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Department of Environment Land and Infrastructure

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Traditional perforations and upcoming laser perforation technology in oil and gas wells

A Thesis

by

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DEDICATION

I dedicate this thesis to my homeland “IRAQ” whom I was raised and brought up in. I dedicate this work to the most important persons in my life and my source of inspiration “my father and my mother” who gave me the happiness, comfort, and supported me a lot in my life.

To my life partner “my wife”, sons and friends to support and encourage me.

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ABSTRACT

Once an oil or gas well is completed, casing and cement isolate the wellbore from the surrounding formation. Fluid communication establishment between the formation and the wellbore needs to perforate the well, either for injection or production. Perforating is the hole creation process in the casing that passes across the sheath of cement and extends some distance into the formation.

The majority of perforation operations use the explosives (shaped charge). A perforator is generally lowered on a wireline through the casing to create an open path between the production string and the formation. As effective as those processes are in hole or tunnel creation, they alter the rock and cause damage to the formation around the created tunnel. The altered region permeability is substantially lower than the formation virgin's permeability.

The petroleum industry welcomes new technologies for perforation which is laser perforation. Laser interact with rock and transform electromagnetic energy into thermal energy. In this method, temperature is controlled in order to spall, melt and remove the rocks. The Laser generates a thermal process that improves the rock's flow properties, particularly in tight formations zones. These properties make it a unique alternative technology to conventional perforating techniques that use shaped charge. Over past two decades, Laser perforation was performed for many rocks types and checked the characterization of rock before and after perforation. It has been proven that perforation by laser can generate large diameter tunnels and improve flow properties, thus enhancing the communication and the interaction between wellbore and formation.

This work provides an overview of the perforation processes for traditional perforation and its methods, equipment, the performance of flow, and the damage caused by them. Also provide overview about the new perforation technology (high power laser) and their tools and how it can improve the perforation performance.

NOMENCLATURE

in	Inch
ft	Feet
m	Meter
cm	Centimeter
g	Gram
sec	Second
µs	Microseconds
HMX	Higher Molecular Explosive
RDX	Research Department Composition Explosive
PYX	Picrylamino
HNS	Hexantristilbene
TNT	Trinitrotoluene
HTX	High Temperature Explosive
API	American Petroleum Institute
GR	Gamma ray
CCL	Casing collar Locator
TCP	Tubing Conveyed Perforator
HSC	Hollow Steel Carrier
HSD	High shot Density
spf	Shots Per Feet
spm	Shots Per Meters
C	Celsius
F	Fahrenheit
Gal	Gallons
cm3	Cubic Centimeter
EED	Electro Explosive Device
lb	Pound
Pu	Under balance pressure
Pr	Reservoir Pressure
Pwf	bottom hole Flowing Pressure
Psi	Pound per Square Inch
EOB	Extreme Overbalance
SCP	Sustained Casing Pressure
3D	Three Dimension
CT scan	Computerized Tomography scan
Kcz	Permeability of Compacted Zone
PI	Productivity Index
q	Oil flow rate
k_o	Effective oil permeability
h	Reservoir thickness
pe	Average reservoir pressure
pwf	Flowing bottom hole pressure
B	Formation volume factor
re	Well's drainage radius
rw	Radius of wellbore
µ	Viscosity

S	Total skin factor
S_{dam}	Near wellbore damage skin
S_{perf}	Perforation skin
S_{crush}	Crushed zone skin
S_{part}	Partial penetration skin
S_{dev}	Well deviation skin
S_{Gravel}	Gravel pack skin
S_h	Horizontal skin
S_{wb}	Wellbore effect skin
S_v	Vertical flow skin
h_{sper}	Perforation spacing
L_p	Perforation length
K_{crush}	Crushed zone permeability
r_{crush}	Radius of crushed zone
rper	Radius of perforation
K_{dam}	Permeability of damaged zone
r_{dam}	Radius of damaged zone
HCL	Hydrochloric acid
CW	Continuous Waves
RP	Repetitively Pulsed
W	Watt
Kw	Kilo watt
KJ	Kilo Joules
mm	Millimeters
Km	Kilometers
Co2	Oxygen Dioxide
SE	Specific Energy
EINC	Incident Electromagnetic wave
EREFL	Reflected Energy
Esc	Scattered Energy
EABS	Absorbed Energy
λ	Wavelength
ROP	Rate of Penetration
SP	Specific Power
CT	Coil Tubing
ΔP	Pressure difference
Q	Flow rate
ρ	Density
N	Perforation number
Dp	Perforation diameter
Cd	Discharge Coefficient
D	Diameter
LSSY	Yellow limestone
oBHA	Optical Bottom Hole Assembly
Kpa	Kilo pascal
mD	Millidarcy

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1 CHAPTER ONE: INTRODUCTION

Perforating is a process applied for creating a flow between the wellbore and the reservoir. Normally it requires initiating holes through the casing, cement sheaths, and formation into the producing zone. This process effectiveness depends carefully on designing the perforation procedure. The importance of perforating process design and application cannot be ignored, as a higher proportion of wells now use a cased hole completion (King, 2007).

Technology is always changing and advancing through time. Rotary drilling replaced cable-tool drilling during the 1920s, and cement casing throughout the well was becoming common. Accordingly, several service companies began to offer bullet perforation in the early 1930s. Perforating guns which fired inside the casing were the foundation of the perforating industry through the 1950s, and the vast majority of perforating jobs performed in the world today involve using perforating shaped charges.

A shaped charge is based on mechanical forces and explosives to make perforation. It creates high shock waves and high jet velocities. These translate into plastic compaction, loss of permeability, and decrease of immediate formation's hydraulic conductivity. The permeability around the perforated zone can decrease by more than 50% and the porosity by nearly 25%. (Asadi & Preston, 1994; Grove et al., 2019). Decreasing permeability around perforation will reduce flow efficiency. Moreover, the success ratio has been challenged. Sometimes, the charges are not fired with 100 percent that means the number of designed perforations is reduced.

Many kinds of research were their purpose to replace the traditional perforation by laser technology (non-explosive technology) in the petroleum industry. Their outcome was a unique set of tools, devices, and methods that may change downhole operations in the future (Batarseh et al., 2003). The lasers can penetrate any rock, enhance permeability, and reduce formation damage. So, it is not only considered as non-damaging technology, but it also improves flow performance.

1.1.1 Completion

The term completion is used to describe all operations in oil or gas wells after the drilling phase which is needed to produce hydrocarbons. Well completion involves all the necessary steps to prepare the drilled well for production. It often begins with the set of casing to the production formation and ends with the installation of tubing and surface hardware. However, the specifics of the completion of the well are quite variable, being dependent on the formation and the operator.

Completion of a formation takes place after open hole logging, and other drilled hole tests have been completed. If the analysis of open hole log and other tests demonstrate that production of economic oil or gas is not possible, then the hole should be abandoned. On the other side, the completion of the well will proceed if the analysis shows commercial promise (Fanchi & Christiansen, 2017).

1.1.2 Open hole completion

The casing is probably set at the producing zone top for an openhole completion, then drills the production interval. Normally, this completion type is used when the production interval is strong and self-supporting. It can be used in vertical, horizontal, or deviated wells (Fig. 1.1 a). The open hole completion advantage is that the entire formation interval is exposed to the wellbore. An open hole sections of the reservoir are more difficult to be effectively isolated than they would have been if the same interval had been cased and cemented.

It may be the optimal solution because the drainage surface is totally available for production, and pressure drops will be limited. In addition, the absence of casing makes the stimulation easier to proceed. On the other side, it is impossible to control the sand and water entry into the hole in open hole completions (Lyons, W. C., & Plisga, 2016).

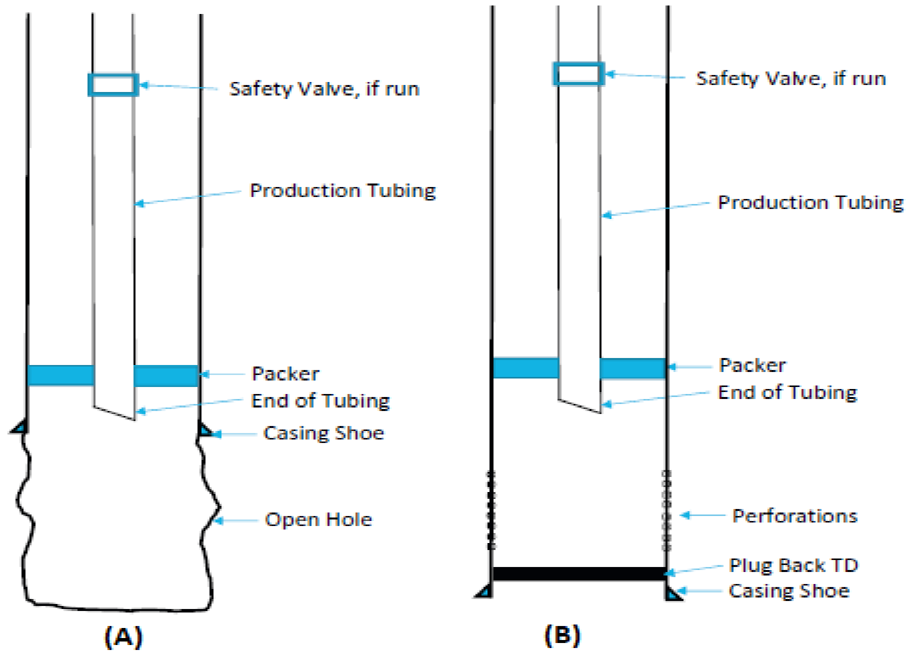


Fig. 1.1 Open hole and cased hole completion

1.1.3 Cased hole completion

Case-hole completion is used more widely for technical reasons relating to hole stability. Once a well has been drilled, a production casing is placed into the interval of production. The casing is cemented to provides the effective isolation between the intervals that produce. The cemented casing is then perforated at the determined locations with a perforator for perforating casing, cement, and penetrating a certain depth of formation to create channels that allow flowing of oil and gas into the well. The majority of wells are cased holes and this type of completion can be employed in vertical, horizontal, and deviated wellbores (Fig. 1.1 b).

The obvious advantage of this type is that the casing and cement provide support for the producing formation. Hence, Typically, cased holes are used when the formation is not strong and therefore can easily fail during production, or when the reservoir is depleting. Another advantage is the more straightforward isolation of separate parts within the producing interval. It might be needed during production to isolate or remove unwanted fluid and to stimulate a certain section of reservoirs more effectively. Since all produced fluids must enter the well through small holes in the casing, the cement and, then out of the formation. (Lyons, W. C., & Plisga, 2016).

1.2 Definitions

High explosives are very powerful explosives that are commonly used in the oil industry, such as RDX, PYX, HMX, HNS, and others. They are characterized in a very short time; extreme energy can be released.

A primary explosive is used in initiators and other instruments for initiating the explosion. It is typically more susceptible to firing than secondary explosives.

A secondary explosive is the principal explosive that is used in charges. It is usually high explosives and is more difficult to initiate, so it needs to be initiated by the primary explosive.

Perforation flow efficiency measures how flow capacity approaches the flow capacity of an ideal hole that has the same length and diameter in a perforated hole. A perforated hole and a drilled hole of the same length and diameter can differ enormously in flow rate. A good efficiency of the flow of perforation is more than 80%.

Differential pressure from the wellbore to formation is over-balance. Differential pressure towards wellbore from formation is unbalanced. In a permeable formation, fluid is always flowing from high pressure to low pressure zone.

Phasing represents the angle between the charges. 0 °, 180 °, 120 °, 90 °, and 60 ° are the most common phasings.

Shot density is defined as the perforation measurement designed per gun unit length. The ranges of shot density normally given in either SPF or SPM range from 1 - 27 spf; The most commonly used densities for the shots are 4 - 12 spf.

Pressure drop is a measurement of flow system impediments. The fluid flow rate through rock is limited by many factors like permeability, differential pressure, the viscosity of fluid, and the flow path length and area. Maximum production is achieved in a well system by reducing pressure drop to a minimum.

2 CHAPTER TWO: TRADITIONAL PERFORATING TECHNOLOGY

2.1 History

The first commercial perforating devices were bullet guns. These guns experienced commercial use firstly in 1932. The thickness of casing wall, casing wall hardness, and the formation hardness limit bullet perforating. Working on shaped charges commenced in the military arena during the 1930s and 1940s. The oil industry accepted this technology in the early 1950s. By the late 1950s, it became the most widely used perforating method (Behrmann et al., 2000).

Alternatives to the explosives have been achieved, usually with a slurry of abrasive material, but using it became slower (King, 2007). The conveyance method also kept up with technological advancement of perforating. By the late 1970s and early 1980s, strategies of perforating were limited with through tubing small gun or casing guns of larger size conveyed by wireline, By the mid-1980s, tubing conveyed perforator (TCP) was firstly used (Behrmann et al., 2000).

2.2 Perforating Method

2.2.1 Bullet Gun Perforating

The bullet gun was the first used perforating mechanism, firstly used in 1932. It is an old technology turning back into use (King, 1995). The bullets should penetrate the casing, cement sheath, and the determined formation with a speed for perforating is almost at 3000 ft/sec (900 m/s). Penetration is easy in low alloy and small casing thickness but in most cases, it is more difficult in casing alloy of higher strength and hard formations. When the perforation process is conducted correctly, the bullet generates a very circular hole entrance but can generate a hole with sharp burrs inside. Fig. 2.1 displays a bullet perforation for the casing.

The length of the hole generated by a gun decreases with increasing strength of formation. Penetration reaches 15 inch –/+ in soft chalks and 2 - 3 inches in dolomite. Whereas the bullets crash the rocks instead of efficiently push and compact them in their path when perforating by a shaped charge. The crashing may be beneficial when the cracking enhances permeability

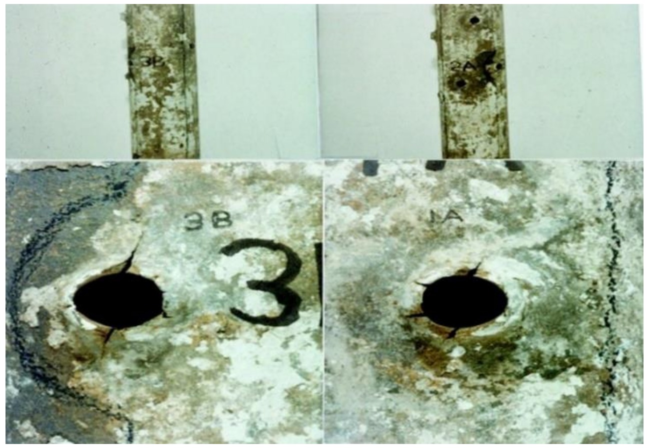


Fig. 2.1: Casing perforated by a bullet in a surface test.

near the perforation (King, 2007).

Bullet perforating advantages are very controlled for hole size and shape. The main drawbacks were that the bullet remained inside the perforated hole, not very good penetration, small-diameter perforations, not effective in thick or high alloy pipe and hard formations, and the perforating density is low (King, 2007; Halliburton, 2017).

2.2.2 Abrasive Perforating Methods

It uses an abrasive-laden fluid with high flow volume to erode or cut off the pipe when the tubing or the nozzle is rotated. When The hard particles like sand impinge on steel, the casing can be cut by 0.25 to 0.3 in. in a short time. Perforations or even 6 in. × 0.5 in. slots can be formed in the casing in 10 to 20 minutes per slot (hole) (King, 2007).

The tools used consist of bodies containing two, three, or four jets in a single horizontal plane equally spaced around the circumference. The body is connected to the end of the tubing string and run in the well. The nozzle concentrates the stream on the surface of steel. The nozzle helps to save energy, reduce the clearance distance effect, and decrease cutting time. Clearance is important between the target and nozzle but not as critical as in non-solids jet cutting (Pittman et al., 1961).

The depth of the tunnel formed by abrasive perforation is particularly short, about 1 to more than 8 in. The abrasive type differs with a job, but the most used material for pipe perforating and cutoff is sand. The other used abrasives are soda glass, calcium carbonate, and another mineral. (King, 2007).

The development of this process has shown that oil well casing, cement sheath, and formation can be perforated or undercut in a relatively short time that there is a point of diminishing returns beyond which a longer pumping time will not produce appreciably deeper penetration. The penetration depth is determined by a drop in pressure across the nozzle, sand grain size, the target hardness being cut and the time of pumping (Pittman et al., 1961).

2.2.3 Shaped Charges

Most wells now use the shaped charge for perforating, it is also called jet perforator. The bullet still not used in the process to create a good hole entrance for limited entry stimulation. The shaped charge was developed in the Second World War for armor-piercing shells. It contains explosive that creates the perforation (Barker & Snider, 1995), It is explained in details in section 2.4.3.

2.3 Types of gun

2.3.1 Hollow steel carrier gun (HSC)

Hollow carrier guns consist of shaped charges put in steel tubes. This gun's design is obtainable for the majority of tubing and casing sizes. They are divided to four main types (Cosad, 1992):

2.3.1.1 Scallop guns

They are so-called due to charges shooting through dished-out areas inside the carrier, which are recovered to the surface and junked. They use with wireline conveyed and through tubing perforating. They are mostly used in hostile conditions or when the debris is undesirable.

2.3.1.2 Port plug guns

The charges are shot through changeable plugs in a reused carrier. They are used with wireline perforating especially for the purpose of deep penetration and with a density of 4 spf is preferable.

2.3.1.3 High shot density guns (HSD)

They are designed for different casing sizes for optimizing penetration rate, shot density, and phasing. Most completions of sand control use HSD guns equipped with charges suitable to get a large entrance hole. All tubing conveyed perforators constitute of HSD guns.

2.3.1.4 The High-Efficiency Gun System (HEGS)

It is used as a wireline conveyed gun instead of a longer carrier port plug guns that are load and run more quickly. This system is obtainable with an outer diameter of 3 1/8 and 4 in. It is characterized with a temperature of 210 ºF and pressure of 4000 psi, that is useful to use it in many shallow wells.

2.3.2 Capsule gun

Capsule guns composed of charges which are covered by a protective cap as illustrated in Fig. 2.2:

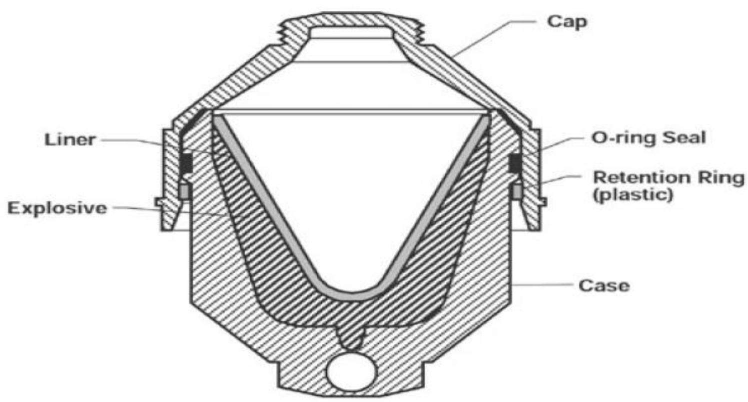


Fig. 2.2: Capsule charge

The charges are loaded to a carrier, that is particularly a group of a flexible strip or wires that are often used as wireline conveyed guns. There is no thick-walled carrier that exist with a configuration of capsule gun. They may be bigger than charges that are utilized in hollow carrier guns, also they can pass through the production tubing. That is useful in through-tubing perforating when small size guns are required to pass, and high penetration is required too. For instance, if tubing size 2 7/8 in. is used in well completion, the operator can use either a 2 in. out diameter HSC gun with explosive charges that weigh 7.5 g or the same size of a capsule gun with charges weigh 12 g. The performance of the capsule charge will be better because of its large size and will penetrate about two times the penetration of the smaller charge.

