pressure in the tubing from that in the annulus for use in completions requiring pressuring up the tubing to set other tools.

PowerEnerjet*
expendable or retrievable capsule perforating system.

PowerFlow*
slug-free big hole shaped charge. Slug-free large entrance hole performance without a solid liner.

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PowerJet*
deep penetrating shaped charge. Superior penetration performance with minimal charge debris exiting the gun.

PowerJet Omega*
deep penetrating perforating shaped charge. Substantial increases in penetration performance beyond the damaged zone.

PowerPivot*
expendable capsule perforating system.

PowerSpiral*
spiral-phased capsule perforating system. Retrievable capsule perforating gun that incorporates shock-absorbing material between the charges to attenuate shock waves during the detonation for significantly increased performance.

p_p
In situ pore pressure.

p_{PCT}
PCT valve operating pressure.

p_{pf}
Perforation friction pressure loss for noncrosslinked fluids.

p_{pumpf}
Pump pressure for firing.

PR
Productivity ratio, a reference parameter of the completion's total efficiency stated as the ratio of the actual productivity index to the productivity index of an undamaged openhole completion in a reservoir with the same geometry and properties.

p_r
Reservoir pressure.

PR_∞
Maximum productivity ratio in Brooks's (1997) conceptual method for estimating the productivity of a natural completion.

p_{ra}
Rathole pressure.

primer
Explosive material linking the detonating cord and the main explosive of the shaped charge.

$\mathrm{PR_{max}}$
Productivity ratio assuming an infinite shot density.

ProCADE*
well analysis software. Reservoir flow modeling to estimate production.

ProFire*
programmable firing head. Firing system that uses hydromechanical technology to precisely control the firing time of the guns for performing multiple operations under pressure.

proppant
Material mixed with fracturing fluid that holds open a hydraulically induced fracture.

p_s
Safety margin pressure.

p_{sep}
Separator pressure.

p_{shear}
Total downhole pressure necessary to shear pins.

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p_t
Theoretical firing activating pressure.

p_{TFTV}
Pressure at the tubing fill tester valve.

p_{tp}
Tubing pressure applied at the surface.

p_{tubing}
Tubing pressure downhole.

p_u
Underbalance pressure.

p_{up}
High-value shear pin pressure.

pup joint
Short length of casing, tubing, or plain-end casing liner.

p_{ur}
Upstream restriction pressure.

PURE*
perforating system for clean perforations. Perforating system that optimizes the well dynamic underbalance to consistently eliminate or minimize perforation damage.

p_{usv}
Pressure upstream of the safety valve.

PV
Pressure vessel.

p_{wf}
Flowing wellbore pressure.

p_{wfs}
Wellbore sandface pressure.

p_{wh}
Wellhead flowing pressure.

Q
Injection rate.

q
Flow rate.

QA
Quality assurance.

QC
Quality control.

QHSE
Quality, health, safety, and environment.

QUANTUM*
gravel-pack packer family. Packers for single-trip production gravel packing with one-piece, self-energizing packing elements and one-piece bidirectional slips that reduce the risk of loss when retrieving or milling.

r
Radial distance.

R&D
Research and development.

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RapidResponse*
client-driven product development.

rathole
Extra hole drilled at the bottom of the well to accommodate expendable completion equipment.

RD
API specification for round threaded connections.

RDX
Cyclotetramethylene trinitramine, an explosive compound.

r_e
Reservoir drainage radius.

reservoir
A subsurface body of rock with sufficient porosity and permeability to store and transmit fluids.

retrievable
Semiexpendable perforating gun system that is retrieved from the wellbore after the perforation.

Reynolds number
The ratio of inertial forces to viscous forces that quantifies the relative importance of these two types of forces for given flow conditions and is used to identify different flow regimes.

RF
Radio frequency.

rigless
Well operation conducted with equipment and support facilities that do not require using a rig over the wellbore.

RITE
Schlumberger maintenance control and tracking system.

Rockwell
Hardness scale of indentation of materials.

ROOX
Remote operated OrientXact system. Oriented perforating gun system with connectors designed for using a remote operated handling system.

RP
API Recommended Practice.

RP 19B
API Recommended Practices for Evaluation of Well Perforators, which supersedes API RP 43.

RP 43
API Recommended Practices for Evaluation of Well Perforators, which was superseded by API RP 19B.

RP 67
API Recommended Practices for Oilfield Explosives Safety.

r_s
Radius of the damaged zone.

RST*
Reservoir Saturation Tool.

r_w
Wellbore radius.

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r_w'

Effective wellbore radius.

s

Skin. Pressure drops across a completion that are caused by formation damage related to drilling and completion operations.

SA

Stub Acme. API specification for threaded connections.

S.A.F.E.*

Slapper-Actuated Firing Equipment. Detonating system immune to electric potential differences.

safety joint

A downhole tool that is designed to part under controlled conditions so that part of the toolstring is left in the wellbore while the running string is retrieved.

sand control completion

The installation of equipment or application of techniques to prevent the migration of reservoir sand into the wellbore or near-wellbore area.

sandface

The physical interface between the formation and the wellbore.