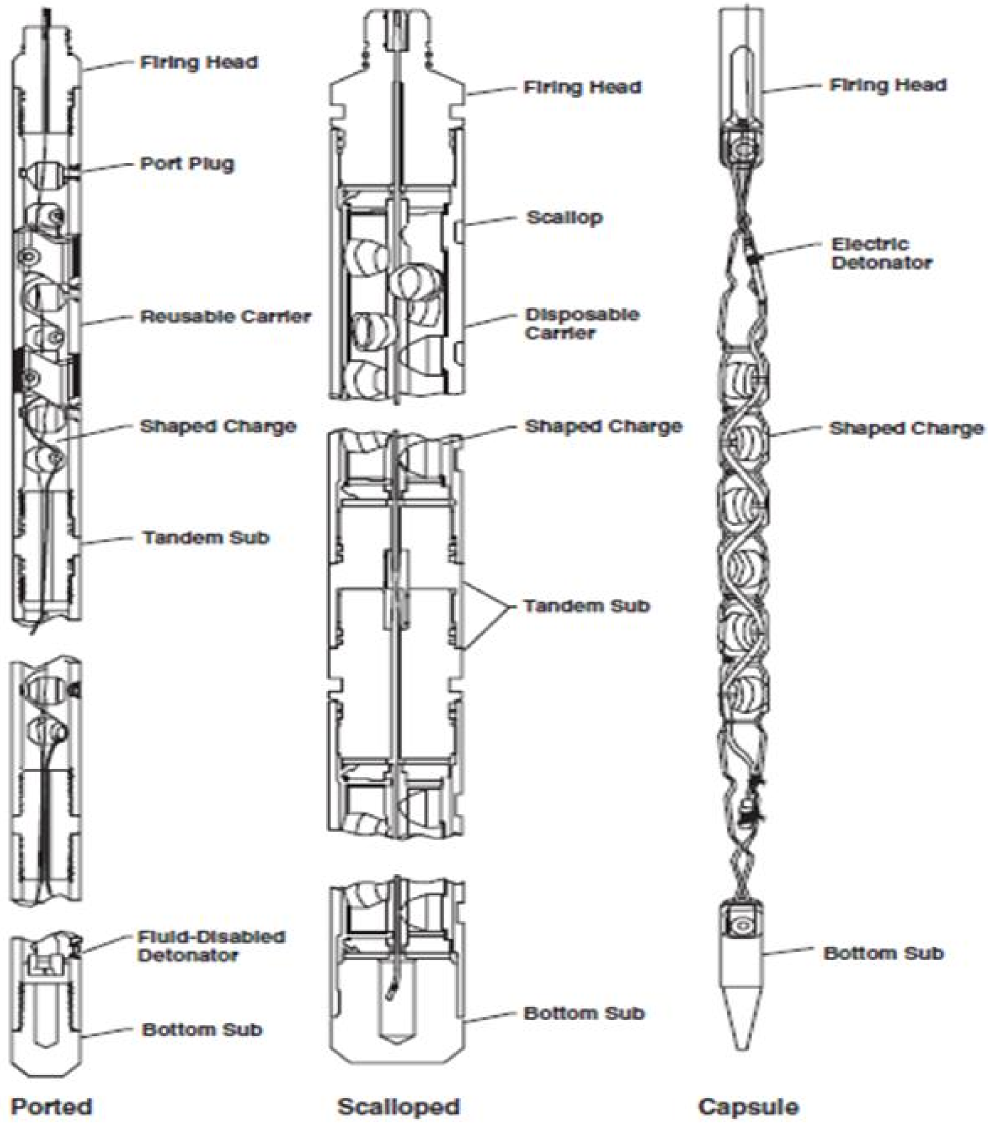


Fig. 2.3: Types of gun system

However, the disadvantage of capsule gun is that the detonating cord and detonator can be exposed to the well fluid influences. Fluid can enter the area between the detonator and detonating cord, so the use of sealing is very necessary, the explosive train is subjected at the same time to the influences of temperature and pressure. The capsule gun uses outstretched charges that pivot on a carrier with a 90º rotation. This makes the charges to stay folded and to pass through the tubing string, and to open during firing. This charge performance may become undesirable because the equipment is more mechanically complicated and leave some debris after firing (Barker & Snider, 1995).

2.4 Components of perforated gun

2.4.1 Initiator or detonator

There are two types of initiators that are used with perforating systems, electric and percussion. The electric initiator used mostly with wireline conveyed systems, it is called an electro explosive device (EED).

2.4.1.1 Hot-Wire Detonators.

It was the first detonator type used in the applications of the oilfield. (Fig. 2.4a) displays the shape and details of a detonator (hot-wire). The main parts are two lead wires, the outer shell, the sealing plug, the bridge wire, and the explosive in the shell. The bridge wire is attached to the lead wires ends, and its resistance value is generally about one ohm. Three types of explosive increments in the shell; an ignition charge, a primer charge, and an output charge or base of a secondary explosive which pressed to high density. The primer charge in some detonators is normally a sensitive explosive like lead azide. Such detonators are very sensitive and must be protected from any source that could provide power accidentally (Motley et al., 1996).

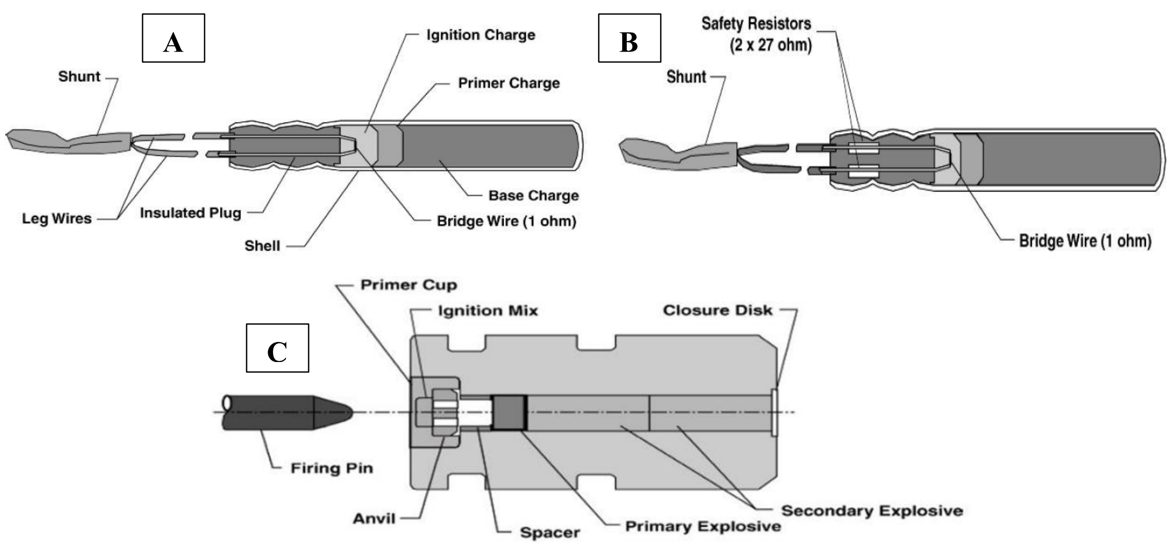


Fig. 2.4: Detonator types

2.4.1.2 Resistorized Detonators

The construction of a resistorized detonator is shown in Fig. 2.4b. It is the same in configuration to the hot-wire detonator with adding of many resistors to the tool. They start to be used widely where safety issues related to hotwire detonators are solved as they have been less sensitive to electrical hazards than a detonator with hot wire (Motley et al, 1996).

2.4.1.3 Percussion devices

It is working when the firing pin impacts the initiator sensitive part (Fig 2.4c). The initiator will create a flash to affect the primary and secondary explosives to do a detonation. Since they do not have leg wires or bridge wires, they may not be sensitive to electrical hazards. However, they have to be handled carefully because they are activated by the impact. The impact force for activation is about 5 to 7 ft-lb (Barker & Snider, 1995).

2.4.2 Detonating cord

Its function is transmitting detonation through the perforating gun by initiating every charge when the detonation wave through a secondary explosive core which covered by a protective sheath. The sheath is composed of one material like a lead or aluminum.

2.4.3 Shaped charge

The shaped charge generates high pressure and also a high jet force in order to penetrate the casing wall, cement, and formation. It is a simple device, composed of a few components shown in Fig. 2.5 (Bellarby, 2009).

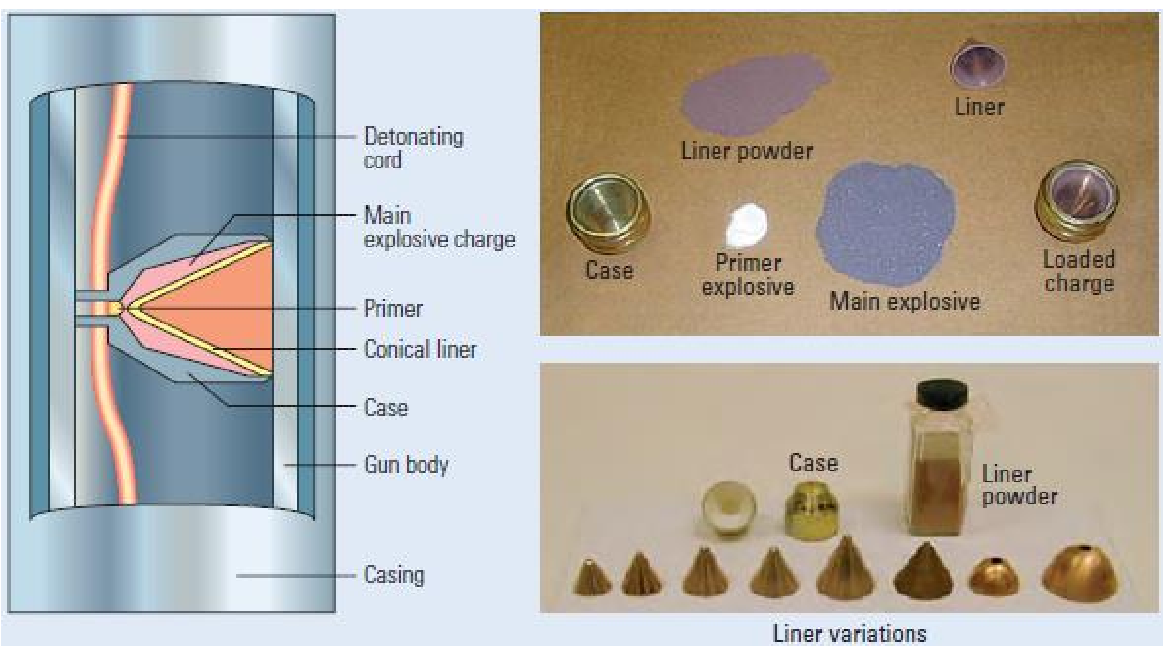


Fig. 2.5: Shaped charge (Baumann et al., 2014).

The quantity of explosives which uses in manufacturing a charge is small, particularly in the order of 6 to 32 g range. There are many charge sizes are available for different casing sizes, so smaller charges used with a very small diameter of the casing and larger charges for perforation of a big hole (Bellarby, 2009).

The weight of shaped charges is usually though to be proportional to the perforation penetration. Although the charge size influences the performance, the gun internal standoff, the liner shape, and the overall design are important. In the application of through tubing perforating, the carriers are small, and the size of charge differs from 2 g to 8 g. The small size charges use in hollow carriers' gun of 1 9⁄16" and 1 11⁄16" and in expendable strips gun uses larger sizes. using 3 ⅛" diameter or larger with hollow carrier guns, and weight usually exceeds 12 g of the shaped charge. Open hole perforating guns that are designed to reach beyond mud damage in an open hole completion may use charges of 90 g or more (King, 2007).

The energy of detonation explosives is directed by the conical case. The energy to a narrow pulse is concentrated by it. The pulse moves with a velocity of 30,000 ft/sec and 5 to 15 million psia are generated. This generated pressure will penetrate the casing and deforms the cement and formation. No wellbore material is destroyed or vaporized in the process, so debris which generated during the perforation process need to be removed by backflow before the perforation becomes effective. The perforation normally lasts only one millisecond to complete (Bellarby, 2009).

The shaped charge consists of four main components:

2.4.3.1 Conical Liner

The conical liner is considered one of the most important parts in the shaped charges. The liner is a source of heavy molecules accelerated by detonation energy and focused on the target material. The cut is formed by the energy which increased by mass of accelerated molecules of the liner. The liner material and shape are the most important parameter (Bohanek et al., 2014).

2.4.3.2 Primer

The primer usually consists of a small amount of secondary high explosive which is slightly destabilized. The primer function is activating the main explosive in the charge (King, 2007).

2.4.3.3 Explosive powder

Shaped charges compose of explosives with great pressure and detonation rate. The explosives with a rate of detonation less than 4500 m/s are considered of a lower result, so that is not compatible with the shaped charges` function (Bohanek et al., 2014).

2.4.3.4 Case

The mission of housing is outlined through the extra focusing of detonation materials towards the liner of the shaped charge. Additionally, the liner provides an unchanged shape of the charge during the performance. The materials that made the housing is characterized by a high density, low price, and other properties (Bohanek et al., 2014).

2.4.4 Explosive selection

The high explosives family classified to two categories: primary and secondary.

Primary high explosives:

They can be used only in initiators; their only mission is that detonation reaction can be started with small input energy. There are many primary explosives for instance lead styphnate and lead azide. These explosives are affected by inputs of energy from heat, flame, and friction.

Secondary high explosives:

They are using in shaped charges, detonators, and detonating cord in the explosive gun. The primary explosives are more sensitive to external motivation than secondary explosives, so, secondary explosives are safer to be handled. Because they are less sensitive, they might be hard to initiate, and when initiated, they release a huge quantity of energy in a few microseconds. TNT is considered a secondary explosive, but it is not used in oil field applications because it is low heat stability. In the oilfield, the most secondary explosives using are HMX, RDX, PYX, and HNS. These explosives vary in thermal stability and there is a quite big range of downhole temperatures. Table 2.1 demonstrates some information regarding these explosives (Barker & Snider, 1995).

Table 2.1: Secondary explosives utilized in oil fields applications

Explosive	Chemical Formula	Density (g/cm^3)	Detonation Velocity (ft/sec)	Detonation Pressure (psi)
RDX Cyclotrimethylene trinitramine	$C_3H_6N_6O_6$	1.80	28,700	5,000,000
HMX Cyclotetramethylene tetranitramine	$C_4H_8N_8O_8$	1.90	30,000	5,700,000
HNS Hexanitrostilbene	$C_{14}H_6N_6O_{12}$	1.74	24,300	3,500,000
PYX Bis(picrylamino)-3,5-dinitropyridine	$C_{17}H_7N_{11}O_{16}$	1.77	24,900	3,700,000

Secondary explosives require primary explosives to be initiated because they are difficult to detonate in the detonator. On the other hand, the primary explosives may be initiated by a small value of heat and friction, so, they have to be handled carefully. The stability temperature of the main explosives is shown in Fig. 2.6:

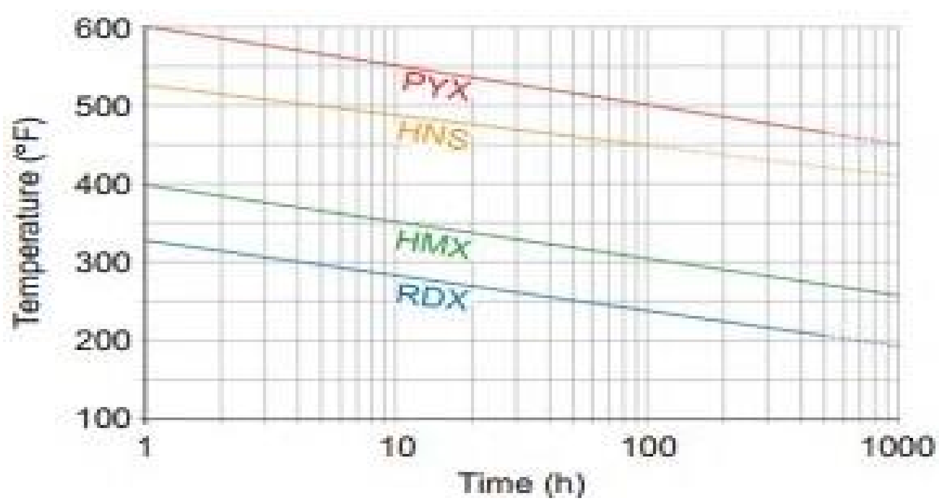


Fig. 2.6: stability temperature for perforating explosives

The above curves are reached by experiments, if the time and temperature limitations are followed, the performance of explosives will not be reduced. No following these limits will increase the risks of the explosive's degradation. That may decrease the power of the explosive, but also creates heat from the exothermal reaction and autodetonation is a possible result of that. The high-temperature explosives are less to be auto detonated for instance; HNS and PYX but they can burn at high temperatures (Jonathan Bellarby, 2009).

2.5 Conveyance Systems

There are many conveyance systems for a perforating gun such as electrical line, tubing, coiled tubing, and may be a slickline. The selection of conveyance based on the length of the interval to be perforated, the scale and weight of guns to be run, the wellbore geometry, and the aim to complete other targets such as underbalanced or overbalanced perforation, gravel packing, fracturing, etc. Well control requirements have to be taken into account and there is special equipment for each system. There is a large difference in cost between the conveyance systems. The lower cost is the wireline especially when a few gun runs are required to accomplish the perforating operations (King, 2007).

2.5.1 Through wireline perforation

In produced oil wells that have a low reservoir pressure, wellhead pressure may be low also, so in this case, wireline can be used with a large-diameter, deeper-penetrating, multiphase casing guns (Fig. 2.7).

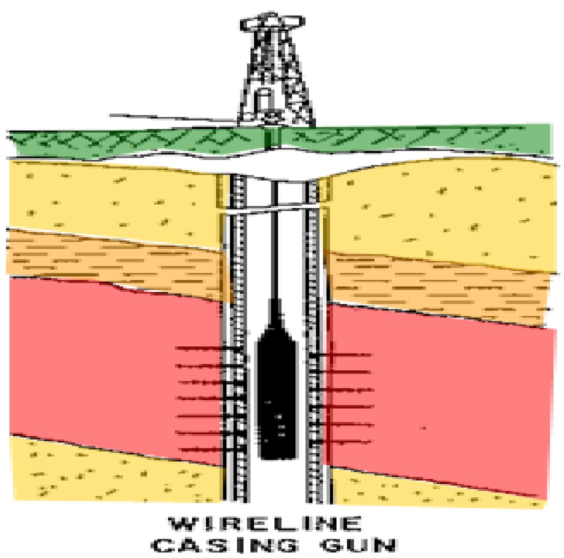


Fig. 2.7: wireline casing gun

The diameter of guns which can be used with wireline differs from 3 3/ 8 in. to 4 in. The operation is simple and effective and provides usually a higher performance than through tubing which is smaller. It can be performed in case of underbalanced. After firing the gun, the reservoir fluid will flow into a wellbore, normally not reaching the surface. When recovering the gun to the surface, tubing and packer can be run without restriction of having high wellhead pressure. The advantage of this technique is to provide a good performance of gun where reservoir pressure and drawdown are limited. It is also the cheapest because surface equipment for pressure control is simple. The maximum length of the gun is approximately 40 ft (Bell, 1984).

2.5.2 Through tubing perforation

Through tubing perforating is the most used method and it was the first method used for underbalanced perforation. The method uses small diameter guns to pass inside the production tubing to perforate the casing of larger diameter as indicated in Fig. 2.8 below. In this method, pressure control equipment is important because the wireline tools have to move into and out of the well under surface pressures often in underbalanced perforating. The equipment provides sealing around the wireline during transferring (Bell, 1984). There are three kinds of shaped-charge perforators are using such as steel hollow carrier, semi-expendable, and fully expendable capsule guns. The diameters range of guns from 1 3/8 to 2 7/8 inches to be suitable with size of tubing used in the well (Bell, 1982).

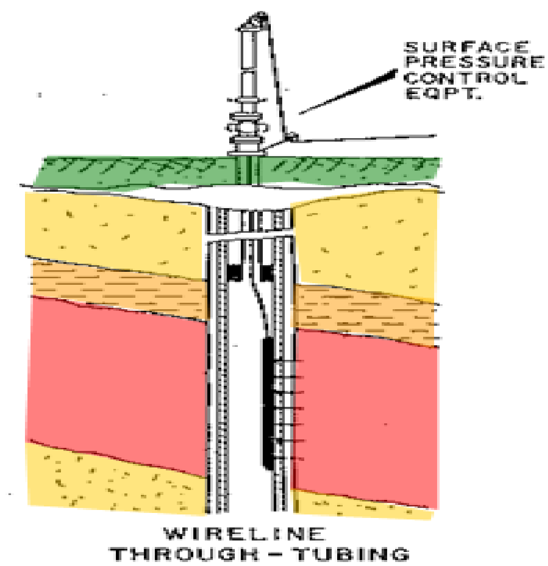


Fig. 2.8 Through tubing gun

Procedure:

The technique involves running tubing with a packer, setting packer, nippling up wellhead equipment, the well must be in underbalanced conditions, and running the gun assembly on wireline. When the guns run into the well through tubing, they are located by a gamma-ray or casing-collar locators, after that, they fired under conditions of underbalanced, the cable diameter used is small with a range of 0.18 to 0.22 in. and surface pressure-control equipment is required to allow equipment to be run in and out of the well with pressure at the surface. After perforating, the well is allowed to flow for a period of 15 – 30 minutes, prior to recovering the gun, to clean the perforated system. Then the gun is recovered at the surface. When many runs are required to perform a complete perforating, the same procedure is followed except that successive guns are connected and the well drawdown to get differential pressure before firing. Balanced-pressure perforating may be used but it is not preferable like underbalanced pressure firing.

In the case of a long interval is required to be perforated, it is desirable to perforate low permeability intervals first, then perforate other intervals with higher permeability. Otherwise, the backpressure caused by flow from the higher-permeability intervals will prevent cleanup of the lower permeability perforations because of the lower permeability interval may be required higher underbalanced pressure to perform the cleanup.

Advantages and Disadvantages:

Advantage: Through tubing perforating method is more economical, especially for remedial operations, where costs of well killing and retrieving of tubing and packer are avoided.

Disadvantages: Smaller through tubing guns performance is reduced when gun phasing is 0°. Smaller diameter guns cannot be used with new high shot density perforation like 6 shots/ft. Wellhead pressure control constraints limit gun length, modifying differential pressure value on multi-gun runs is required and often is not feasible. Some debris is left when using semi expendable guns of high-performance, casing deformation is created and are limited in resistance of pressure and temperature. When operating with high underbalance pressure, gun/cable is blown up the hole, and fishing operations are probable to occur (Bell, 1984).

2.5.3 Tubing Conveyed Perforation (TCP)

Guns are loaded and run with tubing applications for more than 30 years, used in limited perforating operations, this method was applied widely in difficult and low permeability reservoirs where wireline through tubing technique was inefficient. The method now is used in most of oil fields in the world and using this method is increasing relative to other underbalanced perforating techniques (Bell, 1984).

The perforating gun is run on the tubing to the targeted perforating depth. A differential pressure packer, landing nipple, and firing head are connected to the base of tubing. The fluid column that presents in some space inside the tubing might create underbalanced pressure. The charge detonation can be creating by dropping a bar or differential pressure, or sub of wireline, etc. This method can perforate all reservoir thickness in one run. The TCP string configuration is presented in Fig. 2.9.

The perforating depth of TCP is correlated and corrected by using a GR log. A radioactive tool is installed in the locator sub of the string assembly. The correction tool is placed at a predetermined depth with almost 100 m above the locator sub. The recorded radioactivity log is correlated with the radioactivity log which was recorded before in an open hole. The depth of the locator sub is indicated by using a tubing pup joint (Renpu, 2011).

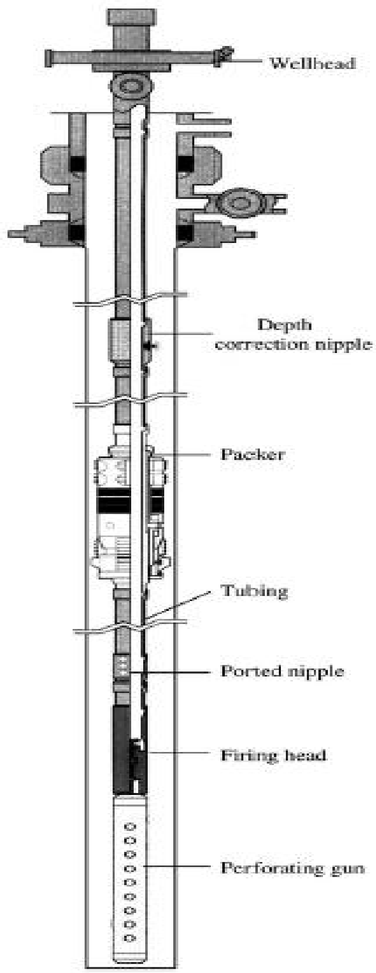


Fig. 2.9: TCP

2.5.3.1 Tubing-Conveyed Perforation Combination Technology

Combined TCP and Put the well into Production Technology. This technology has been extremely applied in producing wells. The technology is considered safe and economical. After perforating, a gun is released and then put the well into production and this process can be performed by one run only. Fig. 2.10 shows Halliburton combined system of TCP and putting into production.

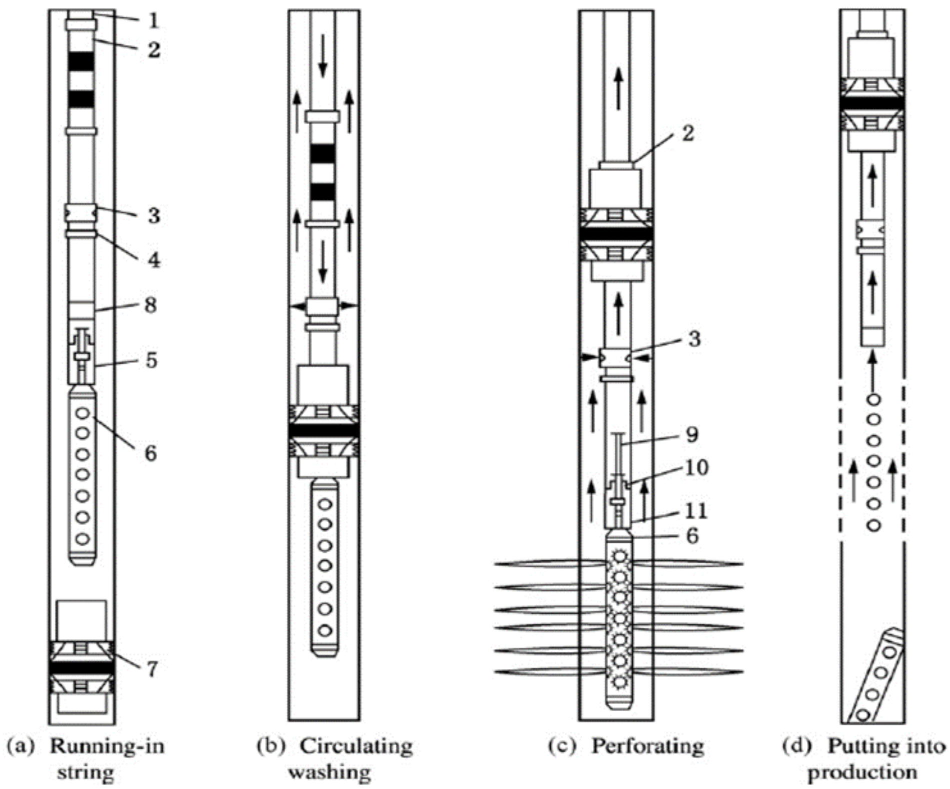


Fig. 2.10: Combined technology for TCP and placing on production. 1, tubing; 2, seal assembly; 3, circulating sub disc type; 4, tubing collar; 5, gravity detonation head and releasing device; 6, perforating gun; 7, packer; 8, guide sub; 9, bar; 10, impact; 11, detonator.

The packer is run firstly by wireline and set at the desired depth inside casing after that TCP string is run-in with a guide sub of the string to pass through the packer, the circulation must perform different times during running in, in order to wash string and remove sullage, and then the string is run further. After the TCP string is set, a bar is dropped from the wellhead in order to fire the gun to perforate. After perforating, the perforating gun and residue drop to the bottom in the rat hole, and then the well is produced (Renpu, 2011).

2.5.3.2 Firing Head types

Firing heads are installed on the top of the gun assembly to allow guns to be assembled safely before installing the firing head. The choice of firing systems depends on safety, availability, flexibility, and cost effective. There are many types of firing head which are operated by mechanical, hydraulic, or electronic means (Robson, 1990):

- **Mechanical firing heads**

The mechanical firing heads were firstly initiated by dropping a bar, which usually has a pin or sharp end that impact the cover of the outer pressure and directly contacted the detonator that consists of primary high explosive.

Dropping a bar is not applied with an increasing inclination of highly deviated and horizontal wells or the existence of tubing with different inside diameter above the guns.

- **Hydraulic firing heads**

In hydraulics firing heads, fluid pressure is applied from the surface through the tubing to fire the gun. The firing pin is actuated by hydraulic pressure. Hydraulically actuated systems can be used in highly deviated wells and are less susceptible to problems caused by scale or debris than electrical or mechanical systems. These firing heads can be used as a redundant activation system.

- **Electronic firing head**

The TCP electronic firing head is used as a detonation system for electric wireline perforating. The e-firing head uses a coded low-pressure command process to replace hydraulic firing heads which use high activating pressures. The e-firing heads are effective for operations requiring multiple pressure actuating tools in the well and complex completions processes that involving a packer setting, and many pressure tests may be needed.

- **Acoustically Activated Firing Head**

This firing head use same electronic firing head but it is attached by the acoustic telemetry system in order to provide two technologies which are TCP e-firing head system and acoustic telemetry system. Using of this technology allows perforation guns to be initiated by using an acoustic signal rather than using a pressure-pulse command in conventional technology.

The wireless command is created by the acoustic system and it is transmitted downhole by a network to the firing head. It responds and the gun is initiated (Shumakov et al., 2016).

2.5.4 Getting on depth

It is very important to determine the exact depth of a perforating gun in the wellbore; it will be useless if the perforations are not performed in the planed interval of the pay zone. Depth correlation considers as one of the most important perforating considerations. The typical methods of depth control use gamma-ray to be correlated to the original open hole gamma-ray system.

The accurate perforation depths always follow the open hole logs, also it is important to realize that drilled depth and logging depth in the cased hole may vary. Drilling depths based on pipe length, and logging depth based on wireline length which is influenced by tension or line stretch, line size, etc. Wireline measurements may still in error even if corrected for stretch. In the depth-measurement device, the wheel and drum on logging trucks must be calibrated for a new cable. Cable wear, stretch, and wheel wear can all produce inaccuracy in depth measurement.

Gamma-ray log run with a perforating gun is the most used method to correlate properly the depth, but this method may not always available, so correlations using cased-hole casing collar logs, CCLs, is also common. The depth correlation should be made with open hole logs, and various corrections may be made if perforating more than one interval is required. The distance from the logging tool (CCL or gamma-ray) to the top perforation is important to be measured in order to adjust exactly the depth.

The correlation of cased hole logs is improved by putting one or two short casing joints (pup joints) in the casing string tally, another method is to use a radioactive tag in the threads of one casing coupling joint near the pay zone top. The completion engineers should ensure to put some type of correlation marker near potential pay zone intervals.

The correlation approach is to use the open hole logs as depths recorded of logging runs that consider as a basis for future reference. This logging contains a GR log that measures the formation radioactivity. When the casing is set and cemented, a GR log and casing-collar log are run in together. The gamma-ray logs should be compatible with an openhole. With gamma-ray logs, the process is simplified and more reliable(Barker & Snider, 1995; King, 2007).

2.6 Perforation techniques

The perforating operation creates a hole due to the high pressure and energy generated by the explosive. The casing, cement, and rock are deformed and crushed by this pressure. In this process, the cement and rock are deformed and pushed inside the perforation as shown in Fig. 2.11. This debris such as crushed cement, rocks, and some amounts of charge remnants must be removed from the perforated holes in order to be productive.

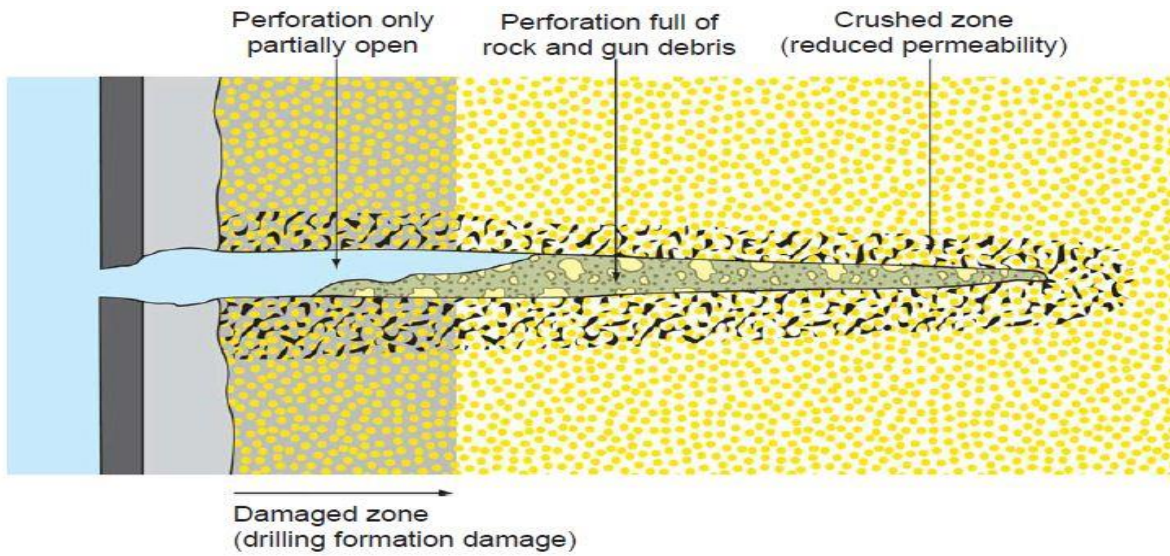


Fig. 2.11: hole immediately after perforation.

Many ways are applied to remove this debris. After perforation, the well is allowed to flow in order to create a pressure drawdown along with the perforated interval. Some debris will flow from some of the perforations. However, when a few of the perforations are cleaned up, the drawdown will be reduced for the remaining perforations and they may not be cleaned up. It is generally about 10 to 25% of perforations share to the flow. It might not matter as these plugged perforations can clean up during time especially when the formation is weak and sand production occurring (Bellarby, 2009).

2.6.1 Underbalanced perforation

Underbalanced perforating is done when the reservoir pressure (Pr) is greater than the bottom hole pressure (Pwf). Underbalanced pressure is calculated as the difference between the reservoir pressure and downhole pressure ($Pu = Pr - Pwf$) (Crawford, 1989).

Underbalanced perforating helps to remove the crushed formation or debris from the perforation due to the pressure of the formation and this will provide better performance for flow channels (Subiaur et al., 2004).

The studies that conducted for more than 100 wells which perforated, tested, and stimulated in underbalanced condition are indicated in Fig. 2.12 and Fig. 2.13 (Bell, 1984). These studies compare the damage generated by perforations by choosing the differential pressures depending on permeability. The ranges of this study were advanced by Bell, who suggested that the underbalanced condition is useful for cleaning which is related to permeability. The Berea core was used for the majority of the test, it is a very high permeability formation, using differential pressures on the order of hundreds psi is suitable to create sufficient flow to clean the perforation. Higher underbalanced pressures are required for lower permeability formation. The strength for unconsolidated formations has to be taken into account and low differential pressure is preferable to use.

In Fig. 2.12 and Fig. 2.13, The scattered points around the line in two figures illustrate that the performance of the perforations might be influenced by other conditions. These conditions used in determining pressure, permeability, and damage from drilling may represent many factors including inaccuracies. In most of the tests performed, the guns were pulled out and checked after a short period of flow. The test included only the wells in which the gun was completely fired.

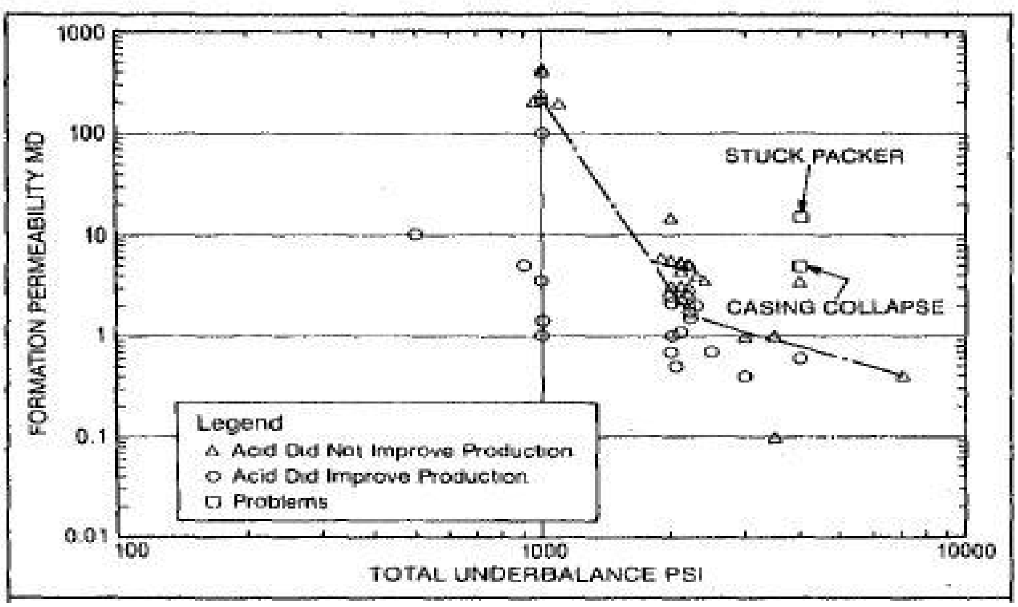


Fig. 2.12: Underbalanced pressure used on TCP in sandstone gas zones (King et al., 1986)

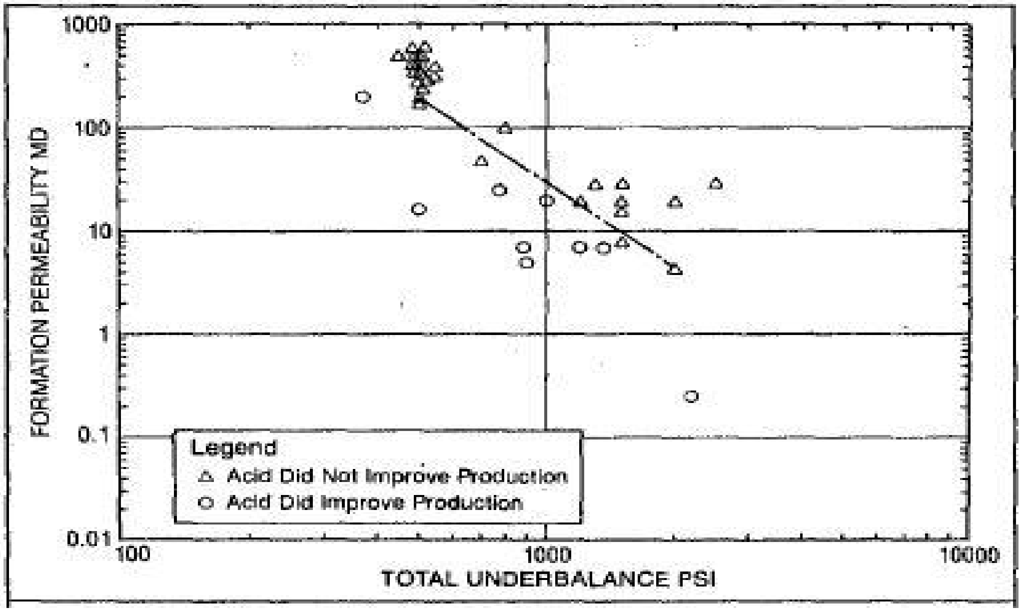


Fig. 2.13: Underbalance used on TCP in sandstone oil zones (King et al., 1986)

In cleaning of perforations, the differential pressure is considered to be of great importance. So, after underbalanced perforating, the flow is very important and cannot be neglected. The fluid volume to flow in order to clean one perforation is assessed to be at minimum of 4 gallons. In low permeability, less than one millidarcy, the differential pressure might be not effective in providing a suitable rate for cleaning. Underbalanced conditions can be used with Through tubing gun, where the gun may be run in well by using a sealing around wireline (lubricator). The expected failure for underbalanced perforating is caused by low formation permeability and no flow started after firing the perforating gun (King, 1995).

Considerations for Underbalanced perforating:

Krueger, Worzel, and Allen investigated the flow rate required to sweep damage, they noticed that the perforation in overbalanced condition leads to plug the perforation. The plugs are composed of charge particles, crushed formation, and mud. Noted that the plugs which generated throughout perforating in overbalanced conditions were particularly difficult to be removed by pressure after flow. Perforating under high pressure in the wellbore creates a flow rate lesser than a perforation with underbalanced pressure (King et al., 1986).

2.6.2 Extreme over balance perforation

The extreme overbalance (EOB) is firstly presented by Arco and Oryx Energy. It is applied for perforating under conditions of high overbalanced pressure and that will create surging on existing perforations. The overbalance creates some small fractures in the formation because the pressure is generally greater than formation fracture pressure and that may enhance productivity in some wells. Many operators applied EOB method with success in different well conditions. Although, this method achieved some successes, EOB cannot be used instead of underbalanced perforating. EOB is used for special applications.

EOB is based on pressuring a big fluid volume in tabular with gas. The pressurized gas and liquid column generate high pressure in the wellbore. The range of overbalance pressure should be 1.4 to 2 psi/ft of well depth based on experimental data and experience. For wells that are not perforated yet, the EOB is used in the same time of firing gun, and the wellbore fluid will flow to the perforations.

The pressure in the opposite of the perforated interval is maintained by the expanding gas to generate small fractures into the formation in order of 10 ft. The extreme overbalance process lasts only tens of seconds and during this process, high flow rates are applied which is not obtained in conventional hydraulic fracturing operations.

EOB may use tubing or wireline conveyed perforators. Different kinds of liquids used such as clear brines, acid, fracturing gels, gels with proppant, resin for sand control. On another side, also it is possible to fill the wellbore with gas (King, 1995).

EOB process is suited for:

1. When the stimulation job in carbonates is unproductive, EOB can be used to breakdown perforation by acid.
2. Generating initial formation breakdown in wells with multilinked layers
3. formations with permeability lower than 1 md especially when a production test is required before doing stimulation operations. (King, 1995)

2.7 Important parameters for perforation design

2.7.1 Shot density

It is the perforations per unit length of the gun. It is expressed in either shots per feet (spf) or shots per meters (spm), the ranges of shot density are from 1 to 27 spf. The commonly used shot densities are 4 to 12 spf. Shot density are designed depending on the completion and production requirements.

If we assume all perforations are open to flow, shot densities of 4 spf with phasing 90" are often sufficient to get flow equivalent to the open hole productivity, the productivity ratios may be increased by shot densities more than 4 spf under specific conditions, like wells with high production rate or also in well of gravel packed. This increase is because the number of open perforations is increased (King, 1995).