Sand Management Advisor

Schlumberger 3D model for predicting if a perforated formation is going to produce sand.

sandstone

Clastic sedimentary rock consisting of grains that are predominantly sand sized.

SBSV

Single-ball safety valve. Full-opening downhole safety valve used to shut in the well in case of an emergency. Run in open position, it is closed permanently in response to annulus overpressure.

SBT

Sealed ballistic transfer. Ballistic transfer that breaches the sealed bulkhead between perforating guns to propagate the detonation through the gun string.

scallop

Recessed profile in the perforating gun body adjacent to the shaped charge.

screen

Pipe with openings in its sides and wrapped with shaped wire, used for completions to block out sand and allow fluids to flow into the well through the screen openings.

screenout

Bridging of proppant along its path toward the edges of the fracture.

s_{dev}

Skin effect resulting from wellbore deviation.

s_{do}

Skin effect caused by formation damage in an uncased completion (open hole).

SDP

Service delivery procedure. A component of the Schlumberger job quality plan, this four-step operational procedure for tubing-conveyed perforating operations addresses design and planning, preparation, execution, and closeout using document templates and tool and operational contingency flowcharts.

s_{dp}

Skin effect caused by formation damage in the perforated completion (cased hole).

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Secure*

detonator. Third-generator S.A.F.E. initiator that requires a specific high voltage and current pulse for detonation.

selective switch

Electromechanical device that enables individual sequential firing of multiple guns in a gun string.

SEM

Scanning electron microscope.

s_f

Skin effect resulting from partial completion.

SFIV*

surface-controlled FIV system. Surface-controlled version of the FIV system.

shale

A fine-grained, fissile, detrital sedimentary rock formed by the consolidation of clay- and silt-sized particles into thin, relatively impermeable layers.

shaped charge

A cavity-effect explosive device used to generate a high-pressure, high-velocity jet used to perforate through the casing, cement, and formation.

shear pin

Pin that breaks when subjected to a predetermined shearing force.

SHORT

See “SHRV.”

shot density

The number of perforation charges per length of perforating gun, typically expressed as shots per foot (spf).

shot spacing

The vertical distance between successive perforations or shots.

SHRV

Single-shot hydrostatic reversing valve, also known as “SHORT.” Operated with annulus overpressure, once the valve is opened it cannot be reclosed while the tool is in the hole.

skin factor

A mathematical characterization of the pressure drops across a completion caused by formation damage during drilling, completion, and stimulation operations.

slickline

Single-strand, nonelectric wireline used to run and retrieve tools and flow-control equipment in oil and gas wells.

SMG

Side-mounted gun. TCP custom short-string perforating gun clamped to the outside of the production tubing and oriented to direct all shots away from the production tubing.

snub

The action of forcing a pipe or tubular into a well against wellbore pressure.

s_p

Skin effect caused by the geometric arrangement of the perforations.

SPAN*

Schlumberger perforating analysis. Software for modeling perforating performance by comparing various gun and charge configurations for the reservoir conditions to optimize the well completion efficiency. The SPAN program includes productivity (including the effects of gravel packing, reservoir boundaries, and partial completion), penetration, and entrance hole calculations for both oil and gas wells.

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SPD
Spring positioning device. Orients perforating guns in the wellbore; typically used in nonmagnetic casing.

s_{pd}
Skin effect caused by perforation damage (unclean perforations).

s_{pf}
Shots per foot.

SPM
Side pocket mandrel. A completion component that is used to house devices that require communication with the annulus. The design of a side-pocket mandrel is such that the installed components do not obstruct the production flow path, enabling access to the wellbore and completion components below.

SRC
Schlumberger Reservoir Completions Technology Center. The Schlumberger R&D facility for well completion and perforating technologies and for manufacturing of shaped charges, located in Rosharon, Texas, USA.

s_s
Skin effect of a single perforation shot.

s_t
Total skin effect.

stable arch
The hemispherical arch formed around a perforation exit hole with mechanical strength sufficient to prevent sand production for a given flow rate and pressure drop in an unconsolidated sandstone.

standoff
The space between the shaped charge and the internal surface of the perforating gun body, which must be sufficient to allow the shaped charge jet to form before exiting the gun body.

stimulation
A treatment performed to restore or enhance the productivity of a well. The two types of stimulation treatments are hydraulic fracturing treatments and matrix treatments.

stinger
Small-diameter projection from a downhole tool that is used to position the tool.

stress cage
Zone created around the perforation by the presence and behavior of crushed-zone material.

surge flow
The first period of transient flow in the newly created perforation that optimizes the well dynamic underbalance to consistently eliminate or minimize perforation damage.

swab
To unload liquids from the production tubing to initiate flow from the reservoir.

swell
Expansion of the diameter of the perforating gun after firing.

SWPT
Shallow-well perforating truck. Two- and four-wheel drive vehicles for completion and perforating operations on wells to 18,000 ft.

SXAR
Automatic gun release. Incorporates X-Tools perforating gun–activated technology to automatically drop TCP guns to the bottom of the well the instant the guns fire.

SXPV
Automatic production valve. Incorporates X-Tools perforating gun–activated technology to open the valve automatically at the instant the guns fire.