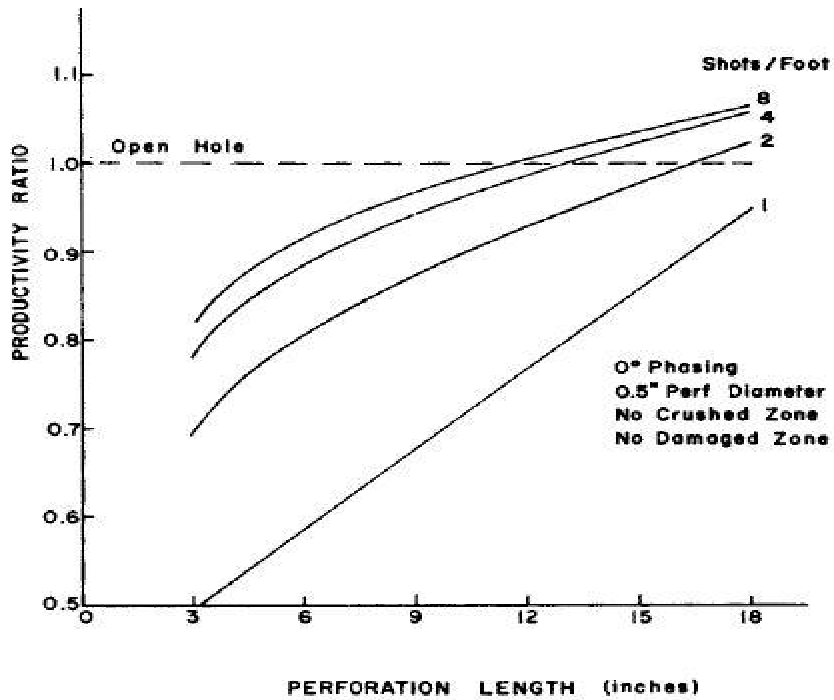


Fig. 2.14: Productivity ratio versus perforation length (Locke, 1981)

Fig. 2.14 illustrate the productivity ratio for different shot densities. The productivity ratio is defined as the ratio of flow rate measured to the ideal flow rate through a perforation with the same diameter and length. The densities are 1, 2, 4, and 8 spf. It is shown that the productivity ratio increases with increasing shot density, this plot depends on a zero-shot phasing. In another phasing, the increase is higher in productivity with shot density due to interference effects at high shot densities with zero phasing (Locke, 1981).

2.7.2 Perforation diameter

The diameter of the charge depends on the type of used gun. Through tubing perforator has small carriers with a diameter of charge differ from 2 g to 8 g with 1 9/16 in. and 1 11/16 in. diameter. In the hollow carrier casing guns, the common diameter is 3 1/8 in. or larger with a charge weight exceed 12 g. The largest charges normally used are casing guns with charges weight more than 50 g (King, 1995).

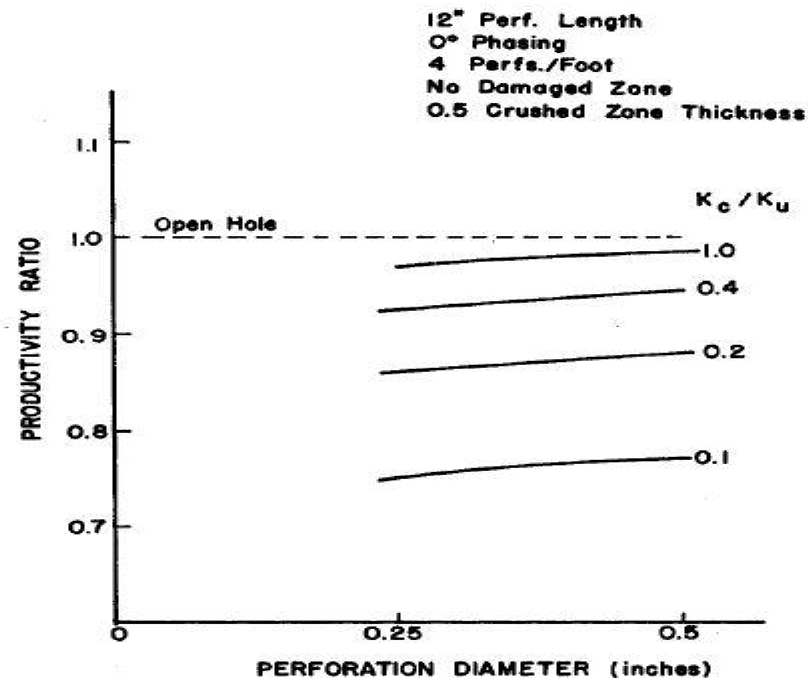


Fig. 2.15: Productivity ratio versus perforation diameter (Locke, 1981)

Fig. 2.15 shows the effect of perforation diameter with different kcz/ku values. Where kcz is the permeability of the crushed zone and k is the virgin formation permeability. It can be seen that the increase in perforation diameter greater than 0.25 in. can expect a slight improvement in productivity. There is a negative effect for a big hole as well, where the big hole charges generate high impact force on the casing wall and may damage it. In weak formations completions which do not require gravel packing or frac job, deep penetrating charges with a high density such as 12 to 16 spf are recommended (Locke, 1981).

2.7.3 Standoff & Gun clearance

These two factors can affect charge performance. A standoff is the space from the charge base to inside of the scallop or the port plug and it is a fixed part in the design of the system. Clearance is the space between the outside of the scallop or the port plug and the casing. The clearance of guns is ranged from zero to 2.3 in for 4 in. hollow carrier, 90º phase gun in the casing (7”, 23 ppf, N-80). It is based on the position of the gun inside casing. Some centralizers are usually used with a gun. If a gun not centralized properly, one side of the gun will touch the casing wall and maximum clearance will happen at the opposite side (King, 1995).

2.7.4 Phasing

The phasing can be defined as the angle between the charges, Fig. 2.16 shows many common angles: 0º, 90°, 60°, 120°, and 180º. In 0º phasing, all charges are aligned in one row and a gun must contact the casing side, so standoff of charges will be minimum. Zero phasing is used only with smaller guns or guns used in the casing of large inside diameter. The zero phasing has some negative effect on casing where arranging all charges or shot in one row decreases yield strength.

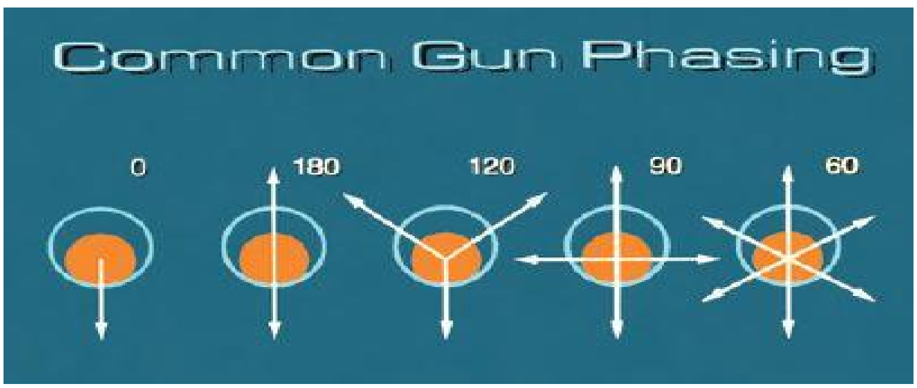


Fig. 2.16: Mostly used charge phasing (King, 2007)

The other common phasing 60°, 90º, and 120º are the most efficient phasing where they create a perforation may a few degrees from the direction of any possible fracture. Carriers with these phases do not require centralization to get good perforations (King, 2007; King, 1995).

The perforating phasing effect on production is shown in Fig. 2.17. This data does not consider permeability damage but is a reasonable for comparison between productivity and phasing. For a certain perforation length., a productivity ratio is higher at 90º phasing of 4 spf (Locke, 1981).

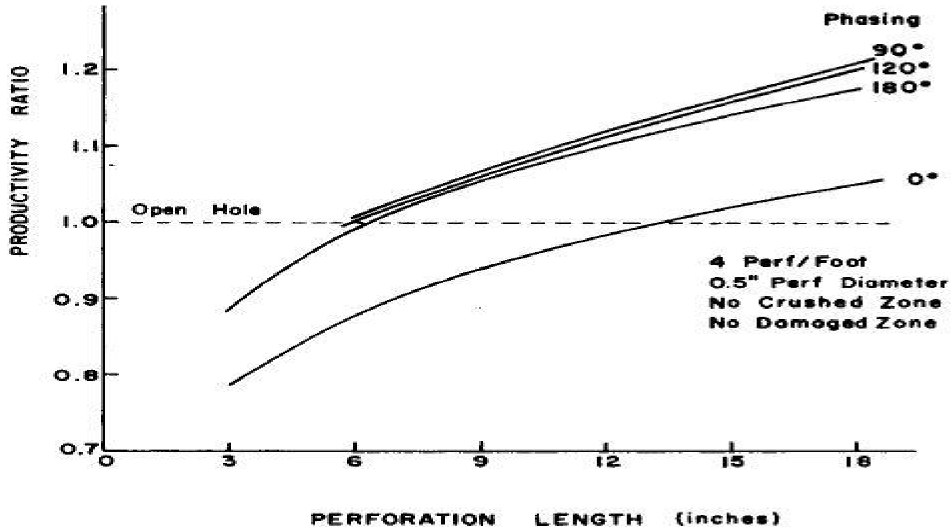


Fig. 2.17: phasing effect on productivity ratio (Locke, 1981)

2.7.5 Temperature effects

The perforating charge is stable for a shorter time at higher wellbore temperatures. Fig. 2.6 shows stable time with temperature for charges composed of different explosives. There are different guidelines for charge selection in high temperature conditions. Most wireline conveyed charges involve 16 to 24 hrs. Tubing conveyed perforator may involve a long time at the bottom hole, it should remain stable for about more than 100 hours to have enough time to run tubing and nipple up the wellhead. The charges used for high temperatures of more than 300º F are more costly. With a charge of high temperature, all gun components should be designed for a time at a required temperature. When charges explode or burn, charge cases fragments remain in a gun. These fragments consider as evidence of that as indicated in Fig. 2.18 (left), also the figure (right) displays a burst gun retrieved after well perforation (King, 2007).

Fig. 2.18: Charge cases and Burst gun fished

3 CHAPTER THREE: PERFORATION DAMAGE AND PERFORMANCE

3.1 Perforation size and geometry

The size and geometry of perforation must be considered under conditions of downhole. It is beneficial to use equipment that can estimate the single perforation geometry. The overall design of perforation can be optimized depending on combined performance of several adjacent perforations. A geometry of perforation is illustrated in Fig. 3.1.

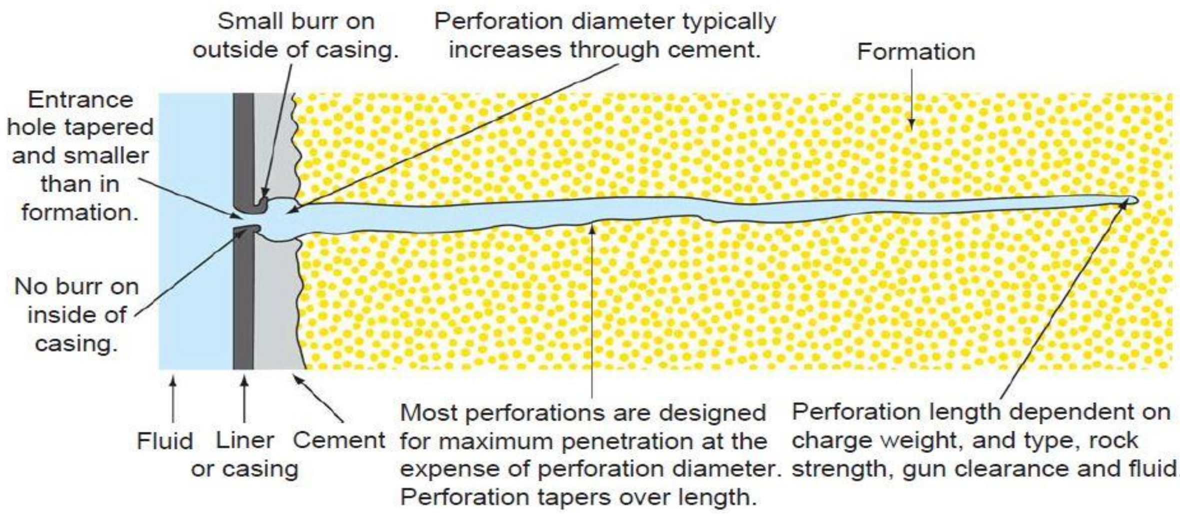


Fig. 3.1: Geometry of perforation

The hole through the casing contains burrs on the outside of the casing and there are no burrs on the inside. The burr on the casing outside is illustrated in Fig. 3.2 but is not matter. The target of most perforation operations is to create maximum depth of perforation. That is obtained by using the shaped charge conical geometry as explained in article 2.4.3.

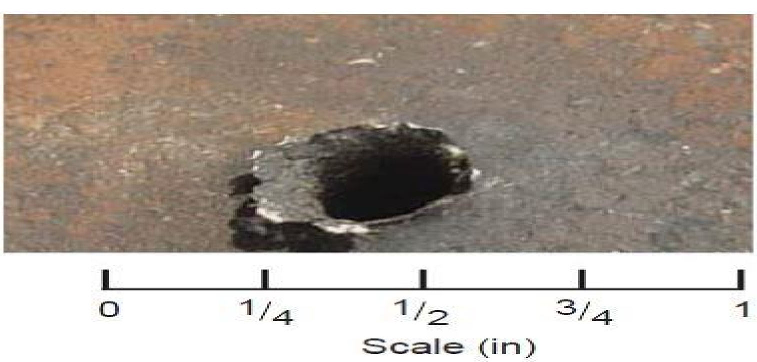


Fig. 3.2 Fig Casing burr

Designing of perforation, setting the length and diameter of a perforated hole, involves physical shoot tests. Theoretically, the tests can be implemented in any material, but it is mostly worlds widely applied on Berea sandstone and concrete. Berea sandstone comes from USA (Ohio), particularly 100 md to 400 md permeability. In concrete, the perforation would be long, but in Berea and other rock depend on the rock strength. Now, API RP 19B (2000) is used to compare different gun usage (Bellarby, 2009).

3.2 The penetration depth of charge

A few models are used to help in predicting penetration. Behrman and Halleck (1988) show too much data to compare the penetration of charges for different strength Berea sandstone formation and concrete. Although linear relationship given that Berea sandstone does not come in with very strong or very weak varieties, care have to be taken in extrapolation to very weak or very strong rocks. The Berea compressive strength range is 5000 to 10,000 psia. For formations of high rock strength, the penetration of perforation may not exceed the damaged area. Some productive layers have compressive strengths of more than 25,000 psia. So, the penetration depth decreases with increasing compressive strength (Blosser, 1995).

In layers with large invasion depth of filtrate and low porosity, a high value of skin factor will generate. Occasionally, laminated layers of soft and hard rock, such as laminated sands in a deviated well, are difficult to be perforated. Special charges were developed for hard rock to solve the problem of little penetration by using conventional charges (Smith et al., 1997).

Most of the models that are used now overestimate the penetration. The coal bed methane or carbonate perforating is also difficult to be predicted because most of the test data is taken from sandstone targets (Grove et al., 2009).

Generally, the gun lies on one side of the well as in Fig. 3.3 below which is not wanted. A small space between the casing and gun is desirable, but a large space may disperse the energy of explosives. Centralization decreases the probability of this problem. Guns will swell during firing, so good clearance is required for retrieving the guns.

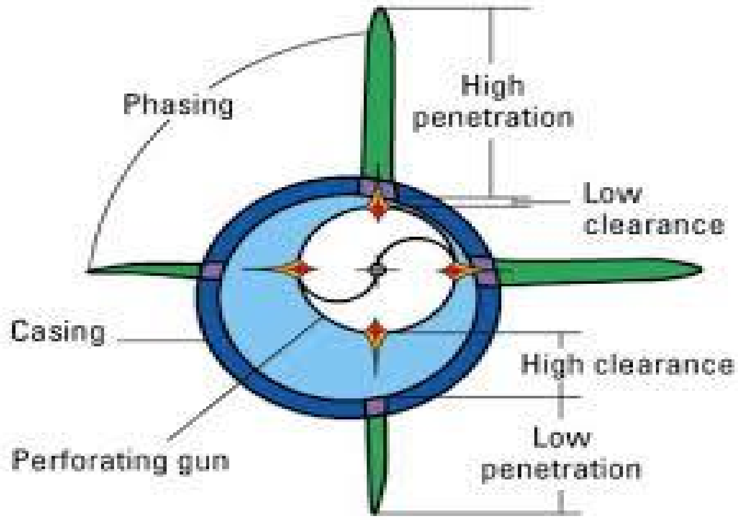


Fig. 3.3 Perforation penetration (taken from Schlumberger Oilfield Glossary, 2020)

3.3 Damage mechanism of cement sheath during perforation

The integrity of cement guarantees a sealing for wells through production period. However, the cement sheath may be damaged during perforation that affect negatively the wellbore sealing integrity. That may create channeling of fluid or sustained casing pressure (SCP) in critical cases. It is very difficult to determine the failure mechanisms of sealing for cement sheath.

Depending on past research, the sealing failure can be affected by variations of downhole pressure or temperature when the well is under production. The failure of sealing integrity likely increases with a higher casing pressure. Increasing casing eccentricity increases cement interface deboning (Andrade et al., 2015; Yan et al., 2020).

In addition to the above factors, the cement sheath damage created by perforation must not be ignored. The shaped charge was used extensively in perforation completion. It produces a high energy impact that will unavoidably generate cracking in the cement sheath and reduce its strength. Fluid channeling reduces the service life for gas and oil wells.

However, few scholars studied the cement sheath sealing integrity after perforation:

Godfrey in 1968, investigates the effect of the shaped charge jet on the strength of cement by doing a perforating test. He obtained that the bond strength of low strength cement decreases significantly after perforation, but it does not affect significantly the high strength cement bond (Godfrey, 1968).

Yan et al. 2019 studied the damaged area of cementing interface after perforation in a cylindrical body by using numerical methods and experiments. The shaped jet induces damage around the tunnel of perforation but is limited to a specific range, and a damage index is used to characterize quantitatively the cement sheath damaged area after perforation. It is indicated that the profile of the damaged zone in the cement-sheath gives a particular shape like a funnel along the direction of perforation. The damaged area increases with the diameter of liner and decreases with the compressive strength of cement (Yan et al., 2019).

Yan et al. 2020 used computerized tomography to explore the damage characterization into the cement sheath after perforation and used software to make analysis for the cement sheath damage mechanism around the hole when conducting a perforation. Perforation density, phase, and compressive strength of cement were studied to know their effect on the damaged area in the cement sheath after perforation**.** It is indicated by the experiment that a compressive zone around all hole are generated by shaped jet and cracks diverged from the hole. The generated microcracks can cause fluid channeling in hydraulic fracturing operations.

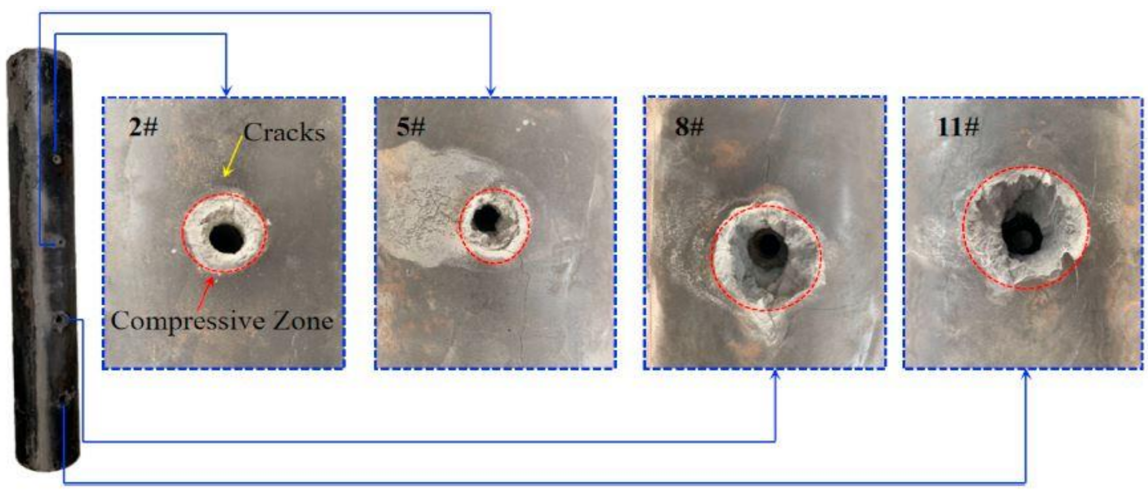


Fig. 3.4 Characteristics of the cement surface damage after perforation.

The damage generated by perforation can be occurred within the cement sheath because of the high pressure and high temperature. A numerical model was constructed to observe the cement sheath mechanical response during perforation by using the software. In the model, the effective stress was used to identify the cement sheath mechanical properties during perforation, after that analysis the range of damage around the hole was done. It is concluded that the damage is generated as microcracks in cement sheath around the hole is near to the interface of cement and formation. The numerical results show that the concentration of stress near the hole transfer with the shaped charge penetration. The high stress is converged around the casing while penetrating the formation. The damage will be higher in cement with higher modulus and less strength around the hole. Also, the damage is higher with higher perforation density and less perforated phase (Yan et al., 2020).

3.4 Damage mechanism of formation

Generally, formation damage is any operation that affects negatively the normal production of the well. The damage of formation in a perforated well composed of compaction damage created by perforating and damage caused by drilling. In this section, we are interested only in the damage caused by perforation. The perforating process can be a source of damage. The main sources of formation damage are in the area which surrounds the perforated hole. The formation damage is induced by a shock from perforating that creates a zone of different permeability and pore structure around the tunnel. This damage creates additional heterogeneity near well bore and which makes the analysis of flow distribution near wellbore is difficult.

Compaction damage may be created by high pressure and high temperature shock wave by using charge perforating. Fig. 3.5 shows that the main damage sources are the charge debris and formation at end of the perforated hole, the pulverized formation close to the open perforation, the grain fracturing zone just behind the pulverized section and then the reduced permeability zone (McElfresh et al., 2004).

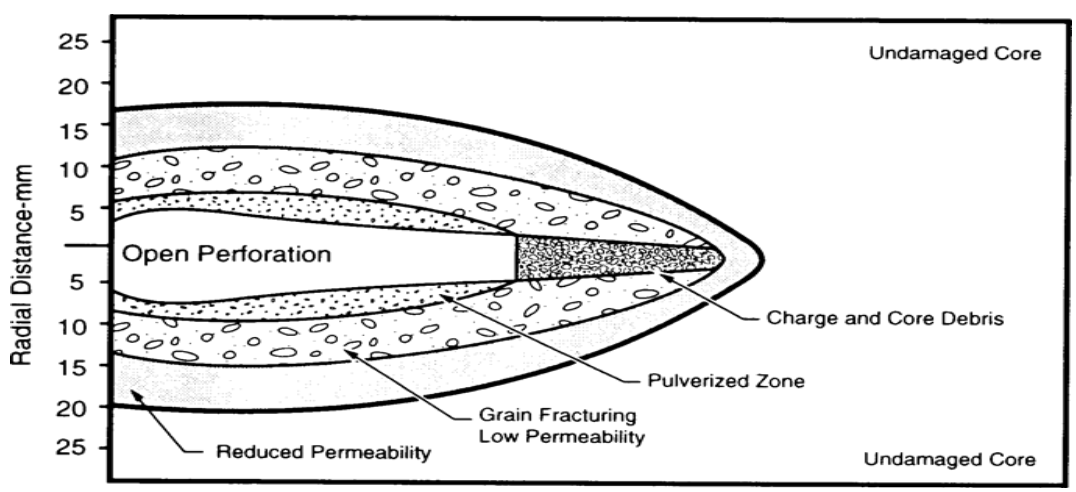


Fig. 3.5: Perforation damage type (McElfresh et al., 2004).

The permeability of the compacted zone sometimes is approximated to be 10% of the virgin formation permeability. This low permeability zone will affect negatively the productivity of perforated well and the effect cannot be eliminated at present.

Asadi and Preston in 1994, studied a perforated core and investigated small pores around perforation and large original pores behind them. An image analyzer and scanning electron microscope were used (Fig. 3.6 & 3.7). The measurement of porosity using the distribution curve of pore size which measured by the mercury intrusion method that shows the distribution of pore size changed much even though the porosity was not changed (Fig. 3.8). The large channels were distributed to small pores, leading to a significant decrease in permeability.

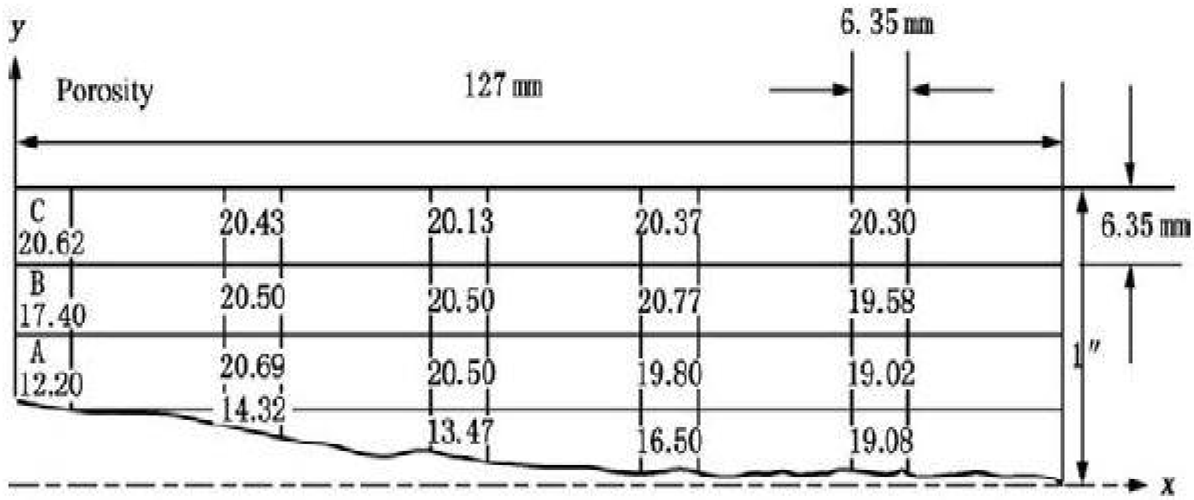


Fig. 3.6: Distribution of porosity (%) around perforation (Asadi & Preston, 1994)

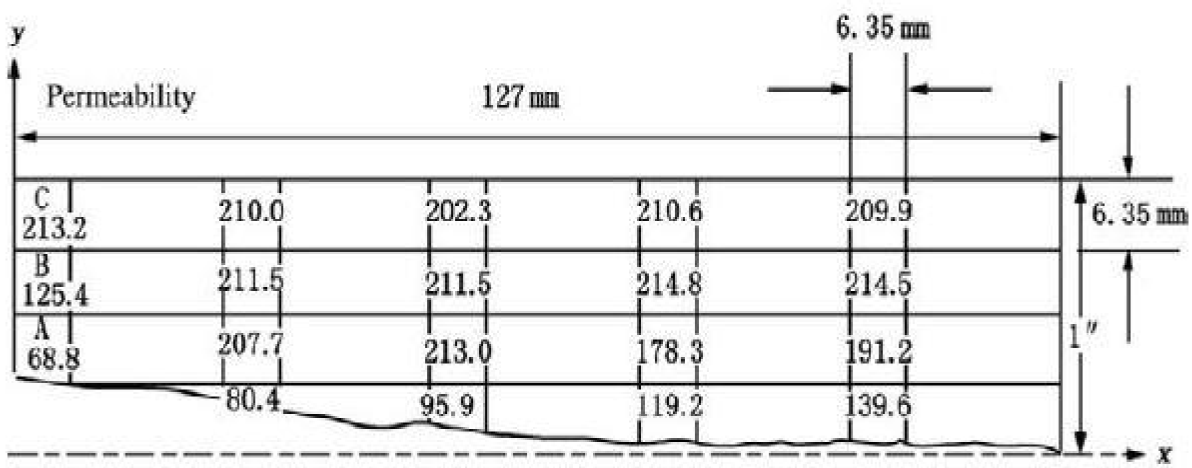


Fig. 3.7: Distribution of permeability (10^-3µm²) around perforation (Asadi & Preston, 1994)

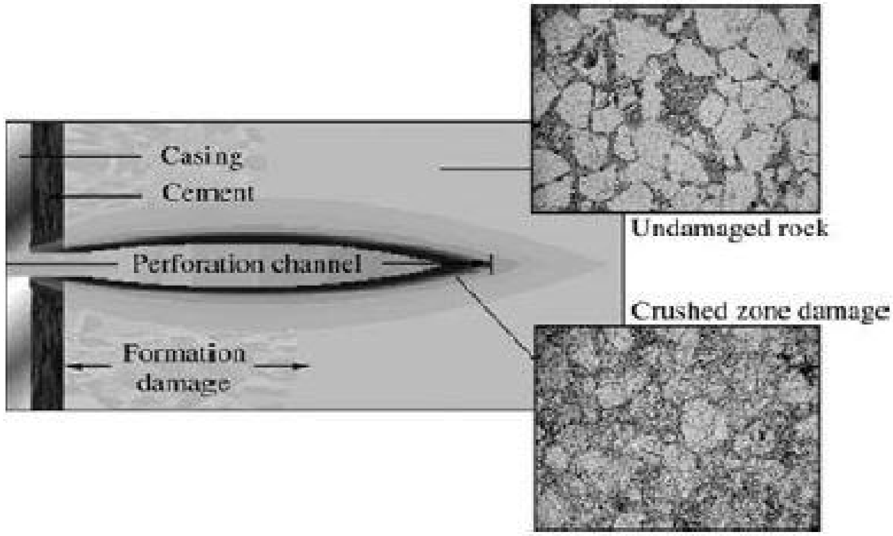


Fig. 3.8: Perforation channels before and after perforating (Renpu, 2011a)

Many strategies are used in completion to reduce the perforation damage like underbalanced perforating, Extreme overbalanced perforating, and conducting stimulation job.

In general, if there is enough flow after perforation, a desirable productivity index (PI) will be obtained. However, if formation is compacted especially in softer formations, additional treatments are required like acidizing.

At high temperatures, treatments by acid may create more damage than treatment with strong acids like HCl. For compacted zone, proper treatment have to be applied only for it and avoid penetrating the native matrix. Since this is not easy to apply, an acid that is reactive only to the fines should be effective to remove this type of damage (McElfresh et al., 2004).

3.5 Skin of damaged zone

The skin factor in a damaged zone is described as a reduced permeability zone near the wellbore. Drilling and completion operation in a well will damage the formation permeability around the wellbore. Skin factor is considered as a measure to define the efficiency of completion and drilling operations. The total skin indicates the flow change near the wellbore due to perforations, wellbore damage, flow convergence, partial penetration.

The process of perforation usually produces skin which tends to increase the resistance to flow. Jet perforators allow the casing and the formation to flow away from the jet plastically. This results in the formation material to be crushed and compacted, then producing a "crushed zone skin.". Permeability of the crushed zone is almost 10-25 % of original permeability.

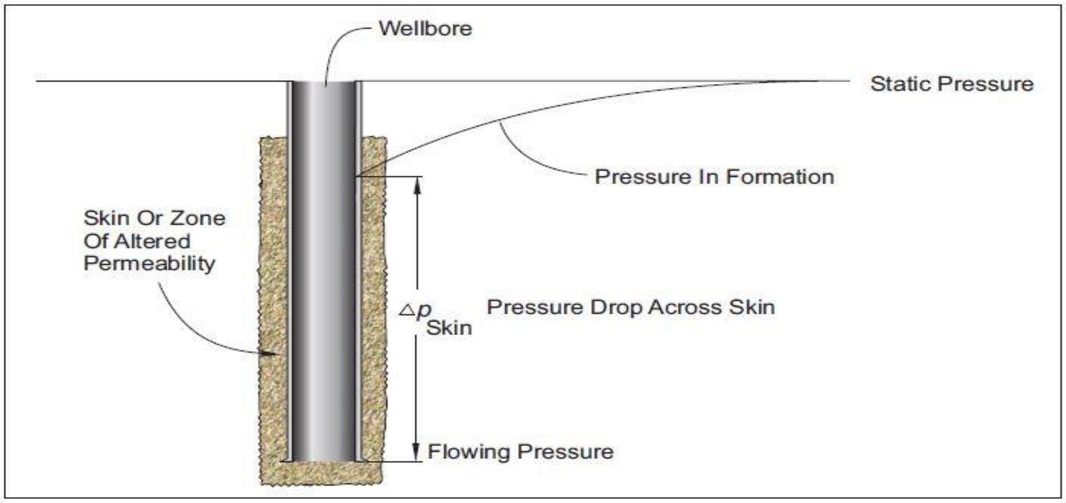


Fig. 3.9: Distribution of pressure in a reservoir with existing of Skin

The way to calculate the skin effect on well performance is by introducing the skin (S) in the productivity index equation. For instance, under steady-state conditions:

$$PI = \frac{q}{p_e - p_{w_f}} = \frac{7.08\times10^{-3}kh}{\mu\, B\left[\ln\left(\frac{re}{r_w}\right)+S\right]} \qquad (3.1)$$

Where:

q = flow rate of oil, bbl/d

k_o = effective permeability, mD

h = thickness of reservoir, ft

Pe = average pressure of reservoir, psia

Pwf = flowing bottom hole pressure, psia

μ = Oil viscosity, cP

B = formation volume factor, bbl/STB

re = radius of well drainage area, ft

rw = radius of wellbore, ft

S = total skin; summation of all components of skin

S_{total} or S includes all skin components, near wellbore damage, perforation damage, deviation of well, partial penetration, , gravel pack etc. It can be written as:

$$S_{total} = S_{dam} + S_{perf} + S_{crush} + S_{part} + S_{dev} + S_{Gravel} \qquad (3.2)$$

Wellbore casing and perforating may induce some additional flow impediment compared to an ideal open hole completion. The additional drop in pressure created by perforations is calculated under the name of ideal perforation skin (S_{perf}). Its value depends on perforation length, shot density, phasing angle, wellbore diameter perforation diameter, and formation anisotropy. Drilling and cementing operations generate a filtrate invasion and mechanical damage that is known as damage skin or S_{dam}.

McLeod, 1983 joined the impact of formation damage mechanical skin and perforation pseudo skin as the following equation:

$$S_{pdc} = S_{perf} + S_{dam} + S_{crush} \tag{3.3}$$

The skin of ideal perforation is composed of three different parts: vertical skin, horizontal skin, and wellbore affect skin. Under the conditions of plane flow, the horizontal skin can be calculated assuming a negligible wellbore effect. A wellbore skin term, Swb, accounts for the wellbore effect on productivity. A convergence of vertical flow to perforations (Sv) induces extra pressure drop and reduces the efficiency of the wellbore. At the end, the skin of ideal perforation can be defined as:

$$S_{perf} = S_h + S_{wb} + S_v \tag{3.4}$$

Karakas and Tariq used the below equation to calculate the influence of the crushed zone around the perforation:

$$S_{crush} = \left(\frac{h_{sper}}{Lp}\right)\left(\frac{k}{K_{crush}} - 1\right)\ln\left(\frac{r_{crush}}{r_{per}}\right) \tag{3.5}$$

Where: S_{crush} is the crushed zone skin, h_{sperf} is spacing of perforation, L_p is the length of perforation, k is the original permeability of , k_{crush} is permeability of the crushed zone, r_{crush} is radius of the crushed zone and r_{perf} is radius of perforation.

Tariq put the below equation to calculate the formation damage:

$$S_{dp} = \left(\frac{k}{K_{dam}} - 1\right)\ln\left(\frac{r_{dam}}{r_w}\right) + \frac{k}{K_{dam}}\ (\mathrm{Sper} + \mathrm{Sx}) \tag{3.6}$$

Where, S_x is the boundary skin, results from the nearness of perforations to the boundary of a damaged zone.

Yildiz, 2006, proposed the following equation by modifying of Karakas-Tariq model.

$$S_{pdc} = S_{dam} + \frac{k}{k_{dam}} S_{per} + S_{crush} \tag{3.7}$$

(Halliburton, 2017; Kabir & Salmachi, 2009; Yildiz, 2006)

4 CHAPTER FOUR: LASER PERFORATION TECHNOLOGY

4.1 Introduction

The word laser means light amplification by stimulated emission of radiation. The laser has unparalleled properties like low divergence and high intensity, also it is adaptable, accurate, and efficient, so it is widely used in industrial applications. These properties make the laser ideal to drive the processes with high accuracy, unique control, and high speed (Kariminezhad et al., 2016).

Many kinds of research were performed, their purpose was to replace the conventional perforation by laser technology in the petroleum industry. Their outcome was a unique set of tools, devices, and methods that may change downhole operations in future (Batarseh et al., 2003).

The lasers can penetrate any rock, enhance permeability, and reduce formation damage (S. Batarseh et al, 2003). The rapid temperature surge on the rock is created by laser irradiation, which leads to a thermo-mechanical dynamic that depends on the distribution of the beam, the rock properties, and the environment (Batarseh et al., 2017a; Gahan et al., 2001).

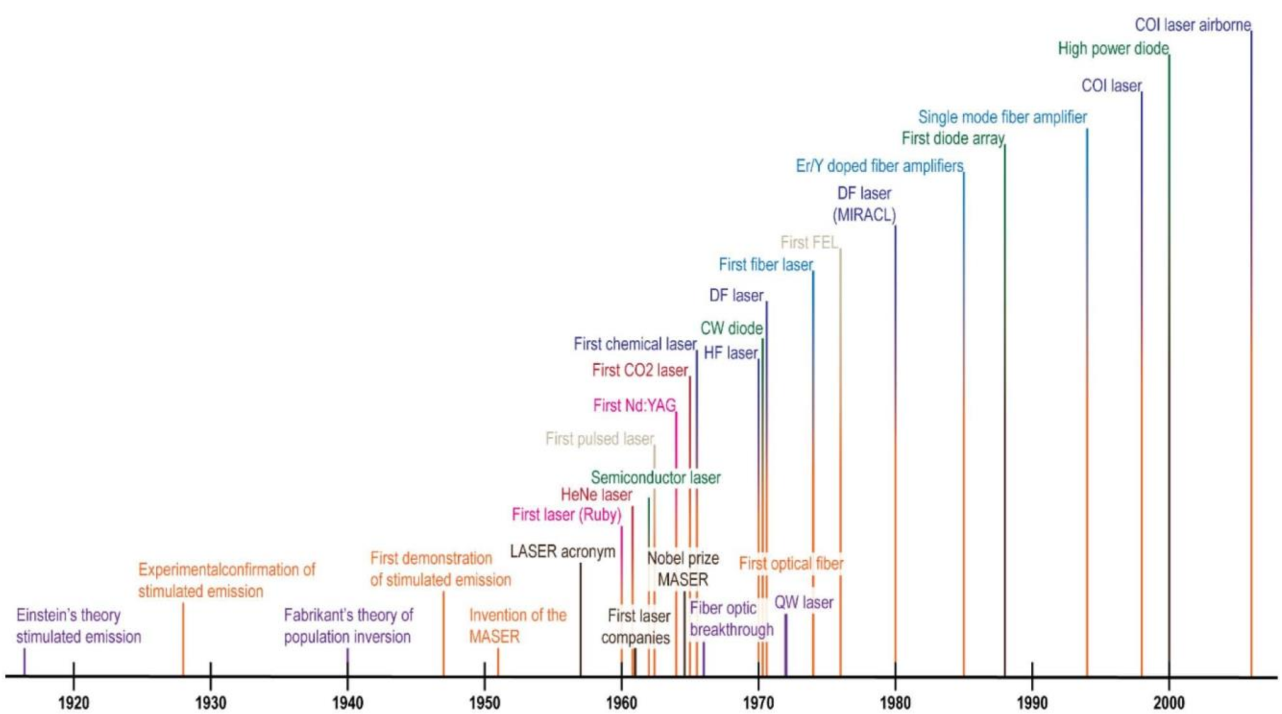


Fig. 4.1: key events timeline in the history of laser (Batarseh et al. 2017 b).

The first lasers generate a few microwatts of power, which was as a race to produce more efficient and powerful lasers. With each step, the technology is advanced to increase output power and improve efficiency. Fig. 4.1 summarizes some of the essential events of laser history (Batarseh et al., 2017b).

Lasers are classified depending on the type of active media, output profile, and output power. The active media is the material at which the light simulation occurs, it is solid, gas, or liquid (Batarseh et al., 2017b). The temporal output profile is a continuous wave (CW), semi-CW, or pulsed. The output power for high power CW lasers are in order of 10^6 W, and some ultra-short pulsed lasers have reached 10^{10} W.

A fiber-based laser will be used as a starting point in field processes. It is a special optical fiber that serve as an active medium. The technology was used in telecommunications networks in the 1970s and then it became a pivotal technology in many industries due to its reliability, high power output, and safety. Today, it is used in many industries due to these reasons. Fig. 4.2 illustrate the power development of fiber lasers over time.

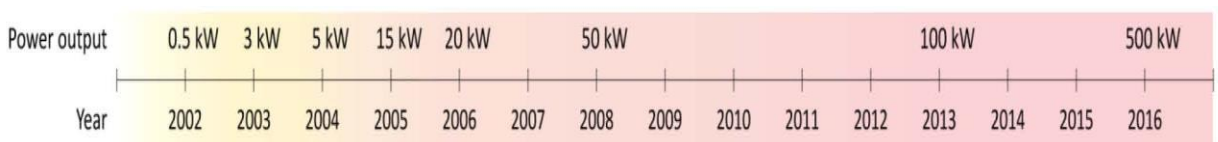


Fig. 4.2: Multimode fiber lasers output power evolution through time.

The application of high-power lasers in perforation decrease the drawbacks of explosive using (safety) and reservoir damage. Cutting of steel, cement, and formation by laser will be preferable because it will not create relatively damage at the interface of the reservoir. The laser used for that must not have limitations in transportation, storage, or applications everywhere.

Besides perforating, the laser can perform other tasks on-site like cutting windows in a casing, lateral holes, long perforations, and removal of some objects that are lost in wells and need drill out or fishing operations (Gahan et al., 2005). The advantages of using lasers are time saving, no formation damage, no debris, less completion time, and lower cost (Hu et al., 2018).

4.2 Laser application history

The first proposal of using laser for rock and soil drilling lasers was in the 1970s, technology became applicable in the late of 1990s when High-powered lasers developed in the program of the Strategic Defense Initiative in the USA during the 1980s. However, in recent years, new developments in the field of photonics have been started to make using lasers for drilling of soils and rocks outside the laboratory environment is possible. These advances are typically great in optical fiber technology and high-power lasers (Da Silva et al., 2017).

The application of laser as an alternative method for conventional shaped charges (explosive) is possible and can decrease the damages of the perforation and significantly increase the production rates (Gahan et al., 2004). The perforating operation may need to operate in thousands of meters of the well depth. especially in the deep pay zone. It requires running the laser beam for long depth without much loss of power transmission. Right now, the fiber optics is the only technology that is flexible to supply a high power for long distance and less power loss (Da Silva et al., 2017).