SXVA
Automatic shock absorber. Uses X-Tools perforating gun–activated technology to prevent damage by absorbing the shock that occurs during TCP operations.

t
Time.

T_{bh}
Bottomhole temperature.

TCF
Trigger charge firing. Retrievable firing head system conveyed on electric wireline or slickline into the well after the perforating guns are positioned.

TCP
Tubing-conveyed perforating. Conveyance of perforating tools and accessories on tubing or drillpipe.

TCR
Tubing-conveyed gun release. Available in mechanically and hydraulically activated systems to release and drop perforating guns.

Teflon®
Registered trademark of E.I. du Pont de Nemours and Company for polytetrafluoroethylene nonstick coating.

TFTV
Tubing fill tester valve.

through-tubing gun
Perforating gun assembly designed to run through the restricted clearance of production tubing and then operate effectively within the larger diameter of the casing or liner below.

tip screenout
Fracturing treatment designed to cause proppant to bridge at the fracture tip through pad dehydration, which stops fracture propagation while continued pumping increases the fracture width.

TME
Thale Missile Electronics Ltd. Formerly Thomson-Thorn Missile Electronics Ltc.

tortuosity
Crookedness of the pore flow path.

tractor
Device that pulls the cable string down the borehole for conveyance in highly deviated and horizontal wells.

Trip Saver*
one-trip operation feature. Mandrel for one-time reopening of the FIV ball valve with applied tubing pressure, saving a trip into the hole with the shifting tool.

tubing puncher
Special application perforating system used to make holes in an interior tubing or casing string with only minimal damage to the surrounding string.

tunnel
Perforation hole through the casing and cement resulting from the passage of a perforator jet or bullet.

turbulent flow
A fluid-flow regime characterized by swirling or chaotic motion as the fluid moves along the pipe or conduit.

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TV
IRDV tester valve.

TVH
True value of a hollow short shear pin.

TVL
True value of a long shear pin.

TVS
True value of a short shear pin.

UBI*
Ultrasonic Borehole Imager. Advanced borehole imaging independent of mud type.

UCS
Uniaxial unconfined compressive strength.

Ultracap*
perforating charge.

UltraJet*
deep penetrating shaped charge.

UltraPack*
big hole shaped charge.

underbalance
Negative pressure differential in which the hydrostatic pressure inside the casing or liner is less than the reservoir pressure.

UNIGAGE*
pressure gauge system. Programmable downhole interface to gauges and sensors.

UPCT*
Universal Perforating and Correlation Tool. Gun gamma ray tool used to correlate formation depths and perforating intervals with reference openhole evaluation logs.

upper completion
Surface system of Christmas tree, valves, tubing hanger, and subsurface safety valve of a permanent completion.

USTP
Universal setting tool with propellant. Combines standard TCP firing heads and propellant setting tools.

VLP
Vertical lift performance. The flow rate the system downstream of the reservoir, such as the tubing, can sustain for a particular sandface pressure.

VRX
Plug dropped to cycle valve in PERFPAC operations.

water cut
The ratio of water produced to the volume of total liquids produced.

wing
Component of a fracture that extends away from the wellbore, typically in a pair in opposing directions according to the natural stresses within the formation.

wireline
Armored electric cable used to convey and mechanically and electrically connect downhole tools to surface data acquisition and control equipment.

WOPT
Wireline oriented perforating tool. Assembly for orienting perforating guns in 5° increments, conveyed on wireline.

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workover

The process of performing major maintenance or remedial treatments on an oil or gas well. Through-tubing workover operations save considerable time and expense by using coiled tubing, snubbing, or slickline equipment to complete treatments or well service activities and avoid a full workover in which the tubing is removed.

workstring

A tubing string, jointed or coiled, used to convey a treatment or for well service activities.

wormhole

A large, empty channel that can penetrate several feet into the formation, caused by the nonuniform dissolution of limestone or dolomite by hydrochloric acid. Wormholes are created during matrix stimulation or acid fracturing of carbonate formations.

WPAT

Wireline perforating anchoring tool. Keeps the toolstring from moving during perforating.

WPIT

Wireline perforating inclinometer tool.

WPP*

Wireline Perforating Platform. Modular downhole orienting and imaging platform for positioning perforating guns and monitoring results in real time.

WPSA

Wireline perforating shock absorber. Assembly containing a crushable element that deforms to absorb and dissipate the transient forces generated during perforating.

WXAR

Wireline-conveyed X-Tools automatic release. Uses X-Tools perforating gun–activated technology to automatically drop perforating guns to the bottom of the well at the instant of the high-order detonation.

x_f

Effective fracture length.

X-Tools*

perforating gun–activated completion tools. Automatic release mechanism linked to the detonating process to operate immediately after the guns fire but before the wellbore reacts.

α

Formation anisotropy in Brooks's (1997) conceptual method for estimating the productivity of a natural completion.

Δp_{skin}

Pressure drop across the skin zone.

μ

Fluid viscosity.

ρ

Fluid density.

σ_H

Maximum horizontal stress.

σ_h

Minimum horizontal stress.

σ_v

Vertical stress.

ϕ

Phase angle.

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