In 1997, Gas Technology Institute (GTI) conducted a study which lasted for two-year to investigate the possibility of using high powered lasers of the military in the oil and gas industry for applications. The study focused on exposure various types of rocks to the effect of powerful lasers to determine if possible apply it in drilling and perforating gas and oil wells (Bakhtbidar et al., 2011; Batarseh et al., 2005; Gahan et al., 2001; Graves & O'Brien, 1999).

In 2009, Aramco oil company, conducted the on-site perforating experiment by using high power laser in gas and oil wells, which considers as the first experiment in this aspect, stated that perforating by laser is more efficient and safer technology in comparison with other perforation technologies (Hu et al., 2018).

In 2011, Kerhavarzi et al., studied using high-power laser in generating tunnels with initiation of fracture in gas and oil wells, Conducting experiments on laser perforation aiming to use it in hydraulic fracturing. During the perforation of the laser tunnels, it was seen that micro and macro fractures were formed, depending on the rock`s thermal properties, the voids volume, and the amount of stress applied. Efficient rock removal mechanisms such as sandstone spallation and thermal dissociation of limestone lead to a significant increase in the permeability of the rock without presenting damage.

In 2012, Valente et al, performed a laboratory experiments with a CO_2 laser with 10.6 μm wavelength and 140 W maximum power and a fiber laser with a wavelength of 980 nm and a maximum power of 215W to investigate the efficiency of laser to perforate granite and travertine. A computer program was used to perform the experiments in order to alternately practice the laser exposure time and the high-pressure nitrogen jet to remove materials. Holes with 8mm diameters created with specific energy ranges from 40 kJ / cc to 150 kJ / cc. Techniques such as X-ray diffraction, X-ray fluorescence and thermogravimetry were applied in the samples to evaluate the chemical concentration of samples, chemical properties, and mass loss respectively (Da Silva et al., 2017).

4.3 Laser types and selection

4.3.1 Laser types

The Laser devices convert the energy into photons that are electromagnetic radiations. Laser technology advances that resulted in research and experiments on rock and laser interactions have considered laser drilling as a unique option in the future. There are many lasers that have been identified and developed to be attractive for drilling and completions of a natural gas reservoir (R. M. Graves & O'Brien, 1998; O'Brien et al., 1999; Sinha & Gour, 2006).

- **Hydrogen Fluoride (HF)and Deuterium Fluoride (DF) Laser:** this type operates with 2.6– 4.2 mm wavelength. It is the laser of U.S. Army that is used for the first tests conducted on reservoir rocks.
- **Chemical Oxygen Iodine Laser (COIL):** It is operating with 1.315 mm wavelength. It has successfully reached a range of 50 km. This high range and precision can be used to control several well problems successfully such as side-tracking, well control, and lateral drilling problems.

- **Carbon dioxide (CO2) Laser** operates with a wavelength of 10.6 mm and power of 1 MW. Both continuous and pulsed wave mode can be operated in this type. Durability and reliability are the most significant characteristic of CO2 laser. However, one of its drawbacks is mostly attenuated through fiber optics due to its long wavelength.
- **Carbon monoxide (CO) Laser**: it is operating with a wavelength range of 5-6 mm. Also, both modes of a continuous and pulsed wave can be operated in this type. Its average power reaches 200 kW.
- **Free Electron Laser (FEL):** works on electrons of high-energy and can be adjusted to any

wavelength in continuous wave mode in the future. Adjusting the laser radiation wavelength would allow the effects of reflection, absorption, scattering, radiation of black body, and plasma screening to be optimized.

- **Neodymium (ND): Yttrium Aluminum Garnet (YAG) Laser:** Operating with wavelength 1.06 mm and with the power of 4 kW lasers are available for commercial use. The research and development of this type of laser show the feasibility of working the laser with a power output of 10 kW or higher.

- **Krypton Fluoride (KRF) (excimer) Laser:** Operating with a wavelength of 0.248 mm with a maximum average power of 10KW. This laser type can operate in Repetitively Pulsed (RP) mode. The term excimer is describing this type because the krypton and fluoride atoms in the molecule are bound in the excited state.

- **HPFL**

It is considered as an alternative to other lasers with carbon dioxide and solid-state. In the past few years, the power of fiber lasers increased from a few watts to kilowatts, providing sufficient power for rock cutting through fiber optics. HPFL represent is more operating efficiency, remote operating capability, and significantly less maintenance and repair requirement. (Bazargan et al., 2013).

The selecting of laser(s) is limited to apply for rock destruction. Only these laser types are chosen as a technique for gas well rock drilling and cutting. They are characterized by laser type, operation mode (CW or RP), wavelength, beam profile power density, etc. The decision to choose which one of them depend on providing optimum and efficient operations.

4.3.2 Laser selection

Depending on high-power lasers availability, the chemical laser was recommended because it provides high power and this power level cannot be reached by other lasers` chemicals base. Developments of high-power laser created new more efficient types, smaller, safer, and cost-effective. This makes many options available for different operations. Not all high-power lasers are considered as candidates for downhole application, the selection depends on power level, efficiency, safety, delivery mechanism, size, and maintenance. Table 4.1 shows a comparison among different lasers used for evaluation and selections.

Table 4.1: Comparison of laser characteristics at 4 kW output power. (Batarseh. S. 2017 a).

	CO_2	LP Nd:YAG	DP Nd:YAG	HPFL
E/O Efficiency, %	5-10	2-3	4-6	16-20
Electric Power, kW (no chiller)	~ 50	~ 130	~ 80	20-25
Footprint, m^2 (no chiller)	6	5	3	0.5
Water, m^3/hr	6-8	20-25	~ 15	<2
Maintenance, Khrs	1-2	0.5	2-3	10-15
Pump Replace, Khrs	n/a	0.5-1	2.5	>50

The fiber delivery lasers are desirable for different causes like the beam conveys by fiber optics cables and the laser source is placed at the surface, a small area required, less maintenance, and use air or water cooled. The researchers are encouraged by this advancement to re-evaluate the application of the high-power lasers in downhole applications in gas and oil wells (Batarseh et al., 2017a).

4.4 Laser and rock interaction

The rocks are fractured with laser application, either by mechanical induction or thermal stress, enough power has to be exerted to the rock to pass the fracture limit. When the mechanism applied on the rock is thermal, enough heat will be necessary to pass the rock melting temperature too.

Nowadays, these energy and power values are exceeded, and the energy necessary to breakdown or remove a unit volume of rock still constant.

This energy is defined as the specific energy (SE) which is the energy needed to remove the rock unit volume for a specific laser system. It is investigated that specific energy is lower in shale then sandstone and limestone (Adeniji, 2014; Gahan et al., 2001; Graves et al., 2002; Sinha & Gour, 2006):

$$\mathrm{SE\ (J/\ cc) = Energy\ input\ /\ volume\ removed}$$

$$SE = \frac{Energy \quad input}{\mathrm{volume \quad removed}} = \frac{E}{\frac{dV}{dt}} = \frac{kW}{\frac{cm\,3}{\mathrm{s}}} = \frac{J}{\mathrm{cm3}} \tag{4.1}$$

The processes to transfer the energy of radiant to solids are three: reflection, scattering, and radiation absorption. So, the energy flux of the incident electromagnetic wave (E_{INC}) is defined as the following formula (Batarseh et al., 2019a; Othman et al., 2019):

$$E_{INC} = E_{REFL} + E_{SC} + E_{ABS} \qquad (4.2)$$

Where:

E_{REFL} is a reflected energy.

E_{SC} is a scattered energy.

E_{ABS} is absorbed energy.

These are three parts of energy flow of the incident wave. Also, specific energy can be influenced by them. The absorbed energy contributes to heat and destructs rock. The reflection and scattering are the energy lost due to absorption energy.

The processes of absorption and diffraction take place within a volume of the material, instead of strictly at the surface. This is because it would be partly reflected, scattered, and absorbed by the first particle as the light interacts with the material. Fig. Fig. 4.3 and 4.4 represent the oblique and normal incidence process, respectively (Batarseh et al., 2019a).

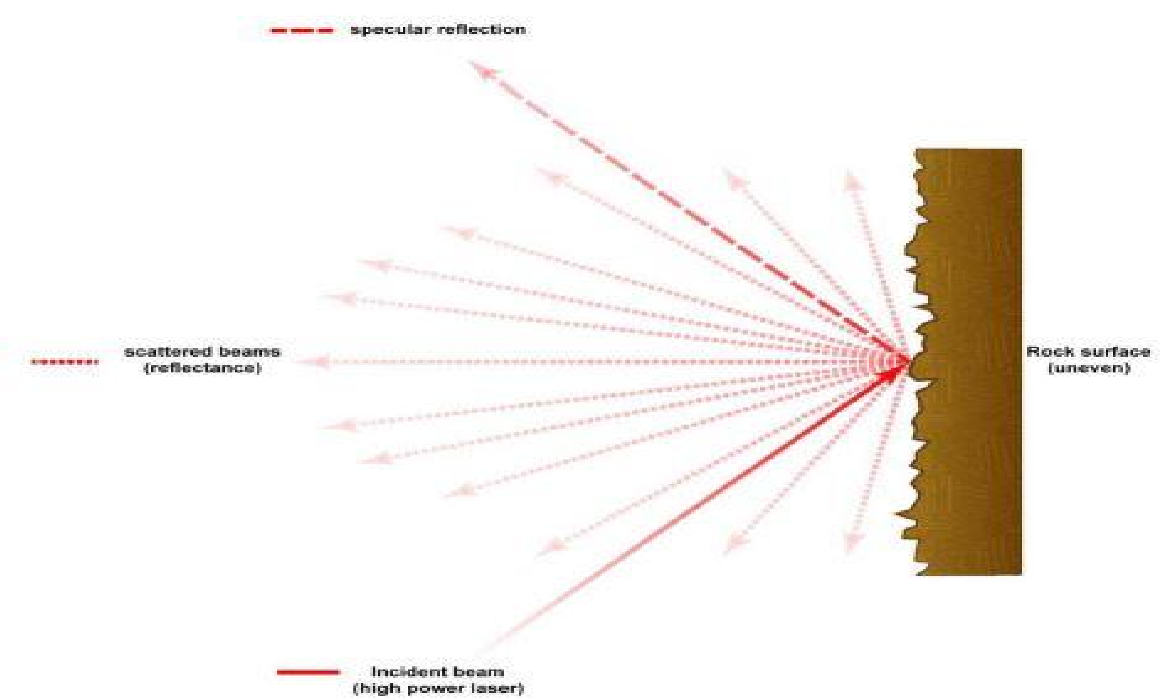


Fig. 4.3: Oblique incidence of reflection and scattering

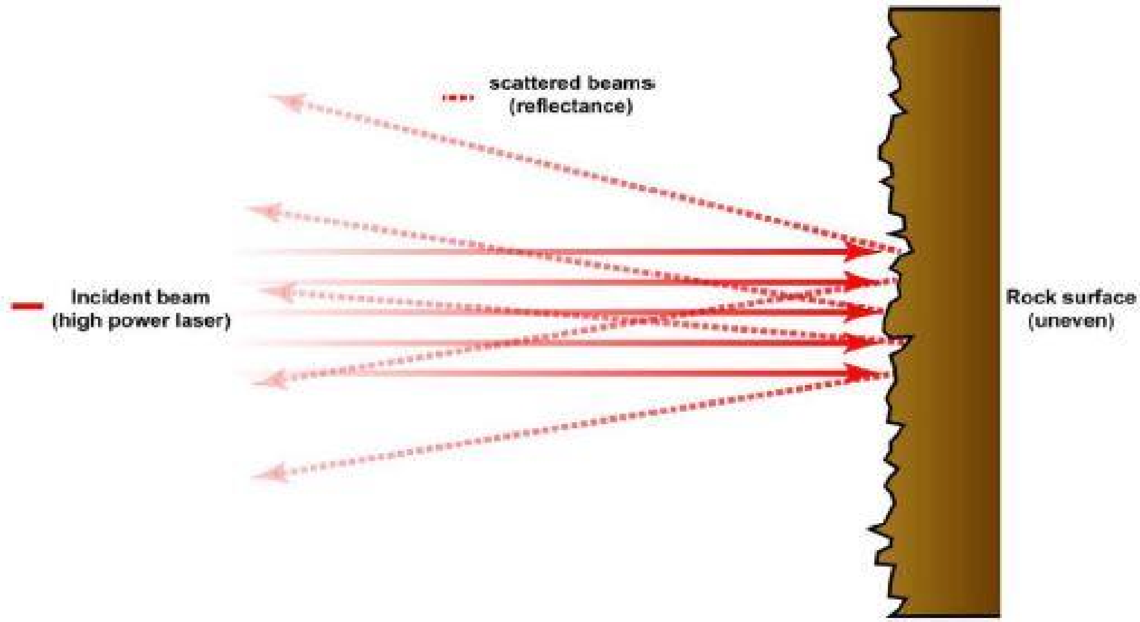


Fig. 4.4 Normal incidence of reflecting / Scattering

Most of the energy is reflected on a smooth surface, it is specified by the solid composition. On a rough surface, a dispersion of the incident radiation has mostly occurred, it is specified by the wavelength (λ). Maximizing the energy required to be transferred in the process of rock destruction relates to minimizing the reflected and scattered fractions of the energy losses.

The four applied mechanisms to destruct and remove the rock are thermal fragmentation, melting and vaporization, mechanical stresses, and chemical reactions. In lasers technology, the prevailing mechanisms are the thermal fragmentation, the melting, and the vaporization.

A thermal fragmentation (spallation) is the most efficient process for rock drilling. In spallation, the rock absorbs heat and thermal stress is created, cracks will develop, the rock weakens and breaks away. The specific energy required for spallation is lesser and rock removal is easier. Penetration rate (ROP) is related to specific energy and specific power by the following formula:

$$ROP = SP / SE \text{ (cm/s)} \qquad (4.3)$$

Despite these concepts have been elucidated in terms of drilling, the same concepts can be applied to perforation. The basic difference between specific power and specific energy is that SP is the power given to the system of the laser while SE is the energy amount that is consumed for the spallation of specific rock. As a result, to enhance the penetration rate, high SP and low

SE must be used. Laser spallation follows the criterion mentioned above and therefore, it is a preferable mechanism over traditional methods. Spallation is related to thermal stresses created in the rock by lasing. The disorder or flaws that happen in rocks are triggering by applying heat by laser. The fails occur along these lines of a flaw and then spalls as shown in Fig. 4.5. Often, lasing can lead to water dehydration in thermally conductive rocks associated with minerals existing in the formation subjected to lasing, and that will lead to mechanical failure and enhance spallation.

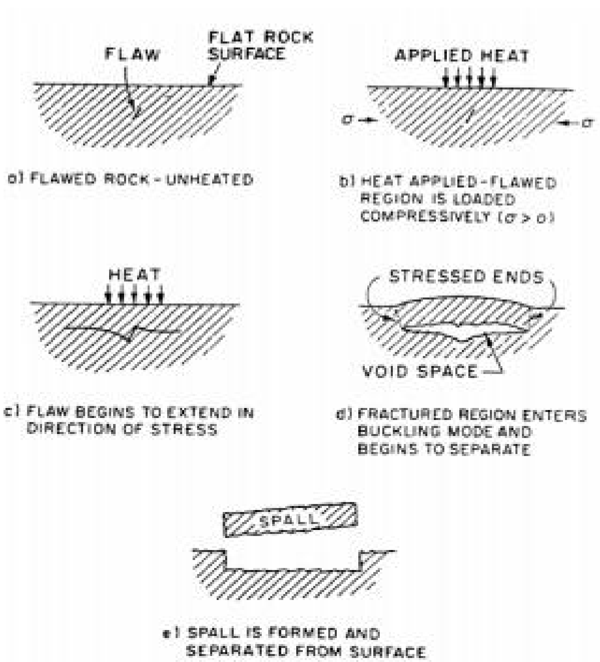


Fig. 4.5: Thermal Spallation

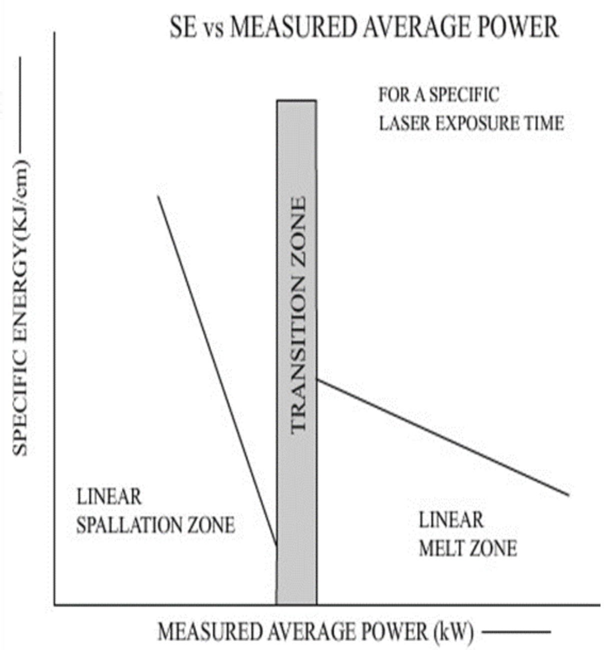


Fig. 4.6: Spallation and melting Zone

The energy of laser can destroy and remove the rock as shown in Fig. 4.6, The spallation zone is on the left, occurs at lower measured average power. The right zone is the melting zone. SE for spallation just before melting is the lowest. At the low power of laser, a lot of energy is exhausted by thermal expansion, mineral decomposition, and fracture formation, little energy remains for rock destruction, Thus, as power increases, rock removal became most effective. When melting is initiated, additional energy is required, and SE values are increasing. As a result, it is preferred to work in the spallation zone and as near to the transition zone (Sinha & Gour, 2006).

4.5 Perforation by Laser

As mentioned above, The technology of laser uses the light power for perforating rocks, where, the energy absorbed by the rock converts to heat, and different thermal processes are driven by a laser such as ablation, dissociation, calcination, melting, or even sublimation (Batarseh et al., 2017a).

The laser technology is a non-explosive and can generate different perforation geometries. It is used to perforate in great control for the tunnel geometry, depth, and shape. It can create a tunnel without compaction or deformation (Batarseh et al., 2003). Thus, several logistics and safety concerns can be reduced such as transportation, storage, and deployment. In the field job, the source of laser has to be mounted on a coil tubing unit. The laser can be transmitted downhole through optical fibers to the bottom hole assembly (oBHA). The optical bottom hole assembly is composed of electronic, optical, and mechanical parts for controlling the beam and generate the desired perforation job. Tripping will be avoided because the tool is controlled and driven from the surface. Once the laser tool is inside the well, multiple jobs can be conducted in the same location or along the well in series.

Laser technology gives the opportunity to develop and create smart systems for perforation. This is available in laser manufacturing where advanced materials are used in laser tools which lead unique performance and capabilities. The tools of laser perforation are expected to provide novel control of the perforation design such as geometry, depth, shape, phasing, orientation, and density. Therefore, laser formation interaction can be easily analyzed and modeled for a wide range of settings in-situ or in a lab. Sensing and real time adaption are needed in laser perforation tools because the parameters of perforation vary with rock type and environment properties. The combining of these systems, a tool can operate in any subsurface condition and adapt for every formation (Batarseh et al., 2017b; Batarseh et al., 2019c).

The laboratory is very important to optimize the processes. Therefore, the interaction between the laser and rock are analyzed using various parameters, sensors, and rock types. For instance, in one test, the laser was planned to generate thousands of shots with various parameters in Berea sandstone (BG1) and Yellow limestone from a quarry (LSSY, Fig. 4.7) (Batarseh et al., 2019c).

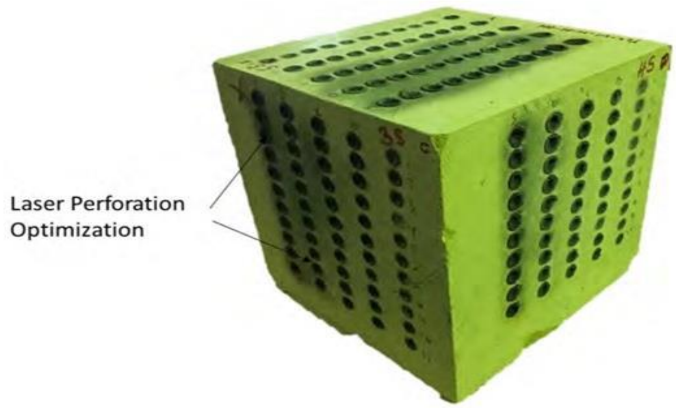


Fig. 4.7: Example of multiple perforations made on Yellow limestone (LSSY) for optimization and development.

4.5.1 Diameter

The perforation size is essential to decrease the hydraulic pressure along the perforated tunnel. So, the perforation diameter of tunnel must be optimized to reduce the friction pressure (ΔP), which is presented by Eberhard and Schlosser 1995:

$$\Delta P = 0.2369 \times \rho \left[\frac{Q}{N \times D_p^2 \times C_d}\right]^2, \quad (4.4)$$

Where: ρ is the fluid density, N is perforation numbers, Q is pump rate, Dp is the perforation diameter, and Cd is the discharge coefficient. These parameters may be changed with time. Since the fluid for fracturing is abrasive, so the perforation friction will be minimized while injection.

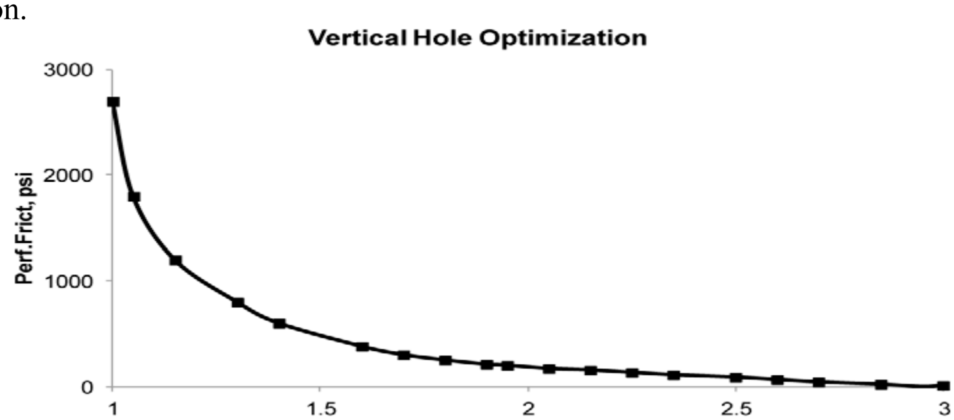


Fig. 4.8: **Friction pressure of perforation as a function of perforation diameter**

The calculated drawdown pressure across a vertical hole is indicated in Fig. 4.8 for (Q = 30 bbls/min, N = 1, ρ = 10 Ib/gal, Dp = 2 in, and Cd = 0.8). In this graph, it can be seen that the perforation diameter has to be large (D greater than 2 in) to decrease friction pressure, this is difficult to be created by conventional perforating. There are no limitations in high power laser to generate large diameter and long depth perforations (Batarseh et al., 2017b; Batarseh et al., 2018).

3.5.2 Geometry

Laser perforation allows to control and optimize the tunnel to improve production and flow. the laser perforation shape and geometry can be influenced by using diffractive, refractive, and scattering optics (Batarseh et al., 2018; Batarseh et al., 2019c).

In subsurface applications, the optical systems depend on lenses, mirrors, and prisms in order to drive the beam. Various optical systems are created for subsurface applications including optical heads to control the beam. They control the beam by using a subsurface medium. The material in the optical path influences the beam bath, which differs from the optical path elongation to absorption, scattering, and non-linear responses. Therefore, the system is able to adapt with various conditions and control the optics to attain the desired effect (Batarseh et al., 2018).

Combining the effect of optical tool and process optimizing will result in clean and long laser perforation. The optimized process in Yellow limestone is shown in Fig. 4.9 by applying CT scan. Where the laser beam is controlled to create the longest tunnel through the core sample.

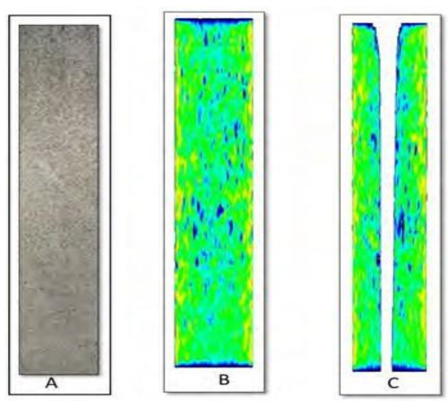


Fig. 4.9 CT Scan indicating a Yellow limestone rock before and after laser perforation. A: the rock top region, B: CT scan before perforation, C: CT scan after perforation.

The beam control also allows generating different perforation shapes cross the perforation direction. When the tool generates the perforation in the formation, the perforation may be collapsed related to the stress state of the formation, where stress around it affects its stability. For instance, if the horizontal stress (maximum) in the reservoir rock more than the tunnel strength, the laser perforation can generate a perforation shape that neutralizes the state of stresses (Batarseh et al., 2019c).

The hole shape can be controlled depending on the energy of laser beam. This can be implemented by using together different lenses. Fig. 4.10 shows the CT images for various tunnel shapes generated with different beam shapes.

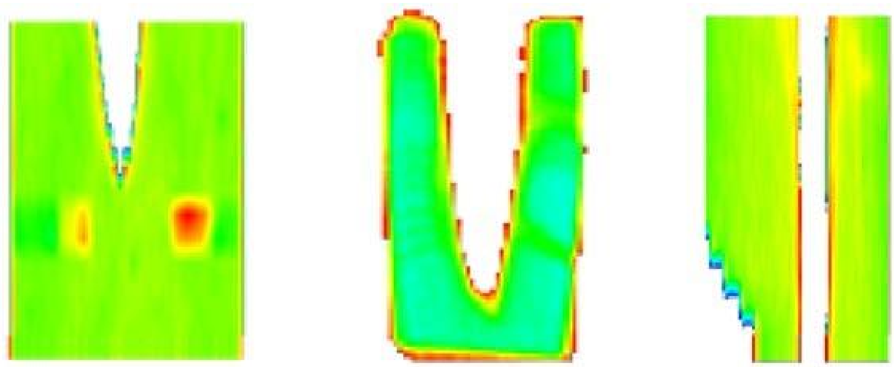


Fig. 4.10: CT scans displays various hole shapes in various rocks

The tunnel geometry influences the flow and sanding. Thus, these effects will be decreased by the controlled shape of the tunnel, bridging, and blocking of the flow will be avoided (Batarseh et al., 2018).

4.5.2 Depth

Laser perforation can be used with any rock type; unconsolidated sand, limestone, carbonate, or granite. Fig. 4.11 shows deep perforation created in an unconsolidated sand core. Different perforation lengths can be generated by the optimized process and optical package. The long tunnels are created by turning the laser for a longer time or increasing laser power, the penetration depth is demonstrated in Fig. 4.12 as a function of power and explosion time (Batarseh et al., 2019c).

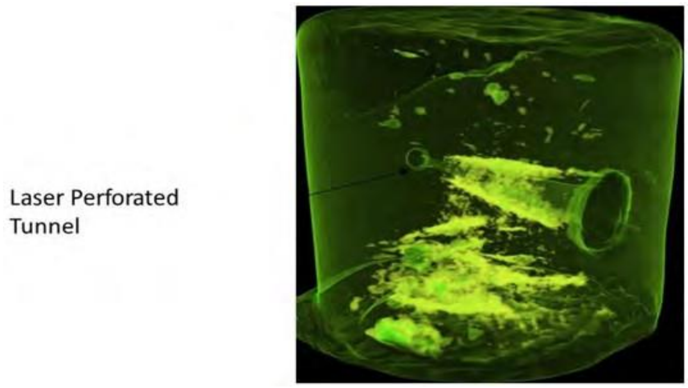


Fig. 4.11: CT-scan in unconsolidated sand laser perforation

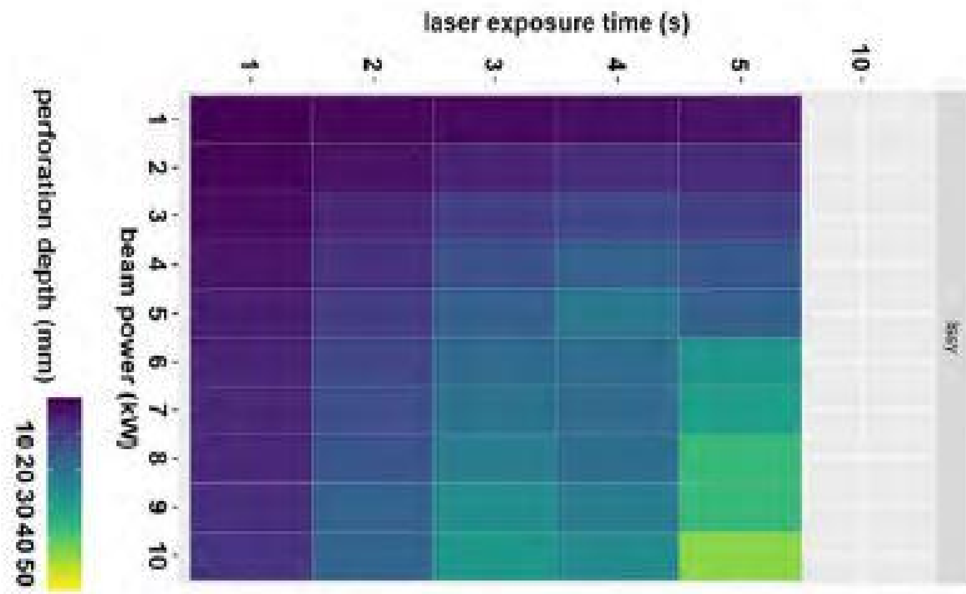


Fig. 4.12 Depth of perforation as a function of time and beam power for Yellow limestone.

To optimize laser penetration, the depth of the hole is directly related to the laser power and lasing time while keeping the diameter constant. To clean cuttings and dust, the hole must be purged, so there is no blockage in the direction of the beam which reduces transferred energy to the rock sample and lowers the penetration. An example showing the relationship between lasing time and penetration depth on the Berea sandstone block is shown in Fig. 4.13, (Batarseh et al., 2012). The image shows CT Scan of the hole with the same dimensions in the same block.

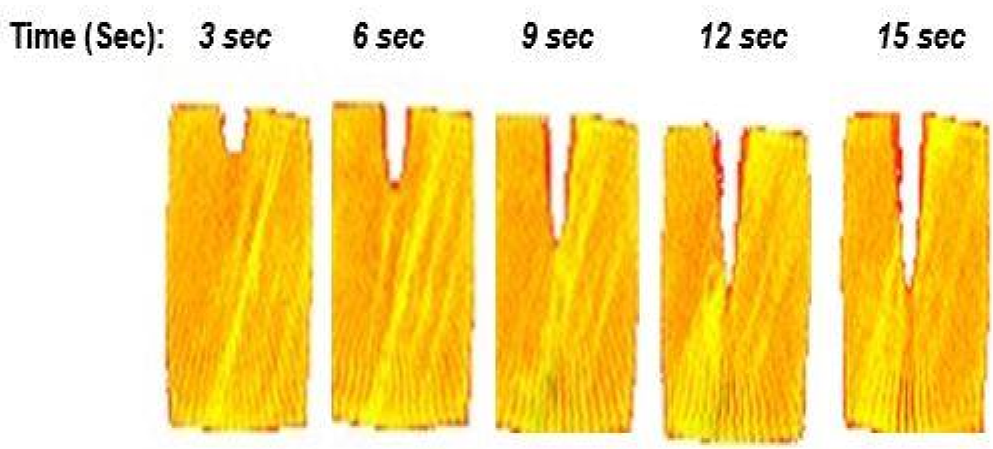


Fig. 4.13: CT Scan shows Lasing Time effect on depth of Penetration in Berea Sandstone

3.5.4 Orientation

The beam can be oriented by optical system in different directions; allowing to control the phasing and azimuth angles in desired direction. The orientation of the tunnel can allow many flow patterns into the well from a perforated zone.

The number of perforations that the laser may generate is not limited. Fig. 4.14 provides an example of dual perforated tunnels (Batarseh et al., 2019c).

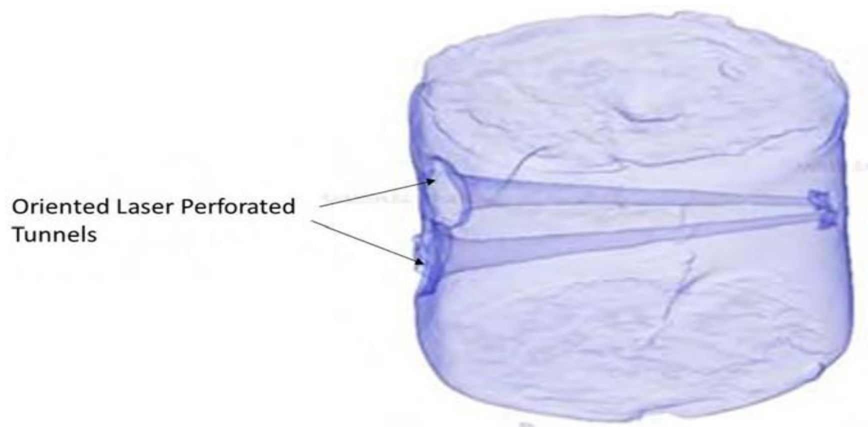


Fig. 4.14: CT-scan of the unconsolidated sand core shows multi laser perforation

4.6 High-power Laser perforation system

A laser perforation system in the field composes of three major components as shown in Fig. 4.15; surface laser and support systems, optical fiber assembly, and downhole tool.

In this system, the laser beam is generated at the surface. Then it is transmitted with a low optical loss for several kilometers below the surface, endure rough conditions, in order to reach the downhole tool. Optical bottom hole assembly (oBHA) transforms it and directs it to the rock.

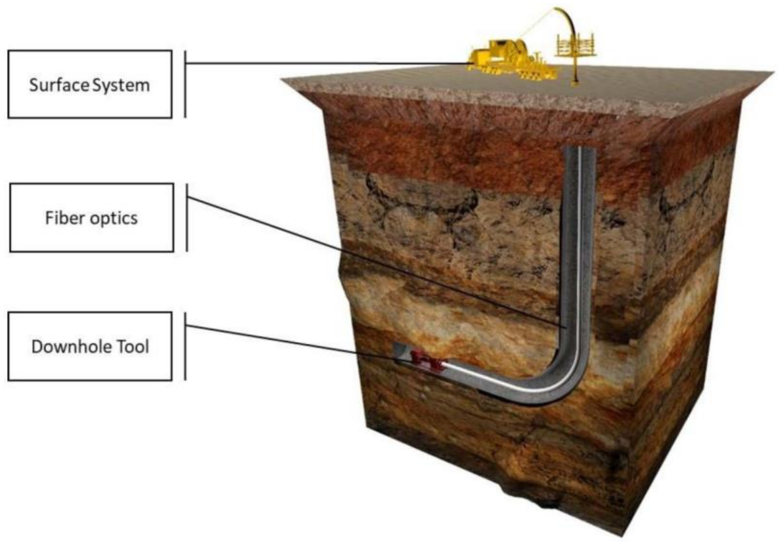


Fig. 4.15: HPL system components for field operations (Sameeh Batarseh et al., 2018)

4.6.1 Surface system

The laser and its support systems on the surface are equivalent to the system used in the research lab which include engines, chillers, fluid and gas purging devices, laser semiconductors, and solid-state lasers, laser-to-fiber couplers, power electronics, and sensing units. All the components mounted in a cabinet on a coil-tubing truck.

The main challenges in this portion of the system are to maximize processing power, enhance the efficiency of the beam, and increase the range of wavelengths. Higher production power may help to evaporate or sublimate underground matter (Batarseh et al., 2003). Nowadays up to 500 kW of laser systems may be acquired directly from various manufacturers. For commercial settings, the selection of beam efficiency and wavelengths is limited. Some of the fiber lasers currently available are multimode. Single mode lasers may prove useful in many applications, however, certain wavelengths may help to reduce fiber optic losses and improve laser-rock coupling (Batarseh et al., 2018).

4.6.2 Fiber Optics

Optical fibers will be used to transmit the beam of high-power laser many miles below the surface. The optical cable is developed to fit into a coiled tube and is designed to resist the downhole environment characteristics. The restricting factors of high-power laser beams fiber optic propagation is attenuation due to the absorption and scattering of the materials. The power vs. distance for a 10kW beam propagating in various fiber materials and designs as seen in Fig. 4.16; Silica, ZBLAN, and hollow core. Attenuation is one of the essential variables that limit the distance and power that fiber is able to transmit (Batarseh et al., 2017b).

Scattering is a physical process that identifies the scattering of waves along with several directions from their original direction related to localized defects or irregularities in the medium they transmit. There are two forms of scattering: linear or elastic, where the incident energy and the scattered beam are maintained, nonlinear or inelastic, where the energy move from the incident wave to the medium takes place.

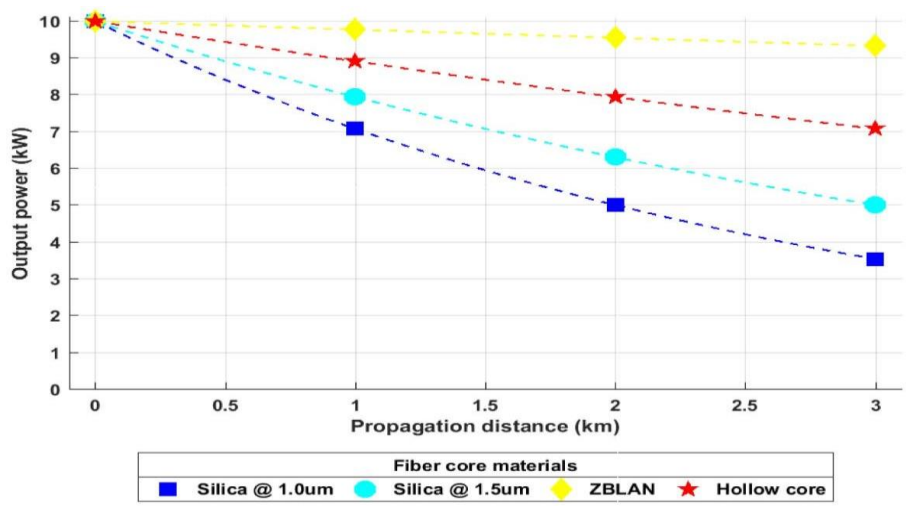


Fig. 4.16: 10kW laser beam optical loss of different fiber types as a function of distance(Batarseh et al., 2019b)

Both scattering mechanisms face a problem that can significantly intervene the light transmission across the fiber. Several approaches have been established during the last decade and today various methods are applicable to tackle them: fiber structure modifications (core zone, photonic crystal fibers, hollow core, random media, temperature gradients, and differential pressure), multi-wave mixing, chaotic amplitude modulation, and acoustic modulation.

Degradation of material is another impact that may affect fiber efficiency. This can occur due to environmental factors and defects in the material. A careful combination of materials, fabrication methods, and fiber designs is the solution for the optimized delivery of high-power lasers through fiber optics (Batarseh et al., 2017b; Batarseh et al., 2018).

4.6.3 Optical bottom hole assembly (oBHA)

The high-power laser gun configuration is displayed in Fig. 4.17. In particular, the system and its function are clearly different from traditional shaped charges gun. The Laser gun's main parts are optical assembly, rotational assembly, perf-port laser/purge, and straight-port laser/purge (Batarseh et al., 2019a).Optical assembly for subsurface operations, the majority

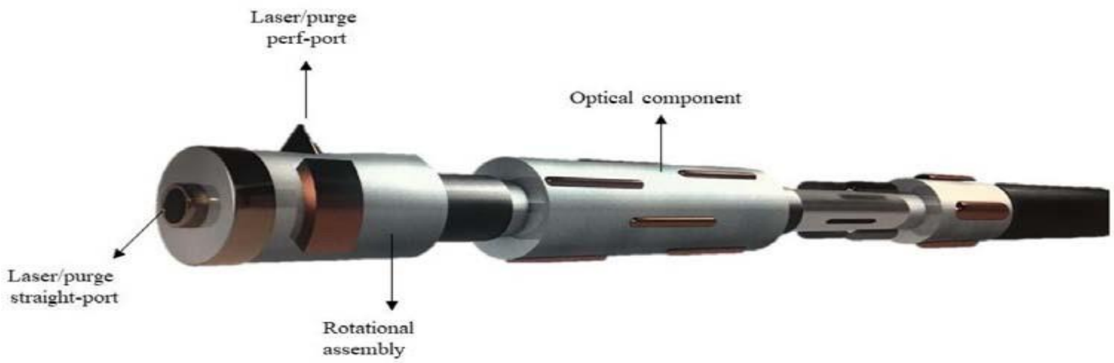


Fig. 4.17: The gun of Laser perforation two laser ports

of optical systems depend on lenses, mirrors, and prisms. The combination of these generates various optical systems for applications in the subsurface; which includes optical heads that focus, de-focus, collimate, and expand or contract the beam.

The energy distribution or ray traction and beam irradiance in different applications are shown in Fig. 4.18 - 4.19. The input beam is 30 mm with a wavelength of 1064 nm and 10 kW power (Gaussian laser beam) in all plots. It can be noticed that the determined irradiance for the output beams (light distribution) indicates the distortion influence on the provided image (visualization or work) plane due to the optical device.

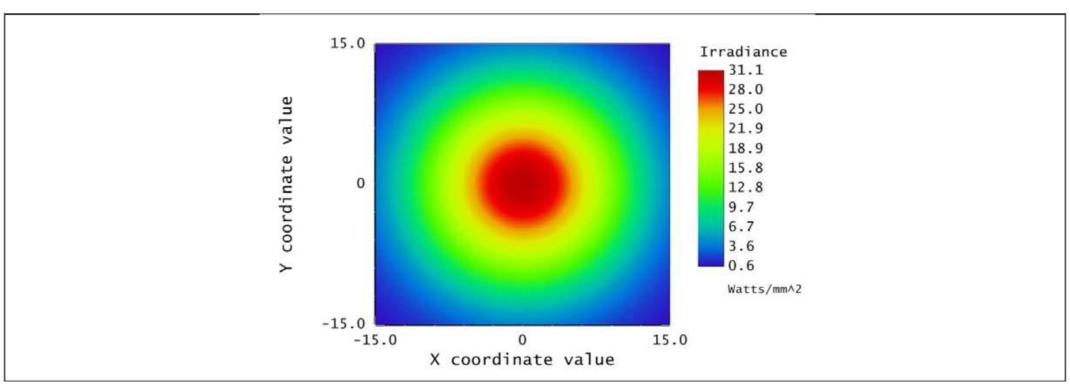
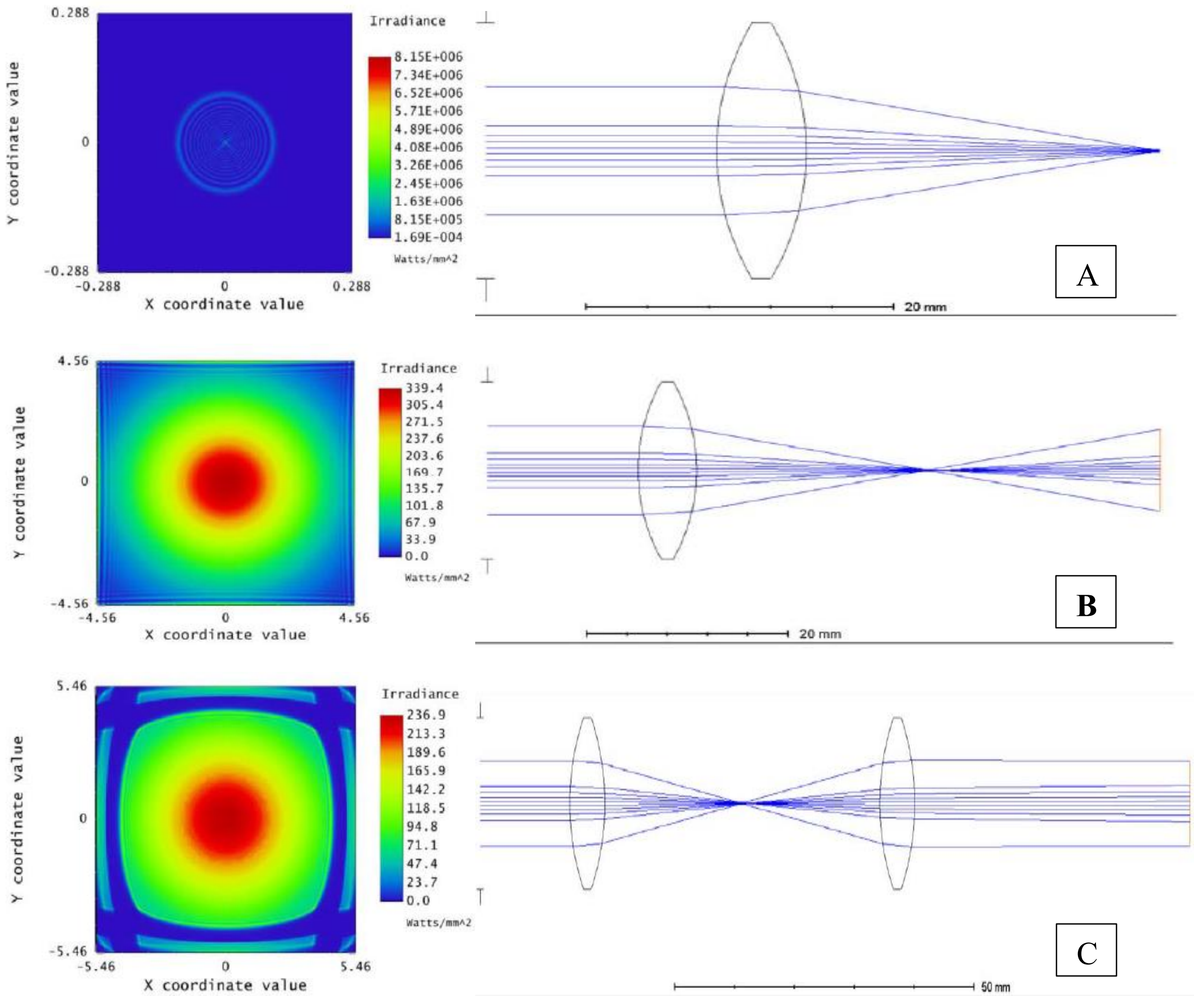


Fig. 4.18: **Gaussian beam irradiance with a beam waist of 30 mm**



Output beam irradiance **Ray pattern**

Fig. 4.19: Light focusing (A), after focusing (B) and collimation (C) using a bi-convex lens (adopted from batarseh 2019a)

4.6.3.1 Rotational assembly

When the beam departs the optical component, the controlled beam (size and shape) enters the rotational assembly. This component has the function of controlling and orienting the beam towards the target through the formation (through casing and cement). Fig. 4.20 indicates the tool's cross sectional with the beam exit in a straight direction for drilling. It contains a mirror that moves backward and forward to enable or deactivate the output; it helps the beam to pass through the port as straight while the mirror is in a flat position.

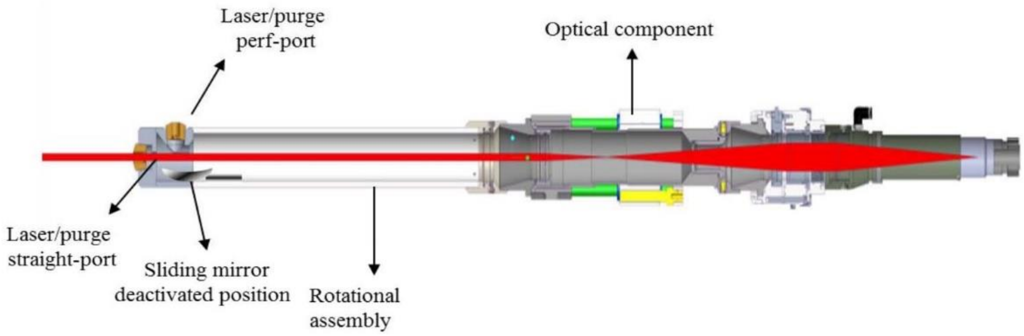


Fig. 4.20 Showing straight beam orientation mode in Laser perforation gun

The mirror is activated in the perforation mode and orienting the beam at an angle that exits through the port of perforation as shown in Fig. 4.21.

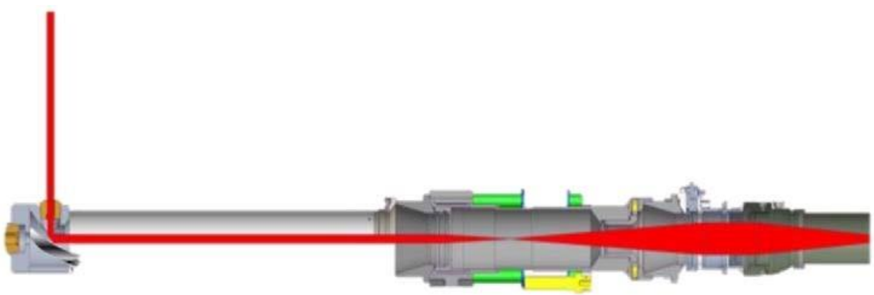


Fig. 4.21 Showing Angle beam orientation mode in Laser perforation gun

The beam's excitation is achieved by beam switching on and off as required, which means there are no need for load and unload as in the case of shaped charges to achieve shot density, the tool moves to the planned target location, perforates, moves up or down and rotates to perforate again. In another design, to achieve several shots per foot the tool splits the beam into many beams at the same time (Batarseh et al., 2019a).

4.6.3.2 Purge

The purge performs various tasks within the system. This removes cuttings, clears the path of the beam, and the assemblies cool down. The purge fluid may be liquid or gas and should have appropriate viscosity to carry the debris from the hole. It also should be transparent to electromagnetic radiation around the wavelength of the beam.

Purge has the function of cooling and lubrication where it cools down the optical assembly which is heated up by the optics during the high-power laser absorption. Thermal management is important in maintaining optics integrity and in preventing variation in optical properties caused by heating.

It clears the laser path; the purge design is critical to maintaining flow for removing the debris and particles away to guarantee a clear path and maximum interaction. Coaxial is the most effective purge, i.e. when the fluid flows in the beam direction.

It helps in the control of formation phase, where the purging often control the rock phase, for instance, when fracturing is needed to be initiated in the formation, the cooler gas or fluid may be used to generate thermal shock and fractures are formed (Batarseh et al., 2018)

4.7 Flow improvement

The laser gun creates communications between the cased hole and the formation in all the rock types, laser created clean and non-damaged hole. The benefit of laser perforation is accurate control of the depth, shape, and quality of the perforation tunnel. Also, the formation is not compacted or crushed.

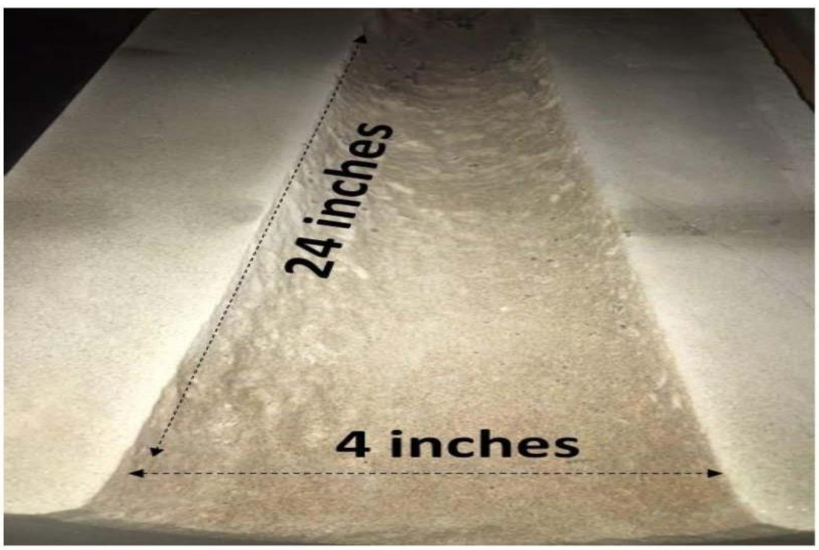


Fig. 4.22: Clean large hole created by Laser perforation

The technology created not only a controlled hole but also increased tunnels with higher permeability and extended to the surrounding matrix. Aside from improving permeability, the advantage of using the laser in perforation is that a large perforated tunnel with a diameter of 4 inches and a depth of 24 inches can be obtained as shown in Fig. 4.22. These tunnel dimensions reduce the friction of the hydraulic fracturing fluid across the tunnel (Batarsehet al., 2019).

Table 4.2 demonstrates the characterizations before and after perforation for the permeability and porosity of different rocks. In all cases, the experimental results show that rock properties can be improved by laser, even tight formations. These depend on rock conductivity where the sandstone has high thermal conductivity. The increment in porosity was 50% in Berea sandstone and in shaly sandstone was about 150%. The increase in permeability was the greatest in Berea sandstone with about 170 % and the increase was less in case of limestone (33%).

Table 4.2: Permeability and Porosity increasing in measurements before and after Laser (Batarseh et al., 2017b)

Sample	Permeability increase %	Porosity Increase %
Berea Yellow	2	57
Berea Gray	22	50
Reservoir Tight Sandstone	171	150
Limestone	33	15
Shale 1	28	700
Shale 2	11	250

4.7.1 Permeability improvement

The increase in permeability due to heat are reported in the laser perforation method, when the high-power laser generated the hole, the heat produced by the laser propagated into the matrix of the rock causes collapse to the clay, creation of micro-cracks and mineral dissociation. The improvement took place in the perforated hole and in the rock matrix around the hole.

Bajcsi et al. in 2015 performed permeability tests on core samples taken from geothermal wells in Hungary using radial infiltration, the samples were mostly siltstone and sandstone. The samples were firstly drilled with traditional drilling for (8-10mm hole size), the permeability of samples measured by air, hydrocarbon and water. The sample then treated by high power laser (1.5 kw power of laser beam) to get the required hole size. Also, the permeability of samples is measured again by air, hydrocarbon, and water.

Permeability was measured in several hundred of samples. The original samples taken from the sandstone reservoir from the lowest permeability sections were measured within a range of

0.01–200 mD. Surprisingly enough, the average permeability of the samples increased by a factor of 1.5 to 4 after laser treatment (Figure 4.23). In some situations, discrete fractures can be noticed in radial directions although there were a few samples where only invisible micro-fissures were formed by the laser treatment. The increased permeability was due to the fractures and matrix; this was therefore considered induced permeability (Bajcsi et al., 2015).

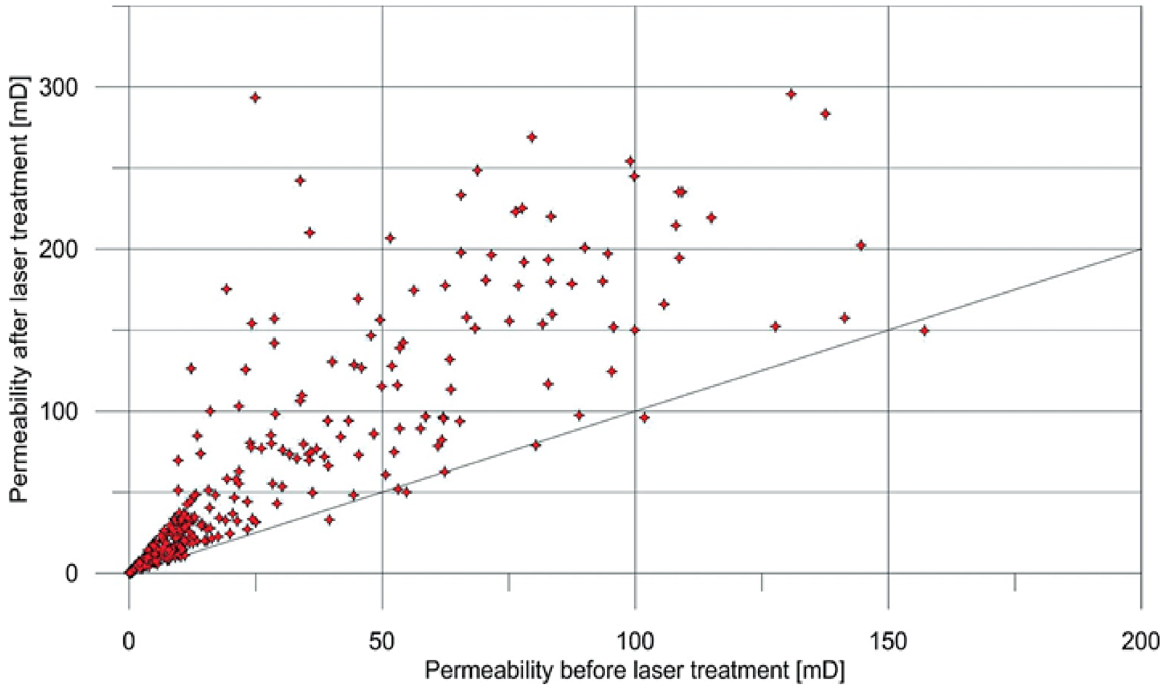


Fig. 4.23: Increases of Induced permeability as a result of heat shock fracturing due to drilling by laser

4.7.2 Calculation about flow efficiency

In 2015, Péter Bajcsi et al. computed the fluid produced from wells perforated by laser versus traditional perforating. From the investigated permeability that showed above, the permeability of lateral perforation drilled by laser is assumed to be similar to that of the original rock matrix. In calculation, they assumed the following properties:

- Perforations density = 6 spf
- Phasing = 60 degree
- Penetration depth = 1.5 ft
- Perforation diameter = 0.3 in.
- 20% permeability of crushed zone extend to depth of 0.5 in.

• Damage of drilling is 50% extend into the formation by 6 in.

• The diameter of the openhole is 6 inches.

• For the laterals, there is no crushed zone, 2 in. diameter, different lateral length, phasing = 60° and 1 lateral/2ft (0.5 spf).

• Ratio of vertical to horizontal permeability (Kv/Kh) = 0.01.

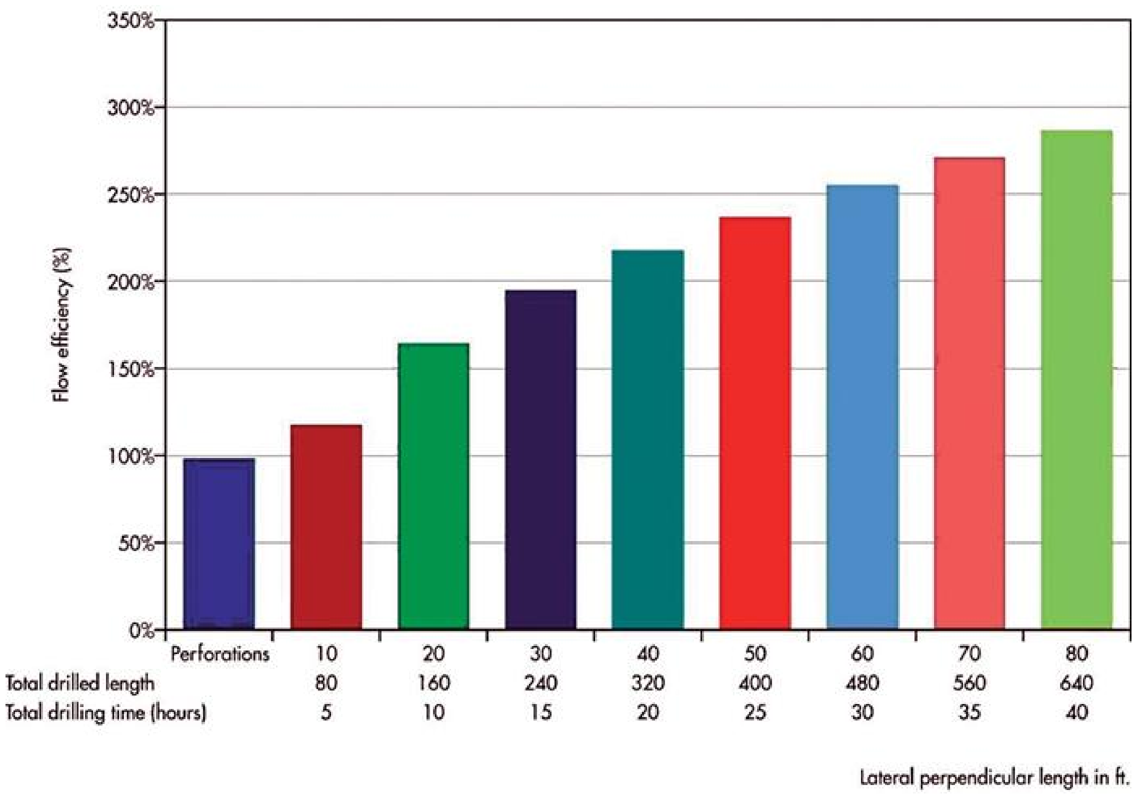


Fig. 4.24: Comparison of perforation Flow efficiency versus laser drilled laterals

Their calculations demonstrated that, compared with existing technologies, short lateral perforations drilled by laser increased the thermal wells productivity or injectivity by potentially up to 250 percent (Fig. 4.24). The increase in productivity depends on the drilled length where the productivity is directly proportional with it (Bajcsi et al., 2015).

Conclusion

1. The perforation with shaped charges is using now to perforate gas and oil wells all over the world. The perforation with this technology is associated with some drawbacks such as; generating of debris that may be left in the tunnel, crush and compact the vicinity area around the charges when they move into the formation, The method has a negative effect on permeability of near wellbore and results in mechanical damage that will inhibit fluid flow from the reservoir toward the wellbore through the perforation tunnel, and finally there are concerns about health and safety during handling the explosives.
2. Perforation with high differential underbalanced pressure may help to clean the crushed zone. But, the weakening of the rock matrix in a damaged zone is irreversible. The surge pressure required to remove debris and clean the tunnels ranges from 200 to 5000 psi depending on perforation because not all the perforations react the same way.
3. Remedial technology has been continuously developed and used, including stimulation methods, to reduce the flow restrictions effect. The damage effects can be decreased but not removed.
4. High-power laser brings advances in laser perforation technology and offers alternative methods of perforation to the shaped charge. High power lasers provide a small surface footprint, non-damaging, safe and cost-effective technology. It is an alternative to shaped charge perforation that based on explosives.
5. Laser perforation prevents the damage caused by shaped charges, eliminates debris and particles, and provides a more secure means of controlling tunnel and hole shape. The laser gun can be used to make large perforations and tunnels (exceed 2 inches in diameter and 24 inches in length), this size minimizes the pressure drop through a tunnel.
6. The laser has enough power to perforate and drill in all rock types regardless of strength and the results show that the harder the rock, the better the laser rock interaction, this is due to the higher density which results in more efficient heat transfer and hence better penetration.
7. The laser-created hole is clean with no compaction. Furthermore, the rock stage can be controlled to melt, spall, or vaporize the formation. After heating or perforation, the laser modifies the rock structure. The net result is a rock transformation that improve its

permeability and porosity and then improve flow efficiency. The purging of high pressure is essential for the process. The fluid purging aids to clear the laser path and remove debris.

8. Laser perforation is considered as a promising technology that can change present practices. The tool is able to perform unlimited oriented shoots as the laser operates by: turning on and off a switch, eliminating the need to tripping, eliminating the load and unload the gun, misfire, handle explosives including logistics, safety, storage, and transportation as the smart laser perforation pistol released the beam downhole.
9. Finally, it must be mentioned that full new technology entry into every industry needs testing and time. It's obvious that it is faced with some issues at the first entry of any new technology. Where, problems can be solved, and new technology can be introduced by spending enough time and developing research.

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